

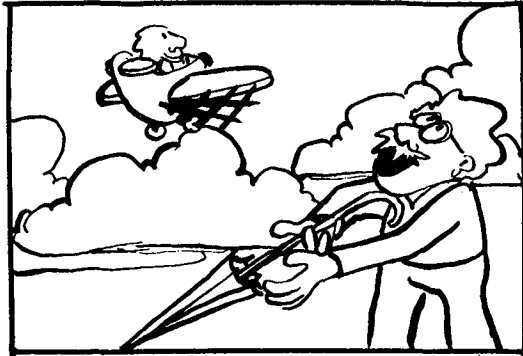
WMA



The Journal of Weather Modification
Volume 13 Number 1 *April 1981*

THE JOURNAL OF WEATHER MODIFICATION

COVER PHOTOGRAPHS



As part of our emphasis on applied programs at the international level, the Editor has chosen a sampling of subjects from several countries for presentation on the cover of Volume 13. As shown from left to right, these are:

Top row:

Dr. Vincent J. Schaefer making CN measurements on the north end of Hokkaido Island, Japan.
Burner units on the large Meteotron, Lannemezan, France.

Cloud seeding pyrotechnics burning on the aircraft racks. U.S.A.

Center row:

Israeli cloud seeding aircraft. Tel Aviv, Israel.

Bruno Federer and rocket launch on Grosversuch IV Program. Switzerland.

M. T. Abshaev and large weather modification radar system. Nalchik, Soviet Union.

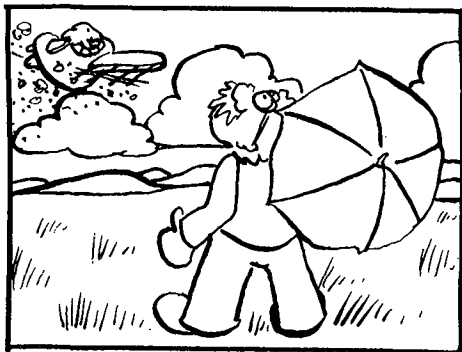
Bottom row:

Cloud seeding aircraft at end of day. U.S.A.

Radar system on operational program.

Vallenar, Chile

Airborne silver iodide generator. Canberra, Australia.



Atmospherics Incorporated photographs
by: Thomas J. Henderson

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EDITOR'S NOTE

It has been 34 years since Dr. Vincent Schaefer placed a few pieces of dry ice in a cold box at the General Electric Research Laboratory in Schenectady, New York and watched the formation of a miniature snowstorm. This serendipitous event, noteworthy because of Vince's keen ability to recognize the importance of the ice crystal production, was the single most important event which has stimulated so many people along the path of cloud physics research and weather modification operations.

More than 30 countries are now involved in some aspect of operational programs. For this reason, the Editorial Board thought it was appropriate to focus attention on the applied aspects of weather modification technology. The papers in Volume 13 are largely of this nature.

But this volume of our professional journal contains much more than a collection of representative applied program summaries. In 1978 the "Early History of Cloud Seeding" was published through the joint efforts of the New Mexico Institute of Mining and Technology at Socorro, the State University of New York at Albany, and the General Electric Company at Schenectady. This historic document has "set the record straight" on the work accomplished during the 1946-1952 period under Project Cirrus. Because so many books and magazine articles are at strong variance with historic facts, the WMA felt it important to publish this report as a lead paper in Volume 13. In the interest of space requirements, the index has been omitted. However, the full publication is available at nominal charge from Project Cirrus Fund, (ES-328), SUNY, 1400 Washington Avenue, Albany, NY, 12222.

Of singular importance are the comments presented by Dr. Bernard Vonnegut in regards the ice nucleation role of solid carbon dioxide. Several conflicting views have found their way into the scientific literature during the past several years and we are grateful to Dr. Vonnegut for his clarification of this very basic and important phenomenon. A reply to Dr. Vonnegut from Dr. B. J. Mason has been included as a sample of the comments received in response to queries on this matter.

The 30th Anniversary Meeting of the WMA was appropriately held in Albany, New York in October 1980. The theme was rightly titled, "The Langmuir Connection". It was an unusual opportunity to meet with, and be hosted by, the ASRC group under Dr. Volker Mohnen. Of particular importance was the opportunity to share the thoughts of such historic and very active individuals as Dr. Vincent Schaefer, Dr. Bernard Vonnegut, Mr. Raymond Falconer and Dr. Duncan Blanchard. The comments from these four persons, presented as a preface to the meeting in Albany, were so filled with substantial background information we've also included their remarks in this volume.

The tone of Volume 13 continues to be one of expanding interest in applied programs at the international level. Nine of the total papers are from authors outside the United States. It is gratifying to accept these summaries by our colleagues in Canada, China, Bulgaria, India, Israel, Mexico, the Soviet Union and Yugoslavia. We hope this international flavor will continue to be a strong part of future volumes of the Journal of Weather Modification.

Thomas J. Henderson,
Editor

- THE JOURNAL OF WEATHER MODIFICATION -
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THE SERENDIPITOUS HAPPENINGS WHICH LED TO WEATHER MODIFICATION

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State University of New York

When I attempt to establish the occurrences in my life which played a role in developing a consuming interest in the natural sciences and, in particular, the atmosphere, it becomes apparent that a very complex sequence of serendipitous events guided my path in that direction for more than sixty years!

As a youngster, three friends and I published a monthly magazine called "Archeological Research" and in its last year, "Exploration". This was an unusual undertaking for teenagers (we started it when 14 and ended at 18 years of age). During its four years of existence we met a very unusual group of older people who were intrigued with our initiative. Among these was Attorney William Campbell, Mayor of Schenectady, Dr. Willis Whitney, Director of the General Electric Research Laboratory (who later employed me), and Dr. Arthur C. Parker, State Archeologist who when I was sixteen invited me to participate in a summer's archeological reconnaissance of the Finger Lake region of central New York. It was Dr. Parker who awakened my interest in science and the atmosphere. It was during our train ride to Auburn, New York, that I first noticed fast moving cirrus clouds which I later determined was an indicator of the jet stream location.

When young, (from the time I was five or six years old) I spent the summers in the Adirondack Mountains of northeastern New York. My mother suffered from "hay fever" an allergic reaction to the pollen of ragweed. To get away from the source of airborne pollen we went to the Bakers Mills area of the Adirondacks where at that time ragweed did not grow. Our rented rooms in a small house of a mountaineer was located on the side of Eleventh Mountain. A year later my father acquired a rough cabin nearby which we have used up to the present time.

Because of its exposure to a wind gap, Eleventh Mt. frequently caused the formation of orographic clouds. These clouds impressed me to such an extent that in letters to my friends in Schenectady I designated our location as "Up where the clouds are made".

In later years I learned that Crane Mountain which dominated our southeastern view was called by the Indians a name which meant "Home of the Thunderer". During our summers in the Adirondacks I also spent time with a friend at Indian Lake about thirty miles west of our camp. There, with Art Burgey I explored the lake and nearby mountains. Upon climbing Snowy Mountain on a day when the sky was filled with fair weather cumulus I became aware of their flat bases and that these were all at the same level in the atmosphere.

During the summer of 1927 I ran a field camp

for Boy Scouts where we improved a portion of the Northville-Placid Trail in the Adirondack Wilderness. There I experienced drizzly orographic rain, fox fire, early morning fog and similar phenomena related to the atmosphere.

In 1932 with the advent of the Winter Olympics at Lake Placid I led a group of 25 outdoor enthusiasts on a winter camping trip to Lake Clear of Heart about ten miles south of the Winter Games. Since this period was the depths of the Great Depression, none of us could afford to stay in town. Thus we stayed in several open face Adirondack lean-tos made available to us by the Lake Placid Club. This was the winter with little snow so that it had to be transported to the ski jump and bob run by truck and train. We encountered deep orographic-produced snow at our camp and spent much of the week mountain climbing on skis on Mt. Marcy and McIntyre and visiting Indian Pass where the first time I noticed soft hail (grape). At the base of the 1400 ft. vertical face of Wallface Mt. I found more than three feet of this interesting precipitation type and discovered it to be the most delightful skiing snow I had ever encountered.

The following year I organized the Schenectady Wintersports Club with the help of our Mohawk Valley Hiking Club which I had formed in January 1929. The Wintersports Club rapidly grew into one of the largest clubs in the northeast. Out of this effort came the snow trains which ran to the North Creek from Schenectady and eventually New York City.

As a precursor to the snow train operation, Dr. Irving Langmuir agreed to take me in his tiny open cockpit Waco airplane to scout out suitable ski slopes close to our three available passenger railroads. Since this was my first experience in an airplane I was not properly dressed to make a lengthy reconnaissance. After scouting the Catskills, the Green Mountains and the Adirondacks, we returned to the Schenectady Airport. In this way I learned at first hand about wind chill and hypothermia. As I remember its aftermath it was several hours and much hot tea before I stopped shivering!

With the "clouds" of World War II thickening in 1940, Dr. Langmuir and I shifted our research studies at the G. E. Research Laboratory of protein monolayers⁽¹⁾, to the filtration of smoke particles⁽²⁾. At this time I discovered the way to replicate snow crystals⁽³⁾. Thus I suddenly became deeply involved in exploring the weather patterns which produced the different types of snow crystals. Shortly after I had the challenge to produce massive areas of artificial fog.

I was quite successful in developing an

effective method to make such a fog by boiling a heavy oil under ten pounds pressure which was then released into the atmosphere at sonic velocity. As this superheated oil vapor emerged from a small orifice, the high velocity vapor entrained a tremendous volume of ambient air. This quickly chilled the hot oil vapor to form a highly uniform aerosol each particle having a diameter of 0.6 microns. This fortunately is the optimum size for producing the maximum scattering of visible light. I built a tiny copper settling chamber which could be taken into the dense cloud near the generator to measure the particle size being produced. This simple device worked beautifully. I then discovered that when in such a dense smoke the sun had a distinctive color. If the generator produced droplets larger than 0.6 microns the sun's disc would appear green or blue. If the particles were smaller than the optimum size the sun had specific tints of red. We then devised a set of six color filters which could be used to determine whether or not the generator was properly adjusted. In this manner I learned a great deal about the size of particles, their optical properties and the mechanisms by which they grew, became electrified, and coagulated or evaporated⁽⁵⁾.

Our field measurements were conducted in the Scoharie Valley which served us as a giant wind tunnel, ten miles long, a mile wide and a thousand feet deep. We utilized a vertical cliff which rose 600 ft. above the flood plain. Our time lapse cameras, infra red cameras, telescopes and other instruments could be used better than in an airplane to evaluate the screening capacity and effectiveness of our fogs.

After World War II we learned that more than 50,000 of our fog generators were built and used for screening troops, ships, ports, civilians and other potential targets from aerial attack during the period before a practical radar was developed. Following these smoke studies we became involved in submarine detection using hydrophones and binaural sound. After this activity which produced a "poor man's" submarine detector for coastal defense we started a research program related to precipitation static, the phenomenon which produces radio static noise when an airplane flies through falling snow.

To study this phenomenon we arranged to go to the summit of Mt. Washington in the White Mountains of New Hampshire to utilize the facilities of the Mt. Washington Observatory. We soon found that the summit of the mountain rarely if ever encounters a storm consisting of only snow particles. Invariably the rapidly rising air caused by the orographic effect produces supercooled liquid water droplets mixed in with the snow particles so that all surface objects were rapidly coated with rime ice. Thus, the fragmentation of snow particles which causes electrification when they shatter on metal surfaces could not be studied effectively at the mountain summit. Despite this problem we learned a great deal about the supercooling of water and the measuring of cloud droplets and precipitation.

Most of our precipitation static studies were eventually conducted on the roof of our laboratory in Schenectady where I learned about the electrical properties of snow and of precipitating clouds⁽⁶⁾. One of the most interesting of these observations was the detection of what I called "ghost" clouds.

These occurred at the end of a snow storm as successive convective clouds passed over the instrumented observatory and showed a cyclic reversal in electric charge. These alternations continued for several cycles after all visible clouds had disappeared.

In 1944 we were asked to conduct a basic study of aircraft wing and propeller icing. Thus the difficulties and problems we had encountered earlier at the summit of Mt. Washington were suddenly transformed into assets. We were thus able to use our experience with the intense storms of Mt. Washington to study their physical properties. With the remarkable insight possessed by Dr. Langmuir and his enthusiastic personal participation in our work on the summit we soon devised effective techniques for measuring liquid water content, average particle size and size distribution. As an adjunct to these measurements we started monitoring atmospheric nuclei especially those which produced ice crystals. In 1948 I commenced a routine observational program of determining the concentration of ice nuclei in the atmosphere at three hour intervals. These measurements indicated⁽⁸⁾⁽⁹⁾ that the concentration of such particles varied by several orders of magnitude and that different air masses showed differing concentration patterns.

With the end of World War II financial support of our work was terminated by the military departments so that our field research activities were severely curtailed. Our basic studies supported by General Electric was confined primarily to the laboratory.

It was at this time (in early 1946) that I devoted most of my effort toward an attempt to discover a means of producing large numbers of ice nuclei under control.

Thus it was that on July 13, 1946, I made another serendipitous discovery. While attempting to make my cold chamber cold enough to continue my experiments (on a hot humid summer day) I put a large chunk of dry ice into my chamber. To my astonishment I saw a dense bluish cloud of ice crystals. Quickly removing the dry ice from the chamber, flushing it until I again could form a supercooled cloud I put in a smaller chunk only to again see the instant formation of another dense cloud of ice crystals. After several such sequences using smaller and smaller pieces of dry ice, I finally found that by scratching a small piece of dry ice with a nail, holding the dry ice a foot above the supercooled cloud I could exert a reasonable amount of control over the number of ice embryos generated as the tiny fragment of dry ice fell into the chamber.

Intensive studies and many experiments over the next few months showed conclusively that the effect of the dry ice (or anything else colder than -40°C (-40°F)) was to produce a micro-environment that caused homogeneous nucleation. I found that anything colder than the critical temperature of -40°C (sometimes called the Schaefer Point) will cause homogeneous nucleation in air supersaturated with respect to ice.

Thus considerably more than 10^{12} ice embryos

can be generated with a gram of dry ice in air supersaturated with respect to ice and colder than 0°C.

Unlike many published accounts (see Vonnegut this Journal), the freezing of cloud drops near the dry ice or the effect on other atmospheric nuclei has little relevance to the role played by dry ice, liquid nitrogen or other very cold materials as they generate fantastic concentrations of ice embryos. These relationships were worked out with a series of experiments using the Diffusion Cloud Chamber⁽¹¹⁾.

When Dr. Langmuir returned from a lecture tour on the West Coast I showed him the dry ice effect on a supercooled cloud. He became quite excited and urged me to make immediate plans to seed a supercooled cloud in the atmosphere.

I proceeded to plan for field experiments, locating a small plane, a pilot who could be ready to fly at short notice, and a source of dry ice. I built and installed a dry ice dispenser in the airplane. We then waited for suitable clouds to appear in our vicinity!

It wasn't until November 13, 1946 that we had what appeared to be a suitable cloud system. Alerting our pilot and Dr. Langmuir I obtained the dry ice, took it to the hangar, crushed the dry ice, storing the fragments in cardboard ice cream containers and put them in the Fairchild monoplane with Curtis Talbot at the controls. By the time we were airborne and reached the four mile long alto cumulus billow cloud at its altitude of 14,000 feet and a temperature of -18.5°C, we were above Mount Greylock in western Massachusetts which is 38 miles by airline east of the Schenectady Airport. I photographed the cloud as we approached it. We entered the top of the cloud as we approached it. We entered the top of the cloud with the dry ice dispenser running. After dropping about three pounds of the crushed dry ice from the plane, the dispenser froze so that I ended the seeding run by opening the window, letting the slip stream pull the remainder of the dry ice into the cloud. Emerging from the cloud we swung around so that I could photograph the dramatic transformation which had occurred in the seeded cloud. Long draperies of snow hung in the otherwise clear air below the cloud. We flew around until the cloud had nearly dissipated when I took a third picture⁽¹²⁾. We then returned to Schenectady to be greeted by a very enthusiastic Langmuir who had watched the seeding effects on the cloud that occurred shortly after Curt announced by radio that we had started our seeding run. In retrospect I now know that the initial effect that Dr. Langmuir witnessed was due to the formation of ice crystals in the super saturated air below the cloud which occurred as the larger particles fell through it and affected the air below.

Three additional successful experiments which I conducted⁽¹³⁾ led to a renewed interest of the U.S. Government in our research activities. Early in 1947 we received a research contract from the U.S. Army Signal Corps which supported a continuation of our field studies. This was soon called "Project Cirrus" following a suggestion I made to Commander Daniel Rex who had been appointed Field Director of our cooperative project.

Through an interesting coincidence, Dr. Bernard Vonnegut who was a member of our group at General Electric during this period, on November 14, 1946 discovered⁽¹⁴⁾ the remarkable effectiveness of silver iodide as a heterogeneous type nucleus for ice crystal formation. This was the day after my dry ice seeding flight over Greylock Mountain.

Following the formation of Project Cirrus we participated in a total of 272 field experiments using Air Force and Navy planes over the Mohawk Valley, the Adirondacks, southeastern Massachusetts and in New Mexico near Albuquerque and Socorro, over the Atlantic east of Florida and in Puerto Rico. During this same period Dr. Langmuir made a series of studies in Central America and Hawaii while I observed thunderstorms in northern Idaho.

None of our Project Cirrus activities could in any way be described as routine operations. Each study was based on an evaluation of previous experiments. All of them were aimed at establishing the possibilities as well as limitations of modifying supercooled clouds with dry ice, silver iodide, and warm clouds with sodium chloride and bulk water. Many interesting effects were observed, photographed and analyzed. These results were published⁽¹⁵⁾⁽¹⁶⁾ in a series of Final Reports and in scientific periodicals. The interesting story of Project Cirrus was published by General Electric and has recently been annotated by Vonnegut and Jiusto and reissued⁽¹⁷⁾.

Follow-up experiments are still underway. The Langmuir group was reassembled about fifteen years ago by my efforts to form the nucleus of the Atmospheric Sciences Research Center at the State University of New York, now directed by Dr. Volker Mohnen.

In a book I have just published⁽¹⁸⁾ in cooperation with Dr. John Day, I have summarized many of the basic experiments that were developed during our Project Cirrus activities.

The Langmuir Connection as our symposium is called is our heartfelt tribute to a very remarkable humanist and scientist. Working with Irving Langmuir, Nobel Laureate, of the General Electric Research Laboratory, "The Boss" as we all affectionately called him, was a profound experience and one that none of us will ever forget. His enthusiasm, knowledge, insight, hunches and leadership provided all of us with a model of scientific greatness. We have all profited greatly from the privilege of our association with him. Each of us has tried to perpetrate Langmuir's basic philosophy and way of life with our students. It continues to be an exciting and rewarding experience.

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THE LIGHTER SIDE OF LIFE WITH PROJECT CIRRUS

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Abstract. There is little science in this article about Project Cirrus. I intended it that way. The scientific findings of the project are summarized in the Early History of Cloud Seeding and in numerous papers in the technical literature. But little has been written about the scientists who made the project possible, and their day-to-day activities. That's too bad, for part of the excitement of science is knowing about the people who do the science, and the things that happen to them in the laboratory. And a lot of these things are funny! Too many scientists forget that fun is a part of science. The Project Cirrus scientists did not. Here then is a brief account of some of the lighter moments I experienced with the scientists of Project Cirrus. Any history of the project is incomplete without it.

It was a cold, clear night in February of 1948. Our cross-country skis moved easily through the snow in the park in Schenectady, New York. Bob Smith-Johannsen and I were training hard for a cross-country race. Bob was an expert at the sport. I wasn't, but knew I could learn rapidly. I had competed during my navy days and at college in perhaps 100 foot races at distances from a half mile to over six miles, and had done a lot of downhill skiing. Why not combine those skills and compete in cross-country skiing? A month earlier, I asked people at the General Electric Company in Schenectady, where I worked, if anyone there competed in cross-country skiing. They told me about Bob. I hunted him up, and soon we not only were training in the park in the evening but often rushed from our work at noon hours to a ski jump we had built. We had time for a quick jump or two before returning to work.

I arrived in Schenectady the previous summer, freshly graduated from Tufts College with an undergraduate degree in general engineering. GE hired me on their Physics Test Program, an arrangement in which you'd spend about three months on each of several jobs in various sections of the plant. Then you and the company would look eyeball to eyeball and decide which job was to become permanent.

I was approaching the end of my second assignment in the company, and hadn't the slightest idea where I wanted to go next. I had a vague notion I wanted to become a scientist but no idea whether I wanted to count electrons in atoms or stars in the sky. My indecision ended abruptly one noon hour as Bob and I were rushing back to the company after a quick workout on the jump. He knew I was looking for a new assignment, and said, "Look, Dunc, we waste a lot of time when I drive to the tube division to pick you up at noon hour. Why don't you take your next assignment with us on Project Cirrus? We could leave the lab together and have more time on the jump." What Bob told me about Project Cirrus sounded exciting, but exciting or not, I agreed that my working there would give us more time on the jump!

The exploits of the Project Cirrus scientists were not completely unknown to me, for the newspapers during the previous year had carried many stories on their work. I was soon to learn that three momentous events on successive days in

November of 1946 led to the establishment of Project Cirrus. These days have become landmarks in the history of cloud physics. On the 13th Vincent Schaefer carried out the first dry-ice seeding of a natural cloud. On the 14th Bernard Vonnegut, with a laboratory cold box, discovered that silver iodide was an effective seeding agent, and on the 15th a paper by Schaefer on his cold box experiment with dry-ice seeding appeared in the magazine Science.

I visited Project Cirrus a few days after my talk with Bob. The research group was small, consisting only of Irving Langmuir, Vincent Schaefer, Bernard Vonnegut, Raymond Falconer, Robert Smith-Johannsen, and Katherine Blodgett. They were all jammed into three or four small rooms in one corner of the GE Research Laboratory. Some of the lab benches had experiments upon experiments that must have stretched far back in time. They reminded me of the layers of material in an archeological dig. Next to Katie's desk in one corner of the main lab a pile of Science magazines rose precariously from the floor to over six feet up. I wondered what might happen if the pile ever fell over, and imagined an alliteration-minded copy editor coining headlines in the local newspaper—"Serious Scientist Suffocated by Science Serials."

Vince Schaefer, a big man with an equally big smile and laugh, listened to my request for an assignment on Project Cirrus. He asked about my interest in atmospheric physics. Not quite knowing what the subject was all about, I told him I found it very exciting. I was hired for a three-month assignment. To this day I doubt that my formal background in academic work had anything to do with Vince's decision to take me on Project Cirrus. Both Vince and Irving Langmuir liked the out-of-doors and liked skiing. While engaged in these activities, they had made the crucial observations that led to Project Cirrus. A real interest in the out-of-doors and in natural phenomena was almost a prerequisite for work on Project Cirrus. Vince knew from Bob I had it, thus I was hired. If I hadn't such an intense interest in skiing, I would not have begun my research career with Project Cirrus.

These curious chance accidents that work to one's advantage, and which are often called blind luck, are really examples of serendipity. At that

time, I had never heard of the word, but before the year was out found that serendipity⁺ was the guiding principle behind many of the discoveries made in Project Cirrus, and indeed in all of science. Irving Langmuir defined it as "the art of profiting from unexpected occurrences."

* * *

On the day I reported to work on Project Cirrus, the first of many stereotypes I had about science was destroyed. My college and navy experience had led me to believe that established scientists treated young scientists-to-be much as a foreman in a factory treats an apprentice, by barking out orders on what was to be done, and by giving exact instructions on how to do it. I expected such treatment from Irving Langmuir when I went to his office to get my research assignment. I knew, of course, that he was a Nobel Prize winner in chemistry and one of the world's great scientists. As for me, I had never worked on a research problem of my own and had never written a paper.

Langmuir, a small man with intense penetrating eyes, began talking immediately. He didn't ask about any of my college work, or what level of research I felt I could handle, or even what kind of research I wanted to do. He started to talk about the formation of raindrops, and before long had sketched out his ideas on the formation of rain by chain reaction. There was excitement in his voice as he discussed some of the problems, and I could sense he was treating me not as that factory apprentice but as a person whom he felt could get equally as excited in the problem. Soon he began to talk about the maximum size of a raindrop before breakup, and told me that the only work done on that was by a German scientist, Phillip Lenard, in 1904. Lenard, Langmuir said, had built a vertical wind tunnel to suspend water drops in free fall, but had not been able to suspend his drops for more than a second or two. Langmuir suggested I take on the job of designing and building such a tunnel. Were I to succeed in suspending water drops in a vertical wind tunnel for an indefinite period of time, I would be able to take pictures of drops in free fall, during collision, and learn all sorts of things about the dynamics of large raindrops.

I left Langmuir's office excited about the challenge of the research problem he had given me. But I had little idea how to go about starting, for Langmuir had left that entirely up to me. All he had given me was a copy of Lenard's 1904 paper, Über Regen, which had been published in Meteorologische Zeitschrift. He suggested I read it. I had run into my first stumbling block on Project Cirrus, for the only German I knew was Heil Hitler!

That afternoon my second science stereotype fell. Vince Schaefer took me across the hall to meet Bernard Vonnegut, whose lab I was to share for the next three months. Now, up until that precise moment my conception of a scientist was a

+I discussed the role of serendipity in Vincent Schaefer's discovery of dry-ice seeding in an article "Science, Success, and Serendipity," published in Weatherwise, 32, 236, 1979.

serious-looking person in a starched, white lab coat muttering incomprehensible equations, and I was certain his lab would be squeaky clean with numerous exotic instruments neatly arranged on benches and shelves. That, I say, was my conception. What I saw that afternoon was an old room, somewhat dark and dingy, in complete disarray with bits and pieces of wire, old test tubes, rubber tubing, and parts of silver iodide generators covering most of the bench space and dribbling off onto the floor. But let's hear what Bernie's brother Kurt has to say about this lab. He described it in the prologue to his novel, Slapstick.

"Bernard worked for the General Electric Research Laboratory in Schenectady, New York, for a while, where he discovered that silver iodide could precipitate certain sorts of clouds as snow or rain. His laboratory was a sensational mess, however, where a clumsy stranger could die in a thousand different ways, depending on where he stumbled.

"The company had a safety officer who nearly swooned when he saw this jungle of deadfalls and snares and hair-trigger booby traps. He bawled out my brother.

"My brother said this to him, tapping his own forehead with his fingertips: 'If you think this laboratory is bad, you should see what it's like in here.'"

I worked and had a desk in a corner of Bernie's lab, and there I built my vertical wind tunnel. And guess what? Before long the mess around my corner of the lab became the equal of Bernie's. And that took some doing! I soon realized that a "messy" lab, far from being a sign of confusion and complacency, more often was a sign of creative activity, a can-do attitude, and the result of repeated experiments, each building upon the failure of the preceding ones. In short, controlled sloppiness, not squeaky cleanliness, is the hallmark of a productive lab. I learned this lesson from Bernie Vonnegut and have never forgotten it.

I quickly mastered the art of controlled sloppiness or, as some call it, the "quick-and-dirty" experiment, and thus was able within a month to run through a dozen or more working models of a vertical wind tunnel. I changed a bit here, a bit there, and in each model was able to smooth the turbulence more than in the one before, and to produce the proper horizontal velocity profile. Finally, I had a tunnel in which I could suspend a large water drop far longer than could Lenard. Aesthetically, the tunnel was not pretty to look at. Parts of it were made of wood, and other parts of heavy construction paper, bits of plastic, and metal screening. Since the top, about 5 feet above the floor, was wobbly, I secured it with several pieces of string that ran from the top of the tunnel to various supports around the room. This was controlled sloppiness at its best!

Though I marveled at how Bernie and Vince used this art to progress quickly in the development of an experiment, I was not yet completely at home with it. Maybe they were just lucky. Perhaps other scientists didn't use it. But one day a

visitor came through the lab. This was not at all unusual. Hardly a week went by without visitors coming to see a demonstration of dry-ice and silver-iodide seeding, and to talk to Langmuir, Schaefer, and Vonnegut. What was unusual was that the visitor was Charles F. "Boss" Kettering, Chief of Research for General Motors, and perhaps the best-known engineer in America. After a demonstration of the cold-box experiment, Vince brought Kettering and his entourage to see a demonstration of the floating of a water drop in the vertical wind tunnel. I began by apologizing for the way the tunnel looked. Kettering broke in immediately and said, "Look, my boy. Don't ever apologize for the way an experiment looks. It's the results that count. I wish more experiments looked like yours." I was elated! Vince and Bernie were right, after all. Controlled sloppiness is a fact of life in science. That, and what Vince was to say in the years to come, "the will to do," is far more important in scientific discovery than concern for appearances.

* * *

Project Cirrus progressed rapidly. New ideas were tossed back and forth among the members of the Research Group, resulting in different approaches to cloud seeding and a variety of new instruments to be used in the field. These were tested from the aircraft of the Operations Group. Feedback between the two groups went well, and often those of us from the lab went along on the seeding missions.

The discoveries, both in the lab and the field, received a lot of publicity. News releases went out frequently from the General Electric News Bureau, to form the basis for stories written by the wire services and national magazines. We had no control over these stories. Some so angered other scientists, a few in the Weather Bureau, that they were ready to come to Schenectady to do battle with Irving Langmuir in the good, old-fashioned way with no holds barred, the winner taking two falls out of three.

Sometimes the stories in the magazines were hilarious, giving us our laugh for the day. It seldom did any good to try to correct them. You always lost. Listen to what happened when I tried to straighten out Newsweek magazine on a story they did on the water drops I photographed in my vertical wind tunnel. But first, some background on drop photography. When I took the first photographs, I was chagrined to find that most of the light used for illumination passed completely through the drop; about all that was photographed were one or two highlights where light was reflected directly back into the camera. I didn't know how to get around this until Vince suggested a solution. He told me to add both a pinch of silver nitrate and sodium chloride to my water. They would react to produce silver chloride, a milky-white, colloidal suspension that would reflect light back from all over the drop, and thus make photography easy. I tried it. It worked beautifully! All the stroboscopic photos taken from then on were of water drops treated in this way.

Some of these photos appeared in Newsweek with a story that said our photographs proved that large raindrops are not really tear-shaped in free

fall, as most everyone believed, but very flat on the bottom and looked like hamburger buns.

Readers responded to this story, and some of their letters were published. One said he wasn't fooled by those pictures. They weren't water, as claimed in the story, but drops of milk. Newsweek printed a reply. They said they checked with the General Electric Company and found that the drops were indeed water but looked like milk because of a special screen. How this "screen" had drifted into the story we had no idea. Anyway, I wrote to the editors of Newsweek and told them it was really silver chloride that made the drops white. An editor wrote back, saying in part...

"Thank you for your recent comments about the photographing of water drops which appeared in the Letters section of our May 30 issue.

"We checked with GE and were told that the original drops were indeed water, photographed by a high-speed stroboscopic camera which flooded each droplet with a large amount of light. In reproduction it was necessary to use a screen to hold the white in the picture of the drop, thus accounting for the milky white appearance. With all these facts, I have no doubt you are acquainted."

As I said, you can't win!

One reader wrote directly to me. He was Vice President for Research of a large company that manufactured motor oil. On the front of each can of oil was a large tear-shaped oil drop. Very pretty, and nicely colored too. He said that the water drops in free fall may look like hamburger buns but large oil drops, with their higher viscosity, would be tear-shaped.

I bought a quart of his motor oil and put a drop in the airstream of my wind tunnel. It floated there beautifully, but it wasn't tear-shaped. It wasn't even hamburger-shaped. It was pancake-shaped, very flat and very unbecoming. I took a picture of this and sent it to the vice president. I didn't hear much from him after this. The company continued to use the tear-shaped oil drop on their cans for years to come. I didn't blame them for not using the true shape of a falling oil drop. Had they done so, they'd also have to print a little sign, "True shape of a falling drop of oil," along with an arrow pointing to the pancake. And who would believe that?

Not only did we have fun reading what others wrote about our work, but we had fun within Project Cirrus. Science is too serious to be taken seriously, and we could see humor in many of the things we did. I remember one day when Vince brought a large group of visitors to see a demonstration of water drops floating in the wind tunnel. I launched into my opening preamble, telling them how important it was to be able to study raindrops in free fall right before your eyes. As always, there was a look of disbelief that the experiment would work. At the proper moment, with a bit of a flourish, I picked up an eyedropper, filled it with water, inserted the open end downward into the blast of air coming from the top of the tunnel, and squeezed out a large drop of water.

Now I had done this successfully a hundred times before, and each time I'd remove the dropper to leave the drop floating freely. But on this particular day the water was torn into tiny droplets the moment it emerged from the eyedropper, and carried upward to splat on the ceiling. I had never seen such behavior before. With a weak smile I told my visitors that the velocity of the airstream must be too high, so I reduced the speed and tried it again. The same thing happened, and by now I could see the visitors getting impatient. Beads of sweat appeared on my brow as I tried a different eyedropper. It didn't work. Nothing worked. And then, looking to the back of the room, I spotted Vince with a large grin on his face, barely able to contain himself. The truth soon came out. Earlier, he had put a few drops of detergent in the beaker of water he knew I would use for the demonstration. The surface tension was so reduced that large drops simply could not remain intact in the blast of air in the tunnel. I replaced the water with tap water with its higher surface tension and the floating-drop experiment was successfully shown to the visitors. Their faith in science was restored!

* * *

The scientists of Project Cirrus, and mainly Irving Langmuir, destroyed the most engrained stereotype I had of science. I believed there was little chance to make discoveries by watching common, everyday phenomena. I reasoned that since they were so common, they had been observed by thousands of people. If there was anything to discover, some of these people would have discovered it. How wrong I was. One summer's day I was on the roof of the research lab amusing myself by dropping large drops of water over the edge of the building and watching them oscillate as they fell to the grass several stories below. Langmuir appeared. He suggested we pour water rapidly from a beaker to produce hundreds of drops. We did. A cloud of drops of many sizes appeared and fell together, some breaking up spontaneously, others breaking in a strange manner when they approached close together. All sorts of interesting breakup phenomena could be seen. Langmuir got very excited and started talking in a rapid, clipped voice. "Blanchard, do you see that? Note the oscillations on those drops! Much like what you found in the wind tunnel. And do you see how they break in the wake of the lower drop? Now I believe..." and he went on to list several hypotheses on what might be happening. In this simple observation he was able to see so much.

I learned a lot from Langmuir that day, a lot about how to observe nature. Years later, I found that his attitude about discoveries being made from simple observations was shared by another Nobel Prize winner, Albert Szent-Györgyi, who said discoveries are made by those who "...see what everybody else has seen, and think what nobody else has thought."

* * *

I left Project Cirrus in September of 1949 to start graduate school. I never returned. Three years later the project came to an end, and the scientists who had taught me so much began to go their separate ways. Today, Bob Smith-Johannsen has his own company on the west coast. Irving Langmuir died in 1957 and Katherine Blodgett in

1979. In the early 1960's Vince Schaefer started the Atmospheric Sciences Research Center, and Ray Falconer became the first member of the new center. Bernie Vonnegut, who was then working at A.D. Little, Inc., and I at the Woods Hole Oceanographic Institution, joined the ASRC in 1968. Four of us from Project Cirrus were back together again. In some ways it was still the same, but in other ways not. We still feel the exhilaration of scientific discovery, but it is unlikely that any of us will ever again be associated with such an adventure as Project Cirrus, whose discoveries ushered in the modern era of cloud seeding.

MISCONCEPTION ABOUT CLOUD SEEDING WITH DRY ICE

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In 1946 I had the good fortune to be at the General Electric Research Laboratory when Vincent Schaefer made the fundamental discovery in his cold chamber that a supercooled cloud can be seeded with dry ice. He demonstrated that very cold substances, such as dry ice or liquid air, could create enormous numbers of ice crystals in such a cloud. The concentration produced by a tiny speck of dry ice was so high and the ice crystals were so small, he recognized at once that the crystal generation was caused by a spontaneous nucleation process. In his original and subsequent publications, he provided evidence that this process takes place in the gas phase and that it does not depend on either foreign nuclei or on the droplets in the supercooled cloud (Schaefer, 1946, 1952a, 1952b).

While I am familiar with studies that support Schaefer's findings, such as Langmuir (1948) and Fukuta, et al. (1971), I am aware of no subsequent experimental or theoretical work that contradicts or sheds doubt on his results and interpretations. I was, therefore, surprised to discover that many cloud physics textbooks and articles present quite a different mechanism of dry ice seeding. These suggest that the dry ice creates ice crystals not by nucleation in the vapor phase, but by the freezing of the supercooled droplets in the cloud. The following excerpts are typical examples.

"Solid carbon dioxide is effective in converting supercooled water clouds into ice crystals because it chills the droplets in its vicinity to temperatures far below their spontaneous freezing point." (Neuberger, 1951)

"A metal rod chilled below -38°F and waived in a laboratory cloud would turn the entire cloud into snow. The rod was cold enough to force a few droplets to freeze. And once this happened, the rest of the droplets froze too." (Cook, 1957)

"When a cloud is cooled below this temperature, the water droplets apparently freeze spontaneously, regardless of the presence or absence of freezing nuclei. This is the process which is involved when clouds are seeded with frozen CO₂, dry ice." (Advisory Committee on Weather Control, 1957)

"...dry ice...caused cloud droplets to crystallize along its path." (Lehr, Burnett, and Zim, 1957)

"He (Schaefer) discerned correctly that dry ice...causes water droplets to freeze spontaneously." (Mason, 1961)

"The physical process in this case probably is the freezing of many droplets by contact with the dry ice surface." (Fleagle and Businger, 1963; revised in second edition, 1980)

"By 'seeding' the supercooled clouds with dry-ice pellets, which freeze some of the droplets on contact,..." (Harper Encyclopedia of Science, 1963)

"Each pellet momentarily cooled a path of droplets to a temperature where freezing would occur homogeneously or otherwise, as the purity of the droplets required." (Byers, 1965)

"Presumably, the temperature of part of the water drops was depressed below -40°; the drops then froze..." (Riehl, 1965)

"...dry ice introduced into the cloud may cool enough drops to their freezing point to produce crystals for later growth by the Bergeron process." (Miller and Thompson, 1970)

"...into a supercooled water cloud in the laboratory they dropped some dry ice (carbon dioxide snow). Immediately some of the water drops froze." (Longley, 1970)

"...pebble-size pieces of dry ice descend and freeze a large fraction of the droplets in their path." (Rogers, 1976)

"When dry ice was thrown into an actual cloud, it transformed the water droplets into ice crystals." (Monroe and Jackson, 1977)

"...pellets of dry ice lower the temperature of supercooled water. The lower temperature makes the water form ice crystals." (Wendland, 1978)

"...use of dry ice, which froze some of the water droplets in a cloud, was first shown to be effective in clearing supercooled cloud decks or fog banks." (Weather Modification Advisory Board, 1978)

"Schaefer quickly realized that the extremely low temperature near the surface of the dry ice pellet (-78°C) had caused the droplets along its path to freeze. We cannot say whether or not he also realized at that moment that the tremendous temporary supersaturation produced by the cooling had activated many aerosol particles as condensation nuclei, and that the droplets formed around them had also frozen." (Dennis, 1980)

Because none of the sources quoted above provides evidence or references supporting the alternate explanation for the action of dry ice, it is not possible to present the arguments in its favor. It is possible, however, to recognize some problems with this idea. For example, if the ice formation process is produced by the freezing of the drops, it is difficult to explain how dry ice produces its seeding effect even in the absence of supercooled droplets, aerosol particles, or ions.

A calculation based on its heat of vaporization shows that one gram of dry ice would be capable of cooling a volume of supercooled cloud of only about 10^4 cm^3 from -15°C to the temperature required for homogeneous nucleation of water droplets, -40°C . If the cloud contained 10^3 droplets cm^{-3} , their freezing caused by the gram of dry ice would produce only 10^7 ice crystals. Even if an additional 10^4 droplets cm^{-3} caused to form on condensation nuclei were to freeze, the resulting concentration of ice crystals would still be orders of magnitude less than the 10^{11} or more ice crystals per gram of dry ice reported in atmospheric cloud seeding experiments (Holroyd, et al., 1978). Although from time to time supercooled drops will be caused to freeze when they are subjected to the low temperature prevailing near to the dry ice, it is clear that this process is of negligible importance when compared to the spontaneous generation of ice crystals resulting from nucleation in the vapor phase.

Every opportunity should be taken to inform teachers and students of cloud physics that a mechanism to explain the seeding effect produced by dry ice that is based on the freezing of droplets in the supercooled cloud is unsupported by either theory or experiment. So long as this misconception persists, it will lead to serious misunderstandings concerning the modification of clouds by the dry ice seeding technique.

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D/DG Met O/4/4

27th January 1981

Dear Bernie,

I'm sorry to have been so long in replying to your letter - I can only plead pressure of other business which has to take precedence over cloud physics these days!

I enclose a reply to your note which I hope will help clarify the misunderstanding. I think that many authors have thought in terms of the dry ice freezing the pre-existing droplets but no one who has actually watched what happens in a cold chamber could believe that.

If you are sending your note to the Journal of Weather Modification, perhaps you would be kind enough to send my note as well.

With kind regards,

Yours sincerely,

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THE MECHANISMS OF CLOUD SEEDING WITH DRY ICE

I agree with Dr. Vonnegut that there appears to be some misunderstanding of the mechanism by which dry ice produces large numbers of ice crystals in its wake while falling through a supercooled cloud. However, he seems to have missed the point that the ice crystal production is probably preceded momentarily by large concentrations of tiny droplets formed spontaneously without the aid of condensation nuclei.

Dr. Vonnegut is correct in stating that the appearance of high concentrations of crystals in the "condensation trails" left by dry ice particles in a cloud chamber cannot be explained by the spontaneous freezing of pre-existing cloud droplets which are far too sparse. In chilling from the air from, say, -10°C to -78°C , enormous local supersaturations are created, sufficient to produce very high concentrations of droplets by spontaneous condensation (above the Wilson 8-fold limit).

These then freeze almost instantaneously as the temperature falls below -40°C . This view was confirmed by the experiments of Maybank and Mason (1959)

(1959) who showed that when a small sample of clean, filtered air was expanded explosively in a water-saturated cold chamber, ice crystals appeared in large numbers only when the supersaturation achieved by the expansion exceeded values at which condensation could occur either spontaneously or upon ions, and if the terminal temperature fell below -40°C . The crystal concentration increased as the terminal supersaturation increased, but reached a maximum of about 4×10^6 per cm^3 of the air involved in the expansion. This was taken as strong evidence that crystal formation was a two-stage process -- condensation followed by spontaneous crystallization of the tiny droplets at temperatures below -40°C . The droplet/crystal concentration was limited to about 4×10^6 cm^{-3} as a consequence of the peak supersaturation and minimum temperature being restricted by the release of latent heat and the abstraction of water vapour by the growing droplets (Mason 1951).

Of course, from the practical point of view, it matters little whether the crystals form by this two-stage process or by direct deposition from the vapour phase as Vonnegut suggests but it does not seem likely that the molecules will condense directly into the ice lattice without first going through the less ordered liquid structure.

In either case Maybank and Mason's figure of 4×10^6 cm^{-3} for the maximum production of crystals suggests a total of about 4×10^{10} crystals produced by 1g of dry ice and this is close to Holroyd's (1978) estimate quoted by Dr. Vonnegut.

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FROM MT. WASHINGTON, N.H. TO SCHENECTADY, N.Y. AND PROJECT CIRRUS

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I had the exciting experience of working on the top of Mt. Washington, N.H. (el. 6,288 ft.) from December 1942 to December 1946. During my assignment at the Mount Washington Observatory, as an employee of the U.S. Weather Bureau, I had occasion to become involved with a number of interesting experiments being carried on there by visiting scientists who made use of the extreme conditions of wind, precipitation, cold weather and persistence of clouds that is found on and around that mountain.

It was in 1943 that I first had the pleasure to meet Vincent Schaefer and Dr. Irving Langmuir. They had come to Mt. Washington from the G. E. Research Laboratory in Schenectady, N.Y. to do experiments related to Precipitation Static and the Icing of Aircraft. Rime ice formation is prominent there during 8 to 10 months of the year. Schaefer and Langmuir brought with them a number of rotating multicylinders and other sphere and trylon configurations to expose in the wind driven fog. We took many measurements of rime ice collection following short periods of collector exposure. The data compilation helped in developing Langmuir's widely referred to reports on Mathematical Investigations of Water Droplet Trajectories and Supercooled Water Droplets in Rising Currents of Cold Saturated Air.

In the late winter or early spring of 1946 I climbed with Schaefer and Langmuir from Pinkham Notch up over the Lion Head trail to the summit of Mt. Washington. As we started out I recall Langmuir saying, "Vincent, look at this completely overcast sky with only one snowflake here and one over there coming out of it." The inference was, with all that cloud and cold temperatures why wasn't there more snow coming out of the cloud? I have always felt that Schaefer's scientific curiosity was aroused by Langmuir's remark (and others). In any event, we went back to the Research Laboratory in Schenectady and during that spring and summer devised an experiment which became the famous cold box experiment. This showed that particles of dry ice introduced into a fog, produced by blowing ones breath into a deep freeze unit, could convert the fog droplets into tiny ice crystals. Schaefer and Langmuir had visions of expanding that experiment into one of dropping dry ice from an airplane into a natural supercooled cloud hoping for the possibility that the cloud would convert into ice crystals and ultimately fall out as the crystals grew at the expense of the liquid droplets.

I recall that Schaefer came back to the Mount Washington Observatory in about August of 1946, just after he had made his discovery in the cold box. He told me of the plan to fly an airplane over a supercooled cloud in the autumn as soon as temperatures were cold enough; hoping they might be able to show that water droplet clouds could be converted to ice crystals by dropping dry ice pellets into them.

On November 13, 1946 as we know, Schaefer, in a rented plane and with Langmuir observing from the airport back in Schenectady, made a flight near Mt. Greylock dropping dry ice pellets into an isolated cloud. As photos show, the cloud converted to ice crystals and snowed out.

Meanwhile I had talked with Schaefer about my leaving Mt. Washington, and he suggested that I might like to come to Schenectady to work with him at the G.E. Research Lab. I made the wise decision to do just that and consider myself most fortunate to have been working closely with Vince Schaefer ever since.

After my arrival at G.E. Dec. 4, 1946, Project Cirrus soon came into being. One of my early jobs was to help develop a suitable dispenser for dry ice pellets. I worked closely with William Kearsley. I helped to supply some of the meteorological data related to studies of the many cloud seeding experiments. Shortly after I arrived at G.E. Bernard Vonnegut joined the Cirrus Group and soon discovered the use of silver iodide as a cloud seeding agent.

In 1948 we were moved to the new Research Laboratory at the Knolls just northeast of Schenectady. There I was assigned to the penthouse of the 7th floor of the new building, and that is where I set up a weather office which I occupied until I left G.E. in May, 1957, only 3 months before Dr. Langmuir passed away.

While still at the downtown Schenectady works, I decided to try sending dry ice up on a helium filled weather balloon to see if any seeding effects could be seen. There was no noticeable effect with clouds. However, when dry ice hanging in a small net was sent up in clear air with only a few clouds around, we could sometimes see the trailing smoke from the dry ice flare into a larger cloud-like formation for a short distance then back to a line of trailing smoke. Those areas where the smoke or cloud flared up was apparently a region of supersaturation. The dry ice produced tiny crystals which grew in the region of excess water vapor into a visible cloud. In recent years Dr. Vonnegut has had a student trying to make use of this effect or at least determine how often we have such conditions in the hope that a cloud might be produced on a night when frost might be expected early or late in the growing season. If a cloud could be developed it might cut down the outgoing radiation enough to prevent the frost from killing the plants.

In 1949 and 1950 it was decided to operate a silver iodide burner at Socorro, New Mexico on certain days of the week regardless of whether there were clouds or not. The idea was to see if there were long range effects of this type of seeding that could be detected downstream from the source.

I began working over daily precipitation occurrences at many stations over the country. After a few weeks I showed Dr. Langmuir some interesting rainfall patterns that suggested there might be a periodic trend to the precipitation at about 7 day intervals. From then on he became much interested in having me maintain daily precipitation data for all major stations which were printed on the Daily Weather Map series. We divided the country into 15 regions and for 40 weeks I was given the job of working up the correlation coefficients, variance analysis and significance factors, etc. for the 15 precipitation regions. The occurrence of precipitation seemed to be on a 7-day period, but at that time, from Dec. 11, 1949 into July 1951, the precipitation was greatest on Tuesdays and least on Fridays and Saturdays as shown in Figure 1.

The periodic seeding at Socorro, New Mexico was stopped in July 1951 because of Great Floods in Kansas, the worst on record up to that time. Langmuir felt there was a chance the seeding might have contributed so he requested that seeding be discontinued.

Interestingly, I followed the precipitation at just Albany, N.Y. for a 7-day periodicity from July 24, 1955 until March 3, 1957 with the striking result shown on Figure 2. The accumulated rainfall or melted snow is shown by three month totals. An amazing periodicity shows up. Precipitation that fell on all the Saturdays and Sundays totaled around 12 inches while all the Tuesdays totaled only around 3 inches. Four times as much rain on weekends as on Tuesdays! A similar plot (noted in Figure 3) for the period following from December 9, 1956 to April 27, 1958 shows the minimum on Wednesday and Thursday with the maximum on Fridays. Rainy weekends generally make more of an impression on us than rainy Tuesdays, but it appears that weather can be quite periodic at times.

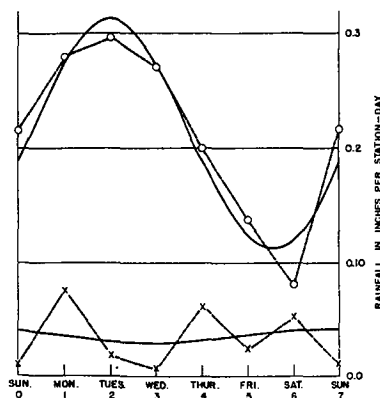


FIGURE 1. Rainfall at 20 group A Stations before and after the start of weekly seeding.

X - for 5 weeks 3 Nov. - 7 Dec. 1949
 O - for 9 weeks 8 Dec. '49 - 7 Feb. '50

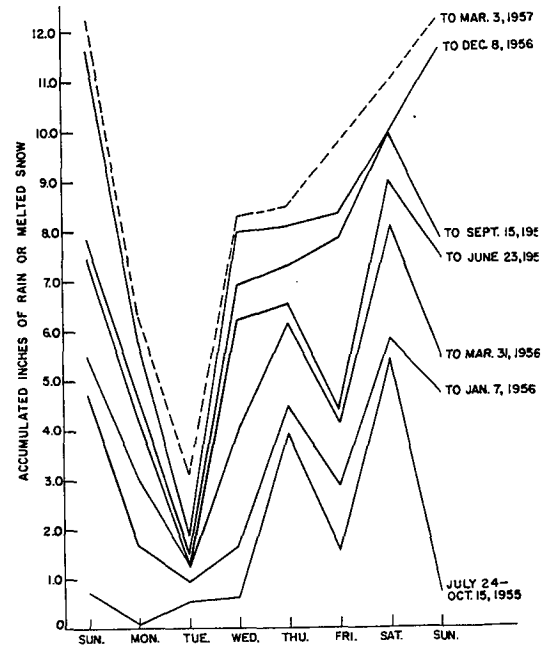


FIGURE 2. Accumulated daily precipitation at Albany Airport by day of the week and by 3-month totals. July 24, 1955 to Dec. 9, 1956.

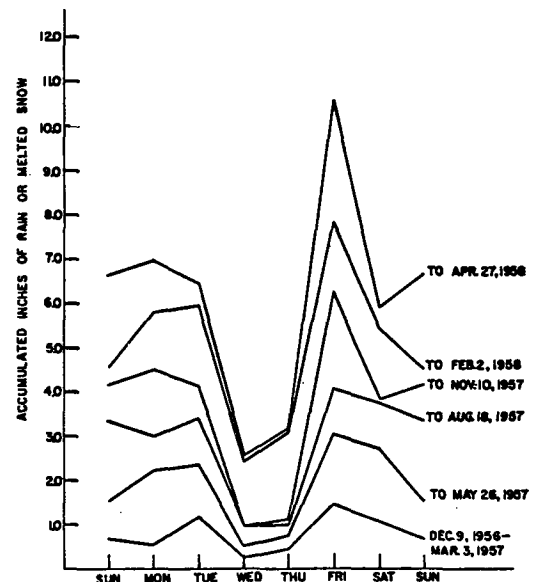


FIGURE 3. Accumulated daily precipitation at Albany Airport by day of the week and for 3 month periods, starting December 9, 1956.

EARLY HISTORY OF CLOUD SEEDING

BY

BARRINGTON S. HAVENS

WITH ITALICIZED ANNOTATIONS

BY

JAMES E. JIUSTO

AND

BERNARD VONNEGUT

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PREFACE

One of the pleasantest writing assignments of my professional General Electric career was that of preparing the history of Project Cirrus. Not only was the subject itself of great interest to me, providing as it did an opportunity to learn something about weather and meteorology, but the work involved made it possible for me to enter into an exciting atmosphere of scientific inquiry and to make the acquaintance of a number of splendid people, with some of whom I was privileged to form lasting friendships. Perhaps the greatest privilege of all was the opportunity to know and work with, however peripherally, that astonishing genius, Irving Langmuir.

Consequently, when Dr. Vonnegut asked me for my cooperation in bringing this 25-year-old history down to date, I was delighted to agree. In the course of that undertaking, I found that the subject had lost none of its fascination and the associations none of their appeal. For the reader's benefit, in order that the revisions may not interfere with the unity of the original narrative, the updating material has been inserted throughout the text in the form of italicized indented paragraphs.

As an entirely personal side light on the matter of the periodic cloud seeding in New Mexico in 1949, and 1950, I found it interesting to recall that at that time I was spending winter weekends at my camp in the foothills of the Adirondacks. I quickly became conscious there of a recurring pattern of weather behavior over a period of many weeks, with periods of clear weather and snowfall alternating with a regularity difficult to reconcile with the random behavior with which I was familiar. It was not until I was later engaged in compiling this history that I learned of some of the debate concerning this complex issue.

Finally, I feel it is necessary to point out that my role in preparing the original account was and has been strictly that of a chronicler, contributing nothing but the services of a professional writer, and taking advantage of every opportunity to rewrite or lift verbatim the original material of others where it served the purpose. After all, this is one of the necessary functions of a conscientious historian.

Barrington S. Havens

Following the discovery of cloud seeding by Vincent J. Schaefer in 1946, an extensive cloud physics research program known as Project Cirrus was carried out at the General Electric Research Laboratory under U. S. government sponsorship. When this work drew to a close in 1952,

a history of its activities was prepared in accordance with the Laboratory policy initiated several years earlier by Dr. C. G. Suits, its director. Barrington S. Havens, a member of the Public Relations Services Division, who had wide experience as a professional writer on the General Electric Monogram and the General Electric Review (no longer published), was given this assignment. He began by collecting existing material and conducting informal interviews with the various participants. From these, with the help of the staff, he was able to prepare the final version (History of Project Cirrus, Report No. RL-756, General Electric Research Laboratory) appearing here, which met with everyone's approval. This, therefore, represents as nearly an accurate account as could have been prepared.

During the period of years since Project Cirrus ended, I (B.V.) have encountered a number of books and magazine articles dealing with cloud seeding in which statements have been made about the early history that are clearly at variance with my own recollections and the facts as related in this history. When I attempted to set matters straight by communicating with the authors, I discovered that almost invariably they were unfamiliar with this accurate account. This is not surprising, for it was never made available to the general public and appeared only in a greatly abbreviated form in the General Electric Review (1952). In view of the continuing widespread activity and interest in cloud seeding, I think it is desirable that this careful history of its beginning be published and made generally available.

It seems worthwhile at the outset to emphasize important and often unrecognized facts concerning the history of cloud seeding. The initial discoveries, that clouds could be seeded with dry ice and with silver iodide, were made not on a government-sponsored research project, but were the result instead of an in-house research project in the General Electric Company Research Laboratory. It is worth stressing that the investigations that led to both discoveries were not conducted with a view of learning how to modify clouds or weather, but as basic research to learn how nature operates. Not until after the basic discoveries had been made was it recognized that they provided the foundation for techniques that could be used to modify clouds in the natural atmosphere.

I (J.J.) began to teach a course titled, "The Principles of Weather Modification". Because there was no text available, I found myself resorting to papers in the literature, technical reports and several other collected articles gathering dust in my files. In order to present a reasonably coherent picture of the evolution of the subject, an attempt was made to track weather modification concepts back to their early origins. It was surprising how often the route led to the

Project Cirrus program.

Bernard Vonnegut called to my attention a report titled, "History of Project Cirrus". When he suggested that this document might be worth publishing in the open literature, my time-consuming searches prompted me to agree. Furthermore, the feeling of excitement and discovery that accompanied that prolific period is everywhere evident in the report; that too seemed worth exposing to students and researchers.

We decided to add illustrations and to trim the report to manageable size but in no way to alter the tone or scientific content of the original manuscript. In order to link the past with the present, and to reappraise certain ideas in the light of a quarter-century of progress, the report was appropriately annotated. We hope these comments, and the epilogue will prove as durable over the coming years as most of the original Project Cirrus findings.

Bernard Vonnegut
James E. Jiusto

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PROJECT CIRRUS NUMBERED FLIGHT TESTS. 81

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I. INTRODUCTION

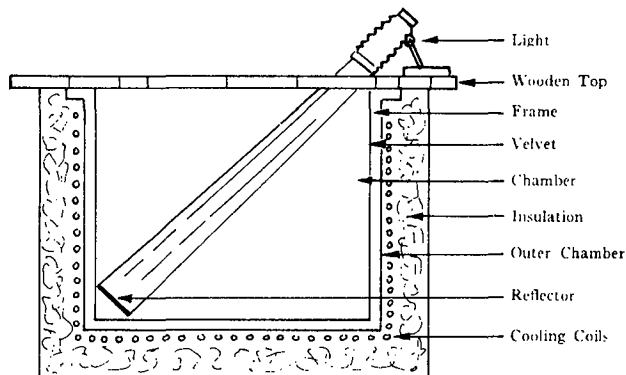
This history of Project Cirrus was prepared at the request of the General Electric Research Laboratory for three reasons. First of all, the project has been --and still is, at this writing--of such unusual interest and significance, that the telling of the story is merited for its own sake. Secondly, the termination of the project is bound to result in an eventual dispersal of the various members of its personnel.† Already Dr. Langmuir has retired from active General Electric employ, and the other members of the project are, and will be, more and more engaged in new and completely different activities. And finally, the broad aspects of the project have such wide implications that it is particularly important that the story be committed to paper "for the record".

†Although most of the various members of the Cirrus personnel did indeed disperse, it is interesting to note that Vincent Schaefer, Duncan Blanchard, Raymond Falconer, and Bernard Vonnegut are currently on the staff of the Atmospheric Sciences Research Center at the State University of New York at Albany.

It has not been easy to organize the raw material in any simple, logical fashion. As is so often the case, the project was very complex, with a number of subdivisions associated with the main activity. Some of these subdivisions ran consecutively, some operated in parallel, and others intertwined or branched off in variously divergent directions.

Where it was possible the material has been arranged in chronological or otherwise logical order. Where it was not possible, the various subordinate topics have been taken up in as nearly a logical order as possible. As a result, cases will be found where the story "gets ahead of itself," and later it becomes necessary to retrace one's steps to pick up the thread.

The history, with the exception of the Introduction and Conclusion, consists of two main parts. The first is the story of the early activities which led to the formation of Project Cirrus. The second is the story of Project Cirrus itself.



Schematic Diagram of Cold Chamber



U. S. Army, Navy, and Air Force personnel of Project Cirrus with G. E.'s Langmuir, Schaefer, and Maynard (4th, 3rd, and 1st from right standing in the rear). Various instruments used in the research can be seen installed on the nose of the B-17 airplane.

II. EARLY HISTORY

It would be difficult, if not impossible, to trace the complete lineage of everything leading up to Project Cirrus. General Electric scientists were not the only ones who studied many of the problems involved. And even when restricting consideration to General Electric research projects, the situation is complicated. The following material, however, is confined as much as possible to work that has a relatively direct bearing on Project Cirrus research.

GAS MASKS AND SMOKE FILTERS

The earliest activity leading directly to Project Cirrus was the study, beginning in 1940, of the fundamental nature of filtration in gas masks. This work was undertaken by Dr. Irving Langmuir and Dr. Vincent J. Schaefer at the request of the U. S. Chemical Warfare Service (1).

Gas masks normally use charcoal to adsorb poison gases, but even in World War I the possibility arose that the enemy might use toxic smokes which could not be adsorbed by charcoal and thus would have to be removed by a filter.

The first step in attacking the problem was to make some smokes of the type for which the filters would be used. In doing so, the scientists studied the particles which composed the smokes. They investigated such things as particle stability, concentration, and measurement. They obtained fairly successful theoretical results and a better understanding of how to build a good filter. And incidentally, they acquired a great deal of detailed knowledge of how to make a smoke which would be non-volatile and would consist of particles far smaller than those of ordinary smokes, and they learned much about their optical properties.

This work was done under a National Defense Research Committee contract. As Langmuir and Schaefer neared the end of the work, a form letter was received in August, 1941, asking if anyone could think of a way to make a white screening smoke that could be used over large areas to cut down the hazard from aerial bombardment. Langmuir and Schaefer wondered whether they couldn't do this by using the methods they had adopted for making smokes for testing filters. They decided to try.

SMOKE GENERATORS

It was found that the easiest way to make smokes and control the particle size was to take some oil and put it into a volatile condition. They heated oleic acid and similar substances up to about 200°C and passed a stream of air over

them to get the vapor mixed with air. Then they quenched the mixture suddenly by blowing in a large amount of cold air. The particles grew in size, and by sudden quenching they found they could stop the growth at any desired point and also make particles of very small size. They were surprised to find that, under certain conditions, the particles were of extraordinarily uniform size.

Further work and experimentation showed that the same thing could be done on a large scale. Larger generators were built, tests were made, and the design was adopted by the Army and used successfully on a large scale during the war (1).

Several years later this technique for producing aerosols by vaporization and subsequent quenching and condensation was applied in modified form by Vonnegut (2) in the design of various cloud seeding generators. It was thereby possible to disperse silver iodide as enormous numbers of submicron particles.

PRECIPITATION STATIC

Quite independently of this work, the Secretary of War asked in 1943 for research into the problems of precipitation static (1). It was believed that the invasion by Japan would have to come very largely from air attacks through the Aleutian Islands, across Alaska, and from the North.

The difficulty in flying aircraft in the Aleutians was very serious. One of the big problems was icing of the aircraft, but even more baffling was the complete loss of radio contact when the planes flew through snowstorms. The planes might become electrically charged, sometimes to a potential of 250,000 volts or more, producing corona discharges from all parts of the plane and causing such electrical disturbances that radio sets could not receive messages. Pilots had particular difficulty in finding their bases and getting down through foggy bad weather. What could be done about it?

Langmuir and Schaefer were interested. They had no particular ideas on the subject, except that it had to do with weather. In their opinion, the best place to investigate similar conditions was the well-equipped laboratory of the Mount Washington Observatory on top of Mount Washington in New Hampshire. Mount Washington in winter has an average temperature of minus twenty degrees C, the wind averages about 27 meters per second, and most of the time clouds sweep over the summit. It seemed to offer the proper conditions for research of this kind.

So equipment was installed at the summit, and Schaefer went there several times during the winter of 1943 to conduct experiments. But he discovered that

anything exposed there during the winter immediately became covered with ice, because the air was full of supercooled water droplets. He and Langmuir became so interested that they hoped they would not have to continue a long study of precipitation static.

AIRCRAFT ICING

It so happened that the Army Air Force was just as much interested in problems of aircraft icing as in precipitation static. This fitted in so well with the new interest of Langmuir and Schaefer that in 1944 they started a study of that project (3). They had much assistance from Victor Clark, Raymond E. Falconer, and others of the observatory personnel, who were already working on riming and icing. Langmuir and Schaefer, however, were able to introduce some new and very productive ideas.

Extensive mathematical calculations were necessary. The first work of this nature was done by Langmuir, and his results were used in connection with cloud studies at Mount Washington. During the later stages of the Mount Washington studies, Langmuir decided to make use of a differential analyzer for these calculations, and in preparing the material for that purpose, he was assisted by Dr. Katharine Blodgett. Thus it was possible to calculate the percentage of water droplets which would be deposited on a given surface under specific conditions. The information was used on data obtained on Mount Washington to determine the number and size of water droplets involved in the formation of rime ice.

Langmuir and Blodgett (4) computed the collection efficiencies of cylinders, ribbons and spheres for impinging droplets. This pioneering work, while published only as an Army Technical Report, is used extensively and described in virtually all current cloud physics texts. The sphere values were also employed by others in early calculations of droplet collision-coalescence processes, although the original theory applied best to the collection of small droplets by large drops. The importance of raindrop coalescence as an effective precipitation mechanism has resulted in continued work on the collection efficiencies of spheres with theoretical refinements still being made (5)(6)(7)(8)(9).

The theoretical studies carried out by Langmuir on drop trajectories represented one of the early uses of a computer to solve a complex scientific problem. It involved the use of the differential analyzer at General Electric, a version of the original one at MIT.

CLOUD STUDIES AT MOUNT WASHINGTON

The theoretical calculations worked beautifully in practice. Langmuir and Schaefer began to acquire a very satisfactory understanding of some features of cloud structure and the growth of cloud particles. They became absorbed in this new interest. Langmuir found he could apply to his smoke generator work the same evaporation-condensation theory he had used to calculate the growth of smoke particles (10).

Although Langmuir and Schaefer felt they had a fundamental theory for some of the factors that caused particles to grow in clouds to the proper size, they didn't believe conditions were right for further study on Mount Washington. It would be far better to study cloud particle growth with airplane penetration of clouds. That would require the development of new instruments.

It was late in 1945. They took the question up with the Army Air Force and the Signal Corps. They were led to think that perhaps somebody might furnish aircraft for experimental purposes of this sort; it seemed that it would be desirable to know something about clouds from a standpoint of national defense. Unfortunately, the research was done on their own to a large extent, testing instruments on Mount Washington; they never got approval for tests in aircraft.

By this time the pair were deeply interested in their cloud study. The thing that struck them most was that, if there are any snow crystals in a supercooled cloud, they must grow rapidly and should tend to fall out. They concluded that in winter, if there are supercooled stratus clouds from which no snow is falling, even though the temperatures in the clouds are below freezing, there simply are no appreciable numbers of effective snow nuclei. Such clouds could apparently be supercooled to very low temperatures.

They thought this presented a problem that should be investigated. Why was it that sometimes snow forms quite readily, with apparently no lack of nuclei on which crystals can grow, and at other times there seem to be no nuclei at all? They concluded there must be something in the atmosphere that causes water droplets to change to ice only at certain times and under various conditions. They decided to make some careful experiments in the laboratory in an attempt to duplicate those conditions.

SCHAEFER'S COLD BOX

During Langmuir's absence in California for three or four months in 1946, Schaefer made what Langmuir described as "some beautiful experiments" (1). During the previous winter he had been studying the behavior of droplets on cold surfaces to see how they supercooled or

froze as the temperature dropped. He had found he could supercool water drops to as low as -20°C on surfaces coated with polystyrene and similar materials. He had realized, however, that such experiments were not simulating supercooled clouds and had sought a better method of experimentation.

He decided to try a home freezing unit of the type used for food storage. He lined it with black velvet so as to get a good view of what happened inside when a beam of light was directed down into the box. He then breathed into the box, and the moisture condensed and formed fog particles which were just like ordinary cloud particles, although the temperature was about -23°C . No ice crystals formed. He tried many different substances dusted into the box to get ice crystals to form, but almost never got any. He got just enough to convince him that, if they were present, he could easily see them.

Schaefer's cold box, an elegantly simple piece of apparatus, was a cornerstone in the developments of Project Cirrus, not only in the discovery of seeding by dry ice, but also of silver iodide and in the evaluation of various aerosol generators used in seeding. In contrast to many important innovations made in research, which are often the result of technological innovations that have become available, this beautiful experiment was really the result of Schaefer's insight alone. The simple technology necessary for making the cold box had been available for several hundred years before Schaefer did the "obvious".

Finally, on July 13, 1946, when the temperature of the chamber was not low enough, he put a big piece of dry ice into it to lower the temperature. In an instant the air was full of ice crystals. The crystals persisted for some moments after he took the dry ice out.

Following this discovery, Schaefer conducted a number of experiments which showed that even a tiny grain of dry ice would transform the supercooled cloud in the cold box to ice crystals. Quantitative experiments were conducted which showed that many millions of crystals could be produced in this manner.

In order to find out if there was something peculiar to dry ice which produced this effect, he worked with other cold materials. For example, he showed that, by dipping a common sewing needle into liquid air and then passing it momentarily through the supercooled cloud in the cold box, similar spectacular effects occurred. This demonstrated that the presence of a sufficiently cold substance was all that was required to produce the effect. Schaefer devised methods and equipment for determining, with considerable accuracy, the critical temperature at which the supercooled

cloud changed to ice crystals (11).

The freezing of supercooled water has been shown to be actually a stochastic process governed by the size (volume) of the drop and rate of cooling as well as the degree of supercooling. However, the probability of freezing and generation rate of ice embryos within a drop becomes so large at approximately -40°C that this temperature is customarily referred to as the spontaneous freezing point of water drops.

VONNEGUT'S EARLY WORK-- CLOUD STUDIES AT M.I.T.

Meanwhile the stage had been set for another important contribution to this pioneering work in meteorology. Before Dr. Bernard Vonnegut became associated with the General Electric Research Laboratory, he was employed at the Massachusetts Institute of Technology, where he had been engaged in various studies during the early years of World War II. In the laboratory of the Chemical Engineering Department he worked on smokes for the Government's Chemical Warfare Service. He measured smokes, smoke penetration, and the effectiveness of smoke filters. Then he became interested in the problem of icing of airplanes and went to work on that in the Meteorology Department, for the Air Force.

Meanwhile, he had been doing some work on the side in supercooling. He found that, by making an emulsion of water drops suspended in oil, he could cool water far below the normal freezing point; it would not freeze until a temperature of -20°C or lower was reached, whereupon the whole mass froze very rapidly (12).

Vonnegut joined the staff of the General Electric Research Laboratory in the Fall of 1945, and he continued his supercooling investigations there. In various contacts with Langmuir and Schaefer, he learned of the work they were doing. Knowing that Schaefer was already working on the supercooling of water, he switched his activity to the supercooling of metals, in order to avoid duplication. He found he could supercool Woods metal by subdividing it into many small, independent particles, and he developed a technique of studying the effect with x-rays. He also worked with tin (12).

Vonnegut had been interested in the work being done by Langmuir and Schaefer and had kept in rather close touch with it. In the fall of 1946, Langmuir asked if he would be interested in helping with the quantitative work being done on the number of ice crystals produced by dry ice. As a result, Vonnegut applied himself to this and other problems in the general study of nucleation.

SILVER IODIDE

It occurred to Vonnegut that some substance very similar to ice in its crystal structure might serve as the nucleus for the formation of ice crystals in Schaefer's cold box. He went through all the known tables of crystal structure and, from over a thousand compounds, selected three substances that he thought might have possibilities: lead iodide, antimony and silver iodide (13).

He dropped samples of each of these three substances into the cold box. The results were almost negligible, although he produced enough effect with the lead iodide to warrant further experiments. He and Schaefer tried iodoform and iodine and obtained ice crystals in small numbers with them, too, but nowhere near as many as with dry ice seeding. The problem continued to intrigue Vonnegut, and on November 14, 1946, he decided to try a metal smoke instead of the powder. He introduced some silver smoke into the box by drawing an electric spark from a piece of silver, and it produced a swarm of ice crystals in the cold box.

The results were so spectacular that he decided to try silver iodide again, but this time as a smoke, for the effect with silver did not persist. First he vaporized silver iodide and then he introduced into the cold box the smoke resulting from the rapid condensation of this vapor. It was a complete success. Further investigation showed that his earlier negative results with silver iodide had been caused by the fact that the silver iodide used was contaminated with sodium nitrate. Powdered silver iodide worked very well when it was reasonably pure. He also found that the reason for the successful use of iodine was again impurity--favorable contamination with silver.

It has come to light recently (15) that the ability of silver iodide to nucleate ice formation in supercooled water had been discovered earlier by Bloch. In 1936 he employed this substance to initiate freezing of supercooled water in a temperature controlling device for a cryostat.

Tor Bergeron, the late Norwegian meteorologist, enunciated a theory to explain the formation of precipitation that now bears his name. He suggested that snow, and rain if the snow melted, could originate by the growth of ice crystals in supercooled clouds. In reminiscences concerning the development of his ideas, he stated, "I knew not enough physics and hadn't read Vollmer's 'Phasenlehre'. Irving Langmuir, V. Schaefer and/or B. Vonnegut evidently had, and it was really a treat when, thanks to Carl Rossby, my wife and I visited Langmuir in Schenectady on the 20th of April 1947, and he devoted half a day to us" (16).

However, the General Electric scientists did not become aware of Vollmer's important work on the theory of nucleation until sometime after the discovery of dry ice and silver iodide seeding.

The problem then became one of finding out how silver iodide worked and of finding methods of generating silver-iodide smoke of small particle size on a large scale. So many nuclei could be produced with silver-iodide smoke that calculations indicated all the air of the United States could be nucleated at one time with a few kilograms of silver iodide, so that the air would contain 100 particles of silver iodide per liter--far more than the number of ice nuclei occurring normally under natural conditions (14).

If one assumes 10^{15} particles of effective silver iodide per gram, a cloud airspace 10 km high, and the area of the United States to be eight million square kilometers, approximately 4 tons of silver iodide would be required to yield 100 particles per liter. In certain rainmaking concepts, it is estimated that the addition of only 1 nucleus per liter of air will stimulate precipitation; under these circumstances, the hypothetical quantity required would reduce to approximately 40 kilograms. Thus, while Langmuir considerably overestimated the effectiveness of silver iodide, the general argument that reasonable quantities are involved is valid.

LANGMUIR'S EARLY SEEDING CALCULATIONS

Meanwhile Schaefer and Langmuir had continued their study of the effects of dry ice. In August of 1946 Langmuir made a theoretical study of the rate of growth of the nuclei produced by dropping pellets of dry ice through clouds of supercooled water (17). He calculated the velocity of fall and time of dissipation of the dry ice, the amount of ice particles that would be formed, their size, the amount of snow which would result, etc. With a reasonable number of pellets dropped along a flight path into the top of a cloud, the limiting factor would not be the number of nuclei but the rate at which they could be distributed throughout the cloud.

He also showed that such a formation of ice and snow particles would raise the temperature of the cloud, and he calculated the amount of temperature change. Thus the air in the cloud would be caused to rise, increasing its upward velocity because of the seeding. The resulting turbulence would spread the ice nuclei throughout the cloud. He anticipated that it would only be necessary to seed a stratus cloud along lines two or three kilometers apart in order to give

complete nucleation of the cloud within a period of 30 minutes or so.

Langmuir recognized that heating would be produced not only from the freezing of the supercooled cloud droplets, but also from the freezing of supersaturated water vapor that is contained in the air between the droplets. For many years the importance of the additional heat released by seeding received little attention, and then Joanne Malkus (18) began her classic studies on the almost explosive growth that sometimes results when cumulus clouds are seeded.

FIRST MAN-MADE SNOWSTORM

Thus the stage was set for an actual experiment with an airplane in real clouds. On November 13, 1946, a Fairchild airplane was rented at the Schenectady airport, piloted by Curtis Talbot, and Schaefer went aloft in search of a suitable cloud (19). It was found over Pittsfield, about 50 kilometers east of Schenectady, at an altitude of 4.3 kilometers and a temperature of -20°C . What happened next is best described by the following extract from Schaefer's laboratory notebook entry for that day:

"Curt flew into the cloud and I started the dispenser in operation. I dropped about three pounds (1.4 kilograms) [of dry ice] and then swung around and headed south.

"About this time I looked toward the rear and was thrilled to see long streamers of snow falling from the base of the cloud through which we had just passed. I shouted to Curt to swing around, and as we did so we passed through a mass of glistening snow crystals!.....We made another run through a dense portion of the unseeded cloud, during which time I dispensed about three more pounds of crushed dry ice.....This was done by opening the window and letting the suction of the passing air remove it. We then swung west of the cloud and observed draperies of snow which seemed to hang for 2-3000 feet (0.6-1.0 kilometers) below us and noted the cloud drying up rapidly, very similar to what we observe in the cold box in the laboratory..... While still in the cloud as we saw the glinting crystals all over, I turned to Curt and we shook hands as I said 'We did it!' Needless to say, we were quite excited.

"The rapidity with which the CO_2 dispensed from the window seemed to affect the cloud was amazing. It seemed as though it almost exploded, the effect was so widespread and rapid.....

"When we arrived at the port, Dr. Langmuir rushed out, enthusiastically exclaiming over the remarkable view they had of it in the control tower of the General Electric Lab. He said that in

less than two minutes after we radioed that we were starting our run, long draperies appeared from the cloud vicinity".

The first seeding flight was of tremendous significance. Not only did it show that the laboratory experiments and calculations were justified, but it also contributed new material to the rapidly accumulating store of seeding knowledge. For example, it suggested that the veil of snow that first appeared immediately below the cloud could not have been produced by snow falling from the cloud but rather was produced directly by the action of the dry ice pellets falling into a layer of air below the cloud which was supersaturated with respect to ice but not with respect to water.†

Subsequent experiments proved that it was also frequently possible to seed a supercooled cloud by flying just below it and dropping dry ice. The thickness of the layer in which such seeding is possible is about 10 meters for each degree C below the freezing point at the cloud base. The ice crystals thus formed may be carried up into the cloud if the cloud is actively growing by convection.

On November 21 Schaefer seeded a supercooled valley fog with dry ice. He found that it was possible to reduce visibility by generating more ice crystals than fog droplets and also to dissipate the fog by dispensing just enough ice crystals to use up the fog droplets, each crystal growing large enough to fall to the ground.

OTHER EARLY FLIGHTS

There were two other seeding flights made by Schaefer with a rented plane that month, one on the 23d of November, and the other on the 29th (20). These tests were made on isolated cumulus-type clouds. The whole of each cloud was changed into ice within five minutes and snow began falling from the base of the cloud. Photographs were taken from the ground every 10 seconds, and these were developed and projected as movies. They showed that with orographic clouds, the air moves into one part and leaves another part; in a matter of five minutes or so an entirely new mass of air is within the cloud. Thus it was found that experiments with small cumulus clouds are usually of little interest, for the effects last but a few minutes.

†At that time I was editor of the General Electric Monogram. The late Thurse Sigman, an assistant editor, was on a newsgathering call at the General Electric News Bureau offices on the day in question. When he returned to the Monogram offices, he announced dramatically: "Well, Schaefer made it snow this afternoon over Pittsfield! Next week he walks on the water". (B.H.)

Another flight test was made on December 20 (20). This time the sky was completely overcast, and by 9 o'clock in the morning the Weather Bureau in Albany reported that it expected snow by 7 o'clock that evening. At about noontime, Schaefer dropped about 11 kilograms of granulated dry ice in the lower part of the cloud at a rate of .3 to .6 kilograms per kilometer, about 300 meters above the irregular and ragged base of the overcast, at altitudes ranging from 2.1 to 2.6 kilometers. A 1 kilogram bottle of liquid carbon dioxide was also discharged into the cloud during this period.

Before and during the seeding flight, a light drizzle of supercooled rain had been encountered, which seemed to evaporate before it reached the ground. Flying back along the line of seeding, after seeding was completed, it was found that the drizzling rain had stopped and that it was snowing. But on reaching the point where the seeding had stopped, drizzle conditions were again encountered. Three more seeding runs were made along the same line.

The plane then descended to 1.3 kilometers, where the visibility was better, and made a reconnoitering flight, checking the places where snow was falling. By this method and through reports received, it was found that snow started to fall in many places in the region. At 2:15 p.m. it started snowing in Schenectady and at many other places within 160 kilometers. It snowed at the rate of about 25 millimeters per hour for eight hours, bringing the heaviest snowfall of the winter. While the seeding group did not assume it had caused this snowstorm, it did believe that, with weather conditions as they were, they could have started a general snowstorm two to four hours before it actually occurred, if they had been able to seed above the clouds during the early morning.

ESTABLISHMENT OF PROJECT CIRRUS

This, then, was the situation in which the research workers found themselves by the end of the year: their work on precipitation static, and then on aircraft icing, had developed through cloud studies into meteorological work of profound significance. But, while their work on precipitation static and aircraft icing had been done under government contract, the work they were now doing on weather research was not. Their last contract had expired at the end of June, 1946, six months earlier.

At this point Dr. C. G. Suits, Director of the General Electric Research Laboratory, reported some of the results of cloud seeding to company officials. While it was clear that weather modification and experimental meteorology were remote from the research which had been the traditional interest of the laboratory and the Company, it was equally

clear that these new results were possibly of very great significance to the country. It was, therefore, decided that the work should be encouraged and pushed forward.

Because the results might have such wide application to the country generally and because much government assistance would be needed in the form of weather data, airplanes, and flight equipment, it was decided a government contract for the continuation of the work should be sought. While the government agency which had sponsored the previous research was not interested in the new work, other government agencies were. Normal contacts with the Signal Corps, for example, had kept that organization in touch with the new research, and Colonel Yates, chief of the Air Weather Service, had asked the Company to submit a bid covering this work in the latter part of September. A formal proposal covering cloud modification and cloud particle studies was submitted to the Evans Signal Laboratory at Belmar, New Jersey (a Signal Corps unit) on September 20. Meanwhile the weather studies were being conducted at General Electric expense, although General Electric anticipated no benefit resulting to the Company from the meteorological work.

The flight test of December 20 added a powerful stimulus to the Company's negotiations with the government. Although the General Electric press release covering it did not claim that the general snowstorm was caused by the seeding, the coincidence of the two events did cause some independent speculation over the possibility of cause and effect.

This question was brought by Suits to the attention of Vice President R. E. Luebbe, general counsel of the Company. It was recognized that the possibility of liability for damage from cloud-seeding experiments was a very worrisome hazard in this new form of cloud experimentation. Since such a threat to the share owners' money would not be balanced by any known gain to the Company's products or business, there was great reluctance to incur risks of uncertain but potentially great magnitude.

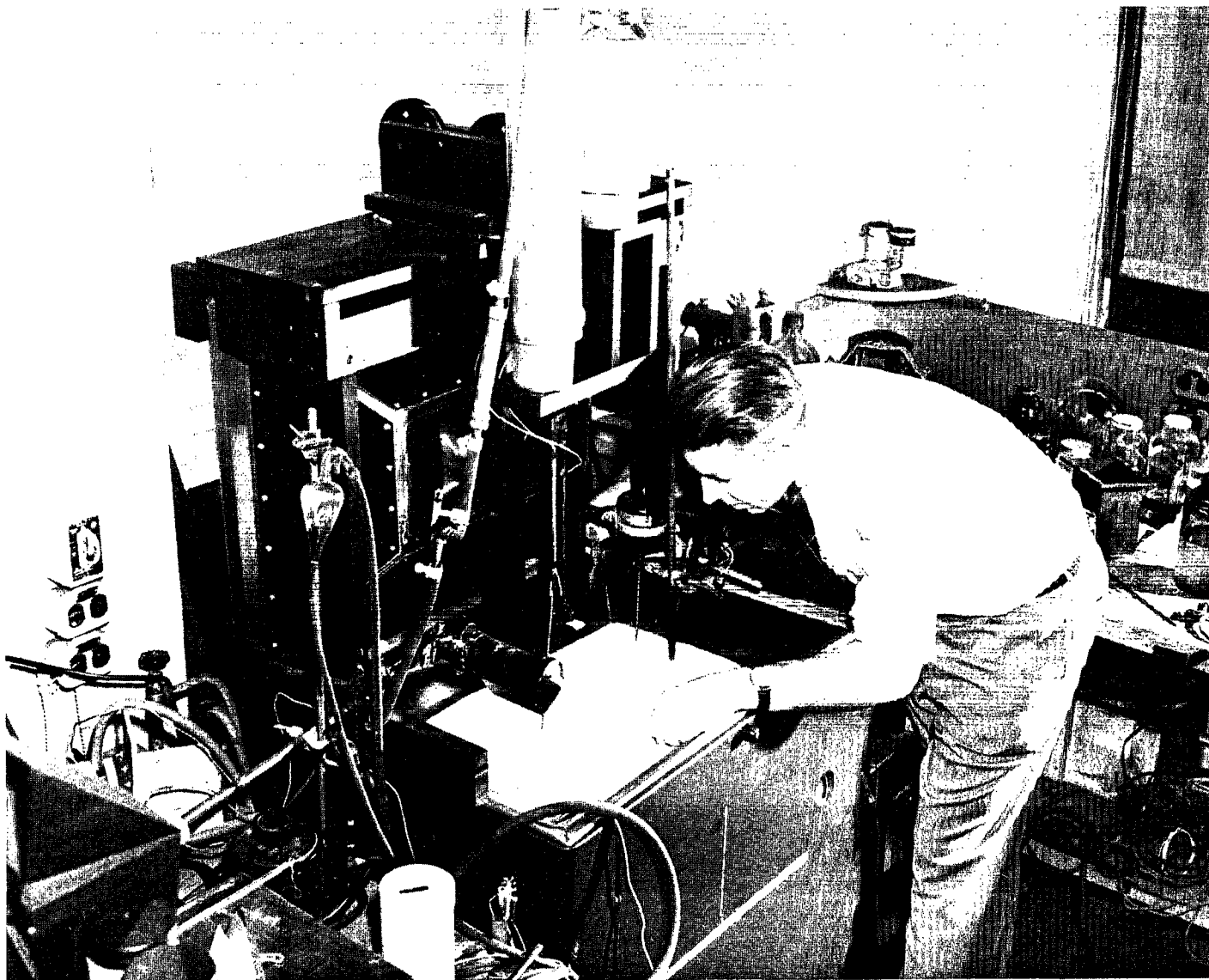
This was another--and particularly important--reason that any seeding experiments be conducted under government sponsorship. No further seeding flights were made until such sponsorship was provided. A contract was, however, received from the Signal Corps covering "research study of cloud particles and cloud modifications" beginning February 28, 1947. It included cloud modification by seeding, plus investigations of liquid water content, particle size, particle distribution, and "vertical rise of the cloud with respect to the base".

An important part of this contract was a subparagraph stating that "the entire flight program shall be conducted by the government, using exclusively government personnel and equipment, and shall be

under the exclusive direction and control of such government personnel". The Research Laboratory immediately notified all those involved in the research "that it is essential that all of the General Electric employees who are working on this project refrain from asserting any control or direction over the flight program. The General Electric Research Laboratory responsibility is confined strictly to laboratory work and reports". The project had joint sponsorship by the U. S. Army Signal Corps and the Office of Naval Research, with the close cooperation of the U. S. Air Force, which furnished airplanes and the associated personnel.

The title of Project Cirrus was not applied immediately. It went into effect officially on August 25 of that year.

The name of "Project Cirrus" given to the government-sponsored research on cloud seeding was conceived by Vincent Schaefer. The act of cloud seeding causes the transformation of a cloud made of supercooled water drops into a cloud of ice crystals. Since such clouds, consisting of minute ice crystals, are known to meteorologists as cirrus, he conceived that this would be an appropriate name. He told Daniel Rex of this, who shortly thereafter proposed this designation at a meeting of the Steering Committee, which accepted it as the official title.



Vincent Schaefer experimenting with a rather elaborate version of his cold box experiment.



Vincent Schaefer, Irving Langmuir, and Bernard Vonnegut in Schaefer's laboratory where cloud seeding was discovered. (Eric Schaal - Fortune Magazine 1947-1978, © Time, Inc.)

III. GETTING ORGANIZED

As described in the preceding chapter, the work done on Project Cirrus and the activities leading up to it were covered by several contracts with the government, as listed in Appendix 1. The first of three Signal Corps contracts was signed in February, 1947; the last of these remained in force until the end of September, 1952.

The total funding over a five-year period resulting from these grants amounted to \$790,116. By contrast, a contemporary project, such as the U. S. National Hail Research Experiment, had a budget for 1972 alone of approximately \$2.5 million.

The over-all direction of the project and the formation of broad matters of policy were entrusted to a Steering Committee consisting of representatives of the three military branches of the government cooperating in the project. Dr. Irving Langmuir and Dr. Vincent J. Schaefer of the Research Laboratory served as consultants on the committee. The governmental personnel were as follows [alternates and succeeding personnel assigned to the project are listed in Appendix 2]:

Signal Corps	Dr. Michael J. Ference, Jr.† Chief, Meteorological Branch Evans Signal Laboratory Belmar, New Jersey
Navy	E. G. Droessler Geophysical Branch Office of Naval Research Department of the Navy Washington, D. C.
Air Force	Major P. J. Keating Chief, Weather Equipment Flight Test Facility Middletown, Pennsylvania

The activities of Drs. Langmuir, Schaefer, Vonnegut and others of the General Electric Company's Research Laboratory staff were limited by the Steering Committee to laboratory work and analysis. The General Electric scientific group came to be known to the personnel of the project as the Research Group. In addition to Langmuir, Schaefer and Vonnegut, this group included Messrs. Kiah Maynard, Raymond Falconer, Raymond

†Dr. Ference tells the story that later in the project when he realized that Langmuir was approaching retirement age, he asked how this would affect his activity. He received the curt and rather gruff response, "You'll know when I'm retired; I'll be dead."

Neubauer, Robert Smith-Johannsen, Duncan Blanchard, George Blair, Myer Geller, Victor Fraenckel, and Charles Woodman.

An Operations Group was established by the Steering Committee early in the life of the project to plan, coordinate, and control all project air operations, assist in the assembly and analysis of all technical data obtained, provide all necessary meteorological information and service required for the efficient conduct of the project, and take whatever action necessary to fulfill those requirements. This group would include all military and civilian personnel necessary to fulfill those functions and act under the direction of an Operations Committee set up to "assume full responsibility for, and, therefore, exercise complete freedom of action in the initiation of plans for, and the control of, all project air operations to be conducted in the vicinity of Schenectady".

The Operations Committee, like the Steering Committee, included representatives of the three services, plus Kiah Maynard of the Research Laboratory of General Electric as consultant. It went through numerous changes of personnel. The initial membership was as follows:

Lt. Comm. Daniel F. Rex, USN,
chairman;
Capt. C. N. Chamberlain, USAF;
Roger Wight, Signal Corps;
Kiah Maynard.

The initial personnel of the Operations Group consisted of six representatives of the Signal Corps, six of the Air Force, and six of the Navy.† Although the number of General Electric people working on the project remained fairly constant at a figure of six or seven, the government representatives varied widely in number. As a consequence, the total personnel of the project varied also, running as high as 40 persons at various times when activities were at their peak. These included crewmen for the planes, weather technicians, and civilian employees for such services as photography. A total of 33 persons went on the Puerto Rico operation (p. 28), and 37 went on the second trip to New Mexico (p. 29).

†If ever there was an impossible assignment, it was the one given to a government scientist in the early days of Project Cirrus. He was told, "Go to Schenectady, spend all the time you can talking to Langmuir; milk him dry." The unfortunate man's eyes took on a glazed appearance after only a brief exposure to the prodigious and inexhaustible torrent of Langmuir's ideas.

FLIGHT PROGRAM

At the outset, and until June 1, 1947, Project Cirrus test flights were made by a Weather Squadron assigned to the Signal Corps. A plane visited Schenectady six times, and a total of five seeding flights were made. Olmsted Field at Middletown, Pennsylvania, was the base of its operations.

It was soon discovered, however, that many delays in carrying out flights could be traced to this geographic separation of the Operations and Research groups. Accordingly, in the summer of 1947, all flight operations were transferred to Schenectady. Headquarters for the Operations Group was established at the General Electric hangar at the Schenectady County Airport.

This massive cast concrete structure was built by General Electric for use in developing and installing special electronic gear for the B-29 aircraft. On the platform of its control tower Langmuir witnessed and photographed the first cloud seeding conducted by his assistant, V. J. Schaefer, on November 13, 1946. With the establishment of Project Cirrus in early 1947, it was arranged for the Project Cirrus flight operations to utilize this nearly new facility built by General Electric, and during the next five years (until 1952), it was headquarters of its flight activities headed by Lt. Comm. Daniel Rex.

In later years, as the General Electric Company transferred its airplane engine development to Cincinnati, the flight facility was abandoned and thus reverted to the County of Schenectady.

Early in 1967 after the hangar and its associated offices had been abandoned for several years, the State University of New York at Albany obtained a lease from Schenectady County and converted it to a major field station and research facility for ten years to 1977. Here Schaefer, Vonnegut, Blanchard and Falconer continued some of their atmospheric studies which had been initiated 25 years earlier!

The facilities expanded until, at the end of 1948, they consisted of a total of 170 square meters of office, operations, and storage space, including a flight tower, weather office, administration office, photographic dark room, Navy cage, Recordak room, operations office, analysis room, and a parachute-and-stock room. In addition to this, about 60 square meters of conference room was available whenever required. A heated room in the hangar served for aircraft installation work and repairs.

To facilitate flight operations, two Weather Bureau teletype circuits were

installed, as well as a Teletalk system connecting all offices. This could also operate a public-address system in the hangar and the ramp. In addition, connections were made through two leased wires to the Boston CAA control center and the Army Airways control center at Middletown, Pennsylvania.

At first the number of aircraft assigned to the project was disappointingly meager, but eventually this situation was corrected. At one time as many as six planes were available--three from the Army and three from the Navy. Active flight operations began with the establishment of the project in March, 1947, and then continued until August, 1950, when the Operations Group was disbanded at the suggestion of the Research Group. (This move was made in the interests of economy, for most of the objectives of the flight program had by that time been accomplished.)

A list of all the flights made by Project Cirrus is attached as Appendix 3. This list includes the flights made in rented planes before the establishment of the project and the carefully numbered and documented flights thereafter.

GROUND OPERATIONS

In addition to the flight program, the Operations Group had the responsibility for conducting numerous operations on the ground. These operations were of two kinds: photography and silver iodide seeding. When it became apparent that such operations would be necessary as part of the project from time to time, a system of numbering each operation was established. A record of all 84 ground operations conducted was maintained by the Operations Group (see Appendix 4).

Weather observation being essential to operations of the type carried on by Project Cirrus, one of the first steps taken by the Operations Group was to set up a complete weather-observing station as part of the facilities at the General Electric hangar. Daily radio contact was established with the Weather Equipment Flight Test Facility at Middletown, Pennsylvania, and circuits for weather teletype services were installed.

The primary requirements of the weather station were as follows:

1. Preparation of aerological flight data prior to take-off on flight tests.
2. Gathering of data after the flight to supplement that obtained in the air on seeding missions, for the area concerned during the time of test.
3. Cooperating with the Research Group in its study of weather analyzing instruments and test flights, and supplying it with such special weather reports as needed for analysis purposes.

In order to meet these requirements, the Weather Station performed the following functions:

1. Daily small-cloud maps were

prepared of conditions during the last hour before take-off on test flights, covering an area having a radius of 300 kilometers from the Schenectady County Airport.

2. Daily flights were made to record the air conditions up to 2.4 kilometers above the airport.

3. Radiosonde data above freezing level were obtained daily from the U. S. Weather Bureau at Albany.

4. Daily surface weather maps were prepared of the complete eastern United States.

5. Data were obtained daily of the winds aloft for the eastern United States.

6. Local weather observations were made hourly.

7. After each test flight, cross-sections of the areas seeded were prepared, based on reports of flight personnel and teletype weather reports.

When the Operations Group was disbanded in 1950 and the facilities at the General Electric hangar were abandoned, the Weather Station was transferred to the penthouse of the General Electric Research Laboratory at the Knolls.

Through the Office of Naval Research, two Navy men had a lengthy assignment to the project as aerologists, and as such they contributed much valuable assistance to the study of general and specific problems encountered in the various research studies. These men were Lt. (jg) W. E. Hubert and H. J. Wells, AGC.

PHOTOGRAPHY

Another very important activity essential to the success of the project was photography of various kinds. From the outset it was found that complete evaluation of the results of the various seeding experiments could not be made without documentary pictures.

Both still and motion-picture types of photography were used. In addition, special techniques were adopted. For example, by means of time-lapse photographs it was possible to speed up movie projection in order to obtain a better grasp of the changes taking place in a cloud. Also, by the use of stereoscopic equipment, it was possible to produce three-dimensional views of cloud systems.

So important was photography considered in the active phase of the project, when the Operations Group was functioning and regular test flights were being conducted, that many civilian professional photographers were employed in addition to those provided by the Signal Corps. On the second New Mexico test operation (p. 29), six photographers made the trip from Schenectady to Albuquerque. During the Puerto Rican test operation (p. 28) over 100,000 frames of time-lapse pictures were taken in color. The load on the darkroom at the General Electric hangar in Schenectady became so great

that a photographic trailer was obtained from the Signal Corps Engineering Laboratories to relieve the congestion.

One print of each photograph was, at the time of the preparation of this report, on file in the Knolls penthouse weather station, plus virtually all motion picture film. All negatives are filed in the photographic vaults of the Signal Corps Laboratory at Belmar, New Jersey.

INSTRUMENTATION

A considerable portion of the time and activity of Project Cirrus personnel was spent on the development of special instruments, tools, and equipment essential to the project. As in any new undertaking in which there is little or no previous experience, many new devices of this type had to be designed, or old ones had to be adapted to special requirements. In addition to Schaefer's simple cold chamber, which became a standard item of meteorological research in the field of cloud physics, the more important equipment developed was as follows:

Dry Ice Dispenser. One of the first instruments which had to be developed was an automatic dry ice dispenser (20). This was devised for use in an airplane, to allow a continuous release of dry-ice pellets during seeding operations.

Dry Ice Crusher. This was a device for reducing blocks of dry ice to usable fragments for seeding purposes (21). It greatly reduced the time required for preparing this material for a seeding run.

Silver-Iodide Generators. A number of different methods for the generation of silver-iodide smokes were studied by Vonnegut early in the history of the project. One method vaporized silver iodide from a hot filament (13). Another involved the use of a small electric furnace (22). A third method vaporized silver iodide from a string in a flame and then caused a very fine smoke by rapidly quenching the flame with a blast of compressed air (13). A fourth introduced silver iodide into flares of the standard fireworks type (22). A fifth technique produced silver-iodide smokes by first producing a silver smoke with an electric arc and then converting the silver particles to silver iodide by the addition of iodine vapor to the smoke (13).

In addition, two other techniques were devised which were well suited to large-scale seeding. In one, a solid fuel, such as charcoal impregnated with a silver-iodide solution, was burned (22) (23). The silver iodide vaporized and then condensed in the form of a fine smoke. In the other technique, a solution of silver iodide and acetone was atomized in a spray nozzle and burned, vaporizing the silver iodide (22,23,24).

The silver-iodide vapor rapidly condensed when it mixed with the cool air of the atmosphere, to form a smoke of very small particles, the size of which could be varied over a wide range. A later design of this generator, adapted for use in flight, was found to be simple and reliable.

Spray-nozzle burners of silver-iodide-acetone solution are still the most common type of generators in use. As was found then (25), in order to enhance solubility, some soluble iodide had to be mixed with the silver iodide and then acetone added to yield a 1-2% AgI concentration.

Camera Clinometer. It became evident in early flights that it would be necessary, when photographing seeded areas, to know the vertical angle at which the camera was pointed. A very simple camera attachment was made to indicate this angle (20).

Flight Instruments. Standard instruments often had to be modified, and new ones were occasionally developed. For example, a device was evolved to record the movement of the airplane "stick" for correlation and measurement of vertical acceleration (20).

Weather Instruments. It was in the field of weather observation and atmosphere studies that most of the instrument development occurred. Some of the early devices were special rods to be mounted on the airplanes to determine the rate of icing (20); an air decelerator to assist in sorting out rain, snow, dust, or cloud particles from the atmosphere as the plane passes through (20, 21); and a cloud-particle gun for sampling the cloud-droplet size distribution in clouds (20, 21). An attempt was made to develop a cloud-particle ranging instrument for airplane use to provide a continuous record of the distribution of particle sizes in a cloud, but without success.

Cloud Drop Meter. An important early development was a cloud meter, designed to provide a measurement of the average effective particle sizes in the various portions of a cloud (26, 20, 21, 27). This device, embodying a continuously moving tape impregnated with a water-sensitive dye, gave a satisfactory indication of the amount of cloud particles collected.

Condensation Nuclei Detector. Another important instrument was developed by Vonnegut for obtaining a continuous record of the concentration of condensation nuclei in a given air sample (28). This involved a simple adaptation of the cloud-chamber technique. Also a very simple pocket-size unit was devised for making spot checks of the relative numbers of such nuclei in a given sample.

Experiments carried out by the Navy showed that the recording condensation nuclei (CN) meter could be used successfully to track ships and submarines by detecting and following the plume of condensation nuclei released by the operation of their internal combustion engines. Development of the original recording condensation nucleus meter devised during Project Cirrus was continued at General Electric under a later classified Navy contract for use in antisubmarine warfare. Subsequent versions of the CN meter proved useful as a research and monitoring tool for air pollution studies. They have since been produced commercially by General Electric and several other companies.

Vortex Thermometer. A development of much significance was the design by Vonnegut of a vortex thermometer for use by airplanes in measuring true air temperature (29). The usual type of thermometer is unsatisfactory for this purpose because of aerodynamic heating caused by the rapid movement of the airplane through the air. The vortex thermometer reduced these aerodynamic effects to a negligible amount. Also, for the first time, it made possible a quite accurate measurement of the temperature in a cloud. Furthermore, an indication of true air speed can be provided by measuring the difference in readings given by a vortex thermometer and one exposed in the normal manner, because the deviation from true temperature of a normal thermometer varies with the speed of the plane. But it was found that the vortex whistle (next paragraph) showed greater possibilities for this application.

Vortex Speed Indicator. An outgrowth of the development of the vortex thermometer was the adaptation of the principles involved to the production of a musical note. As the pitch of the note thus produced varies with pressure, such a whistle could be used as the basis for measurement of true air speed and air mileage for airplanes (30).

Rain Catcher. A tool found very useful in rain studies aloft was a rain catcher, developed to give the average value of the precipitation in the air for approximately each thousand feet of flight. The device involves the use of a rain scoop, a tube whose exit velocity can be controlled, and a group of storage containers (31).

Portable Cold Chamber. A simple but effective cold chamber was designed by Schaefer, which could be carried about for field studies. It consisted of a small rectangular wooden box lined with copper sheeting and having a copper inner chamber. A charge of five pounds of crushed dry ice was found to hold the temperature below -10°C for three hours (32, 33, 34).

Ice Nuclei and Crystal Detectors. Since one of the important properties of the atmosphere as related to the persistence of supercooled clouds is the presence of ice-forming nuclei, considerable effort was expended in the development of an instrument which would provide a continuous, automatic record of the quantity of such nuclei in the air at any given time. Two developmental instruments were devised, but difficulties were experienced with both of them, and neither was brought to a satisfactory degree of perfection. One made use of the tendency of a thin water-soluble film of polyvinyl alcohol to supercool. The latter determined the concentration of ice forming nuclei by counting the ice crystals formed in a cold box (35). Air from the cold box was drawn rapidly past an electrically heated wire. When an ice crystal collided with the wire, it created a sudden cooling and a decrease in electrical resistance, which could be readily detected electrically.

Uniform Particle Generator. A useful tool in the study of cloud physics was an apparatus for producing particles of uniform size, developed during the work on one of the ice nuclei detectors (35). With it, extremely uniform particles were produced in sizes down to about 10 microns diameter by feeding water through a fine glass capillary set into oscillation by a jet of compressed air.

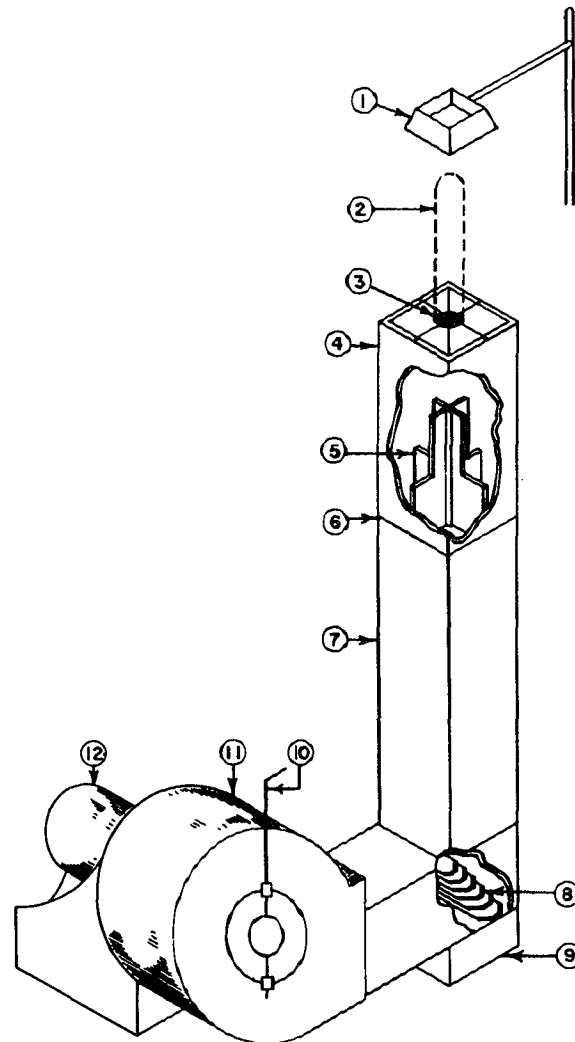
Salt Particle Detector. An apparatus was constructed that detects and counts aerosol particles, such as salt particles, by the pulses of light they produce when they enter a hydrogen flame. Observations showed that the concentration of large sodium-containing particles in the atmosphere is subject to considerable fluctuation (36).

Cloud Chamber. A very simple but effective adaptation of the continuous cloud chamber was developed by Schaefer, using water instead of alcohol (37, 38). It gave promise of considerable value in conducting quantitative experiments with a controlled atmosphere. It consisted of a closed, vertical, glass cylinder in which a constant moisture and temperature gradient was obtained by humidifying the top with a moist piece of blotting paper and cooling the lower part with dry ice. This device produced regions of supersaturated vapor under conditions of extreme cleanliness and provided a valuable tool for the study of nucleation.

Aerosol Precipitator. A very simple apparatus was constructed to precipitate aerosol particles from the atmosphere on a strip of paper. It was found useful in the study of condensation nuclei in the atmosphere.

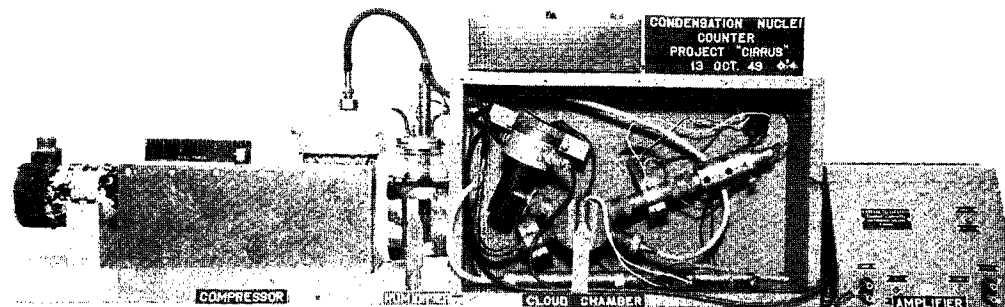
Snowflake Recorder. This device was developed to record the type and concentration of snow crystals reaching the ground during the storm period of the winter season. It utilized a strip of paper on which was rubbed a water-sensitive dye (39).

Cloud Type Indicator. By measuring the daylight from a small portion of the northern sky, it was found that the variations in reflection caused by blue sky or various cloud types which passed this area produced a curve which could be interpreted in terms of particular types of cloud (40).

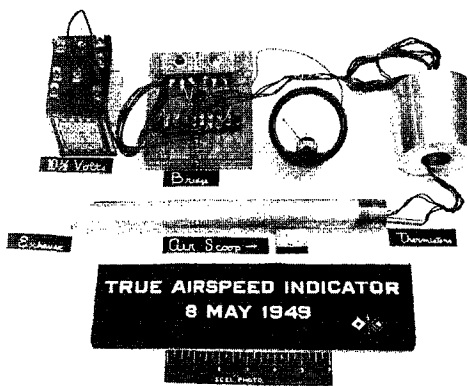


- ① BACK PRESSURE CONTROL
- ② REGION OF DROP STABILITY
- ③ 2 1/2" DIA. 14x17 MESH SCREEN
- ④ UPPER SECTION OF TUNNEL
6"x6"x15"
- ⑤ BRASS PLATES
- ⑥ 14x17 MESH SCREEN COVERING ALL
OF CROSS SECTION
- ⑦ LOWER SECTION OF TUNNEL
6"x6"x27"
- ⑧ DEFLECTING LOUVERS
- ⑨ SUPPORT FOR TUNNEL
- ⑩ BUTTERFLY VALVE
- ⑪ BLOWER
- ⑫ 1/2 HP 110 V AC MOTOR

Vertical Wind Tunnel for the Suspension of Water Drops in an Air Stream



Condensation Nuclei Meter Flown in B-17 Airplane



Differential Vortex Thermometer
Used to Measure True Air Speed

IV. LABORATORY STUDIES

The interest and activity in cloud seeding and the fundamental physics of clouds, following the initial experiments, were so varied that it is difficult to give an orderly account of the progress in this field. Research both in the laboratory and in the atmosphere continued to reveal new and interesting facts. The following pages contain summaries of the more important laboratory studies which were conducted in this field by the Research Group of Project Cirrus.

PERSONNEL

It would be difficult, if not impossible, to list the names of all the people contributing to these laboratory studies, but the following twelve persons played important parts either continuously throughout the life of the project, or at one time or another during its existence.

Dr. Irving Langmuir, under whose direction the project evolved, planned the methods and techniques for the various programs, analyzed flight results, and set up procedures for the routine analysis of such results. He also provided convincing mathematics for many of the theories evolved.

Dr. Vincent J. Schaefer, who worked with Langmuir in the planning of the project, carried out both field and laboratory experiments on the fundamental processes involved in changes of cloud forms.

Dr. Bernard Vonnegut also carried out extensive field and laboratory experiments on subjects associated with the project. Particularly he concentrated on theories and techniques associated with the use of silver iodide for seeding.

Raymond E. Falconer worked on various phases of instrumentation of the flight plans, on laboratory studies, and on other related problems. He worked closely with Langmuir in his rainfall periodicity studies. After the termination of the Operations Group, the establishment and maintenance of a weather station in the Knolls penthouse was his primary responsibility.

Victor Fraenckel served as General Electric representative on the Steering Committee and as contract liaison man.

Kiah Maynard was the Research Laboratory representative on all flight tests and on the Operations Group when it was active. He gathered data and maintained records of all flight tests. He was associated with Falconer in the operation of the weather station at the Knolls penthouse.

Raymond L. Neubauer was associated with the later stages of the project in the

development of instruments and studies of silver-iodide smokes.

Robert Smith-Johannsen, associated with the project during its earlier history, was principally concerned with the study of the supercooling of water.

Duncan Blanchard was temporarily associated with the project in connection with the study of water droplets.

Myer Geller, temporarily associated with the project, contributed important calculating work.

Charles Woodman, temporarily associated with the project, contributed important mathematical work.

Arthur Parr, a Research Laboratory machinist, built almost all the special equipment and developmental instruments involved.

ICE NUCLEI

One of the most important phenomena associated with the study of the physics of clouds is the formation, distribution, and relative abundance of nuclei for the formation of ice crystals. This subject, therefore, occupied the attention of the principal members of the Research Group to a large extent during the course of the project.

Considerable work was done in developing instruments and methods for detecting the presence of, and counting, such nuclei in the atmosphere. Relatively early in the history of the project, a station was established by Schaefer at the observatory atop Mount Washington for regular observations of the concentration of such ice-forming nuclei, and these observations continued over five years. Subsequently, Schaefer found in the laboratory that certain kinds of soils, when dispersed as a dust, were moderately good nuclei under certain atmospheric conditions (41).

Other investigators have since confirmed that soil particles are among the most effective ice nuclei occurring in the atmosphere, and Kumai (42) identified soil clay nuclei (kaolin and montmorillonite) in snow crystals using electron microscopy. However, a clear understanding of the nature and origin of natural ice nuclei is still lacking; the range of possibilities varies from the bottom of the atmosphere to the top--from soils, plant leaves (43), steel mill effluent, and automobile exhaust (44) to meteor dust (45).

At the time of writing this report [1952] the number of ice nuclei needed to initiate a chain reaction in a supercooled cloud is not yet known, but evidence found early in the history of the project, suggesting that a critical concentration is found in the range of 10,000 to 50,000 nuclei per cubic meter,

has consistently been strengthened since (46).

Observations of ice nuclei were also conducted at the Research and Development Division of the New Mexico School of Mines at Socorro, with whom the Project Cirrus scientists maintained a close liaison.

New Mexico Institute of Mining and Technology had, through the leadership of its President, Dr. E. J. Workman, developed a very able and productive group of scientists in atmospheric physics, studying such phenomena as cloud circulation, thunderstorm electricity, and aerosols. Workman and his associates, S. E. Reynolds, Benjamin Seeley, and William Crozier, contributed much to Project Cirrus through discussions and cooperative research programs, as well as by generously extending the use of all of their apparatus and facilities. The friendships and exchanges of ideas between scientists of New Mexico Tech and Project Cirrus continued after the project ended. In 1963, six years following the death of Dr. Langmuir, New Mexico Tech completed the construction of a cloud physics observatory on Mount Baldy, near Socorro, which Workman named Langmuir Laboratory (48).

A significant fact resulting from the Mount Washington studies was that relatively high concentrations of active ice-forming nuclei rarely occur in the atmosphere (47). If the observed results are a true representation of the average mean condition of the atmosphere, it is obvious that, by the artificial introduction of sublimation nuclei into the atmosphere, man possesses a powerful method of modifying many cloud systems.

One prolific source of ice-forming nuclei might be the Great Plains and the more arid regions immediately adjacent to the Continental Divide. Wind storms, dust devils, and strong convective activity could easily account for the formation of ice-forming nuclei aerosols (47). It seems probable that the smoke produced by forest fires is a poor source of such nuclei (47). An attempt was made to determine the role that bacteria and the spores of fungi might play in this respect (47) and to evaluate the role of industrial smokes of various kinds (49).

Adiabatic Expansion of Gas. An important contribution to the early knowledge of meteorological phenomena was made through Vonnegut's observations that, when gas is cooled to below -39°C by adiabatic expansion, very large numbers of ice crystals are formed (50). For example, the low temperature produced at airplane propeller tips and wings can seed supersaturated air or supercooled clouds, resulting in persistent vapor trails or cloud modification. Cwilong

had reported (51) that ice crystals could be produced by this method, but he apparently had not appreciated the enormous numbers which are so produced.

Such vapor trails (produced by adiabatic cooling of air in wing tip and propeller vortices) are generally transient, small-dimension phenomena of lesser importance than implied. Condensation trails, involving the release of water vapor in engine exhaust, can and do produce persistent streaks or cloud sheets in ice-supersaturated air.

It was found that the adiabatic expansion resulting from the bursting of a rubber balloon a millimeter in diameter produced over 10,000,000 ice crystals. Schaefer made a popgun which did the same thing, lending itself to careful control of temperature, pressure, and humidity.

These air expansion experiments provided corroboration of conclusions already reached with dry ice and furnished additional quantitative data on nucleation which were found very useful.

Chemical Effects. An interesting effect noticed by Vonnegut while carrying out some studies of ice crystals in a cold chamber was that the presence of normal butyl alcohol caused the crystals to form as hexagonal columns instead of hexagonal plates (52). This phenomenon was studied by Schaefer in some detail, but no practical application of the findings was developed.

Spontaneous Ice Formation. Project work done as early as 1946 indicated that ice crystals formed spontaneously in water-saturated air when the temperature reached the neighborhood of -35 or -40°C . Schaefer conducted considerable research into this subject and determined that the critical temperature was -38.9 ± 0.1 degrees (53). This phenomenon is probably of considerable significance in relation to the formation of cirrus clouds and ice crystal fogs in the free atmosphere.

Crystal Structure, Growth and Multiplication.

(a) Schaefer's study of the various types of snow crystals, which started before the establishment of Project Cirrus, continued throughout the project. In 1948 he published a simple yet inclusive list of ten types of solid precipitation for classification purposes (54).

This classification of snow (p. 22) was agreed upon by the International Commission on Snow and Ice in 1951. It is still widely used throughout the world although some researchers now employ the more detailed classification of Magono and Lee (56).

(b) Experiments by Schaefer in 1949 indicated that snow particles tend to shed minute fragments of ice when they are placed in air slightly warmer than their own temperature. An ice-forming nucleus appearing in a supercooled cloud grows rapidly, especially in the temperature range of -12 to -16°C, where the difference between the partial vapor pressure of ice and of water passes through a maximum. When the crystal becomes large enough, it sheds a considerable number of ice particles as it falls through the cloud. These particles then serve as new nuclei and repeat the cycle. In this manner, a few ice-forming nuclei in a cubic meter of cloud may start a chain reaction which, within a few minutes, could shift a supercooled cloud to a mass of snow crystals (55).

A fundamental problem confronting cloud physicists today is how to account for the high concentrations of ice crystals found in some clouds. These enhanced concentrations of crystals are sometimes 1 to 4 orders of magnitude greater than the ice nucleus concentrations just below the cloudbase. An ice-multiplication mechanism is suggested. One possibility is that mentioned above [and updated (57)], while Mossop (58) has listed and evaluated some 12 other possibilities. Recently Hallett and Mossop (59) have presented rather convincing laboratory evidence that a riming-splinter mechanism at temperatures near -5°C may explain many of the field observations.

SILVER IODIDE

After the discovery that silver-iodide smokes serve as excellent nuclei for the formation of ice crystals, the project was faced with the problem of finding some way of generating the smoke efficiently and in quantity. It was found that smokes consisting of exceedingly fine particles could be easily produced by vaporizing silver iodide at a high temperature and then rapidly quenching the vapor. This was readily accomplished by burning silver-iodide-impregnated charcoal or injecting a spray of silver-iodide solution into a hot flame. Simple generators based on this principle were made which could produce 10^{14} nuclei per second--enough to seed from 4000 to 40,000 cubic kilometers of air per hour (14).†

A very interesting discovery resulting from one of Vonnegut's studies is that silver-iodide particles do not react immediately as ice-forming nuclei when

†Equivalent to approximately 100 nuclei per liter to 10 per liter, respectively.

introduced into a supercooled cloud of water droplets. Even 50 minutes after introducing a smoke sample into the cold chamber, ice crystals could be seen to form at a measurable rate. The general conclusion reached as a result of this study was that the rate of reaction at -13°C is 30 to 40 times faster than at -10°C (25).

According to this interpretation, nucleation by silver iodide is a stochastic affair. The probability that a silver iodide particle in a supercooled cloud will nucleate an ice crystal within a given time is determined only by the temperature and is quite independent of the length of time that the particle has been in the cloud. To date, this concept has received little attention in the scientific literature of cloud seeding, and apparently has neither been accepted nor rejected.

The first unambiguous results in cloud seeding using silver-iodide generators were obtained in 1948, when silver-iodide nuclei produced by one of Vonnegut's generators installed in an airplane resulted in cloud modification similar to that produced by dry ice (60).

Most investigators all over the world had little trouble in duplicating the effects produced by seeding supercooled clouds with dry ice. This was sometimes not the case, however, when clouds were seeded with aerosol particles intended to serve as freezing nuclei, such as silver iodide. In some cases the failure probably resulted from using substances that had little or no activity in nucleating ice. For example, nuclei consisting of lead oxide or potassium iodide were used in the 1948 Weather Bureau experiments instead of silver iodide (61). In other cases negative results were obtained probably because the silver iodide was improperly dispersed as an aerosol. An account of this is to be found in reports of Australian experiments carried out in 1952, in which it is said of silver iodide, "This agent proved to be much less effective than dry ice, and in most cases no visible results appeared." (62)

Experiments were conducted to determine whether the burning of charcoal particles used in silver-iodide seeding from an airplane would be seriously affected by the moisture in clouds. It was concluded that such burning is not seriously affected if the charcoal is thoroughly ignited (22).

Some experiments were conducted to discover the value of a turbojet burner

as a silver-iodide smoke generator. It was decided that such a method might be of value if larger generators were needed than those already in use (23).

Experiments were also made in tracing silver-iodide smokes after their release by seeding generators (60).

The nature of silver iodide is such as to suggest the possibility that its effectiveness as a seeding agent might be reduced by the action of ultraviolet and near-ultraviolet radiation from the sun. Accordingly, an investigation was made to determine its rate of decay under expected conditions of radiation in the free atmosphere. The results of work in this field, not only by Project Cirrus but also the New Mexico School of Mining and Technology, suggested that far greater quantities of silver-iodide particles might be required for seeding operations under conditions of bright sunlight than would be needed at night or under conditions of cloud cover. But later work and observations indicated that the effect of sunlight might not be as bad as was forecast (63, 64).

This summation appears valid despite conflicting results of several subsequent investigators that indicated photo-deactivation rates of silver iodide anywhere from a factor of 2 to 10^6 per hour. Apparently the decay rate is inversely proportional to particle size, humidity and purity of the aerosol. Because of the high humidity within clouds and the "impurities" inherent with solution burners, typical silver iodide seeding operations probably involve photolytic decay rates of less than a factor of 10 per hour.

Experimental work showed that it is possible to convert supercooled ground fogs to ice crystals by releasing silver-iodide smokes (13).

RAINDROP STUDIES

Although many of the details are still lacking, studies conducted by Project Cirrus began to provide answers to the question of how rain is formed. In 1947, reports were received of successful results obtained by dry-ice seeding of cumulus clouds over Hawaii having a temperature above the freezing point. Langmuir examined theoretical calculations he had prepared in 1944 in studies relating to work at Mount Washington Observatory. As a result he developed a theory which agreed very well with the reactions reported (64).

According to Langmuir's theory, actively growing cumulus clouds having an average drop size of 20 microns, a liquid water content exceeding 2.5 g/m^3 , and a vertical thickness of more than a mile are in a favorable state for

starting a chain reaction. This could be achieved by introducing water drops greater than 50 microns in diameter into the actively growing part of the cloud.

Large drops in such a cloud would fall at a greater velocity than would small drops. In falling, they would overtake and collide with the small drops and thereby increase in size. In time the large drops would become so large that surface tension could no longer hold them together, and they would break up into two or more smaller drops. These in turn would grow and break up, and the number of large drops would increase in this manner by a chain reaction.

The process would not be sufficient to produce large numbers of raindrops in a cloud without a vertical updraft. However, in the case of clouds with suitable updraft conditions, many stages of the chain reaction are carried out, resulting in the production of rain.

To determine the validity of several of the important phenomena involved in this theory, various studies were initiated in the laboratory and experiments were conducted in the field. Blanchard devised a splendid method for studying the properties of free-falling water droplets in air, using a vertical wind tunnel.

A large variety of these vertical wind tunnels are in use today. One of the largest (1.8 m throat diameter) is at the State University of New York at Albany (67). A very sophisticated version can be found at the University of California at Los Angeles (68).

A series of striking stroboscopic photographs was made, showing the oscillations, gyrations, pulsations, and fractures that go on as water drops fall at their terminal velocity (65). Another activity concerned itself with devising means of sampling raindrops and measuring diameter (65). His chain-reaction theory led Langmuir to postulate that cumulus clouds having sufficient updrafts could be seeded with a few large water drops. Seeding with water drops was carried out with apparent success in tropical clouds (69), as will be discussed (p. 25).

CONDENSATION NUCLEI

Condensation nuclei play an important role in the behavior of the atmosphere. In 1948 Vonnegut devised a method of obtaining a continuous record of the concentration of condensation nuclei in the atmosphere (28). Various experiments were conducted with this equipment, both aground and aloft. The results suggest that the continuous measurement of the concentration of condensation nuclei may be very useful in meteorological investigations.

It is now well recognized that the concentrations of "large" (greater than $\sim 0.1\mu$) condensation nuclei strongly influence the microstructure and stability of clouds (71). Smaller "Aitken" nuclei (less than 0.1μ) measured with expansion counters, play a significant role in atmospheric conductivity, visibility, haze, gas-particle reactions, and several yet-to-be defined pollution processes.

ELECTRICAL PHENOMENA

It was observed in 1943 by Schaefer that interesting atmospheric electrical measurements could be obtained by connecting one end of a shielded cable to an insulated needle presented to the sky and the other end to a sensitive recording microammeter, one side of which was well grounded (70). Among the interesting observations made during successive years was that this instrument indicated the passage of charged clouds over the observation point.

Continuous records were kept by Falconer from 1948 on, using the data provided by this equipment, and an attempt was made to correlate the measured corona-discharge currents with other meteorological phenomena, such as frontal passages, wind direction, precipitation, and reflected light from the northern sky, particularly with apparently clear skies (72).

When Workman and Reynolds announced in 1948 their discovery of the formation of a large electrical potential when water containing small quantities of certain salts is in the process of freezing, Schaefer decided to check the experiments by an independent investigation. Accordingly, test equipment was set up and observations were made. The Workman-Reynolds electrical effects were immediately observed. The results of this experiment have very important implications with respect to the development of lightning in thunderstorms (73).

Some qualitative experiments were made by Vonnegut and Neubauer to determine the effects of high voltage on the formation of water drops (74). It was found that streams of highly electrified, uniform droplets about 0.1 millimeter in diameter could be produced by applying potentials of from 5 to 10 kilovolts, ac or dc, to liquids in small capillaries. Aerosols of uniform size and having a particle radius of a micron or less could be formed if the capillary was positively charged and if liquids having low electrical conductivity were used. Aerosols formed in this way showed the colors of higher-order Tyndall spectra.

STUDY OF CLOUD TYPES

In connection with an investigation of snowstorm intensities, Schaefer started measuring variations in sky brightness using a light-sensitive instrument. Falconer subsequently carried on the measurements in more detail. It was discovered that the variations in the curve made by this instrument were a rather good indicator of the type of cloud cover prevailing during a day. There seemed to be a typical trace for each general cloud type. Test installations were made by Falconer at various points aground and aloft, and considerable data were gathered (40).

Such an instrument might be useful in automatic weather stations, to give some indication of sky conditions in remote locations.


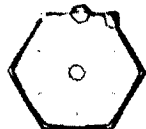




















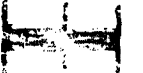














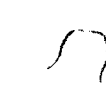


ANALYTICAL WORK

Of great significance, both in connection with activities of the Research Group and with those of the Operations Group, was the analytical work performed by Langmuir. It constituted one of the most important contributions to the project.

From the outset he studied and analyzed the various test flights, and extensive reports were prepared analyzing cumulus and stratus cloud seedings. His analysis of the cumulus seedings over Hawaii and the chain-reaction theory of rainfall which resulted have already been mentioned. Langmuir paid particular attention to the seeding operations carried on in New Mexico, and to the possible effects of silver-iodide seeding, and these activities are described more fully in a later section of this report (pp. 29, 37, et seq.).

Such a large quantity of data was accumulated by flight, field and laboratory activities during the more active period of the project that the Research Group finally suggested early in 1950 to the Technical Steering Committee that flight operations be terminated at Schenectady in order that the accumulated data might be evaluated and reports prepared on the findings.

TYPES OF FROZEN PRECIPITATION

CODE	GRAPHIC SYMBOL	TYPICAL FORMS			TYPE
1					PLATES
2					STELLARS
3					COLUMNS
4					NEEDLES
5					SPATIAL DENDRITES
6					CAPPED COLUMNS
7					IRREGULAR CRYSTALS
8					GRAUPEL
9					SLEET
0					HAIL

Snow Crystal Classification developed by V. J. Schaefer and adopted by the International Commission on Snow and Ice in 1951.

V. CIRRUS AND STRATUS STUDIES

CIRRUS CLOUDS

The significance of cirrus clouds and the role they play in various weather phenomena were, of course, subjects of intense interest to the Project. Various studies of and experiments with such cloud forms were conducted, although more attention was paid to stratus and cumulus clouds.

A regular daily observation program was begun in 1947 to explore the possibility of inducing the development of cirrus-type clouds under clear sky conditions. It was believed that supersaturation with respect to ice probably occurs fairly frequently at temperatures warmer than -39°C in air devoid of foreign-particle nuclei. Lacking such nuclei, a considerable degree of supersaturation could develop, as is often shown by the generation of so-called vapor trails behind high-flying aircraft.

To explore these possibilities, Falconer initiated a project in which balloons carrying dry ice in open-mesh bags were released on a daily schedule and followed by theodolite. Many of these produced visible trails of ice crystals, and in several instances the trails were quite noticeable (20, 21, 27, 39).

Several seedings were also carried out from an airplane in clear air, using both dry ice and silver iodide. In clear air supersaturated with respect to ice, the seeding operation produced a cloud of ice crystals. The results of these operations indicated that, if the humidity is low, even at temperatures below -39°C , appreciable supersaturations with respect to ice can exist without the formation of ice crystals. Ice crystals can then be created, however, by seeding with either dry ice or silver iodide (24).

In six of the Project Cirrus test flights a considerable effort was directed toward obtaining photographic evidence of the appearance of the tops of natural cirrus clouds. It was found that, despite the various irregularities seen from below, the tops of such clouds are extremely flat.

Most meteorologists and weather students agree that a cirrus cloud formation is often associated with the overrunning of cold air by a warmer tongue of moist air. Whenever the moisture conditions in the warm overriding air reach saturation with respect to water and the colder air below has a temperature of -39°C or colder, ice crystals will form spontaneously at the inversion interface. The number of primary crystals that form will depend on the concentration of condensation nuclei and ice nuclei in the moist air mass. The number and size of secondary crystals that form will probably be

some multiple of the effective number of condensation nuclei. Since these conditions for the ice-crystal formation are of a marginal nature, the variability and often unique appearance of true and false cirrus clouds may be closely related to these spontaneous crystal formation phenomena. Based on this reasoning, Schaefer concluded that it is likely that the concentration of supercooled water droplets at the transition temperature of -39°C is of primary importance in the formation of cirrus crystals (53).

Langmuir, analyzing the behavior of cumulus clouds, described an action which he called cirrus-pumping. This occurs when, with few or no nuclei present, the cloud rises to great heights. If it rises to a height when the temperature gets down to -39°C or thereabouts, minute ice crystals are formed in great numbers, almost instantaneously. These have a lower vapor pressure than any supercooled water droplets present and rapidly grow at their expense. This, in turn, liberates a large amount of heat simultaneously over the whole top of the cloud, and this upper part rises still further, forming a cirrus crown shaped something like a pancake.

The pancake grows in dimension and gets thinner, and it sometimes drifts gradually off to one side, so that it assumes the general appearance of an anvil--a type of cloud characteristic of the tropics. One large cloud of this type, said Langmuir, might sometimes produce cirrus clouds which would spread over 25,000 square kilometers. Outside of the tropics, they may often occur during the summer in semi-arid regions such as New Mexico, Arizona, or Idaho (75).

STRATUS CLOUDS

Much more attention was paid to stratus clouds. The flight test of December 20, 1946, for example, was conducted when the sky was completely overcast, and it produced snow (1). In the flight test of March 6, 1947, under the auspices of Project Cirrus, seeding was conducted on stratus clouds. Looking down on the cloud, it was observed, first, that a deep groove had been produced along the top of the seeded area, and snow fell. Soon the sky cleared up in a spectacular fashion, so that there was a cloudless area 32 kilometers long and 8 kilometers wide where the seeding had taken place. There were no other breaks in the overcast in any direction (76). Further tests on stratus clouds produced similar results.

The conclusion was therefore reached in the earliest days of the project that cloud seeding could produce holes in stratus clouds. Thus a plane should be able to clear a hole for itself. The result would be not only to increase visibility but also to eliminate icing

conditions. Langmuir made an exhaustive analysis of the photographic data obtained on these early test flights, reaching some very interesting conclusions regarding the nature and behavior of stratus clouds (77).

It was soon found that a very useful technique in seeding stratus clouds was to seed in patterns--L shapes, race-track shapes, Greek gammas, etc. Thus it would be possible to watch for modification of the clouds following the same pattern. And invariably modification did occur, agreeing with the pattern of the seeding. In many cases clear areas were produced in the cloud deck.

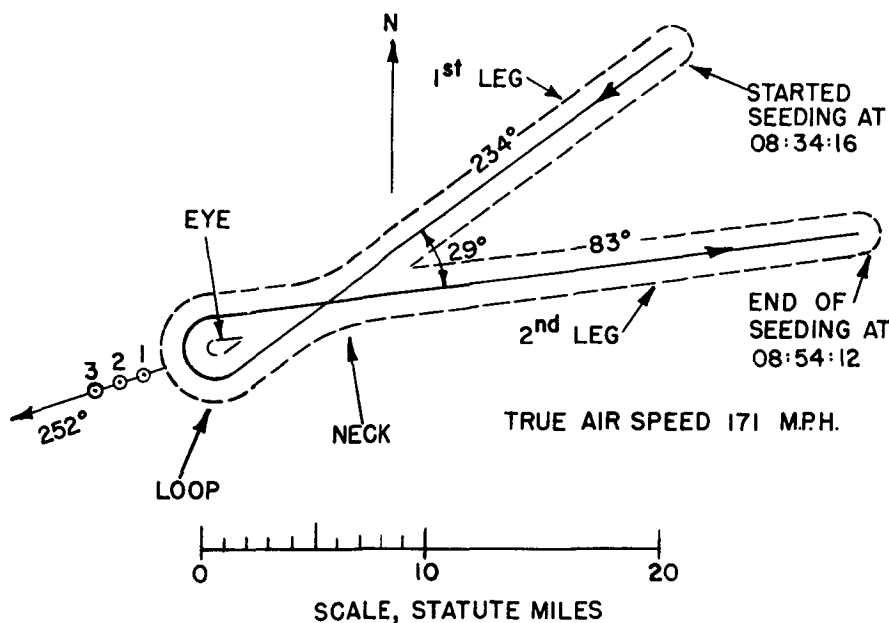
Among the stratus cloud studies made by the project were:

(1) The effect of seeding supercooled stratus clouds with various amounts of dry ice and silver iodide;

(2) The optimum quantity of seeding agent required to produce large cleared areas in an otherwise solid deck of supercooled clouds.

These results were duplicated by several investigators in various locales (78, 79, 80, 81). Vickers and Church (82) conducted an extensive series of experiments to determine the optimum clearing of stratus clouds with dry ice. Among their findings was evidence that seeding effectiveness increased linearly with decreasing cloud temperature and that about 2 kilograms of dry ice per kilometer constituted an optimum seeding rate; 1 kilogram per kilometer was nearly as good, but rates less than .5 kilograms per kilometer were generally ineffective.

The clearing of supercooled fog on an operational basis has been accomplished at many airports around the world (83). Dry ice, liquid CO₂, or liquid propane are customarily employed. In this country the preponderance of fog (~95%) is of the warm fog type (warmer than 0°C) where such nucleants are ineffective.



The dimensions and shape of the seeded Gamma Pattern from photopanel data. The position of the three point drops, 20 grams, 2 grams, and 200 grams, are indicated by the small circles marked 1, 2, and 3 at the left of the loop. The two dashed lines parallel to the seeding track show the approximate maximum development of the modified clouds one hour after seeding.

VI. CUMULUS STUDIES

The most spectacular, fruitful, and controversial results produced by the activities of the project were those resulting from the work on cumulus clouds. This work, which started in the earliest days of the project, continued throughout its duration and led to some other very interesting activities.

Flight tests on November 23 and 29, 1946, were made on isolated cumulus-type clouds. The whole of each cloud was changed into ice within five minutes after seeding, and snow began falling from the base of the cloud (20). But it was realized that experiments with small cumulus clouds were of little interest, for the effects lasted but a few minutes. Other experiments were conducted with cumulus clouds in the early days of the project and, although many of them were made to snow, the results were of comparatively little interest.

By the summer of 1947, however, some spectacular results were obtained with cumulus clouds, especially with thunderstorms. These were so impressive that it was decided to make some studies of cumulus clouds and thunderstorms in New York State's Sacandaga Reservoir territory, not far from Schenectady.

This reservoir is situated just south of the southeast corner of the Adirondack Mountains. Evidence pointed to the probability that this large body of shallow water provides the moisture which feeds thunderstorms in eastern New York State. It was believed that the unusual conditions there could be used to observe the effect of seeding the intense thunderstorms which developed. Actually, no seeding was performed there, although many photographs were taken and considerable time was spent in a study of conditions in that area. It was found that storms elsewhere were better developed and less transient in nature, hence more suitable for field investigations.

HONDURAS

In 1948 and 1949, Langmuir visited Honduras, Guatemala, and Costa Rica to study tropical cloud formations, and particularly to learn what was being done by Joe Silverthorne, a commercial cloud seeder, in seeding clouds for the United Fruit Company. The work was being conducted for the purpose of testing out the possibility of controlling rainfall, and particularly in the hope of stopping blow-downs that result from winds associated with thunderstorms, which occasionally destroy large stands of fruit trees.

At Langmuir's suggestion, Silverthorne tried out a number of experiments early in 1949 and made many worthwhile observations. It was sometimes desired to

produce rain, and sometimes it was desired to prevent rain. On the one hand, by overseeding the top of a high cumulus cloud, rain would be prevented. The top of the cloud would float off to a higher altitude, where it would be blown away by the counter trade wind. If, on the other hand, the cloud was seeded just above the freezing level, heavy rain might be produced. Similarly, water seeding by means of water-filled balloons released from airplanes might dissipate a cloud and produce rain at low altitudes, but it seemed that in such instances dry-ice seeding would be much more effective.

April 18, 1949. The results of the flight on this day, with Langmuir accompanying Silverthorne aloft, were so outstanding as to merit detailed comment (69). The following is extracted from an account of the flight by Langmuir in the Project Cirrus report to the government of July 30, 1951:

"We flew up to Point Sal and found a mass of dry air above the moist air coming from the sea at an altitude of about 6000 or 7000 feet (2.0-2.1 kilometers) From a height of about 8000 feet (2.4 kilometers), looking south, a whole panorama of high cumulus clouds could be seen rising above the smoke, which extended up to about 11,000 or 12,000 feet (3.3-3.6 kilometers) further inland, although it was much lower than this near the sea.

"A large cloud was found which rose, I believe, to a height of about 25,000 feet (8.3 kilometers), and we seeded it by making a series of short passes into the cloud at an altitude of approximately 21,000 feet (6.3 kilometers)--two pellets [dry ice] about one inch (2.5 centimeters) cubed being dropped into the cloud at 50-second intervals during these passes. The whole circuit of the cloud was made, and then the plane moved off a short distance, enabling us to see the effect produced.

"A band around the cloud, perhaps 500 (150 meters) or 1000 feet (300 meters) high, was observed which obviously consisted of ice crystals and which ultimately detached itself from the lower part of the cloud and floated off as a huge mass of ice crystals that could be seen for a long time.

"After the top of this cloud had turned to ice crystals and had detached itself, there was left under this cloud nothing but a group of lower clouds that reached only about 14,000 feet (4.2 kilometers), which was below the freezing level. Later we flew down among these clouds and found that cloud bases had gone down from 12,000 feet (3.6 kilometers) to about 7000 feet (2.1 kilometers). It was difficult to see whether any rain was falling because of the smoke, but from the lowering of the cloud base we concluded that rain had fallen from the lower part, while the top of the cloud had detached itself and floated off towards the northeast.

"Shortly after seeding this cloud with 10 to 12 pellets, we picked out a smaller cloud nearby whose top reached about 20,000 feet (6 kilometers) and dropped one single pellet of dry ice one inch (2.5 cm) cubed on this cloud. About 8 or 10 minutes later we found that this whole cloud had changed to ice crystals. We flew through the ice crystal cloud and verified the fact that they were entirely ice crystals. You could see them blowing into the cabin, and we also found that the cloud gradually dissipated. It probably rained out from the lower part of the cloud but this was done in the smoke level where we could not see it, and the top of the cloud then gradually mixed with the surrounding dry air which had been deprived of its source of supply of moisture from below.

"In other words, on this day we had beautiful examples of two effects that can be produced by seeding with pellets of dry ice. First the seeding of the top of the cloud can cause the top to float off from the lower part. However, in this case some of the ice crystals reach the lower part of the cloud and cause rain to dissipate it. In the other seeded cloud, which was much lower and reached only a few thousand feet above the freezing level, the whole cloud rapidly dissipated as the upper part changed to ice and the lower part rained out."

The results of the flight of April 18 constituted for Langmuir a wonderful demonstration of the effectiveness of single large pellets of dry ice for modifying large cumulus clouds. It quickly became obvious to him that the set-up for carrying out cloud-seeding experiments in Honduras was unique. Silverthorne made flights virtually every day, and, somewhere within a 150-mile (240 kilometer) range, clouds were nearly always found suitable for seeding. Such clouds were almost always orographic and associated with certain mountains.

Many interesting experiments were conducted, and almost always the clouds could be profoundly modified with single pellets of dry ice. The latter part of Silverthorne's seeding operations used 10-20 pellets, presumably to make sure the crystals were more uniformly distributed.

PRIEST RIVER STUDY

Meanwhile the study of cumulus clouds had been approached from another angle. Early in 1948 a visit was paid to the Research Laboratory and Project Cirrus by H. T. Gisborne of the Northern Rocky Mountain Forest and Range Experiment Station, United States Forest Service. Gisborne was in charge of fire research for Region No. 1. He wanted to learn more about cloud modification studies.

This fitted in nicely with Schaefer's interest in the same subject. He was

anxious to study thunderstorms in a good breeding ground, and Gisborne wanted to see if anything could be done to reduce forest fires by thunderstorm modification. As a result, Schaefer visited the Laboratory at Priest River, Idaho, in July of that year (1948). He conducted quite a study of conditions there and made rather complete recommendations for a plan of future activity--a plan which should produce beneficial results from both standpoints: Gisborne's practical aspects and Schaefer's theoretical ones (74, 84).

Actually, the recommendations were never put into effect. A considerable force for the completion of the project disappeared with the death of Gisborne. Although the project is still incomplete, interest still exists, however, both at Schenectady and at Priest River.

In the mid-fifties, the U. S. Forest Service resumed its interest in attempting to modify lightning damage by cloud seeding. Project Skyfire was formed which involved several cooperating groups including Schaefer (then with the Munitalp Foundation). In 1956 a silver-iodide ground seeding program was initiated in Montana in hopes of limiting the size of crystals and the charge separation taking place in deep cumulus clouds. Preliminary results suggested a 33% reduction in the number of lightning strikes but at a statistically insignificant level. Project Skyfire was expanded to include experiments in interior Alaska where, in 1957, more than 5 million acres of forest land were burned by lightning fires (85).

RESULTS IN HAWAII

Further data, supplied from still another source, had some unexpected and very interesting implications and results. Early in 1947 a request for information on techniques of dry-ice seeding was received from the Pineapple Research Institute of Honolulu, Hawaii. This information was supplied by the Research Group of Project Cirrus, which had been supplying similar information to meet numerous requests stimulated by the published reports of the historic snowmaking flight over Pittsfield in 1946. But in this case there was an unexpected aftermath.

In October, Honolulu newspaper accounts were received in Schenectady, describing experiments carried out over the island of Molokai by Dr. L. B. Leopold and Maurice Halstead of the Pineapple Research Institute. A few weeks later, copies of a preliminary report were received from these two men, describing interesting results obtained by dumping dry ice into cumulus clouds having temperatures above the freezing point.

This was an important development. Although Langmuir had given some thought to the effects of seeding nonsupercooled clouds, he hadn't done much about it, and this new work caused him to restudy theoretical calculations he had prepared in 1944 in connection with the work at Mount Washington (86) (p. 4). He now had a new approach to the subject of weather modification: the growth of rain.

RAIN CHAIN REACTION

Prior to and during the period of the Project Cirrus experiments, the prevailing view among meteorologists was that practically all rain of any importance occurred through the action of the Bergeron (ice crystal) process. For a time at least this view was accepted almost without reservation by the scientific staff of Project Cirrus. This assumption, that the Bergeron process was the primary rain-forming mechanism, necessarily engendered the belief that the newly developed techniques of cloud seeding were more effective and foolproof than we now know them to be. As we now recognize, much of the rain that is formed, not only in warm, but also in supercooled clouds, is produced by a rapid droplet collisional process that may or may not involve ice. It is now generally recognized that under certain conditions cloud seeding might possibly decrease rather than increase the formation of precipitation, by turning the cloud to ice crystals and thereby preventing an efficient drop coalescence or accretion process from taking place. The Hawaiian observations of the acceleration of rain production in a nonsupercooled cloud and the subsequent observation of warm cloud precipitation in Puerto Rico kindled the interests of Project Cirrus in rain formation in warm clouds and led to Langmuir's formulation of the chain reaction theory of rain formation which follows.

A typical large drop of water grows in size as it falls through the cloud, growing faster and faster until it gets so big that it breaks up, producing smaller droplets. If there are rising air currents, the little droplets will be borne aloft into the cloud again, growing in size as they go, until they get so big that they start falling again. This process continues in a chain reaction, causing the whole cloud to produce heavy rain. Under the right circumstances, according to this theory, seeding with water would be just as good as with dry ice (87).

It was recognized that the ambient cooling effect of dry ice was not

instrumental in any possible modifications of warm clouds. Rather the frost that forms on dry ice was believed to melt after the dry ice had sublimed, leaving large droplets to seed the cumuli.

The outgrowth of this, in turn, was considerable work by Project Cirrus to test Langmuir's theory and apply some of its principles in practice. For example, to determine the validity of several of the important phenomena which his theory postulated, extensive laboratory studies were conducted on the growth of water droplets and of the behavior of droplets floating in the air (65, 88). Later, the Research Group did considerable work in the study of the drop size and size distribution of various types of precipitation (89, 66).

As another approach to the subject, an extensive series of experiments was conducted to explore the possibility of inducing precipitation or other modification in growing cumulus clouds by water seeding (69).

The complete exposition of the theory by Langmuir was a beautiful example of theoretical analysis and mathematical calculation (87). Among other things, it reviewed the knowledge of cloud physics which had already been gained in the light of the new theory, summing up the probable behavior of both stratus and cumulus clouds. It went so far as to suggest that the chain reaction could, under the right conditions, be started by introducing even a single drop of water into a cloud, although the action would be most rapid when many large drops were introduced near the top of the cloud. It outlined the probable behavior of self-propagating storms. It postulated that the phenomena that occur in artificial seeding with dry ice or with water are essentially no different from those that occur spontaneously in nature. "However," it went on, "there will frequently be cases where the cloud is not yet ready or ripe for spontaneous development of snow or rain, although it may be possible to produce these effects by seeding." It concluded with the following summary:

"When we realize that it is possible to produce self-propagating rain or snow storms by artificial nucleation and that similar effects can be produced spontaneously by chain reactions that begin at particular but unpredictable times and places, it becomes apparent that important changes in the whole weather map can be brought about by events which are not at present being considered by meteorologists. I think we must recognize that it will probably forever be impossible to forecast with any great accuracy weather phenomena that may have beginnings in such spontaneously generated chain reactions."

Langmuir's chain reaction hypothesis relating to the continuous breakup of large raindrops was largely ignored for the next decade or two. Ironically, at the First International Conference on Weather Modification in 1968, sponsored by the American Meteorological Society, several independent investigators and papers dealt with this subject. Thus, there is revived interest in and more acceptance of the mechanism (91), although clear-cut experimental evidence is still lacking (92).

STUDIES IN PUERTO RICO

All these studies and tests which had been made, and theories which had been evolved as a result, with regard to the nature, behavior, and modification of cumulus clouds were an important background to another significant milestone in the history of Project Cirrus. That was the expedition to Puerto Rico in February, 1949 (90).

The objective of this trip was mainly to determine the type and physical characteristics of the clouds that occur in Puerto Rico during the winter months, particularly the month of February, and, if suitable clouds were encountered, to develop and possibly to evaluate water-seeding techniques. Considerable personnel took part in the project, a supply of planes was available, and a large quantity of photographs was made.

At least two new precipitation sequences were observed, and considerable data were accumulated to permit a better understanding of the processes involved. Also studied was the trade wind inversion, a dominant feature which controls cloud and precipitation development in the West Indies region during February. A better understanding of this phenomenon should lead to a better understanding of tropical meteorology.

The cumulus clouds were observed to have a different character than those common in the eastern United States. Contacts made with interested local people in Puerto Rico were expected to lead to the accumulation of some excellent supplementary data on raindrop size, convergence of winds, and the observation of double orographic cloud streams from the Liguillo Mountains.

The carrying out of successful ground-air operations on three different occasions, using time-lapse photographs as part of the ground coverage, demonstrated conclusively to the members of the project the value of carrying out such studies of clouds which develop in definite cloud-breeding regions. Similar regions in the United States known to possess such developments were Albuquerque, New Mexico, and Priest River, Idaho. Schaefer had already visited Priest River, and arrangements had been made for investigations and experiments there.

Also, a test mission had been conducted at Albuquerque the previous year, details of which will be found in the next section of this report.

Despite the fact that no suitable clouds were found for testing out water-seeding techniques during the period, many valuable results were obtained which it was expected would lead to a much better understanding of the formation of rain in tropical clouds. One of the very significant results of the expedition was the observation of the important effect of salt nuclei on the formation of precipitation in thin tropical clouds. Said one of the reports: "This seems, on first sight, to be of great importance in explaining the rain showers which are of daily occurrence and random distribution in the vicinity of Puerto Rico. Rarely is rain observed from such clouds in the eastern United States." Said Langmuir:

"Observations in Puerto Rico in 1949 and in the Hawaiian Islands in 1951 have shown that the rainfall depends on relatively large particles of sea salt in the air, in accord with the publications of A. H. Woodcock and Mary Gifford. Calculations of the rate of growth of salt particles indicate that it should frequently be possible to induce heavy rainfall by introducing salt into the trade wind at the rate of about one ton per hour in the form of fine dust particles of about 25 microns in diameter. The heat generated by the condensation may liberate so much heat as to produce profound changes in the air flow and the synoptic conditions in neighboring areas" (93).

Several groups subsequently have experimented with the seeding of warm clouds with water to stimulate precipitation, the most notable effort being that of the University of Chicago (94). Clouds were seeded from above with water drops (median diameter of 250μ) at reported rates of 300 liters and 1000 liters per kilometer in both Puerto Rico and the central United States. While neither seeding rate produced observable radar echoes in the United States, the higher rate did show a statistically significant increase in precipitation in Puerto Rico. Thus some positive results were obtained in maritime clouds, but the amount of water required to "prime the pump" was considered impractical.

More feasible is the concept of releasing large ($10-20\mu$) salt particles into the cloud updraft to produce large drops capable of stimulating droplet growth by coalescence. Initial experiments were conducted by Mordy et al. (95) in Hawaii. Encouraging calculations by Bowen (62) were followed by further trial experiments in East Africa (96),

later in India (97, 98) and recently in the United States (91). The Indian experimenters suggested that a 20% increase in rainfall might be expected in summer monsoon conditions.

EARLY WORK IN NEW MEXICO

Although interest in cumulus clouds and thunderstorms was high among the members of the Research Group in 1948, the cumulus season passed in the vicinity of Schenectady without any significant flights having been carried out. It was realized that the best results could be obtained from the seeding of cumulus clouds in a region where storms originate rather than in a region which, like the Schenectady area, is traversed by storms. Chairman Stine of the Operations Committee had experience as a forecaster in New Mexico, and he strongly recommended that region as a base for experiments with cumulus clouds. This recommendation was seconded by Schaefer, who knew of the work being done in this field by Dr. E. J. Workman's group at the New Mexico School of Mines and who had obtained a promise of cooperation from Workman.

Accordingly, it was decided to attempt a flight to Albuquerque, New Mexico, to determine whether the radar and other facilities of Dr. Workman's group would be of assistance in this respect. In view of the waning cumulus season even at the location, preparations were made to carry out full-scale tests if proper clouds were formed. As a result, members of the project spent three days at Albuquerque during mid-October of 1948. A working arrangement was quickly made with Workman and his staff for radar tracking and photography of the tests to be made. Two seeding flights were made, one on October 12 and the other on October 14. The second of these two flights was performed under such satisfactory conditions that the results obtained were considered particularly significant (99).

For example, an exceptionally complete aerial photographic record was made of the conditions of the cloud that was seeded from one of the planes, including 176 photographs 10.1 X 12.8 centimeters, plus pictures taken every 45 seconds of a group of instruments giving time, altitude, air speed, heading of the plane, and other pertinent information. Every time a photograph was taken of the cloud, another picture would be taken of a clock and the other instruments. In this way an invaluable flight record was made of the test.

Further data were collected on the ground. Time-lapse movies were made of the clouds as seen from the station, as well as a series of still pictures, and radar was used to detect any rain that might fall. Although some excellent supporting data were thus obtained, unfortunately it was not as complete as it might be, because of a failure of the radio

communications between the airplane and the radar station. But significant radar observations were made, and photographs were taken of the radar scope, giving a complete set of records of radar observations for a considerable period of time.

Four seeding operations were conducted on the October 14 flight. The details of these seedings and the results obtained were discussed at considerable length by Langmuir in an occasional report (99). His findings indicated that rainfall was produced over an area of more than 100,000 square kilometers as a result of the seeding--about a quarter of the area of the State of New Mexico. And substantially all of the rain for the whole of New Mexico that fell on October 14 and 15 was concluded to be the result of the seeding operations near Albuquerque on October 14. "The odds in favor of this conclusion as compared to the assumption that the rain was due to natural causes are many millions to one."

An early estimate by Langmuir was that about 100 million tons of rainfall was produced. Later, using the rain reports from 330 stations given in a U. S. Weather Bureau publication, he concluded that the original estimate was unduly conservative (99). Said he: "The evidence indicated that the rain started from near the point of seeding shortly after the time of seeding and then spread gradually at a rate which at no place exceeded 10 meters per second, over an area of at least 31,000 square kilometers north to northeast of Albuquerque with an average of about 0.89 centimeters. This corresponded to about 300 million tons."

SILVER IODIDE AT NEW MEXICO

So satisfactory were the tests conducted at Albuquerque in 1948 that it was decided to make a further study of cumulus clouds at that location in the middle of July the following year. Much more elaborate plans were made for this second expedition; for example, not one but a number of airplanes took part, and virtually all the members of the Research and Operations Groups went along.

Prior to the arrival of the main body of the project, Langmuir and Schaefer investigated the general cloud situation in the various mountain regions nearby and decided the cloud systems along the Rio Grande Valley near Albuquerque were superior for their purpose to anything they could find in other parts of Arizona and New Mexico. In addition, the excellent radar, photographic, and shop facilities of the Experimental Range of the New Mexico School of Mines appeared to be ideal for carrying out the operations planned.

Between July 13 and July 22 a total of ten flights was conducted, on eight of

which two or three planes participated. Excellent cooperation was enjoyed in every phase of the operation, and an extensive mass of data was obtained both in the air and at the ground stations which were set up. Seeding operations with varying amounts of dry ice and the ground operation of a silver-iodide generator were the subjects for the flight studies (75).

Again the dry-ice seeding was successful, and the results of the various airborne seeding operations were quite satisfactory. But a new factor was introduced into this second expedition which put an entirely different aspect upon the results and had a tremendous influence on the course of future investigations and analysis. This was the effect of ground seeding with silver iodide.

As usual, close attention was paid to changes in weather conditions, in order to observe any correlation between such changes and the dry-ice seeding. Although Vonnegut was conducting some silver-iodide seeding on the ground, this was disregarded by Langmuir, who was concentrating on the airborne dry-ice seedings. Consequently, when he noticed some weather conditions which could not be explained by the airborne seeding, he was puzzled. Then he suddenly became conscious of the fact that Vonnegut had been trying to call the ground seeding of silver iodide to his attention, and he immediately realized that this might explain the discrepancies he had observed. Further study convinced him that this was, indeed, the case.

Not only that, but the results of the seeding activities in New Mexico the preceding year were reconsidered in the light of this development. And it appeared reasonable to conclude that the similar widespread effects produced in October, 1948, were the result of the silver-iodide seeding which was done at that time, rather than of the dry-ice seeding, which had been the previous interpretation.

Langmuir made, as was his habit, an exhaustive analysis of the available data and presented a striking summary of his findings (75) from which the following is quoted:

"I wish particularly in this paper to describe the more widespread effects that were produced by the operation of the silver-iodide generator on the ground during July, 1949, near Albuquerque. The first seeding with silver iodide during this stay in New Mexico was on July 15, 1949, but the generator was not run for more than a couple of hours on each day thereafter until the 19th, when it was operated for a short time only, late in the afternoon. On July 20 it was not operated at all, but on the 21st it was operated for 13 hours, starting about 5:30 a.m. and using 300 grams, or a total of 2/3 pounds of silver iodide.

"Tests made by Dr. Vonnegut have shown that each gram of silver iodide dispersed

under these conditions produced 10^{16} sublimation nuclei that are slowly effective at -5°C but very rapidly effective at -10°C .

The statement concerning the number of nuclei per gram that would be effective at -5°C was not based on actual measurements of the number of nuclei effective at this temperature. Instead, it was an extrapolation founded on the suggestion by Vonnegut that, if given enough time, all the nuclei becoming effective at -20°C would also eventually initiate ice crystals at -5°C (see annotation, page 19).

This estimate of the number of particles active at -5°C is probably much too high. Even granting the assumption that the nucleation process is stochastic, it is likely that most of the particles will either be precipitated or deactivated long before they serve as ice nuclei. A more realistic estimate can be based on cold box measurements [see Fletcher (100)]. These show that a well designed aerosol generator that produces 10^{16} particles per gram effective at -20°C and approximately 10^{15} per gram at -15°C will yield only about 10^{11} effective nuclei per gram at -5°C .

"The new probability theory....has served [as] a valuable guide in devising an objective method of evaluating the distribution in space and time of the rain which follows the operation of the silver-iodide generator on the ground or in the airplane flights near Albuquerque. To illustrate the results, we will analyze the data obtained on two days, October 14, 1948 (Flight 45) and July 21, 1949 (Flight 110).

"These days were chosen because large amounts of silver iodide were used, but no seeding was done on the immediately preceding days. Furthermore, the wind direction on both days was rather similar. On both days the Weather Bureau predicted no substantial amount of rain. Both mornings were nearly cloudless, and on both days SW winds prevailed from the cloud bases at 12,000 feet (3.6 kilometers) up to 20,000 feet (6 kilometers). At lower and higher altitudes and later in the day there were also winds from the E, W, and NW. On both days, visual effects indicated thunderstorms and heavy rain over wide areas were observed a few hours after the start of the seeding operations.

"In the July operation our techniques had been improved compared to those of the preceding October. In October radar observations covered only a period of about an hour in the afternoon, for at that time it was not suspected that the rain that lasted well on to the morning of the 15th had anything to do with the seeding.

"On July 21, 1949, however, we had complete radar coverage from early in the morning until late at night. Photographs of the clouds were taken not only from planes but from the ground, including time-lapse motion pictures with photographs every few seconds.

"Shortly before 8:30 a.m. on July 21, 1949, a single large cumulus cloud began to form about 25 miles (40 kilometers) S of the field station near Albuquerque in a sky that was otherwise cloudless. This cloud was located near the Manzano Mountains, and the silver-iodide smoke had been blowing from the N about 10 miles per hour (4.5 meters per second) so that it should have reached the position of the cloud.

"Between 8:30 and 9:57 the cloud grew in height slowly at the uniform rate of 160 feet per minute (.81 meters per second). At 9:57, when the top of the cloud was at 26,000 feet (7.8 kilometers) (temperature -23°C), the upward velocity of the top of the cloud increased quite suddenly, so that the cloud rose 1200 feet per minute (6 meters per second) until at 10:12 it had reached 44,000 feet (13.2 kilometers) (temperature -65°C).

"At 10:06, when the top of the cloud was 36,000 feet (10.8 kilometers) (temperature -49°C), the first radar echo return was obtained from the cloud at an altitude of 20,500 feet (6.2 kilometers) (temperature -9°C). The distance given by radar was 25 miles (40 kilometers) at an azimuth of 165° , which was exactly where the cloud was found to be from visual observations. The area of precipitation in the cloud was about one square mile at that time and was deep within the mass of the cloud. Within four minutes, the precipitation area had increased to seven square miles (18 square kilometers), and within six minutes after the first echo appeared, the precipitation had extended upward to 34,000 feet (10.2 kilometers), where the temperature was -43°C .

"The chain reaction in this cloud started at low altitude at a time and place which agreed well with the trajectory of the silver-iodide smoke.

"The first flash of lightning was seen at 10:10, four minutes after the first radar echo was detected. In all, perhaps a dozen flashes of lightning formed from this cloud, and very heavy rain was seen to fall to the ground. The top of the cloud moved towards the W, but the lower part of the cloud, from which the rain was falling, moved gradually to the NE.

"At 10:45, a second cloud about eight miles (13 kilometers) still further to the NE developed a radar echo, and from that time on during the day there was an increasing number of rainstorms giving very heavy showers in the neighborhood. During the late afternoon 1.2 inches (3 centimeters) of rain fell at the station where the generator was located.

The phenomena observed near and at Albuquerque from the ground and the radio reports of exceptionally heavy rain at Santa Fe gave immediate evidence of the success of this operation in producing heavy rain."

Langmuir's report then analyzes river flow data and rain gauge data for the region. In discussing the rain gauge data, he says:

"The Weather Bureau observer with Project Cirrus in New Mexico stated that he considered it possible or even probable that seeding operations carried on there could have increased the naturally occurring rain by five per cent, but certainly not more than 10 per cent. If this were true, it would be possible to conclude that seeding operations have economic value only if experiments are carried on many hundreds of days, and a statistical analysis is made of the rainfall data for all of these operations.†

"The rainfall data actually show, however, that the rainfall on both October 14, 1948, and July 21, 1949, was exceptionally high and could not have possibly been accounted for as the result of naturally occurring rain. This proof is made by the analysis described in this paper.

"The map of the State of New Mexico, which represents about 120,000 square miles (307,000 square kilometers), was divided into eight octants or 45° sectors radiating out from Albuquerque. Then concentric circles having radii of 30 (4.8 kilometers), 75 (120 kilometers), and 125 (200 kilometers) and 175 miles (280 kilometers) were drawn on the map. This divided the whole state into 27 regions whose average distances and directions from Albuquerque were known.

"By entering on the map for each of these regions the average rainfall for Flights 45 and 110, a comparison could be made of the distribution of the rain on those two days. An objective way of evaluating the similarity between such two distributions is to employ the statistical device known as the correlation coefficient. This was found in this case to be $+0.78 \pm 0.076$. The chance that such a high value would occur among these figures if one set of them were shuffled giving a random distribution on two days could thus hardly be the result of chance. There must be an underlying cause.

"We believe that the close similarity in distribution is dependent not only on the rather uniform synoptic situations over the states that prevailed on these days, but also depended on the fact that on both days the probability of rainfall depended on the nuclei that spread radially out from Albuquerque, the

†A prophetic negative statement that now appears to be the rule rather than the exception.

concentration decreasing as the distance from Albuquerque increased.

"The next step was to investigate just what characteristics of this distribution were so similar on these two days. On each of the two days, nearly all of the rain that fell occurred within four of the eight octants. If each sector were divided into four to six parts arranged radially so that each would contain equal numbers of observing stations (about eight per region), the analysis showed that the average rainfall rose rapidly to a maximum in intensity about 30 miles (48 kilometers) from the point of seeding and that in each of the four sectors it decreased regularly as the distance from the source of the silver-iodide smoke increased. In fact, this decrease followed quite accurately equations (2) and (3), which indicated that the rainfall depended on the concentration of nuclei, and this, in turn, varied inversely in proportion to the distance from the source.

"This analysis makes it possible to separate the effects of the artificial silver-iodide nuclei from that of the background of sublimation nuclei that were already present in the atmosphere.

".....We must conclude that nearly all of the rainfall that occurred on October 14, 1948, and July 21, 1949, was the result of seeding.

"The agreements between the intensity of the average rainfall in separate regions and the theoretical equations were so good in each of the four sectors on October 14 and July 21 that the probability factors for each sector ranged from 10^2 to 10^3 . Taking all the octants together, the probability factor rose to about 10^8 to 1.

"For each of the eight octants that gave appreciable rain, the rain started progressively later as the distance from the source of the silver iodide increased. The advancing edge of the rain area thus moved from Albuquerque on July 21 at a velocity of about 14 miles per hour (6.3 meters per second) and on October 25 at a speed of about 25 miles per hour (11 meters per second). These velocities agree well with the wind velocities observed at various altitudes.

"The method of correlation coefficient can be applied to the relation of the time of the start of the rain to the distance from Albuquerque. This indicates that there is another probability factor which is the order of 10^8 to 1.

"Taking these results altogether, it seems to me we may say that the results have proved conclusively that silver-iodide seeding produced practically all of the rain in the State of New Mexico on both of these days.

"I have not mentioned what happened on the other days. The results, although somewhat more complicated due to the overlapping of the effect of seeding on successive days, are almost as striking as those of Flights 45 and 110, in which

we used silver-iodide seeding. Very high probability factors are found, which help confirm the results indicated by the analysis of Flights 45 and 110.

"The total amounts of rain that fell in the state on the two days as a result of seeding were found to be 800 million tons on October 14, 1948, and 1600 million tons on July 21, 1949. If these units are not so familiar to you, I may say that on October 14, 1948, the total amount of rain resulting from seeding was 160 billion gallons and on July 21, 1949, 320 billion gallons.

"Dr. Vonnegut has measured the number of effective sublimation nuclei produced by the type of silver-iodide smoke generator used in our New Mexico experiments for each gram of silver iodide used....One thus finds that, to get a 30-percent chance of rain per day within a given area in New Mexico, the cost of the silver iodide is only \$1 for 4000 square miles (10,000 square kilometers).

"If similar conditions prevailed over the whole United States, the cost per day to double the rainfall would be only of the order of a couple of hundred dollars. This verified an estimate that I made in November, 1947, in an address before the National Academy of Sciences that 'a few pounds of silver iodide would be enough to nucleate all the air of the United States at one time, so that it would contain one particle per cubic inch (60 per liter), which is far more than the number of ice nuclei which occur normally under natural conditions.' Such a distribution of silver-iodide nuclei 'in the atmosphere might perhaps have a profound effect upon the climate'."

The report then discusses a new theory which Langmuir had developed of the rate of growth of snow crystals in supercooled clouds containing known numbers of sublimation nuclei. After a brief exposition on the basis of this theory, he says:

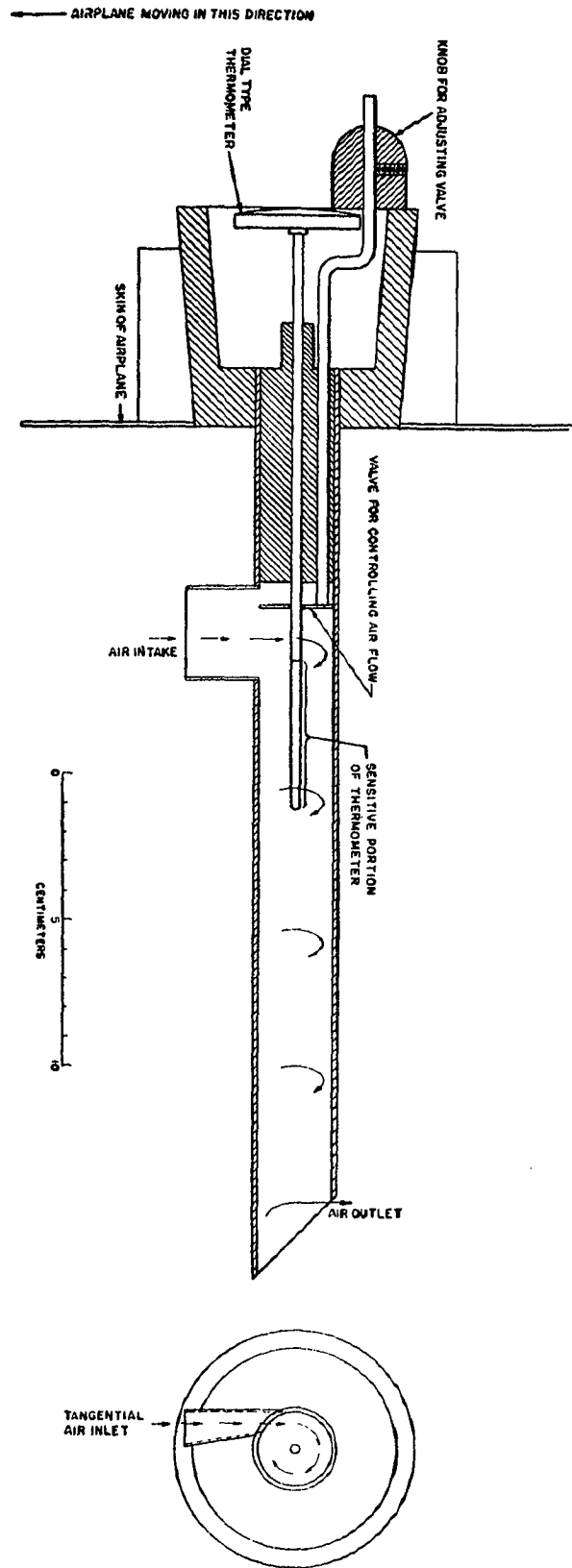
"From the probability theory of the growth of showers from artificial nucleation, one obtains the result that the total amount of rain produced by operating a ground generator increases in proportion to the square of the amount of silver iodide used. Thus, with three times as much silver iodide one would get nine times the rainfall. The intensities of the showers would be no greater, but they would extend over a greater area.

Virtually all recent precipitation augmentation experiments refute the dramatic rainfall increases suggested above. The effects induced by cloud seeding have proven to be extremely complex, and they vary with locale, season, stage of development of a cloud, and the dominant precipitation mechanism(s) governing specific clouds. It is now known that seeding can reduce rainfall (101) as well as increase it, with maximum

increases generally being of the order of 10-20 percent--National Academy of Sciences Report 1350, 1966.

"It is very important that regular tests on certain selected days of each week be carried out throughout the year, using amounts of seeding agents just sufficient to obtain conclusive statistical data as to their effectiveness in producing widespread rain. It is to be expected that the results will vary greatly in different parts of the country, because of the changes in synoptic situations."

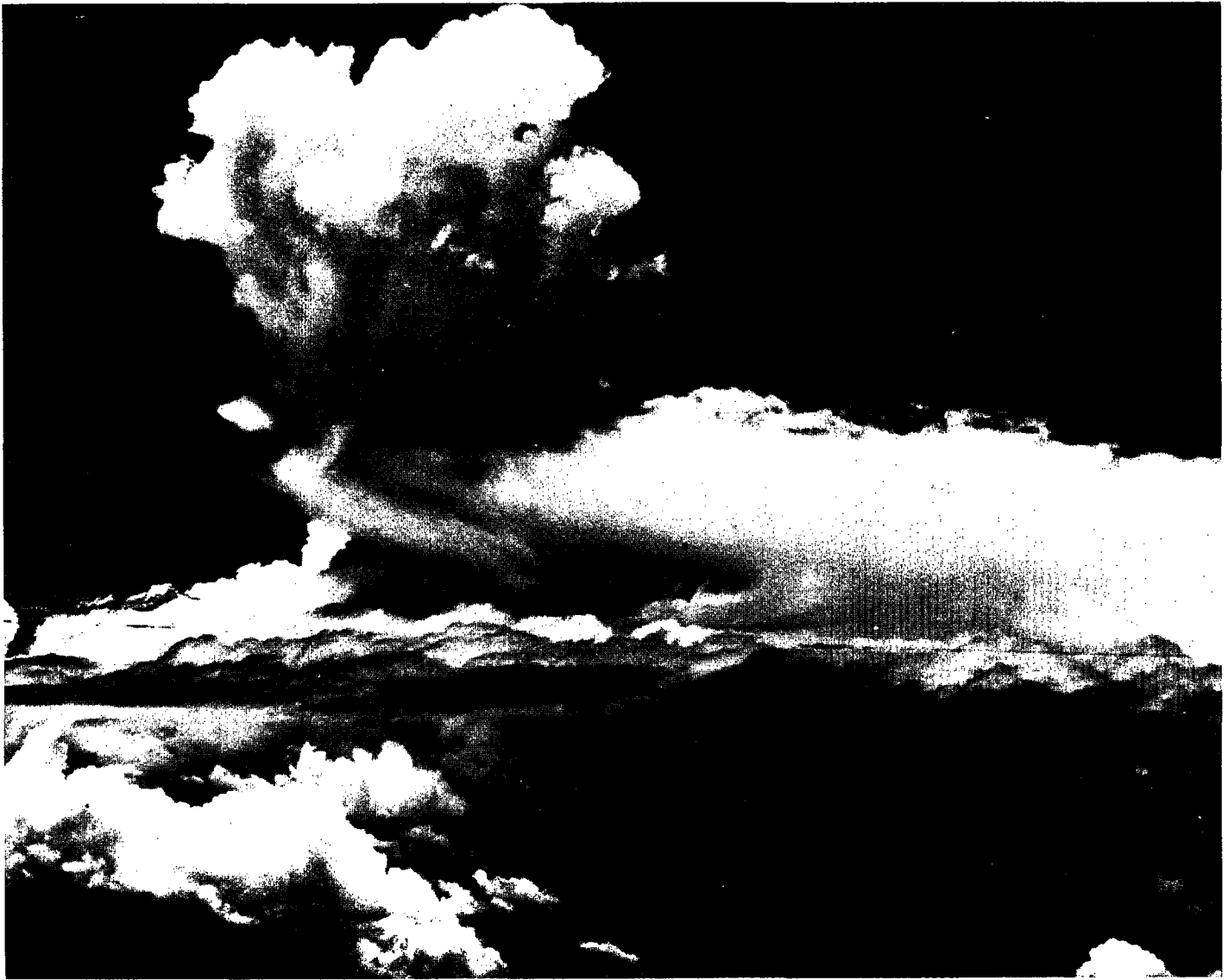
The significance of the two test projects at New Mexico is thus apparent. They indicated not only the possibilities of silver-iodide seeding from the ground, but they suggested a widespread effect on the weather of the nation. And, as a result, the project conducted some experiments in periodic seeding which were destined to have a profound--and controversial--significance.



Vortex Thermometer



New Mexico Cumulus Before Seeding. On a July morning in 1950 near Socorro, New Mexico, these small cumulus clouds at 15,000 feet were the only ones to be seen. At 9:58 a.m. one of these clouds, about 15 miles from Socorro, was seeded by making one pass through it at 2,500 feet above the base with a spray nozzle silver iodide burner in operation.



Cumulus Cloud After Seeding. The cloud tops soon changed from a hard white appearance to a grey cirrus-like structure. In 20 minutes it had grown greatly in size.



Fully Developed Seeded Cloud. The cloud continued to grow, and in a little over an hour it had become a small thunderstorm, producing rain. On the same day some distance away seeding with dry ice produced similar results.

VII. PERIODIC SEEDING

NEW MEXICO WORK

By this time, a rather close liaison had been established with Workman and his co-workers at the New Mexico School of Mines. So, in view of the significance of Langmuir's analysis of the effects and possibilities of silver-iodide ground seeding, and in order to test as soon as possible his ideas on periodic seeding, a schedule of operations on this basis was established without further ado at New Mexico.

Starting in December, 1949, a silver-iodide ground-based generator was operated there on a schedule so planned as to introduce, if possible, a seven-day periodicity into the weather cycles of the nation. Seeding was performed eight hours a day on Tuesday, Wednesday and Thursday of each week. This schedule of regular weekly periodic seedings used about 1000 grams of silver iodide per week, and it continued with a few modifications until the middle of 1951.

Data were gathered by Falconer, and almost immediately Langmuir found evidences of a definite weekly periodicity in rainfall in the Ohio River Basin. Again, he conducted an exhaustive analysis of the facts and performed mathematical calculations to determine the probabilities that these variations in weather could have taken place by pure chance.

He reported his findings and his conclusions to the National Academy of Sciences, October 12, 1950 (102); to the American Meteorological Society of New York City on January 30, 1951 (102); and also to the New York Academy of Sciences on October 23, 1951 (93). He pointed out that, during 1950, there was a marked and statistically highly significant seven-day periodicity in many weather elements. The significance was so high, said he, that it could not be explained on the basis of chance and could not have occurred from natural causes. The analysis involved not only rainfall but also pressure, humidity, cloudiness, and temperature over much of the United States.

In his paper to the New York Academy of Sciences (93), Langmuir said:

"Almost immediately, that is, during December 1949 and January 1950, it was noted that the rainfall in the Ohio River Basin began to show a definite weekly periodicity. A convenient way of measuring the degree of periodicity was to calculate the correlation coefficient CC between the rainfall on the successive days during a 28-day period, with the sine or the cosine of the time expressed as fractions of a week, the phase being taken to be 0 on Sundays.

"Just before the start of the periodic seedings, the correlation coefficient CC(7) based on the seven average values for the successive days of the week of the 28-day period amounted to only 0.23, but in the next 28-day period the value of CC(7) rose to 0.91.

"Table 1 gives the average rainfall in inches per station day during 140 days at 20 stations designed as Group A in the Ohio Valley Basin, representative of an area of about 600,000 square miles (1,500,000 square kilometers). The successive rows correspond to five successive 28-day periods. It will be noted that the average rainfall on Monday was 0.272", whereas on Saturday it was only 0.064", a ratio of 4.3:1. The next to the last column gives CC(28), the periodic correlation coefficients for each 28-day period, and the last column gives the phases in the successive periods. Taking the 35 separate values for the 4-week averages given in the table, one gets $CC(35) = 0.689$ with a phase of 1.60 days. This result is statistically highly significant.

"These periodicities in rainfall were evident at almost any set of stations in the northeastern part of the United States. Table 2 gives the rainfall on successive Tuesdays and Saturdays during a 12-week period during the winter of 1949-1950 at Buffalo, Wilkes-Barre, and Philadelphia. This periodicity is almost the same as that found in the Ohio River Basin but with a one-day phase lag. The striking contrast between the total rains on Tuesdays and Saturdays runs parallel to the total number of days on which rains of 0.1" (2.5 millimeters) or more occurred on Tuesdays and on Saturdays.

"Maps have been prepared giving for 24 successive 28-day periods the distribution of correlation coefficients, CC(28), among 17 subdivisions of the United States, these data being based on daily weather reports of 24-hour rainfall at 160 stations. During the first five 28-day periods there were always several adjacent subdivisions that showed high weekly periodicities in rainfall. After May 1950, however, the periodicities became somewhat sporadic, although highly significant periodicities over large areas still occurred during more than half of the periods after July 1950. Presumably the large amount of commercial silver-iodide seeding in the western states (not done with a weekly periodicity) masks the effects of the periodic seedings in New Mexico. By a map, the areas were shown in which known seeding operations have been carried on in 1951. In 15 states west of the 95° W meridian (excluding Texas) about 550,000 square miles (1,410,000 square kilometers) or 37 percent of the total area of these states were under seeding contracts during 1951.

"Maps for the months from December 1949 through 1950, taken from the

Monthly Weather Review, illustrated the distribution of abnormally large rainfalls over the United States. The heavy rains nearly always occurred in a band extending from the southwestern to the northeastern states.

"An analysis of the periodicity in the rainfall induced by periodic seeding was presented in a paper read October 12, 1950, before the National Academy of Sciences. The areas having a high weekly periodicity were generally the same as those showing the highest abnormalities in rainfall. Such heavy rains can only occur if the winds and the barometric pressures cause an adequate supply of moisture to flow from the Gulf of Mexico. The periodicities in the pressure differences between Corpus Christi and Jacksonville were studied. During the first 140 days after seeding began, there was a highly significant weekly periodicity indicating a periodic air flow from the Gulf.

"The upper air temperatures, even up to the stratosphere, showed a high weekly periodicity over more than half of the United States. Nine stations representative of an area of 1,300,000 square miles (3,300,000 square kilometers) gave 950 mb temperatures having CC(28) greater than 0.5. These data were published, in detail for Chicago and in summary for eight other stations, in the Dec. issue of 'The Bulletin of the American Meteorological Society', and a statistical analysis was given which proved that these periodicities were highly significant. Mr. William Lewis and Mr. E. Wahl, Bull. Amer. Met. Soc. 32:192-3 (1951), and Mr. Harry Wexler, Chem. Eng. News 29:3933 (1951), maintained, however, that these data on the periodicities in temperature were not truly significant and similar weekly periodicities have frequently occurred in the past.

"The degree of periodicity in upper-air temperatures observed in 1950 during April, July, and November shows a statistical significance of a much higher order of magnitude than those referred to by Lewis, Wahl, and Wexler. To illustrate this, an analysis has been made of the temperatures at the 700 mb level at nine stations in the United States at the intersections of the 80, 90, and 100° W meridians with the 35, 40, and 45° N parallels.

"The value of CC(28) at these nine points of intersection ranged from 0.50 to 0.85. The area represented is 1.5 million square miles (3,800,000 square kilometers).

"Recently we have extended this grid of regularly spaced stations to include the intersections of the 45°N parallel with the 70°W and 110°W meridians, these points giving CC values of 0.66 and 0.65 respectively. The 30°N, 80°W intersection just off Jacksonville, Florida, also gave a correlation of 0.65. We thus have an area of two million square miles or 2/3 of the area of the United States in

which CC(28) exceeds 0.50 with a mean value of CC(28) = 0.67.

"We have also examined these periodicities at corresponding points for preceding and for following periods. The 28-day period in May showed low correlations. On the other hand, the two preceding periods gave highly significant values. Apparently the high periodicity in the upper air temperatures started about January 25, 1950, and continued on until about May 1, 1950, covering an average area of about half of the United States.

"For the nine points of intersection during a 28-day period in April, 1950, the total variance of the temperature was determined by taking the total sums of the squares of the deviations of these temperatures from their mean and dividing by 27, the number of degrees of freedom. The data obtained in this way are called the 'total variance'. By multiplying these values for each of the nine stations by the corresponding square of the correlation coefficient CC(28), one obtained the 'periodic component of the variance'.

"Exactly similar calculations were made for a 28-day period in April, 1949, when there was no periodic seeding..... The average values for all these nine points show that the 'periodic variance' in 1950 was 18 times as great as in 1949.

"Table 4 gives the corresponding values of the 'residual component of variance' obtained by subtracting the 'period variance' from the 'total variance'. These data then indicate how all the other kinds of periodicities, beside the seven-day periodicity, compared with one another in the two years. It will be seen that there is only about 10 percent difference between the average variance of this type for 1950 and 1949.

"It seems, therefore, that the temperature fluctuations in 1950 essentially differed from those in 1949 only in the superimposition of an extremely high seven-day periodicity."

As indicated in this extract, Langmuir's conclusions were contested by representatives of the United States Weather Bureau.

EASTERN U. S. WORK

In addition to the periodic seeding conducted in New Mexico, similar seeding was initiated in the Schoharie Valley, New York, and at the base of Mount Washington. An interesting result of the seeding at Mount Washington was observed by Joseph B. Dodge, who has charge of the Appalachian Mountain Club lodges in the White Mountains for skiers and mountain climbers. Dodge, who knew nothing of the seeding, pointed out that, judging by the maps of snow coverage in Maine and New Hampshire there were two bands of snow running at a

diverging angle in the direction of those two states and coming to a point back at Mount Washington. This was a season in which there was not much snow, but along the line of these two bands there had been exceptionally heavy snow. The results of further study indicated that the lack of snow may have been caused by overseeding, but that along the two lines of heavy snow there had been just a light amount of seeding.

LATER PERIODICITY

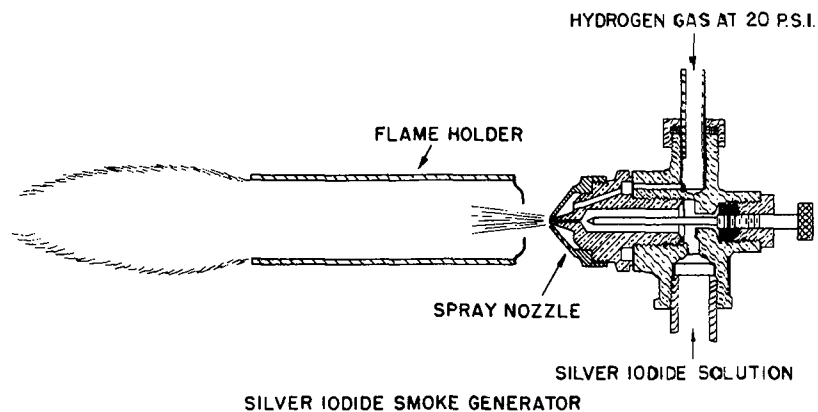
Early in 1952, during the course of their normal analyses of weather conditions throughout the United States, Falconer and Maynard again found evidence of periodicity. Further study showed that the periodicity was on a seven-day basis and that it progressed regularly from west to east. The correlation coefficients were calculated by Maynard and found generally to be of a very high order. For one 28-day period the correlation coefficient was the highest so far obtained for the country as a whole.

It was thought possible that this phenomenon might be caused by a corresponding periodicity in the commercial seeding going on in various parts of the west. Inasmuch as the periodicity in the weather progressed uniformly across the United States, it was possible to trace it on a map back to a likely point of origin. The commercial seeding organization active in that area was then asked by Schaefer for a schedule of its seeding operations, which it willingly furnished. It was found that the commercial seeding had a periodicity corresponding to that observed in the weather.

Langmuir, in analyzing the data thus obtained, observed that it would be difficult to determine cause and effect. In other words, it would be difficult to know whether the periodicity in weather was caused by periodic seeding or vice versa, for commercial seeding organizations generally do not seed at any random time but rather choose for seeding those days when weather conditions are propitious. If the conditions are "good" for the production of rain, the operator seeds. As a result, although it might rain naturally, the seeding may increase the quantity of rain--and it may produce rain when none would have fallen naturally. On the other hand, if conditions are not right for rain, the operator does not seed, for seeding will not produce rain except when meteorological conditions are suitable.

Meanwhile, F. H. Hawkins, Jr., of the U. S. Weather Bureau, in the May 1952 issue of the Monthly Weather Review, called attention to the same periodicity and stated that, as far as could be determined, no seeding which was under way that spring could compare in periodicity with the marked spacing of rainfall at that time.

Langmuir, however, examined the data on western seeding operations and was able to show that the observed periodicity in weather conditions coincided with the schedule of commercial operations. He reported his findings to this effect at the annual meeting of the Institute of Mathematical Statistics in East Lansing, Michigan, on September 4, 1952.





Irving Langmuir at his desk at the time of Project Cirrus.

VIII. HURRICANES AND FOREST FIRES

In addition to the normal studies and tests with which Project Cirrus concerned itself, there were two additional activities in which it engaged early in its history. One was a study of tropical hurricanes and the other, an attempt to cause rain in a forest-fire area. Both took place in 1947.

HURRICANE STUDY

The hurricane study was planned by the various participating government agencies for the purpose of determining whether seeding operations could be carried out in such storms. These agencies hoped that the experience thus gained would permit the planning of further operations in the future, with the hope of possibly steering or in other ways modifying tropical hurricanes.

It was planned to study a "young" storm as soon as possible after it had assumed the form of a hurricane. A group of General Electric personnel was requested to act as consultants on these operations.

After a week of intensive organization and briefing, both groups were maintained in "stand-by" position, but the season progressed for some time without any suitable storms occurring. Finally on October 10, 1947, word was flashed from Miami, Florida, that a storm was forming below Swan Island in the Caribbean Sea. Plans were immediately activated, and the next evening the project's two B-17's were at Mobile, Alabama. The storm had traveled with such high speed, however, that by that time it was crossing Florida. The unit flew to MacDill Field, Florida, the next day, joining forces with the 53rd Weather Reconnaissance group. Plans were laid for take-off early in the morning of October 13. The storm was expected to be from 480 to 640 kilometers east of Florida by that time.

The following account of the observed features of the storm, the seeding operation, and observed effects was prepared by Lt. Com. Daniel F. Rex, at that time chairman of the Operations Group (27):

"The storm consisted of an eye approximately 30 miles (48 kilometers) in diameter, surrounded by a thick wall of clouds extending from about 800 feet (240 meters) up into the cirrus overcast at 20,000 feet (6 kilometers) and being some 30-50 miles (48-80 kilometers) thick radially. Several decks (4 or 5) of stratified shelf clouds extended out from the outer wall, the upper-most deck having tops at 10,000 feet (3 kilometers). These shelf clouds appeared as large areas (100-200 square miles) (250-500 square kilometers) of solid, thin (1000-2000 feet thick) (300-600 meters)

undercast, separated by large breaks through which the surface was often visible. An exceedingly active squall line, appearing as an almost continuous line of cumulonimbus with cirrus tops to an estimated 60,000 feet (18 kilometers), was observed as a spiral extending out from the center-base at 20,000 feet (6 kilometers) near the outer wall, lifting to 35,000 feet (10.5 kilometers) at the edge.

"Approach to the storm center was effected from the southwest, this course bringing the group into the storm's right rear quadrant. After a brief reconnaissance flight around the outer wall, the decision was made to seed a track over the uppermost cloud shelf and at a distance from the center sufficient to permit the control aircraft to fly contact 5000 feet (1.5 kilometers) above the seeding aircraft.

"A formation intrail was used, with the seeding aircraft (B-17 No. 5560) leading at cloud top level. The photoreconnaissance aircraft (B-17 No. 7746) followed the seed ship, 3000 feet (.9 kilometers) above and 1/2 mile (.8 kilometers) astern, with the control aircraft (B-29 No. 816) trailing 500 feet (150 meters) above and 15-20 miles (24-32 kilometers) astern.

"Seeding commenced at 29.8 degrees North, 74.9 degrees West at 11:38 EST at an altitude of 19,200 feet (5.8 kilometers), the outside air temperature being approximately -5°C. Continuous seeding was effected along a straight course to 30.2 degrees N, 73.9 degrees W, thence to 30.8 degrees N, 73.1 degrees W, at which point (12:08 EST) seeding was stopped. During this 30-minute period 80 pounds (36 kilograms) of solid carbon dioxide was dispensed along the 110-mile (180 kilometer) track. In addition, two mass drops of 50 pounds (22 kilograms) each were made into a large cumulus top at 30.7 degrees N, 73.4 degrees W.

"Upon completion of this phase, all planes flew a reverse course back along the seeded track, taking visual and photographic observations. No attempt was made to penetrate through the wall of the storm into the eye or to seed in or near the above-mentioned squall line, owing to the failure of the group's homing aids (radio, compass, and visual flares). It was thought that such an attempt, although desirable, would likely result in a separation of the aircraft, with subsequent abortion of the primary mission.

"Visual observation of the seeded area showed a pronounced modification of the cloud deck seeded. No organized trough was observed; rather, the overcast previously observed appeared as an area of widely scattered snow clouds. The disturbed area covered perhaps 300 square miles (770 square kilometers). No convective activity was seen to follow the seeding process at any time during the mission."

In addition to this account by Rex, the following brief conclusions were prepared, after the test, by Schaefer, who carried on observations from the B-29 (103):

"1. Many suitable clouds for seeding operations occur in this type of hurricane.

"2. The seeding operation produced an area showing snow showers and stable snow clouds with light rain in the above-freezing region. The stable snow clouds covered considerable area and might have persisted long enough to affect other supercooled clouds. I concur with the estimate of Commander Rex that about 300 square miles (770 square kilometers) showed modification due to seeding operation.

"3. The region where profound effects might have been produced was in the extremely active squall line mentioned by Commander Rex. This was not attempted for the reasons indicated.

"4. No build-ups were seen following the seeding operation. This was to be expected, owing to the thin character of the supercooled clouds along the seeding path.

"5. Owing to the complex structure of this 'old' storm, it is believed that a 'young' hurricane would provide much more satisfactory data for estimating the effect of seeding operations.

"6. The operation pointed out the importance of making future studies a part of the hurricane reconnaissance program. Experimental seeding should be made by a group quite familiar with the structure of the particular storm, stationed in fairly close proximity, so that a number of forays would be made in rapid succession.

"While the hurricane study project secured important information and provided excellent training for the Project Cirrus personnel, the time required for planning such an operation and in analyzing the data raises the question of whether the results justify further activities of this kind by this particular group until the urgent and much simpler operations are completed at Schenectady."

Langmuir made some interesting observations with regard to the nature of the hurricane (1). Speaking of the results of the seeding test, he said: "The main thing that we learn from this flight is that we need to know enormously more than we do at present about hurricanes." He concluded:

"It seems to me that next year's program should be to study hurricanes away from land, maybe out considerably beyond Bermuda, out in the middle of the Atlantic....I think the chances are excellent that, with increased knowledge, we should be able to abolish the evil effects of these hurricanes."

An interesting feature of the seeding experiment was that the hurricane changed its motion from

a northeasterly to a westerly course that took it across the coast into Georgia. Conceivably this unusual behavior may have been the result of the seeding; however, an analysis by Mook, et al. (104), suggests that the track was "....the normal outcome of accompanying anomalies in the general circulation...."

Fifteen years were to elapse before a concerted field program to assess hurricane abatement was launched. In 1962 Project Storm-fury--a joint Department of Commerce (NOAA) and Department of Defense (Navy) program--was formed with its principal objective experimentation to reduce the intensity of hurricanes. From 1962 to 1971, only three hurricanes were seeded because of rigid safety precautions imposed on when and where a tropical storm could be seeded. Hurricane Debbie, seeded on 18 and 20 August 1969, gave some evidence of responding to the treatment by a measured decrease in maximum wind velocity on both days (105). An elaborate system of seeding and monitoring such storms has been developed as well as numerical models (106) to aid in interpreting the results.

OPERATION RED

On October 29, 1947, a flight operation was carried out in Vermont and New Hampshire. At that time severe forest fires were raging uncontrolled in various parts of New England. Although it was not the policy of Project Cirrus to carry out such a widespread operation, it was felt that it would be worth the additional effort required to make such a flight for the experience to be gained, particularly since it would be possible to use Schenectady as the base of operations.

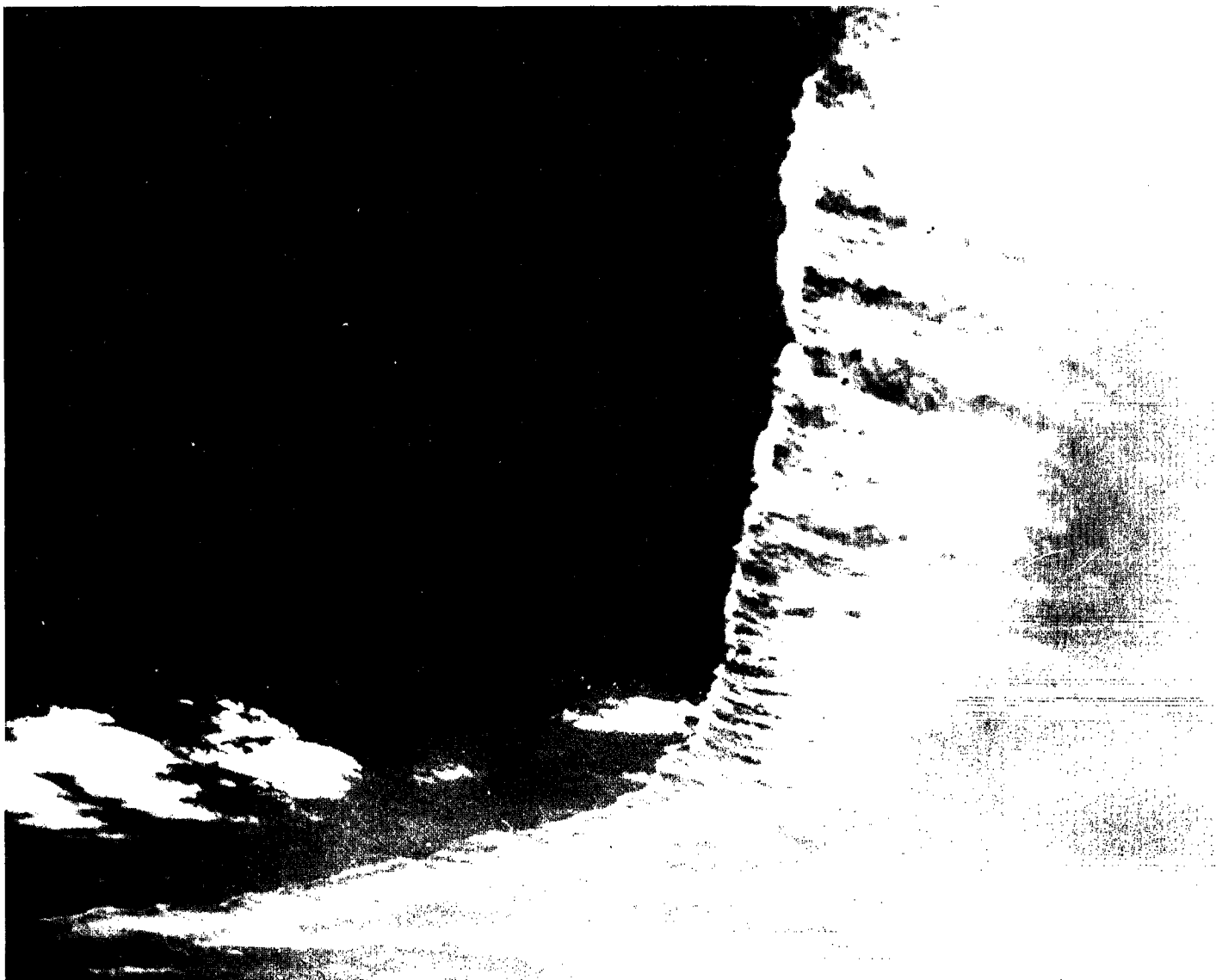
The flight was well planned from an operational point of view, but the results were not spectacular, because of the absence over much of the area of suitable clouds--contrary to a forecast the previous day. Instead of encountering a cloud deck at 5.4 kilometers as indicated by the forecast, the top of the stratus was about 3 kilometers, with isolated cumulus reaching a maximum of about 4.2 kilometers.

Seeding operations were carried out by two B-17's, the one normally in use by Project Cirrus and another furnished by Major Keating of Olmsted Field of the Signal Corps Weather Squadron. The site of operation was over some of the stratus near Montpelier, Vermont, and in the cumulus developments. Practically all of the latter showed the effect of seeding after five to eight minutes. Subsequent reports indicated the development of some fairly intense local showers along the flight path.

The next day word was received from Alan Bemis of the Massachusetts Institute of Technology Radar Research Group that there had been a sudden increase in radar echoes in the vicinity of Concord, New Hampshire shortly after the seeding runs. Fortunately Bemis had learned of the proposed operations and had made it a point to obtain complete radar coverage of the area in which the two planes operated. He subsequently supplied the Operations Group with a reel of 35-mm film of the radar scopes as recorded by his group on October 29.

The results obtained by the radar group under Bemis emphasized to the members of Project Cirrus the effectiveness of this type of instrumentation as an adjunct to their cloud-modification studies. It raised the hope that a close relationship between the two research groups might be effected.

In the opinion of Langmuir the result was inconclusive, because scattered showers began to form that day, starting about one or two hours before Project Cirrus seeded.



Clear Air Seeding. When the moisture in the atmosphere is supersaturated with respect to ice but unsaturated with respect to liquid water, seeding can produce ice crystal cloud formation. These clouds were produced by dispensing crushed dry ice under such conditions.



Clear Air Seeding. This cloud of ice crystals, about five miles in diameter, was produced by releasing silver iodide from a B-17 airplane at an altitude of 25,000 feet.

IX. COOPERATION WITH OTHER PROJECTS

It was only natural that the activities of Project Cirrus should stimulate others to undertake experiments in cloud seeding. Considerable publicity resulted from Schaefer's historic snow-making flight over Pittsfield in November, 1946, and the fact that the Research Laboratory of the General Electric Company was involved took the affair out of the class of cheap sensationalism and provided a background of authenticity that provoked the interest of scientists and weather students the world over, as well as others with varying motives. Continuing publicity of further General Electric and Project Cirrus weather research and experiment caused further interest. Many inquiries were received asking for information in general, and assistance in particular, in connection with specific projects. No attempt will be made to list all of these, but some are of particular interest.

PINEAPPLE RESEARCH INSTITUTE, HONOLULU, HAWAII

On March 24, 1947, a request for dry-ice seeding techniques was received from the Pineapple Institute of Honolulu, Hawaii. Although the records do not show it, presumably the information was needed because of the importance of rain on pineapple growing in Hawaii, and the Institute wanted to keep abreast of any developments.

At any rate, available information was supplied by Project Cirrus. Later newspaper accounts were received at Schenectady describing experiments carried out over the island of Molokai in 1947 by Dr. Luna B. Leopold and Mr. Maurice Halstead. Still later, copies of a preliminary report (107) were received from these men, describing interesting results obtained by dumping dry ice into cumulus clouds having a temperature above the freezing point. As described previously (p. 27), this led to Langmuir's famous theory of the chain reaction of a rain-storm.

MILLIKEN AND FARWELL MOBILE, ALABAMA

For two or three seasons, some time about 1947 and 1948, experiments were conducted in the cloud seeding of thunderstorms with dry ice by the firm of Milliken & Farwell, a sugar company of Mobile, Alabama. Activities concentrated on big cumulus clouds in the neighborhood of the Mississippi delta. Information was requested from Project Cirrus, and Langmuir cooperated actively. He later reported very interesting results and said the photographs taken were the best he had ever seen.

UNITED FRUIT COMPANY, HONDURAS

On preceding pages an account was given of the work done by Joe Silverthorne in seeding clouds for the United Fruit Company in Honduras. This work was carried on for the purpose of testing the possibility of controlling rainfall, and particularly in the hope of stopping blow-downs that result from winds associated with thunderstorms, which occasionally destroy large stands of fruit trees.

Langmuir visited Honduras in 1948 and 1949 and cooperated actively with Silverthorne. His observations convinced him of the effectiveness of single pellets of dry ice in modifying large cumulus clouds; almost always the clouds could be profoundly modified with single pellets (69).

NEW YORK CITY WATER SHORTAGE

This famous case received a great deal of publicity. In order to keep the record straight as to what happened and the part played by Project Cirrus, a brief account of the case, as told by Langmuir, is incorporated.

Although the work was done by and for New York City, it was another case of General Electric having some connection with the activity. When Langmuir presented a paper on weather modification to the American Meteorological Society in New York in 1950, New York was in the midst of a water shortage. At a news conference associated with the AMS meeting, newsmen asked Langmuir if seeding could be of any use in alleviating New York's water shortage. He replied that he knew nothing about New York; his only experience had been in the west.

The newsmen then asked what Langmuir would advise for New York. He replied that the best thing for New York to do would be to get a good meteorologist and have him look into it. That advice was reported by the New York Herald Tribune. Later, when the supply of water was becoming less and less, this paper ran an editorial saying that things were getting desperate and that it was up to the city to do something about it. Seeding was mentioned in the editorial, and also Langmuir's advice to get a good meteorologist.

As a result, Stephen Carney, then New York's water commissioner, got in touch with Langmuir and arranged for a meeting. Carney and two others visited Schenectady. Schaefer recommended Dr. Wallace E. Howell, director of the Mount Washington Observatory, who had been actively associated with Project Cirrus and the General Electric scientists even before the project started. Howell's services were retained as a result.

Howell's experiments have never been published, and opinions vary about the results obtained. An interesting result

was a group of lawsuits totaling in the neighborhood of \$2,000,000. The possibility of such suits had been mentioned in the general discussions which preceded the actual seeding, and at that time Langmuir had commented that it would be entirely possible that such suits would be cheap compared with the results which might be obtained. The city, he said, had already been committed to spend \$600,000,000 to add from 20 to 30% more water to its available supply, and if they could get as little as 20% more water by seeding, it would be worth the \$2,000,000 and any interest on it.

COMMERCIAL SEEDING IN THE WEST

A tremendous amount of interest in the possibilities of controlling precipitation was aroused in the west, especially in the great agricultural regions where an adequate supply of water is highly important and a drought can have catastrophic consequences. Many cooperative groups of water users were formed, and organizations sprang up for the purpose of engaging in cloud seeding on a commercial basis. At the time of writing (May, 1952), some 1.4 million square kilometers of the United States west of the Mississippi were subject to cloud seeding by commercial operators, according to current estimates (News release, James Stokley, for release May 12, 1952).

Although many private individuals have undertaken to do their own seeding, most of this work has been done by a small number of commercial organizations. Topping the list is the Water Resources Development Corporation, with offices in Denver, Colorado, and Pasadena, California, whose rainmaking contracts were reported to cover an area of over 1.2 million square kilometers, or about 12 times the area under irrigation in the United States. "Farmers and ranchers paid millions of dollars for the services of this organization, which contemplates extending its operations to Central America, South America, South Africa and Europe."† Others include the Precipitation Control Company, Phoenix, Arizona; North American Weather Consultants, Pasadena, California; Olson & Taylor Corporation, Shelby, Montana; and Wallace E. Howell Associates, Cambridge, Massachusetts.

So many and so active are the organizations for this purpose, that there has been some concern over the effects of introducing such quantities of silver iodide into the atmosphere. Studies by the Research Group of the project indicated that silver iodide can continue in

the atmosphere for an almost indefinite period, and although its usefulness can be inhibited by sunlight, the practical effects of such photochemical decay are not significant when the silver iodide is within or below the clouds. Finally, the described analyses and calculations of Langmuir indicate that periodic silver-iodide seeding in New Mexico produced a tendency toward periodic rainfall and temperature fluctuations that extended significantly all over the United States. Currently, some members of the Research Group feel that there is a definite possibility that some abnormal flood conditions of recent years have been caused, at least to a contributing degree, by commercial seeding operations in the west.

Few cloud physicists would subscribe to this view today; precipitation increases by seeding are far more modest than then supposed. The Rapid City, South Dakota, flood of 1972, when nearby seeding was under way, brought this question into sharp focus (108).

In addition to the commercial operators, who seed for the benefit of others, at least one electric power company has done extensive work in this field for its own benefit. This is the California Electric Power Company of Riverside, California. This company's use of seeding stems from its concern over an adequate supply of water to operate its hydroelectric generating stations. Not only does it credit the seeding with increasing its hydroelectric output by many millions of kilowatt-hours, but it also declares it has produced millions of extra tons of water for the city of Los Angeles.

Interesting cloud-seeding experiments were also conducted by John A. Battle, consulting meteorologist of Beaumont, California, in California, for the San Diego County Weather Corporation and the Santa Ana River Weather Corporation. The experiments were conducted over the entire area of San Diego County plus the Santa Ana River drainage area in Orange, Riverside and San Bernardino Counties. The two corporations responsible represented various water agencies in those regions, where the relative scarcity of water makes any possibility of increasing the annual rainfall attractive.

Silver iodide was used in the seeding. Unseeded areas were used for control zones, in comparison with seeded areas. About 20 percent more rain fell in the target area than in the control area; in other words, 1.7 billion cubic meters of additional water. Statistical analyses indicated that the chances that the cloud seeding did not have a positive effect on the measured precipitation varied anywhere from 1 in 12 to 1 in 10,000, depending on the area involved (109).

†Page 2, Senate report #1514 (5/12/52) on "Creating an Advisory Committee to Study and Evaluate Experiments in Weather Modification."

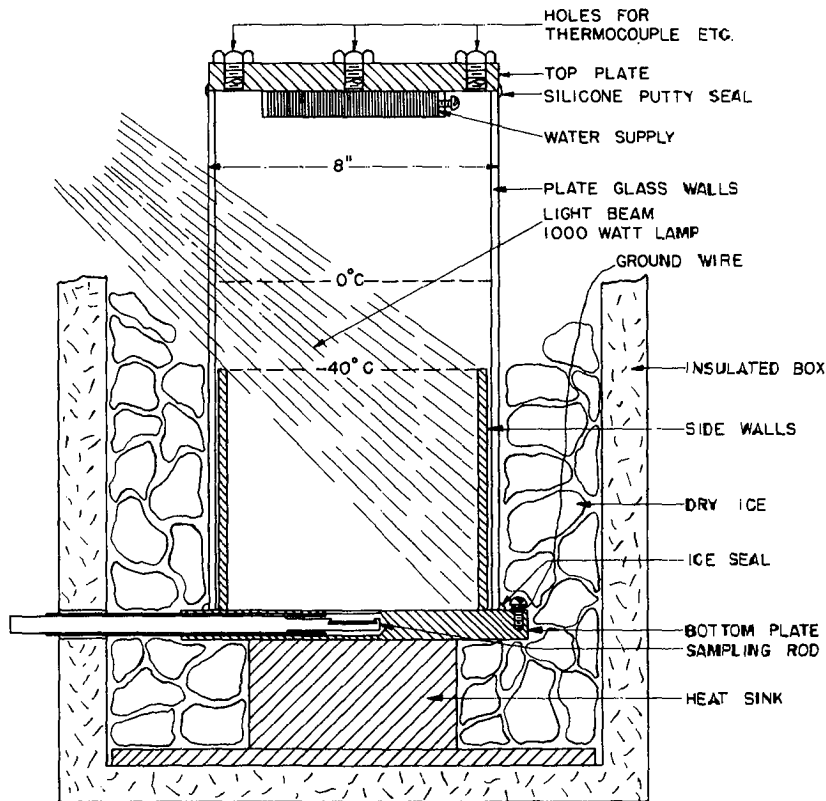
Much of the cloud seeding currently taking place in this country is still concentrated in the west, where the need for water is more acute. For example, the Bureau of Reclamation initiated a 5-year pilot program in southwestern Colorado in 1970 to determine whether the winter snowpack could be increased to add to the flow of the Colorado River (110). This river provides water for seven states and, by treaty, the country of Mexico. Prior experiments in Colorado (111) suggested that a 16% increase (or 2.3 million acre-feet) (3×10^9 cubic meters) of water could be added to the Colorado River Basin.

These and many more countries are now engaged in various theoretical and experimental studies of weather modification. In 1971 the first International Conference on Weather Modification was held in Canberra, Australia, attesting to the world-wide interest in the subject. Two subsequent international weather modification conferences, sponsored by the World Meteorological Organization, were held in Tashkent, USSR, in October 1973 (400 participants were present representing some 28 nations), and in Boulder, Colorado, in July 1976 with high participation.

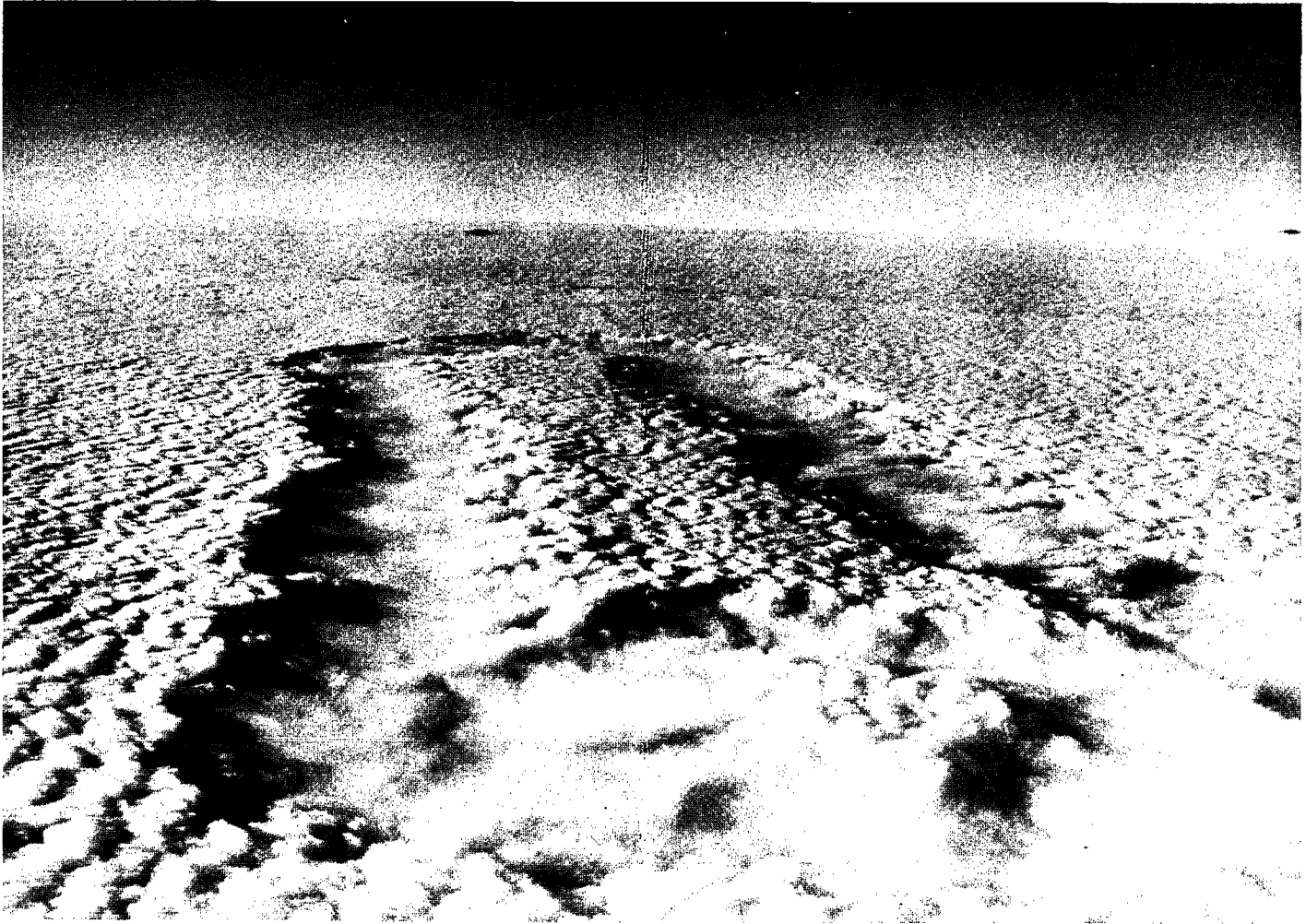
The WMO is now planning an international field experiment to assess the rain-making potential in a country with marginal rainfall--the so-called Precipitation Enhancement Program (112).

WORK OF OTHER GOVERNMENTS

Active research in cloud seeding has been carried on in many foreign countries. Again, the work was stimulated by the reports of successful tests made by Project Cirrus, and in virtually all cases the foreign work was based on information either obtained by direct contact with Project Cirrus or through the study of published data. Among the foreign countries engaged in such work are Canada, Cuba, Peru, England, France, Switzerland, Israel, Algeria, Tanganyika, Union of South Africa, Formosa, Japan, and Australia.



Continuous Cloud Chamber



Racetrack pattern approximately 20 miles long produced by dropping crushed dry ice from an airplane. The safety pin like loop at the near end of the pattern resulted when the dry ice dispenser was inadvertently left running as the airplane began climbing to attain altitude from which to photograph the results.

X. CONCLUSIONS

Contract DA36-039-sc-15345 (the last in the series) terminated September 30, 1952, after a little over five years of the active life of Project Cirrus as a government-sponsored activity. By that time all the early exploratory phases of cloud seeding and allied research concerned with the physics of clouds were virtually complete. So many other research projects had been stimulated that continued progress in the search for new basic knowledge of weather phenomena seems assured.

OVER-ALL RESULTS

It is not, of course, easy to predict the ultimate results of the work done by Project Cirrus. But it seems certain that the pioneering and spectacular work of the General Electric scientists in cloud physics, cloud seeding and weather modification will eventually have a profound influence on domestic and world economics.

Says the report accompanying Senate Bill 2225:

"If practical, weather control promises tremendous benefits for a small investment. Research work in the field involves no test plants or production facilities and very little expensive equipment. The seeding agents, carbon dioxide or silver iodide, are inexpensive, yet when used in small quantities they apparently produce weather phenomena of the highest magnitude. If these phenomena cause only a small increase in precipitation, this small increase can be economically important.

"An inch of rain, converted into runoff and concentrated into a reservoir, can produce electric power worth hundreds of thousands of dollars. A small fraction of an inch of extra rain, falling on crops during the period of germination, can greatly increase crop yields. But artificial nucleation may have useful potentialities in addition to that of stimulating rainfall. It may have possibilities for increasing snowpack in mountainous areas, for holding back and 'softening' rainstorms, thereby reducing soil erosion, for inhibiting hail, for breaking up hurricanes, and for precipitating out and thereby cutting holes in clouds so that aircraft can operate."

Some of the possibilities inherent in cloud seeding as evaluated by Project Cirrus scientists follow:

Widespread Weather Modification. The results of the various New Mexico tests, coupled with observations of the effects of other ground seeding with silver iodide, point to significant possibilities in the widespread modifying of weather conditions. Such work could easily have profound economic, political, and military effect.

Modifying Orographic Clouds. Orographic clouds, which form as moist air is forced to rise when it encounters a barrier such as a mountain range, are very common in mountainous regions, and they often form continuously for many days. Relatively little precipitation from them reaches the earth, except as rime deposits on trees and rocks or as scattered snow crystals. If techniques could be devised to cause a widespread and effective precipitation of such clouds, the depth of the snow pack in the vicinity of mountains might be markedly increased. Such a result would be of much importance, since the snow pack on mountain slopes is very valuable in stabilizing the streams which flow from such regions. These streams are important for electric power and water supply. (See contribution to this knowledge by California Electric Power Co., p. 70.)

Producing Regions of Ice Nuclei. The production of high concentrations of ice nuclei or potential ice nuclei in specific regions of the free atmosphere is an interesting possibility. Cold middle clouds, even though having no appreciable moisture, may be used as "holding reservoirs" to store ice crystals until they come into contact with lower clouds of greater thickness or are entrained into cool or cold cumulus.

An example of this type of seeding occurred during the hurricane project in October, 1947 (p. 41). A relatively thin layer of stratus clouds covering an area of nearly 770 square kilometers was transformed to snow crystals. The subsequent fate of the crystals is still a moot question, but if a considerable number of them had been entrained into the lower levels of a line of towering cumulus observed during the flight and situated in the southeast quadrant of the storm, the entrainment might have exercised a profound effect on the subsequent development of those cumulus clouds.

Similarly, the ice crystal residue from seeded, but small, cumulus clouds may be entrained at a low level into much larger cumulus forming in their vicinity. In this way, an effect of considerable magnitude is produced as the supercooled regions are injected at a lower level than would otherwise be possible.

It will take much careful study to establish methods for utilizing this type of seeding. Eventually, it may become of great importance.

Modifying Stratiform Clouds. The widespread modification of stratus clouds by artificial means is possible at the present time whenever such clouds are supercooled. Under such conditions, the clouds may be either further stabilized by overseeding, or precipitation may be triggered by using the optimum number of ice nuclei. Observed results of the seeding of stratus clouds indicate that holes can be made by this method, which is bound to be of value in aircraft operations.

Modifying Supercooled Ground Fogs. Supercooled ground fogs formed by advection or radiation may be modified and even dispersed if care is exercised to prevent overseeding. Too high a concentration of ice nuclei introduced into such fogs might actually make the fogs worse.

As previously mentioned, the clearing of supercooled fogs has been accomplished at several airports around the world with modest amounts of nucleating agents. In theory one should be able to overseed a supercooled fog and make so many tiny crystals that they remain suspended and worsen fog visibility. In practice, however, it has proven difficult or impossible to overseed fogs, or clouds, even with extremely large quantities of dry ice or silver iodide. It appears that sufficient crystal growth still occurs and that crystal-crystal aggregation to form larger falling snowflakes can take place (113).

The prevention of the formation of ice fog is another possibility from the proper manipulation of seeding techniques. By introducing an optimum number of sublimation nuclei into the air in regions where such fogs are troublesome, it may be possible to continuously remove from the air the moisture responsible for the formation of this interesting but often troublesome type of ground fog.

The ice crystals generated in the vortices of airplane propellers plus the moisture added to the air by the combustion exhaust of the plane are the causes which generally lead to the formation of ice fogs at airports. Whether the removal of supersaturation with respect to ice by seeding methods will be of sufficient magnitude to prevent the ice-fogging effects produced by plane operations can be determined most conclusively by actual experiment.

Protection of Aircraft. There is no question about being able to modify icing clouds in the vicinities of airports and along heavily traveled air lanes. The problem rather, is whether it may have a practical application. Low clouds which restrict visibility for landing approaches around airports, thick clouds in which planes must cruise as they wait for permission to land, and thick clouds which might deposit a serious icing load on the plane as it tries to climb up through them--these comprise hazards to safe plane operations. And when such clouds are supercooled, they may sometimes be profoundly modified.

The simplest means for carrying out such cloud modification would be to employ a plane, well equipped for flying under serious icing conditions, for patrolling the air lanes. The plane

would report weather and cloud conditions and, whenever serious supercooled clouds occurred, would carry out seeding operations.

In flying through a supercooled cloud, the airplane itself may produce a fairly effective modification. The vortices which form at the trailing edges of the wings and particularly from the propeller tips form large numbers of ice crystals.

Modifying Thunderstorms. It may be possible that silver-iodide seeding from ground generators would be particularly useful in modifying orographic "towering" cumulus to prevent their growth into thunderstorms. By determining the air trajectory from the ground into the cold part of the cloud, potential ice nuclei may be sent aloft by a very simple procedure. If subsequent experiments indicate that it is important to seed such clouds at a temperature only a few degrees colder than the freezing point, it may become necessary to use dry ice dispensed from planes or carried into the clouds by free balloons or projectiles.

Towering cumulus also forms over flat country at times when the atmosphere is conditionally unstable. Dangerous and often deadly lightning strokes, torrential rains, destructive winds, and sometimes hail and tornadoes are the end products of such developments. Since the high, vertical thickness of a supercooled cloud seems to be the basic requisite in the formation of a thunderstorm, it may be quite feasible by proper seeding methods to prevent this phase from developing.

The manner in which the seeding is done may produce a wide variation in the end results obtained. By seeding each cumulus tower with large numbers of crystals shortly after it rises above the freezing level, the cloud would be continuously dissipated and no extensive regions of supercooled cloud could develop. On the other hand, it might be desirable to seed such clouds to realize the maximum possible energy release. This presumably would involve seeding each cumulus tower just previous to the point of its maximum development. If this could be done effectively, it might be possible to build the storm into a much larger one than would develop under natural conditions.

Preventing Hail. The possibility that hailstorms might be prevented by seeding techniques is of considerable economic importance. A great amount of basic information is needed on the various properties of storms that produce hail. In some parts of the country where severe hail damage is frequent, storms are formed over certain mountain ridges and peaks that serve as cloud barriers. Such clouds should be particularly suited for modification by ground generators, since the air trajectory is definitely related to the flow of air up the mountain and into the clouds.

Over the past decade, one of the most actively pursued weather modification efforts has been hail suppression. The concept of heavy seeding with silver iodide or lead iodide to reduce the sizes of hail pellets (via competition) has been employed. In Russia, claims of crop damage reduction of up to 70 to 90 percent have been reported (114). Conversely, the National Hail Research Experiment in the United States led to inconclusive statistical results, with the suggestion that the seeding method involved may actually have increased hail-fall (115).

APPARENT LIMITATIONS

As in any of the physical phenomena, there are definite limitations to the degree in which experimental meteorology may be employed in modifying clouds in the free atmosphere. Some of these apparent limitations may disappear as our knowledge increases, although most of the restrictions now recognized are imposed by known physical laws.

Foremost of these restrictions is the factor of cloud type and size. Certain clouds, such as the fair-weather cumulus, have such a small volume and restricted area that, even though they are easily modified when supercooled, their total liquid-water content is inconsequential. Another complicating factor is that the air below larger clouds is sometimes so dry that a considerable amount of precipitation evaporates before it reaches the ground.

Another type of cloud which is difficult to modify is the warm ground fog formed by radiation or advection. Such fogs are often extensive and of considerable economic importance, especially from the standpoint of airplane traffic control. But the natural structure of a fog precludes any simple method of modifying it. Generally, the vertical thickness is not more than 100 meters or so, with a cloudless sky above. This rules out the possibility of modifying from above by forming precipitation in higher clouds to "rain out" the fog.

A highly practical means of modifying warm fog has continued to elude weather modifiers, although some effective results have been obtained by rather costly heating of the air (British Project Fido; U.S.A.F. Arcata and Vandenberg A.F.B. experiments; Paris Orly-Airport System). More marginal techniques have produced limited clearing by helicopter downwash of dryer air from above (116) and by seeding the fog with giant hygroscopic nuclei (117, 118). The latter technique represented a variation of the air-drying approach

used by Houghton and Radford (119), one of the few scientific weather modification programs preceding Project Cirrus.

Another weather situation where no method of relief is now apparent is in the case of drought. This condition generally results from the stability of a complex weather pattern in a manner which, at present, is not very well understood. Drought is generally accompanied by either cloudless skies or clouds of small vertical and horizontal development, because of strong inversions or thick layers of dry air.

The development of convergence is an important feature in the formation of appreciable amount of rainfall in many parts of the world. As a rule, such developments are generally accompanied by the occurrence of natural precipitation, which continues so long as the convergent movement is present. About the only thing that artificial modification of clouds might do under such atmospheric conditions is to initiate the precipitation cycle a few hours before it would start naturally, or under some conditions, to delay the onset of precipitation by overseeding.

Another possibility is that appropriate seeding might increase the amount of precipitation beyond what would naturally occur. This premise underlies several recent projects, recognizing that rigorous statistical design of experiments becomes increasingly important in order to distinguish between natural and modified rainfall (119).

CONTROVERSIAL ASPECTS

As is so often the case with the proposal of striking or revolutionary new concepts in science, the validity of the observations and conclusions of the members of the Research Group, both before and after the establishment of Project Cirrus, was challenged by many. As a result, quite a school of opposing thought has been built up. This is a normal, healthy condition of affairs, and the results would be of no particular consequence were it not for the fact that the possibilities inherent in artificial weather modification have such great economic significance.

Although criticism and challenge have by no means been confined to any one person or group, the spearhead of the opposition, so to speak, has been the United States Weather Bureau. This unit has kept a watchful eye on all the developments associated with Project Cirrus. In many cases it designated observers to work with the project on specific operations. It has conducted experiments of its own to test the validity of Project Cirrus findings,

notably the Cloud Physics Project, jointly conducted by the Weather Bureau and the United States Air Force.

The running controversy between representatives of the Weather Bureau and Langmuir is summarized in an article (120) available in his office files. In it Langmuir discusses and answers the various criticisms and challenges. He summarizes the importance of the situation in the following paragraphs:

"The possibility of such wide-scale control of weather conditions, of course, offers important military applications, but since nearly all meteorologists are much influenced by the opinions and the attitudes of the Weather Bureau men, the opposition on the part of the Weather Bureau and other groups has, up to the present, prevented the starting of any military applications. It was, therefore, of the utmost importance to clear this matter up without getting too much publicity."

Langmuir has since explained orally that, in view of this situation, he has resorted to the use of publicity only when other methods of bringing matters to a head had failed. At the time of the preparation of this report, however, both he and the other scientists associated with Project Cirrus had begun to feel that it would only be a matter of time before the Weather Bureau would change its attitude. It is believed that the described results obtained by the California Electric Power Company (p. 46) have had a great deal to do with that change of attitude.

Some picture of the Weather Bureau side of the controversy may be found in testimony (121) presented during hearings before Senate subcommittees on three bills, as follows:

S.5, a bill to provide for research into and demonstration of practical means for the economical production, from sea or other saline waters, or from the atmosphere (including cloud formations), of water suitable for agricultural, industrial, municipal, and other beneficial consumptive uses, and for other purposes.

S.222, a bill to provide for the development and regulation of methods of weather modification and control.

S.798, a bill to authorize the Secretary of Agriculture to conduct research and experiments with respect to methods of controlling and producing precipitation in moisture-deficient areas.

The attitude of the Weather Bureau is summarized in a statement presented to the above groups on March 14, 1951, by W. F. McDonald, assistant chief of the United States Weather Bureau, and a further clarification of Weather Bureau views is found in the subsequent questioning of Mr. McDonald by members of the committees.

The fact that the challenges to the validity of Project Cirrus claims are not confined to the Weather Bureau is also indicated during the same Senate

hearings. Statements were made at those hearings by other individuals not associated with the Weather Bureau, and some of those individuals did not agree with the findings of Project Cirrus. Among them were Hans H. Neuberger, professor of meteorology and chief of the Division of Meteorology, Pennsylvania State College, Charles L. Hosler, a staff member of that college, and Henry G. Houghton, professor of meteorology and head of the Department of Meteorology, Massachusetts Institute of Technology.

The Weather Bureau (now the National Oceanic and Atmospheric Administration) has assumed a major role in the investigation of weather modification potential. Their recent projects include Project Storm-fury (hurricane modification as mentioned), Great Lakes snowstorm redistribution (122), Florida cumulus rainfall enhancement (123, 124), participation in the National Hail Research Experiment, lightning abatement (125), fog modification and numerous basic research studies in weather modification.

LEGISLATION

For various reasons, national legislation has been suggested, and actually introduced, to regulate and control artificial weather modification. Of the three bills referred to in the preceding paragraphs, two (S.222 and S.798) specifically covered this proposed regulation and control (S.222) and authorized the Secretary of Agriculture to conduct research and experiments (S.798).

Since that time a new bill was drafted and introduced in the Senate, 82d Congress, second session: S.2225. This bill would create a temporary advisory committee of nine persons to study and evaluate experiments in weather modification, continuing no longer than July 30, 1955. The committee would report to Congress at the earliest possible moment on the advisability of the Government regulating, by means of licenses or otherwise, the activities of persons attempting to modify the weather. The advisory committee would consist of five members appointed from public life by the President plus the Secretaries of Defense, Interior, Agriculture, and Commerce, or their designees. The bill was referred to the Committee on Interstate and Foreign Commerce on October 8, 1951, and reported out with amendments on May 12, 1952.

The General Electric attitude toward legislation was summed up at the above hearings by Vice President and Director of Research, C. G. Suits, and by Schaefer and Vonnegut, who accompanied him to the hearings. Said Suits, in part:

"These facts which underlie experimental meteorology are not in the

controversial area; they have been demonstrated and proven. What controversy has arisen has been concerned with such matters as (1) the economical importance of induced rainfall--by 'induced rainfall' I mean artificially induced rainfall

(2) where long-range effects of cloud seeding exist, and (3) whether induced rainfall may not have occurred naturally in the absence of seeding. There is a great mass of information bearing on these questions, and it would not be possible to discuss it all here.

"It is my considered opinion, however, that the results of the most recent work are of the very greatest importance to the Nation. We have at hand a means of exerting a very considerable degree of control of weather phenomena. Precisely how much control can be accomplished will come from further study. Much work remains to be done, and it would be a national tragedy if legislation did not provide a proper framework for developing the full potentialities of weather modification methods. It would be hard to imagine anything more important to the country than weather modification and control."

Another extract from the Suits statement:

"I wish to be very clear on one point. The work my company has done in this field, initially at our own expense and more recently under a Signal Corps contract with the participation of the Office of Naval Research and the United States Air Force, has had no single practical application within the Company. The work originated as an unexpected result of one of the many fundamental investigations which we undertake in the search for new knowledge. It was continued because the leaders of my company and responsible representatives of the Government believed that the possibilities of weather modification might be of great importance to the Nation as a whole. On December 27, 1950, my company announced that for the present and until further notice it does not intend to enforce any of its patents relating to weather modification by the artificial production of snow and rain.

"A contractor of the Government for research in this field, where the general public is the intended beneficiary, should not be subjected to the uncertainties of legal liability hazards which are inherent in experimental weather modification. The provisions of S.222 would greatly minimize the legal hazards which now exist. Some such solution of this problem must be found if private agencies are to engage in research in this field, and by that I mean under contract with the Government."

Other aspects of the need for legislation were voiced at that time by Schaefer. The following quotes from his statement illustrate these other aspects:

"It is very important, in my opinion, that weather studies involving

experimental meteorology be conducted in such a manner that all of the modifications attempted by man-conducted seeding operations be known and controlled. If this is not done, the effort of attempting to understand the reactions which occur is a hopeless one....

"It is obvious that some type of national legislation is of the utmost importance at this time to protect the public in the future from unscrupulous individuals who would play on the gullibility, hope, or desperation of individuals or groups in need of water or other relief from an undesirable climatic situation."

Vonnegut, also, in his statement read at those hearings, urged the adoption of suitable legislation. In addition to the reasons voiced by Suits and Schaefer, he added others, which are found in the following extract:

"The problems of weather control are so large and of such nationwide importance that only Federal legislation can insure that this powerful new tool will result in the greatest good for the largest number of people. In the absence of this legislation, I believe that the development of the benefits to be derived from cloud seeding may be greatly retarded or prevented and that possibly much harm can result from storms, droughts, or floods produced by uncontrolled seeding.

"Theory has predicted and experiments are confirming the fact that a few pounds of silver iodide released into the atmosphere in the form of fine particles can exercise a profound influence over the weather hundreds of miles away from the point of release. Clearly no private individual or group can be permitted to carry on operations likely to affect weather conditions over thousands or hundreds of thousands of square miles.

"The potentialities, both for good and bad, which attend silver-iodide seeding are so large that the development and use of this technique must be placed in the hands of the Federal Government.

"Secondly, it is highly desirable that the Government pass laws regulating cloud seeding, in order to promote the rapid development of this science. Many facts are yet to be learned concerning the best methods of seeding to obtain desirable results. These facts can be determined only by experiments in the atmosphere. The analysis of the results of cloud-seeding experiments is a complicated and difficult problem. If, as in the case at present, many seeding experiments are being independently and simultaneously carried out in many places, the problem of analysis becomes even more difficult and frequently impossible. Federal regulation is necessary to insure the rapid development of the benefits of cloud seeding.

"Thirdly, the science of weather control can be of such great benefit to the entire country that the responsibility for its advancement must rest with the

Government. Legislation should provide funds for research by Government and by private groups into fundamental scientific problems connected with the weather."

At the time of the preparation of this history, no national legislation had yet been enacted to cover any of the needs outlined in the foregoing.

The Federal Government now makes adequate provisions for reporting field activities and requiring Environmental Impact Statements (Public Law 205, 92nd Congress), but has refrained from entering into matters of licensing and control. The latter is generally deemed the responsibility of individual states. While more than half the states have some form of weather modification statutes, few are considered to be ideal (126).



This photograph of Langmuir (Raymond Falconer on his right) was taken in 1956 when he appeared on the NBC television show, "Today", with Dave Garroway. He utilized this opportunity to urge again that some governmental agency carry out hurricane seeding experiments. In 1963 such a program was initiated by the U. S. Navy and the U. S. Weather Bureau.

Epilogue (1978)

In retrospect, it appears accurate to state that Project Cirrus activities stirred the imagination of scientists the world over. It also incurred the skepticism of some and stimulated the profit motive of a few anxious to capitalize on a new technology. An important by-product, if not the most important effect, was the stimulus the weather modification discoveries provided to the field of cloud physics. McDonald (127) recounts the very slow progress being made in cloud physics during the 1900's, when such research was apparently only of academic interest. He states:

"When, after 1946, there seemed to exist some prospect of control over a natural phenomenon whose economic value is so high, support of cloud physics research jumped by what I would estimate must surely have been a factor of two to three orders of magnitude, and total numbers of workers in the field must have increased by a factor of something like two orders of magnitude."

Led by a vital Nobel Laureate and comprised of several investigators unique in their own right, the small Project Cirrus group in slightly more than five years accomplished what must be considered remarkable. During that short span, theories were expounded on precipitation mechanisms in cold and warm clouds; effective cloud seeding agents including dry ice and silver iodide were discovered; ground and aircraft generators were developed not too dissimilar from those in use today; and a variety of new instruments and techniques was devised to monitor cloud behavior. Amidst all this, over 180 aircraft experiments and 84 ground experiments were conducted--from Puerto Rico to Honduras to Hawaii and in some dozen states in between.

As Havens' account suggests, few of the weather modification concepts being pursued today were overlooked by the Project Cirrus group, although in-depth study obviously was not always possible. The work on supercooled stratus-type clouds, which the project title denotes, has solidly withstood the test of time.

Ironically, as a portion of the research turned to deep, complex cumulus clouds, some of the arrows went wide of the mark. Langmuir's convictions on rainfall periodicities and the degree to which rainfall could be increased were far too optimistic according to present views. Considering the variability of weather and the extent to which statistics can lead to conflicting interpretations even today, perhaps one should not be surprised. Not to be overlooked were Langmuir's pioneering theoretical efforts in droplet growth by diffusion, hydro-meteor collision efficiencies, the chain-reaction mechanism involving droplet

breakup, and the importance of latent heat release in cloud development and modification.

The extensive studies of silver iodide and many other ice nucleating substances continues. Other inorganic materials, such as copper oxide, copper sulfide, and cuprous iodide, have been found to nucleate ice formation at temperatures only several degrees below the freezing point. Some of these substances have a crystal structure apparently unrelated to that of ice. By suitable modifications of their surface, the ice nucleating capability of silicate particles possibly may be improved (128). Organic substances bearing little similarity to ice have been found to serve as effective nuclei, for example, phloroglucinol (129) and metaldehyde (130).

Studies have been carried out to investigate the effect of crystal lattice parameters. The structure of silver iodide, which is approximately 1.5% larger than ice, has been reduced in size by the substitution of either bromine for the iodine or by copper for the silver (131, 132), with an improvement of the ability of these modified crystal substances to nucleate ice formation. These and other studies have shown that the efficacy of ice nuclei is a very complicated matter depending on a variety of factors acting together, such as lattice parameter, surface electrical potential, solubility, photochemistry, particle size, the surface distribution of hydrophilic sites, the nature of the soluble iodides used in producing the solutions of the silver iodide, etc. It appears, however, that the discovery of a material greatly superior to silver iodide is not very likely.

Project Cirrus's investigations of ways that man can intentionally affect the weather cast a new light on how man's activities might unintentionally have a large influence on weather processes. Along with the scientific study of deliberate weather modification, a new vigorous research activity is developing to explore how man may be affecting his environment by the gases, aerosols and heat he emits into the atmosphere in the course of his many activities. Studies indicate that there may be far more unintentional cloud seeding as a result of pollution than was appreciated during the early days of Project Cirrus. In recent years several international workshops on inadvertent weather modification have been held. These are undoubtedly only the first of many similar ones that will be held in the future on this subject.

Environmentalists have been justly concerned that cloud seeding might disrupt ecological balances and pose hazards when seeding materials enter the water supply. Recent studies (133, 134) suggest that there is little cause for concern on this score.

One might anticipate because Project Cirrus involved the cooperative activity

of personnel derived from four separate and frequently competitive organizations--the U. S. Army Signal Corps, the U. S. Air Force, the U. S. Navy, and the General Electric Company--that this would have posed serious organizational problems. Such was not the case. What rivalry existed was friendly, morale was high, and a strong spirit of cooperation existed throughout the course of the project.

It seems apparent that the coming years should witness a definitive evaluation of several weather modification concepts. Progress in the field may come grudgingly because of budgetary priorities, environmental and legal concerns, and the realization that substantial data are needed for statistically significant findings.

Since the termination of Project Cirrus, two powerful new tools have become available to investigate cloud seeding. The modern computer makes it possible by modeling to study the effects on systems ranging in size from small clouds to giant storms. Weather satellites now provide a new detailed view from above of the dynamics of weather processes that will doubtless give new insights into how seeding affects the behavior of weather processes.

Inadvertent weather and climate modification likely will overshadow planned modification--if not already the case--as the global population increases and becomes more industrialized. The problems will be both challenging and exciting, but in terms of rapidly mobilizing, coordinating, and executing a cooperative program similar in pioneering scope to Project Cirrus, history is not likely to repeat itself.

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APPENDIX 1

CONTRACTUAL HISTORY

The two research projects, involving first the work on gas masks and smoke filters and then the work on smoke generators, extended over a period from October 1940 through February 1944. This work was done under two contracts (NDCrc-104 and OEMsr-131) with the Office of Scientific Research and Development.

From October 1943 through June 1946, precipitation static research was carried on under Signal Corps contract W-33-106-sc-65 and, subsequently, under Air Force contracts W-33-038-AC-9151 and W-33-038-AC-15801.

The meteorological research which became Project Cirrus, was supported for a time by the General Electric Company. In February 1947, the first of three Signal Corps contracts (W-36-039-sc-32427, W-36-039-sc-38141, and DA-36-039-sc-15345) was signed. The last of these remained in force until the end of September 1952.

APPENDIX 2

ALPHABETICAL LIST OF PERSONNEL

Mrs. Margaret Bakuzonis, GE
Raymond Bellucci, civilian mathematician
S/Sgt. C. S. Belote, USAF, radio operator
S/Sgt. Roy E. Berry, USAF, crew chief
George Blair, GE
Duncan Blanchard, GE
Major D. Blue, USMA
Dr. C. J. Brasefield, Signal Corps,
Steering Committee Alternate
1st Lt. Mitchell B. Bressette, USAF,
navigator
Vincent Bruck, Signal Corps, photographer
Robert C. Bullock, Signal Corps
Major E. Cartwright, USAF
Theodore Catellie, Signal Corps photog-
rapher
Cmdr. R. A. Chandler, Navy, Steering
Committee Alternate
Capt. Clarence N. Chamberlain, Jr.,
USAF, pilot
T/Sgt. Vernon H. Davis, Signal Corps,
Supply Sgt.
M/Sgt. Eugene R. Dickson, USAF, crew
chief
E. G. Droessler, ONR, Steering Committee
Mrs. Analee Durant, secretary
Lt. Max A. Eaton, Navy, Steering
Committee
Robert F. Egger, AL2, USN, radio and
radar operator
Raymond Falconer, GE
Lt. Cdr. Elwood B. Faust, USN, pilot
Dr. Michael J. Ferrence, Signal Corps,
Steering Committee
Charles S. Ferris, civilian electrician
Victor Fraenckel, GE
S/Sgt. Russell C. Friedl, USAF, crew
chief
1st Lt. Carl J. Fuhrmann, USAF, pilot
Myer Geller, GE
Miss Constance Godell, secretary
Cmdr. G. D. Good, Navy, Steering Com-
mittee Alternate
T/5 C. E. Hall, Signal Corps, driver
Cpt. Francis N. Ham, Signal Corps,
driver
Roger Hammond, GE News Bureau, communica-
tions media liaison
Lt. Cdr. B. K. Harrison, USN, pilot
1st Lt. Ted E. Hoffman, USAF, pilot
T/Sgt. C. E. Hughey, USAF, crew chief
Thomas J. Hurley, Signal Corps, photog-
rapher
Lt. J. W. Iler, USN, pilot
Cpl. Billy G. Jackson, Signal Corps,
photographer
Cpl. Ernst S. Johnson, Signal Corps,
photographer
T/Sgt. Martin M. Kalich, USAF, radio
operator
Major P. J. Keating, USAF, Steering
Committee
John Kelly, Signal Corps, civilian tech-
nician
Major Rudolph C. Koerner, Jr., Signal
Corps
Cpl. James W. Land, Signal Corps,
Supply Sgt.
Dr. Irving Langmuir, GE
William Lewis, U. S. Weather Bureau
cons.
Kiah Maynard, GE
AERML E. R. Millan, USN, aerologist
S/Sgt. H. E. Millett, USAF, crew chief
Landon Morris, Signal Corps, photographer
Raymond L. Neubauer, GE
S/Sgt. J. H. Niven, USAF, radio operator
William N. Perry, ADC, USN, pilot
Capt. John A. Plummer, USAF, pilot
Harold Pontecorvo, Signal Corps,
photographer
Alexander Preede, Signal Corps,
photographer
T/Sgt. William M. Ratcliffe, USAF,
crew chief
Carl R. Remscheid, AG1, USN, aerologist
Lt. Cdr. Daniel F. Rex, USN
Edward Rudzik, AD3, USN, engineer
AERML R. F. Rayan, USN, aerologist
Capt. Michael A. Sbarra, USAF, pilot
Dr. Vincent Schaefer, GE
Lt. Cdr. Paul J. Siegel, USN, pilot
Robert Smith-Johannsen, GE
Donald Southard, Signal Corps,
photographer
Col. N. C. Spender, USAF, Steering
Committee
Samuel Stine, Signal Corps
George Swistak, Signal Corps, photog-
rapher
ACMM Adam Szepekowsky, USN, chief
Lt. Cdr. C. E. Tilden, USN
Lt. David D. Tracy, USAF, navigator
Lt. Col. J. Tucker, USAF, Steering
Committee Alternate
1st Lt. Henry W. Tutt, USAF, pilot
Dr. Bernard Vonnegut, GE
Howard J. Wells, AGC, USN, aerologist
CAERM G. B. West, USN, aerologist
Roger Wight, Signal Corps (civilian)
Capt. Carl F. Wood, USAF, pilot
Charles Woodman, GE

APPENDIX 3

PROJECT CIRRUS UNNUMBERED FLIGHT TESTS

<u>DATE</u>	<u>LOCATION</u>	<u>OPERATION</u>
11/13/46	Pittsfield	DI seeding
11/23	Schenectady	DI seeding, isolated cumulus
11/29	Schenectady	DI seeding, isolated cumulus
12/20	Schenectady	DI seeding
03/06/47	Schenectady	DE seeding
03/07	Schenectady	DE seeding
03/12	Schenectady	DE seeding
04/07	Schenectady	DE seeding
05/08	Schenectady	DI and SI seeding
08/05	Schenectady	Instrument check
08/06	Schenectady	Instrument check
08/07	Schdy-Westover, MA	Weighing
08/11	Schenectady	Instrument calibration
08/13	West Point	DI and SI seeding
08/15	Schenectady	SI seeding
08/18	Schenectady	Instrument check
08/20	Schenectady	Instrument check
08/21	Schdy-Indian Lake	DI and SI seeding
08/25	Schenectady	DI and SI seeding
08/27	Schenectady	Instrument check
08/28	Schenectady	Instrument check
08/29	Schenectady	Instrument check
09/19	Schenectady	Dry run for hurricane
09/25	Schenectady	Instrument check
09/30	Schenectady	Instrument check
10/07	Schenectady	Tracing SI
10/10	Schdy-Mitchell Field	Hurricane study
10/11	Olmstead, PA-Brookley, AL	Hurricane study
10/12	Brookley-McDill, FL	Hurricane study
10/13	Florida	Hurricane study
10/14	McDill-Olmstead, PA	Hurricane study
10/15	Olmstead-Schdy	Hurricane study
05/31/48	Schenectady	Water drop tests, pumping
06/02	Schenectady	Water drop tests, balloons
10/18	Schenectady	DI seeding
11/30	Schenectady	Stereoscopic camera test
12/14	Schenectady	Info. Flight #3 - balloon soundings
02/07/50	Boston-Schenectady	Observation - tie-in with Ground Operation #75

PROJECT CIRRUS NUMBERED TEST FLIGHTS

<u>FLIGHT NUMBER</u>	<u>DATE</u>	<u>LOCATION</u>	<u>OPERATION</u>
1	09/11/47	Schenectady	DI seeding
2	10/20	New Hampshire	Forest-fire seeding; Oper. Red
3	11/12-13	Olmstead, PA; Brookley, AL	Water seeding
4	11/17	Schenectady	Racing SI
5	12/11/47	Schenectady	SI seeding
6	12/12	Schenectady	DI seeding
7	01/13/48	Schenectady	DI pattern seeding
8	01/14	Schenectady	DI seeding
9	01/22	Schenectady	None
10	01/28	Middletown, PA	Servicing
11	02/02	Schenectady	DI pattern seeding
12	03/09	Schenectady	DI pattern seeding
13	03/31	Sacanadaga Reservoir	Training

<u>FLIGHT NUMBER</u>	<u>DATE</u>	<u>LOCATION</u>	<u>OPERATION</u>
14	04/07	Schenectady	DI seeding
15	04/07	Schenectady	DI pattern seeding
16	04/08	Schenectady	DI seeding
17	04/13	Schenectady	DI pattern seeding
18	04/15	Schenectady	DI seeding
19	04/19	Schenectady	DI seeding
20	04/21	Schenectady	DI seeding
21	04/28	Schenectady	DI pattern seeding
22	04/28	Schenectady	Observation
23	04/29	Cape Cod	DI seeding--MIT project
24	04/30	Schenectady	Seeding
25	05/07	Schenectady	Water seeding
26	05/07	Schenectady	Nothing
27	05/18	Schenectady	DI pattern seeding
28	05/21	Schenectady	DI seeding
29	06/03	Off New Jersey Coast	DI cumulus seeding
30	07/09	Schenectady	Water seeding
31	07/16	Schenectady	DI seeding
32	07/20	Schenectady	DI and water seeding
33	07/26	Lake George	DI seeding
34	07/30	Glens Falls	DI and water seeding
35	08/03	Catskill, NY	DI seeding
36	08/04	Schenectady	Water Seeding
37	08/06	Schenectady	Water seeding
38	08/09	Schenectady	DI and water seeding
39	08/10	Schenectady	DI seeding
40	08/31	Schenectady	DI and water seeding
41	09/01	Schenectady	Water seeding
42	09/16	Schenectady	Calibration
43	09/22	Lake George	Photography
44	10/12	Albuquerque, NM	Water ice and DI seeding
45	10/14	Albuquerque, NM	SI and DI seeding
46	10/13	Schenectady	Water ice and DI seeding
47	10/14	Schenectady	Water ice seeding
48	11/15	Schenectady	DI seeding--pattern
49	11/16	Schenectady	DI seeding--pattern
50	11/17	East of Albany	DI seeding--pattern
51	11/23	Schenectady	DI pattern seeding
52	11/24	Schdy and Amsterdam, NY	DI pattern seeding
53	11/24	Schdy and Rome, NY	DI pattern seeding
54	12/01/48	Schdy-NW of Albany	DI pattern seeding
55	12/08	S of Utica	DI seeding
56	12/09	N of Schenectady	DI seeding
57	12/21	E of Albany	SI & DI seeding; pattern
58	12/22	Albany & East	DI seeding; pattern
59	01/14/49	W of Coxsackie	DI seeding; pattern
60	02/04	Puerto Rico	Survey
61	02/05	Puerto Rico	Survey & water seeding
62	02/05	Puerto Rico	Water seeding
63	02/06	Puerto Rico	Survey
64	02/08	Puerto Rico	Water seeding
65	02/08	Puerto Rico	Survey
66	02/10	Puerto Rico	Survey
67	02/11	Puerto Rico	Survey
68	02/11	Puerto Rico	Survey
69	02/12	Puerto Rico	Survey
70	02/12	Puerto Rico	Survey
71	03/03	S of Lake Ontario	DI & SI seeding; pattern
72	03/04	Sprakers, NY	Temperature soundings
73	03/10	Albany	SI seeding; pattern
74	03/15	W of Syracuse	DI seeding
75	03/16	Ft. Dix, NJ & return	Testing vortex thermometer
76	03/17	Schenectady	Temperature soundings
77	03/24	Schdy-Rome-Middletown- Amsterdam	Testing cloud meter; photo
78	03/25	E of Albany	Testing vortex thermometer
79	03/30	Schenectady	DI pattern seeding
80	03/31	Albany vicinity	DI pattern seeding
81	04/07	Schenectady	Testing vortex thermometer
82	04/08	Schenectady	DI seeding

FLIGHT NUMBER	DATE	LOCATION	OPERATION
83	04/18	Schenectady	SI pattern seeding
84	04/22	West Point & return	Testing vortex thermometer
85	04/25	Schenectady	Instrument testing
86	04/28	Rome, NY, & return	Observation
87	05/03	Schenectady	Testing condensation nuclei meter
88	05/05	Schenectady	Instrument testing
89	05/05	Ashokan Reservoir	DI seeding
90	05/09	Schenectady	Instrument testing
91	05/10	Schenectady	Instrument testing
92	05/11	Little Falls & Rome	Instrument testing
93	05/16	Schenectady	Instrument testing
94	05/18	Schenectady	Instrument testing
95	05/24	Schdy-Rome & return	Testing condensation nuclei counter
96	05/24	Schenectady	Instrument check
97	05/27	Schenectady	Testing vortex thermometer
98	06/09	Schenectady	Testing vortex thermometer, high altitude
99	06/17	Ballston Spa	Salt water seeding
100	06/22	Winchester, VT	DI seeding
101	06/29/49	Schenectady	Instrument test
102	07/06	Schenectady	Instrument test
103	07/13	Albuquerque, NM	DI seeding
104	07/14	Albuquerque, NM	DI, liquid CO ₂ & water seeding
105	07/15	Albuquerque, NM	DI & liquid CO ₂ seeding
106	07/16	Albuquerque, NM	DI seeding
107	07/18	Albuquerque, NM	DI & SI seeding
108	07/19	Albuquerque, NM	DI seeding
109	07/20	Albuquerque, NM	SI ground & DI air seeding
110	07/21	Albuquerque, NM	SI ground & DI air seeding
111	07/22	Albuquerque, NM	SI ground & DI air seeding
112	07/23	Albuquerque, NM	SI ground & DI air seeding
113	08/24	Schoharie Valley	Observing ground seeding
114	09/01	Schoharie Valley	Observing ground seeding
115	09/02	Schoharie Valley	Observing ground seeding
116	09/06	Schoharie Valley	Observing ground seeding
117	09/20	Schoharie Valley	Observing ground seeding--tie-in Ground Operation #13
118	09/23	Schenectady	Testing vortex thermometer
119	09/26	Schenectady	Testing vortex thermometer
120	09/27	Schenectady	Testing vortex thermometer--tie-in Ground Operation #16
121	09/28	E of Schenectady	DI seeding; Ground Operation #17
122	10/12	Schenectady	Temperature sounding; Ground Operation #24-25
123	10/13	Schenectady	Instrument testing; Ground Operation #26
124	10/18	Schenectady	Observation
125	10/17	Rome	Temperature soundings; Ground Operation #34
126	10/24	Albany	Observation
127	11/01	Schenectady	Temperature soundings; Ground Operation #34
128	11/10	Schenectady	Observation; GO-39
129	11/16	---	GO-41
130	11/17	---	GO-42
131	11/16	Schenectady	Instrument test; GO-41
132	11/30	Schenectady	Instrument test; GO-46
133	11/30	Schdy-Indianapolis	Instrument test & weather observation
134	12/01	Indianapolis-Schdy	Instrument test; GO-47-48
135	12/13-14	Schenectady	Calibrating vortex thermometer; GO-53-54
136	12/15	Schenectady	Snow replicas; vortex thermometer; GO-55
137	12/16	Cape Cod	DI seeding; joint with MIT
138	01/04/50	Mt. Washington	SI detection; GO-63
139	01/20	Schdy-Mt. Washington	Instrument check; DI seeding
140	01/30	Schenectady	Snow replicas; GO-71
141	01/30	Schenectady	Calibrating vortex thermometer; GO-71
142	02/03	Schenectady	DI clear-air seeding

<u>FLIGHT NUMBER</u>	<u>DATE</u>	<u>LOCATION</u>	<u>OPERATION</u>
143	02/06	Schenectady	Snow replicas; vortex thermometer
144	02/10	Schenectady	Photos; snow replicas
145	02/20	Schenectady	Clear-air seeding
146	02/28	Schenectady	DI seeding; snow replicas
147	02/28	Schenectady	DI seeding; snow replicas
148	03/03	Schenectady	Attempted vapor trails
149	03/17	Schenectady	Instrument calibration
150	03/20	Schenectady	Snow replicas
151	03/21/50	Schdy-Dayton, Ohio	Weather reconnaissance
152	03/22	Dayton-Schenectady	Weather reconnaissance
153	04/10	Schenectady	Snow replicas
154	04/12	Schdy-Amsterdam	SI seeding; GO-83
155	04/18	Schenectady	Observation
156	04/19	Schenectady	SI seeding
157	04/25-26	Schdy-Boston-Bangor- Massena-Rochester-Schdy	SI seeding
158	05/08	Mt. Washington	SI seeding
159	05/23	N of Schenectady	DI clear-air seeding
160	06/06	E Troy & Albany	DI seeding
161	06/23	Albuquerque, NM	DI cumulus seeding
162	06/26	Albuquerque, NM	DI cumulus seeding
163	06/27	Albuquerque, NM	DI cumulus seeding
164	06/27	Albuquerque, NM	DI cumulus seeding
165	06/28	Albuquerque, NM	DI cumulus seeding
166	06/29	Albuquerque, NM	DI cumulus seeding
167	06/30	Albuquerque, NM	DI cumulus seeding
168	07/01	Albuquerque, NM	DI cumulus seeding
169	07/05	Albuquerque, NM	Tracing ground SI; DI seeding
170	07/06	Albuquerque, NM	Tracing ground SI; DI seeding
171	07/07	Albuquerque, NM	DI seeding
172	07/08	Albuquerque, NM	DI & SI seeding
173	07/11	Albuquerque, NM- Burbank, CA	Gathering weather data
174	07/12	Burbank-Gt. Falls, Ont.	Gathering weather data
175	07/13	Gt. Falls-Schdy	Gathering weather data
176	10/26	Mt. Washington	DI seeding (joint)
177	05/15/51	Mt. Washington	SI seeding (joint)
178	04/08	Schenectady	SI & DI seeding
179	04/24	Schenectady	Observation
180	05/09	Schenectady	DI, liquid CO ₂ & SI seeding
181	05/15	Schenectady	DI & SI seeding

APPENDIX 4

PROJECT CIRRUS GROUND OPERATIONS

NUMBER	DATE	LOCATION	OPERATION
1	03/08/49	Schdy Co. Airport	Cloud photography (still)
2	03/23	Schdy Co. Airport	Cloud photography (still)
3	04/06	Schdy Co. Airport	Cloud photography (still)
4	06/06	Schdy Co. Airport	Cloud photography (still)
5	07/02	Schdy Co. Airport	Time lapse movies
6	07/24-29	Albuquerque, NM	
7	08/23	Schoharie Valley	SI seeding
8	08/25	Schoharie Valley	SI seeding
9	08/30	Schdy Airport	SI seeding
10	08/31	Schoharie Valley	SI seeding
11	09/07	Schoharie Valley	SI seeding
12	09/08	Schoharie Valley	SI seeding
13	09/20	Schoharie Valley	SI seeding--tie-in Flight #117
14	09/21	Schoharie Valley	SI seeding
15	09/22	Schoharie Valley	SI seeding
16	09/27	Schoharie Valley	SI seeding--Flight #120
17	09/28	Schoharie Valley	SI seeding--Flight #121
18	09/29	Schoharie Valley	SI seeding
19	10/04	Schoharie Valley	SI seeding
20	10/05	Schoharie Valley	SI seeding
21	10/05	Schdy Airport	Time lapse movies
22	10/06	Schoharie Valley	SI seeding
23	10/11	Schoharie Valley	SI seeding
24	10/12	Schoharie Valley	SI seeding--Flight #122
25	10/12	Schdy Airport	Time lapse movies
26	10/13	Schoharie Valley	SI seeding--Flight #123
27	10/18	Schoharie Valley	SI seeding--Flight #124
28	10/19	Schoharie Valley	SI seeding
29	10/20	Schdy Airport	Time lapse movies
30	10/20	Schoharie Valley	SI seeding
31	10/25	Schoharie Valley	SI seeding
32	10/26	Schoharie Valley	SI seeding
33	10/27	Schoharie Valley	SI seeding--Flight #127
34	11/01	Schoharie Valley	SI seeding
35	11/02	Schoharie Valley	SI seeding
36	11/03	Schoharie Valley	SI seeding
37	11/08	Schoharie Valley	SI seeding
38	11/09	Schoharie Valley	SI seeding
39	11/10	Schoharie Valley	SI seeding--Flight #128
40	11/15	Schoharie Valley	SI seeding
41	11/16	Schoharie Valley	SI seeding--Flight 129, 131
42	11/17	Schoharie Valley	SI seeding--Flight #130
43	11/22	Schoharie Valley	SI seeding
44	11/23	Schoharie Valley	SI seeding
45	11/29	Schoharie Valley	SI seeding
46	11/30	Schoharie Valley	SI seeding--Flight #132, 133
47	12/01	Schoharie Valley	SI seeding--Flight #134
48	12/01	Schdy Airport	Time lapse movies
49	12/02	Schdy Airport	Time lapse movies
50	12/06	Schoharie Valley	SI seeding
51	12/07/49	Schoharie Valley	SI seeding
52	12/08	Schoharie Valley	SI seeding
53	12/13	Schoharie Valley	SI seeding--Flight #135
54	12/14	Schoharie Valley	SI seeding--Flight #135
55	12/15	Schoharie Valley	SI seeding--Flight #136
56	12/20	Schoharie Valley	SI seeding
57	12/21	Schoharie Valley	SI seeding
58	12/22	Schoharie Valley	SI seeding
59	12/27	Schoharie Valley	SI seeding
60	12/28	Schoharie Valley	SI seeding
61	12/29	Schoharie Valley	SI seeding
62	01/03/50	Schoharie Valley	SI seeding
63	01/04	Schoharie Valley	SI seeding--Flight #138

<u>NUMBER</u>	<u>DATE</u>	<u>LOCATION</u>	<u>OPERATION</u>
64	01/05	Schoharie Valley	SI seeding
65	01/10	Schoharie Valley	SI seeding
66	01/11	Schoharie Valley	SI seeding
67	01/12	Schoharie Valley	SI seeding
68	01/16	Schdy Airport	Time lapse movies
69	01/25	Schoharie Valley	SI seeding
70	01/26	Schoharie Valley	SI seeding
71	01/30	Schdy Airport	Still photos; Flight #140,141
72	01/31	Schoharie Valley	SI seeding
73	02/01	Schoharie Valley	SI seeding
74	02/02	Schoharie Valley	SI seeding
75	02/07	Schoharie Valley	SI seeding--Flight unnumbered
76	02/08	Schoharie Valley	SI seeding
77	02/09	Schoharie Valley	SI seeding
78	02/14	Schoharie Valley	SI seeding
79	02/16	Schoharie Valley	SI seeding
80	02/21	Schoharie Valley	SI seeding
81	03/07	Schdy Airport	Time lapse movies
82	---	---	---
83	04/12	Schdy Airport	Time lapse movies; Flight #154
84	04/24	Schdy Airport	Still photos

APPENDIX 5

PROJECT CIRRUS REPORTS

Note: These reports were prepared by members of the Project Cirrus staff and were widely distributed. Most of them were subsequently published as papers in scientific journals.

1. "Meteorological Research"

- I. General Summary of Cloud Studies Project
Vincent J. Schaefer
- II. Summary of Results Thus Far Obtained in Artificial Nucleation of Clouds
Irving Langmuir
- III. Techniques for Seeding Clouds with Ice Nuclei
Vincent J. Schaefer
- IV. Instrumentation Developments for the Cloud Study Project
Raymond E. Falconer
- V. Nucleation of Ice Formation by Silver Iodide Particles
Bernard Vonnegut
- VI. Typical Data Obtained from Photographs of a Seeded Area
Raymond E. Falconer
- VII. Proposed Flight Plans for Cloud Studies
Irving Langmuir, Vincent J. Schaefer, and Bernard Vonnegut

2. "Meteorological Research", Supplement to Section V, General Electric Progress Report on Meteorological Research. This portion of the report, by Bernard Vonnegut, dealing with various techniques for generating silver iodide smokes, was originally given the classification of Confidential but was later declassified.

- 3. Occasional Report No. 1: "The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures Above Freezing", Irving Langmuir, W-36-039-SC-32427, 15 April 1948.
- 4. Occasional Report No. 2: "A New Plane Model Cloud Meter", R. E. Falconer, V. J. Schaefer, W-36-039-SC-32427, 15 May 1948.
- 5. Occasional Report No. 3: "Some Experiments on the Freezing of Water", Robert Smith-Johannsen, W-36-039-SC-32427, 1 June 1948.
- 6. Occasional Report No. 4: "Smoke from Smelting Operations as a Possible Source of Silver Iodide Nuclei", Raymond E. Falconer, Bernard Vonnegut, W-36-039-SC-32427, 15 July 1948.

7. Occasional Report No. 5:

- I. Production of Ice Crystals by the Adiabatic Expansion of Gas
- II. Nucleation of Supercooled Water Clouds by Silver Iodide Smokes
- III. Influence of Butyl Alcohol on Shape of Snow Crystals Formed in the Laboratory

Bernard Vonnegut, W-36-039-SC-32427, 15 September 1948.

- 8. Occasional Report No. 6: "Variation with Temperature of the Nucleation Rate of Supercooled Liquid Tin and Water Drops", Bernard Vonnegut, W-36-039-SC-32427, 15 October 1948.
- 9. Occasional Report No. 7: "Observations on the Behavior of Water Drops at Terminal Velocity in Air", Duncan C. Blanchard, W-36-039-SC-32427, 1 November 1948.
- 10. Occasional Report No. 8: "A Method for Obtaining a Continuous Record of the Type of Clouds in the Sky During the Day", Raymond E. Falconer, W-36-039-SC-32427, 1 March 1949, RL-145.
- 11. Occasional Report No. 9: "The Detection of Ice Nuclei in the Free Atmosphere", Vincent J. Schaefer, W-39-039-32427, 1 February 1949, RL-138.
- 12. Occasional Report No. 10: "Studies of the Effects Produced by Dry Ice Seeding of Stratus Clouds", Irving Langmuir, W-39-039-32427, 1 February 1949.
- 13. Occasional Report No. 11: "The Possibility of Modifying Lightning Storms in the Northern Rockies", Vincent J. Schaefer, W-36-039-SC-38141, 1 February 1949, RL-134.
- 14. Occasional Report No. 12: "Report on Cloud Studies in Puerto Rico", Vincent J. Schaefer, W-36-039-SC-38141, 1 April 1949, RL-190.
- 15. Occasional Report No. 13: "Silver Iodide Smoke", Bernard Vonnegut, W-36-039-SC-38141, 1 July 1949, RL-227.
- 16. Occasional Report No. 14: "Vortex Thermometer for Measuring True Air Temperatures and True Air Speeds in Flight", Bernard Vonnegut, W-36-039-SC-38141, 1 September 1949, RL-247.
- 17. Occasional Report No. 15: "The Distribution of Raindrops in Natural Rain", Duncan C. Blanchard, W-36-039-SC-38141, 15 November 1949, RL-283.
- 18. Occasional Report No. 16: "The Use of Sooted Screens for Determining Raindrop Size and Distribution", Duncan C. Blanchard, W-36-039-SC-38141, 15 November 1949, RL-284.

19. Occasional Report No. 17: "Experiments with Water Drops and the Interaction Between Them at Terminal Velocity in Air", Duncan C. Blanchard, W-36-039-SC-38141, 15 December 1949, RL-285.
20. Occasional Report No. 18: "Some Correlations Between Variations in the Atmospheric Potential Gradient at Schenectady and Certain Meteorological Phenomena", Raymond E. Falconer, W-36-039-SC-38141, 1 December 1949, RL-287.
21. Occasional Report No. 19: "Continuous Recording Condensation Nuclei Meter", Bernard Vonnegut, W-36-039-SC-38141, 1 January 1950, RL-300.
22. Occasional Report No. 20: "The Occurrence of Ice Crystal Nuclei in the Free Atmosphere", Vincent J. Schaefer, W-36-039-SC-38141, 15 January 1950, RL-308.
23. Occasional Report No. 21: "Progress in Cloud Modification by Project Cirrus, Irving Langmuir, W-36-039-SC-38141, 15 April 1950, RL-357.
24. Occasional Report No. 22: "Cause and Effect Versus Probability in Shower Production", Irving Langmuir, W-36-039-SC-38141, 15 July 1950, RL-366.
25. Occasional Report No. 23: "A Gamma Pattern Seeding of Stratus Clouds, Flight 52 and a Racetrack Pattern Seeding of Stratus Clouds, Flight 53, Charles A. Woodman and Irving Langmuir, W-36-039-SC-38141, 1 June 1950, RL-363.
26. Occasional Report No. 24: "Results of the Seeding of Cumulus Clouds in New Mexico", Irving Langmuir, W-36-039-SC-38141, 1 June 1950, RL-364.
27. Occasional Report No. 25: "Study of Tropical Clouds", Irving Langmuir, W-36-039-SC-38141, 1 July 1950, RL-365.
28. Occasional Report No. 26: "Periodic Fluctuations in the Ohio Basin Moisture Balance, LTJG W. E. Hubert, H. J. Wells, AGC, U. S. Navy, W-36-039-SC-38141, 15 January 1951, RL-485.
29. Occasional Report No. 27: "Seven-Day Periodicity in Upper Air Temperatures Induced by Localized Silver-Iodide Seeding", LTJG W. E. Hubert and H. J. Wells, AGC, U. S. Navy, W-36-039-SC-38141, 15 January 1951, RL-486.
30. Occasional Report No. 28: "Concentration of Ice Crystal Nuclei Under Various Weather Conditions", LTJG W. E. Hubert and H. J. Wells, AGC, U. S. Navy, W-36-039-SC-38141, 15 June 1951, RL-541.
31. Occasional Report No. 29: "Detection and Measurement of Aerosol Particles by the Use of an Electrically Heated Filament", Bernard Vonnegut and Raymond Neubauer, W-36-039-SC-38141, 1 September 1951, RL-555.
32. Occasional Report No. 30: "A Vortex Whistle", Bernard Vonnegut, DA-36-039-SC-15345, 1 November 1951, RL-599.
33. Occasional Report No. 31: "Spray Nozzle Type of Silver Iodide Smoke Generator for Airplane Use", Bernard Vonnegut and Kiah Maynard, DA-36-039-SC-15345, 15 February 1952, RL-635.
34. Occasional Report No. 32: "A Continuous Cloud Chamber for Studying Small Particles in the Atmosphere", Vincent J. Schaefer, DA-36-039-SC-15345, 1 March 1952, RL-654.
35. Occasional Report No. 33: "The Formation of Ice Crystals in Ordinary and Nuclei-Free Air", Vincent J. Schaefer, DA-36-039-SC-15345, 1 March 1952, RL-655.
36. Occasional Report No. 34: "Thin Films of Supersaturated Solutions for Detecting, Counting, and Identifying Very Small Crystalline Particles", Bernard Vonnegut, DA-36-039-SC-15345, 15 April 1952, RL-677.
37. Occasional Report No. 35: "The Concentration of Ice Nuclei at the Summit of Mt. Washington", Vincent J. Schaefer, DA-36-039-SC-15345, 1 August 1952, RL-722.
38. Occasional Reports Nos. 36 and 37: "Production of Monodisperse Liquid Particles by Electrical Atomization", Bernard Vonnegut and Raymond L. Neubauer; "Multiple-Stage Dilution of Aerosols by Use of Aspirators", Bernard Vonnegut, Myer Geller, and Kiah Maynard, DA-36-039-SC-15345, 1 October 1952, RL-747.
39. Occasional Reports Nos. 38 and 39: "Counting Sodium-Containing Particles in the Atmosphere by Their Spectral Emission in a Hydrogen Flame", Bernard Vonnegut and Raymond L. Neubauer; "Effect of Halogens on the Production of Condensation Nuclei by a Heated Platinum Wire", Bernard Vonnegut, DA-36-039-SC-15345, 1 October 1952, RL-748.
40. Occasional Report No. 40: "Variations in the Concentration of Condensation Nuclei in the Atmosphere", Raymond E. Falconer, Kiah Maynard, and B. Vonnegut, DA-36-039-SC-15345, 15 April 1953, RL-825.

THE PRECIPITATION STIMULATION PROJECT OF THE CITY OF NEW YORK, 1950

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Preface. - World War II upset New York City's plans for water supply development, and by 1946 demand exceeded minimum safe yield. Through 3 years of normal rainfall the city stayed lucky. Then in 1949 drought struck. LIFE ran a photograph showing stone walls on the bottom of Croton Reservoir that had been covered since 1852. By Christmas, Cardinal Spellman had asked the faithful to pray for rain, Mayor O'Dwyer had outlawed car-washing, and Water Commissioner Steve Carney had launched Shaveless Fridays. Restaurants served water only on request.

On January 25, 1950, when Irving Langmuir read a paper at a New York meeting of the American Meteorological Society, reporters were ready. *Could cloud seeding help the city?* "Highly probable," said Langmuir. "** * * ought to be consulted,*" said a New York Times editorial. In mid-February, Langmuir came to visit Carney. When they emerged from the Commissioner's office to face the reporters, they were smiling. No, for liability reasons General Electric would not seed the city's clouds, but they would recommend "a meteorologist of the new school of thinking."

That day Vince Schaefer telephoned me. "You might get a call from New York City," he said. I called Ken Spengler for advice, not knowing at the time that he had been in close touch with Dr. Reichelderfer, Chief of the Weather Bureau, about how to keep the city's enthusiasm from going off the track. "It might as well be you," he told me, and added "It would benefit the profession if you asked a top fee, \$100 a day."

The LaGuardia terminal had just opened. When I got off the airplane there a few days later, I hurried through its cold, sagging arms where the fill was still settling, unaware that a red-carpet delegation with reporters in attendance was waiting to conduct me to the Mayor's office. By bus and subway, I beat them to City Hall. On February 21st O'Dwyer announced my appointment as special rainmaking consultant, and by March 15th a plan of action had been agreed upon and funds appropriated. Weather modification turned over a new leaf.

Exactly a week later, a process server handed O'Dwyer a summons in a suit to keep the city from spoiling the tourist season in the Catskills. No restraining order was issued, so the city would go ahead anyway. For once, justice moved swiftly. On May 11th, Justice Pecora for the New York Appeals Court handed down the first weather modification decision in history.

"This Court must balance the conflicting interests between a remote possibility of inconvenience to the plaintiffs' resort and its guests with the problem of maintaining and supplying the inhabitants of the city of New York and surrounding areas, with a population of 10 million inhabitants, with an adequate supply of pure and wholesome water. The relief which the plaintiffs ask is opposed to the general welfare and the public good; and the dangers which plaintiffs apprehend are purely speculative. This Court will not prevent a possible private injury at the expense of a possible public advantage."

Then the Palisades Amusement Park offered me \$200 a day to quit.

* * * * *

On November 7, 1950, Impelletieri was elected Mayor and Commissioner Carney was out. Three weeks later, Esopus Creek rose up out of bed, shucked off several bridges, and lay down in a new bed. A lawyer named Gottlieb rounded up some Catskill villages and filed suit against New York City - - - and me - - - for \$2.5 million. Nothing came of the suit, but the seeding stopped. When I handed in my final report, the city's Corporation Counsel tucked it into a black attache case, which he locked.

Now, after a sleep half again as long as Rip Van Winkle's, here is that report. Plus ça change, plus c'est la même chose.

* Present affiliation, Office of Atmospheric Resources Research, Water and Power Resources Service, Denver Federal Center, Denver, CO 80225. Originally dated February 20, 1951, this report is published now for the first time in its 30th anniversary year as a matter of historical interest. Several appendixes, omitted for the sake of brevity, may be obtained from the author.

I. SUMMARY

In an effort to augment the water supply of the city of New York, cloud seeding was carried out in the region of the Catskills on 36 occasions when the weather was judged auspicious, over a period of 31 weeks between April and December 1950. The precipitation in the Catskill region during that period exceeded the amount that would have been expected, on the basis of comparison with precipitation amounts in surrounding areas, by an amount tentatively estimated at slightly over 4 inches. On several separate occasions when cloud seeding was done, there was relatively greater rainfall in areas where the seeding might reasonably have been expected to be effective. It appears likely, from the evidence, that the cloud seeding augmented the precipitation on several occasions, and that it caused the rainfall over the Catskills during the test period to be about 17 percent heavier than it would otherwise have been yielding about 24 billion gallons of additional water to the city.

If these tentative results are substantiated, the dependable yield of the Esopus and Schoharie watersheds can be increased as much by rainfall stimulation as by the addition to them of the Rondout and half the Neversink watersheds, at approximately one two-hundredth the annual cost of watershed development for equivalent new yield. Because of eventual large savings in new construction that may result, if dependable yield of watersheds now developed and under development can be increased as much as the present study indicates, a 5-year program of study and experimentation is recommended for the purpose of making a more thorough evaluation of artificial precipitation potentialities while at the same time helping to protect the city against recurrence of a critical water shortage before completion of the Delaware system.

II. INTRODUCTION

The rainfall and snowfall stimulation experimental project conducted by the city of New York has had two objectives. The first, and most immediate, was to help replenish the reservoirs of the water supply system, which in the late months of 1949 reached a serious stage of depletion, necessitating a widespread publicity campaign coupled with stringent regulations on the use of water in the city, to avoid failure of the water supply. The second objective, concerned with the longer-range view of the water supply problem, was to evaluate the artificial stimulation of precipitation as a means of increasing the minimum safe yield of the watersheds now in use or under construction, in order to make possible the more efficient use of these works, thus postponing the requirements for further construction. In order to contribute as much as possible to alleviation of the shortage that existed when the project was initiated, actual cloud seeding was begun as soon as possible, and was continued, with some interruptions, until the weather situation made the production of more rainfall undesirable. The evaluation of the activities followed the actual operations.

The following sections of this report give accounts of the inception of the project and its administration, the operations carried out, an evaluation of the results, and a discussion of their significance with regard to the objectives of

the project. Finally, tentative findings are stated and recommendations are made with regard to further extension of the work.

III. ADMINISTRATION

Origins

The origins of the rainfall stimulation experimental project across the interference with the normal program of the city for the construction of waterworks that was caused by shortage of materials during the recent war. Construction of new watershed and aqueduct systems that were planned for completion in the mid-1940's was halted during the war, and will now not be complete until 1956. In the meantime growth of the city, and of demands for water, continued unabated, until in 1946 the use of water exceeded the safe minimum yield of the supply system. During the following 3 years, rainfall was near or above normal, and no shortage was experienced; but in the summer of 1949 deficient rainfall, combined with unusually high demand, brought about a critical situation. A broad campaign of publicity for water conservation was instituted in the autumn of 1949, and many regulations governing both private and industrial uses of water were promulgated. Continuation of the drought through the autumn caused the situation to worsen until early December, when the reservoirs reached a low of about 30 percent of capacity at a season when storage is normally increasing.

In the meantime, the first experiments that indicated the possibility of artificial stimulation of rainfall and snowfall were conducted in 1946; and during 1949, wide publicity was given to experiments conducted in New Mexico and elsewhere by the General Electric Company that gave promise of outstanding results for the augmentation of water supply in deficient areas.

Organization

Hoping that artificial stimulation might help to alleviate the critical water shortage in New York City, officials of the Department of Water Supply consulted with experts of the General Electric Company and others, and in February 1950 asked the author of this report to prepare a detailed plan for an experimental program to be conducted by the city for rainfall stimulation. This program is appended to this report as appendix I.

On the basis of the proposed plan, the precipitation stimulation project was instituted on March 14, 1951, by Mayor O'Dwyer and the New York City Board of Estimate, and established as an activity of the Department of Water Supply, Gas, and Electricity, with the active cooperation of the Police Department Aviation Bureau to supply necessary flight services. The project was under the general supervision of the Commissioner of Water Supply, Gas, and Electricity, and under the immediate direction of the Meteorological Consultant.

Full cooperation in the project was offered by the Chief of the U.S. Weather Bureau, and after consultation with him the cooperation of the Weather Bureau was arranged to apply to three specific activities: issuance of special forecasts of cloud levels, winds aloft, and temperatures aloft, for cloud seeding missions, to be prepared by the Airways Forecast Center at

LaGuardia Airport; a climatic study of the precipitation climate of the Catskill region to be carried on jointly with the staff of the project, to provide a basis for evaluation of the results of the experiments; and the good offices of the Weather Bureau in attempting to obtain on loan from the U.S. Air Forces a radar set for the use of the project staff.

The Department of Water Supply, Gas, and Electricity arranged to supply operating crews for silver iodide smoke generators to be located in the region of the Catskill watersheds and to supply chemicals for the generators through its laboratory division.

It was recognized that circumstances making the stimulation of rainfall undesirable might arise, even during the water shortage, due to the threat of flood or other circumstance of public or engineering importance. The Commissioner of Water Supply, Gas, and Electricity, therefore, undertook to pass upon the plans for each individual cloud seeding mission and to suspend the operation at any time that a threat to the safety of property or the general public appeared likely, and at any time that engineering considerations made operation undesirable. These responsibilities were discharged largely through the Chief Engineer of the Department of Water Supply and his Deputy.

Execution

Soon after the beginning of flight operations on March 28, 1950, it became apparent that the radio navigation equipment in the Police aircraft was insufficient for the accomplishment of instrument flight procedures required for the cloud-seeding missions, and the use of these aircraft by the project thereafter was limited to occasions when all necessary flying over civil airways could be done under contact flight rules. This limitation, in combination with restriction of the altitude range by lack of oxygen equipment, proved so severe that very few missions using the aircraft were attempted.

After the first mission attempted with the Police aircraft had failed because of weather operating limitations, the Sperry Gyroscope Company offered to afford the city use, for cloud-seeding missions, of one or another of its three "flying laboratories," airplanes outfitted with experimental and demonstration radio navigation equipment. However, only one mission was flown for the project by the Sperry plane, difficulties being experienced because of other demands on the airplanes, legal complications regarding indemnification in case of possible suits for damages, and finally the outbreak of the conflict in Korea. Although other attempts were made to make satisfactory arrangements for flight services, none were found feasible within the budget limitations.

A Type APQ-13 radar set was promised for loan from the U.S. Air Force, through the good offices of the U.S. Weather Bureau. The major components of the set were received at Mitchell Field in April for transfer to the city of New York, but several essential components were missing from the shipment. Attempts to obtain these parts were fruitless, and the radar set was never put into service for the project.

Surveys were made to locate possible sites for an operating base for the project in the Catskill region, and three satisfactory sites were

selected that would afford excellent radar coverage of the watershed region and the area to the southwest of it. Attempts to lease one or another of these sites for the erection of a field operations and radar station met with considerable local feeling as well as legal complications. By early summer, with the program of seeding operations going satisfactorily and with the availability of a radar set still uncertain, plans for the station were postponed and later abandoned.

During the course of the experimental period, a series of conferences was held between the project director and representatives of the Scientific Services Division of the U.S. Weather Bureau, regarding the climatic and evaluation study mentioned previously. It was arranged that the city of New York would advance a certain sum toward the cost of the study, representing reimbursement for the clerical time spent on it, while in view of its interest in the subject matter the Weather Bureau would contribute the services of its professional staff and machine records equipment, as required. Delays in effecting the transfer of funds held up the work for a considerable period of time, and the study had not, at the end of the experimental period, reached a point where results applicable to the evaluation had been achieved.

In order to fill the gap left by the deferment of results from the joint study with the Weather Bureau, arrangements were made late in the experimental period to carry out some salient features of the evaluation study with the assistance of student help on a per diem basis. It is the results of this evaluation that are reported in a later section of this report.

IV. OPERATIONS

Immediately upon insitution of the rainfall stimulation project on March 14, 1950, construction of silver iodide smoke generators was begun at the maintenance shops of the Department of Water Supply, Gas, and Electricity, and modification of two of the airplanes of the Police Aviation Bureau was begun to fit it for the dispensing of Dry Ice from the air. Equipment for storing and granulating the Dry Ice was procured and installed at the hangar of the Aviation Bureau, and on March 26 the project was prepared to begin.

Between the time when equipment first became available and the termination of the project, omitting periods when operations were interdicted by order of the Commissioner of Water Supply, Gas, and Electricity, there was a period of 210 days available for rainfall-stimulation experiments. During this period, a total of 36 cloud-seeding missions were carried out, on occasions when the weather conditions were judged suitable for rainfall stimulation. A summary of these missions is shown in table I. One mission was by airborne operation alone; two were conducted both from the air and from the ground, and the remainder from the ground alone.

Most of the time, both silver iodide smoke generators were used on the cloud-seeding missions, but occasionally only one was dispatched. Operations were interdicted from April 1 to April 5 and from April 21 to April 25, 1950, because of high water in Esopus Creek due the spring melting and the consequent risk of flood, again from November 26 to November 28, 1950, due to high water, and from December 4 until the end of the period due to

Table I. - Cloud Seeding Operations
During Rainfall Stimulation Experiments

Date	Type of operation	Amount of AgI used (g)	Amount of rainfall (in)
April 1	Interdicted		
April 5			
April 13	Airborne		0.23
April 19-20	Ground	510	1.20
April 21			
April 25	Interdicted		
April 26	Ground	155	0.09
April 29-30	Ground	940	0.64
May 1	Ground	260	0.07
May 6	Ground	385	0
May 11	Interdicted		
May 15	Ground	656	0.19
May 18	Interdicted		
May 20	Air and ground	296	0.02
May 23	Ground	340	0.05
May 26	Air and ground	560	0.23
May 31	Ground	630	0.07
June 1	Ground	905	0.67
June 3	Ground	1765	0.59
June 10	Ground	1800	0.98
June 24	Ground	1465	0.44
June 27	Ground	350	0
June 29	Ground	995	0.30
July 5	Ground	200	0.31
July 11	Ground	815	1.12
July 12	Ground	1108	0
July 13	Ground	658	0.48
July 17	Ground	665	0.02
July 30	Ground	433	0.04
July 31	Ground	375	0.18
Aug 1	Ground	1200	0.16
August 7	Interdicted		
Sept 10			
Sept 15	Ground	533	0.05
Sept 19	Ground	572	0.05
Oct 3	Ground	275	0.01
Oct 9-10	Ground	425	1.16
Oct 10	Ground	35	0.88
Nov 2	Ground	90	0.17
Nov 9	Ground	130	0
Nov 25	Ground	125	4.27
Nov 26			
Nov 28	Interdicted		
Nov 29	Ground	95	0.07
Dec 3	Ground	150	0.18
Dec 4			
etc.	Interdicted		

turbidity of the water and the poor condition of streambanks. On May 11, May 18, and from August 7 to September 10, operations were interdicted for other than technical reasons.

There were seven occasions when missions that should have been conducted were missed because of imperfect advance weather forecasts. There were approximately 25 occasions unfavorable for cloud seeding from the ground when airborne missions should have been operated if suitable aircraft had been available.

Detailed descriptions of the individual cloud-seeding missions, the related weather conditions, and the ensuing rainfall, are included in appendix II.

In addition to doing cloud seeding, the project provided vortex thermometers and two portable cold chambers for instrumentation of

the two Police aircraft assigned for the project. The vortex thermometers make possible the measurement of true air temperature within a cloud, and the cold chambers make possible detection of silver iodide sublimation nuclei in the air.

V. EVALUATION

The fundamental problem in the evaluation of results of the rainfall-stimulation experiments is the establishment of a "measuring stick" for use in comparing the rainfall observed in the course of the experiments with the amount of rain that would be expected to have fallen naturally, if no seeding had been done.

Since it is not possible to repeat the rainfall-stimulation experiments under controlled conditions, comparing the results on each occasion of seeding with those of a repetition of exactly the same situation without seeding, an indirect comparison must be substituted for the direct one. This substitution introduces inexactitude into the comparison, which can be overcome by considerations of a sufficiently large body of data so that reliable means can be established.

As a first step in accomplishing this end, two areas far enough from the Catskill watersheds to be outside the area influenced by seeding but near enough to be affected by the same storms were selected, and storm-rainfall amounts at each of these areas were correlated, storm by storm over the record of several years, with the storm-rainfall amounts in the watersheds. The tabulation and analysis of these data were carried out by the Scientific Services Division of the U.S. Weather Bureau under a cooperative agreement with the city of New York.

One of the two areas selected for comparison was the vicinity of Binghamton, N.Y., chosen because it contained several stations having a long period of record and because it lay almost due west of the watersheds. (It had been shown in a previous study by Thom that stations lying in an east-west line show a higher correlation of rainfall amounts than stations equally far apart on a north-south line.) The second comparison area selected was the vicinity of Mount Pocono, N.J., chosen because the terrain there most nearly resembled that of the Catskills.

In order to make possible the employment of statistical concepts such as the correlation coefficient, it was necessary first to find means of overcoming difficulties posed by the extreme skewness of the distribution of natural rainfall amounts, amounts less than the mean being encountered many more times than amounts greater than the mean. It was found by the Scientific Services Division that the normal Gaussian distribution function can be transformed mathematically by the use of the incomplete Gamma function to a distribution that very closely resembled the observed distribution of precipitation amounts. This transformation was employed to convert the precipitation quantities into quantities that could be analyzed by standard statistical means to derive the correlation coefficient, the standard error of estimate, and other parameters of the probability method. This work will be reported upon separately by the responsible investigator.*

* Thom, H.C.S.: A statistical method of evaluating augmentation of precipitation by cloud seeding. Tech. Report No. 1, Final Report of the Advisory Committee on Weather Control, Vol. II, U.S. Government Printing Office, 1957, pp 5-25.

The tabulation and correlation of the precipitation amounts at the two selected areas with that in the Catskills showed that the correlation was not sufficiently high to detect an artificial effect of the magnitude anticipated on the precipitation in the Catskills. This approach was therefore given up, and it was decided to attempt selection of control areas as near as possible to the zone of expected influence for each seeding mission individually, depending upon the location of the silver iodide smoke generators and the direction of the winds at the ground and aloft. Work on this phase of the evaluation is still under way in the Scientific Services Division, but results are not available at the date of this report, delays having been experienced in approval of funds for the work.

When it became evident that the evaluation being carried on cooperatively with the U.S. Weather Bureau would not arrive at a point where returns would come from it before the end of the experimental period, a separate evaluation was begun by the consultant, with the assistance of several students at the Massachusetts Institute of Technology employed on a part-time basis for the purpose. It was the purpose of this evaluation to arrive as quickly as possible at a qualitative representation of the results by methods as rigorous as possible under the limitations of time, and if possible by methods permissive of quantitative interpretation as well.

The method selected compares the precipitation amount measured at a particular gauging station for a particular storm during the experimental period with the precipitation amounts of all storms at the same station during a comparison base period, to determine, for example, whether it is most nearly equal to the heaviest, or the second heaviest, or third heaviest, etc., precipitation amount that occurred in individual storms during the base period. By this comparison, each precipitation measurement is assigned a number that represents its rank-standing in comparison with a large number of other storms at the same station. The number 1, for example, would indicate that the precipitation amount was most nearly equal to the heaviest precipitation amount for a single storm during the entire base period, while the number 46 would indicate a precipitation amount equaling that of the 46th-heaviest storm during the base period. If the base period is sufficiently long to contain a representative sample of storms, then each rank number has an equal probability of recurrence. Representation of the storm intensity by its rank-standing thus avoids the difficulties introduced by the skewness of the natural rainfall distribution. At the same time, since the precipitation at each station is compared with the previous performance at the same station, the expression of local influences (such as position of the gauge with respect to nearby mountains) that remain unchanged throughout the base period and the experimental period is eliminated, and only differences in the intensity of the storm remain when comparison is made

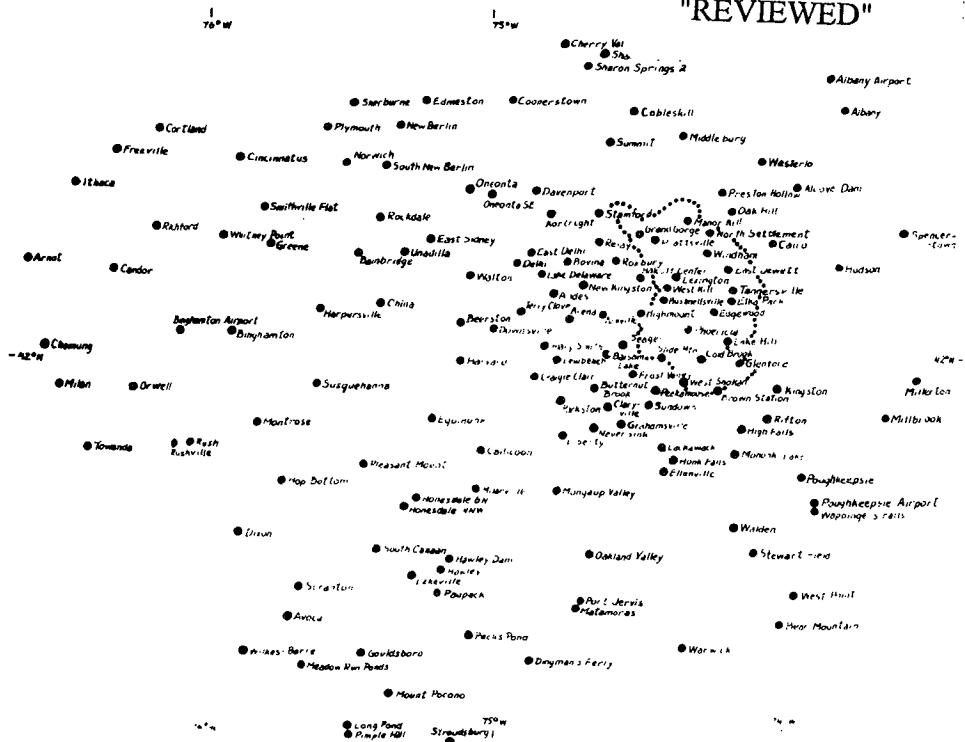


Fig. 1. Precipitation gauging stations

between one station and others surrounding it. The details of the method by which precipitation amounts were converted into rank-standings for the nearly 100 stations that were used in the evaluations are described more fully in an appendix to this report.

The period from January 1, 1937, to December 31, 1949, was used as the base period for the evaluation, since it is the longest period during which an adequate network of stations was available. This period encompassed more than 1,400 precipitation-bearing storms.

Evaluation of individual cloud-seeding missions was accomplished for the 12 missions (in 11 storms) that were followed by occurrence of 0.31 inches or more of rainfall averaged over the Catskill watersheds. Since these 11 storms yielded a total of 12.74 inches of rain, as against a total of 2.19 inches for the remaining 24 missions, the evaluation embraces more than 85 percent of the rainfall that ensued in the Catskill watersheds after the seedings. The results of these evaluations are shown in figures 1 to 12. These figures are maps of the rank-standing of each storm at each gauging station, together with the location of the silver iodide smoke generators and the direction and strength of the wind at the freezing level (generally between 10,000 and 14,000 feet above sea level) this wind generally being representative of the direction of travel of showers. The longer arrow represents the travel of the air in 1 hour at that level. The shorter arrow represents the direction only of the wind near the ground level. The map is on a scale of 1:1,000,000. The numbers represent rank-standings, reports of zero precipitation being indicated by a dash (-). The few entries of clock times represent the time of ending of the hour of heaviest rainfall, as indicated by a recording rain-gauge. The locations of the smoke generators are shown by bulls' eyes.

Figure 1 shows the gauging stations used in the evaluation. The position of the Esopus and Schoharie watersheds in this and the succeeding figures is shown in dotted outline.

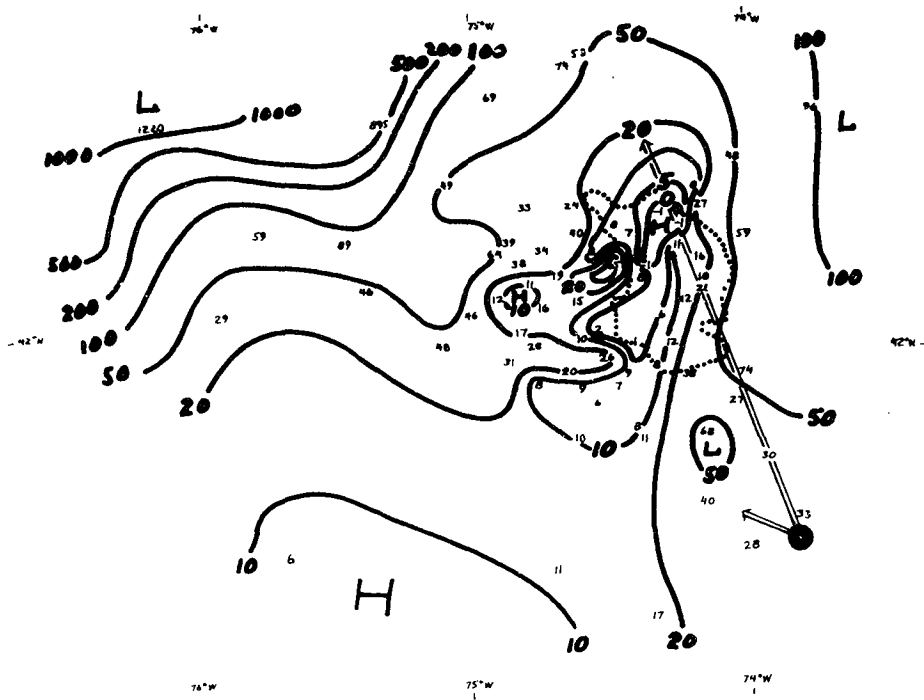


Fig. 2. Rankings of precipitation, Nov. 25, 1950

Figure 2 represents the occasion when the heaviest rainfall followed cloud seeding, in the extraordinary storm of November 25, 1950. This storm was so unusual that extended comment upon it is in order. The following description of it by Mr. E. C. Johnson of the Weather Bureau station at Albany, New York, is quoted from the Weather Bureau publication "Climatological Data".

On the morning of November 24th a very cold mass of air was present in the interior of the country and advancing southeastward over the Gulf States. A low pressure system with warm and moist air appeared over North Carolina and Virginia. The normal eastward drift of the latter system was blocked by a near-stationary high pressure cell in the North Atlantic Ocean. Consequently, the low pressure area advanced northward across Pennsylvania to New York State and then curved westward to Ohio and lower Michigan, before occluding on the 26th. Under the dynamic processes of the contrasting air masses, the low pressure system rapidly increased in intensity and magnitude. Its winds increased to gale force and were accompanied by heavy precipitation. In the warm sector of the storm, precipitation was in the form of rain but on the cold side it fell in the form of snow. Twenty inches or more was reported in south western New York.

The course of the storm reached New York State on the 25th, with winds increasing in velocity in the early morning, and reaching gale velocities later in the day and evening. Some peak gusts that were reported are as follows: New York International Airport 94 m.p.h., Utica 91, Syracuse, 90, Albany 83, New York City 76, Binghamton 70. Sustained velocities of between 50 and 60 m.p.h. were generally reported in much of the state, while a velocity of 66 m.p.h. over a 5-minute period was recorded at the Albany Airport. In a few instances, the highest velocity of record was reported by Weather Bureau Stations.

For the State, as a whole, this was the most damaging storm of record, although western and extreme northern portions suffered no serious major losses. Elsewhere damage was severe. Trees were blown down in forests and across highways and power and communication lines, as well as on buildings and automobiles. Buildings were unroofed and demolished, show windows blown in, signs blown away, and telephone, telegraph and electric poles toppled. Towers of several radio stations were overthrown. In the coastal sections of Long Island wind-swept water and high tides inundated several areas, forcing inhabitants to abandon their homes. Flooding enforced a closing of the field at LaGuardia Airport. Thousands upon thousands of buildings throughout the State were without electric service and thousands of telephones were out of service. * * * The storm was

reported to have been instrumental in the death of 32 persons in the State. The number of those injured by falling trees, buildings, and signs, and by flying glass and wind-blown objects is unavailable, but undoubtedly is in the hundreds. Hundreds of hunters were marooned in the Adirondacks until fallen trees could be removed from roads and trails. Heavy rain resulted in serious flash flooding in portions of the Catskill area, while some flooding was reported in the Genesee River Valley and other scattered areas. However, streams returned rapidly within their banks after the storm."

Quoting also from a description of the same storm by Mr. L. F. Conover, head of the U.S. Weather Bureau station at Harrisburg, Pennsylvania, as carried in the same publication:

During this memorable 25th day of November, winds rose to hurricane force over many eastern counties, heavy to excessive rains sent streams above flood stage in southeastern counties. Extremely low barometric pressure, combined with high onshore winds, produced record high tides which inundated the tidal areas. The gales caused damage as far inland as Clinton, Centre, Huntingdon, and Franklin Counties. Heavy rain fell over the Susquehanna River basin, with sleet and freezing rain over much of the central and western mountain sections of Pennsylvania. * * *

The heavy, drenching rains reached their peak during the early afternoon of the 25th over most of the eastern counties. Streams rose above banks rapidly, and moderate flooding was in progress from the headwaters of the Allegheny River basin to the Delaware River. A number of stations in the Reading-Scranton area reported new 24-hour precipitation totals. Pottsville had 6.86 inches. * * * In the Philadelphia area, crests approached the 1936 levels; much damage resulted from standing water unable to run off rapidly enough by natural drainage."

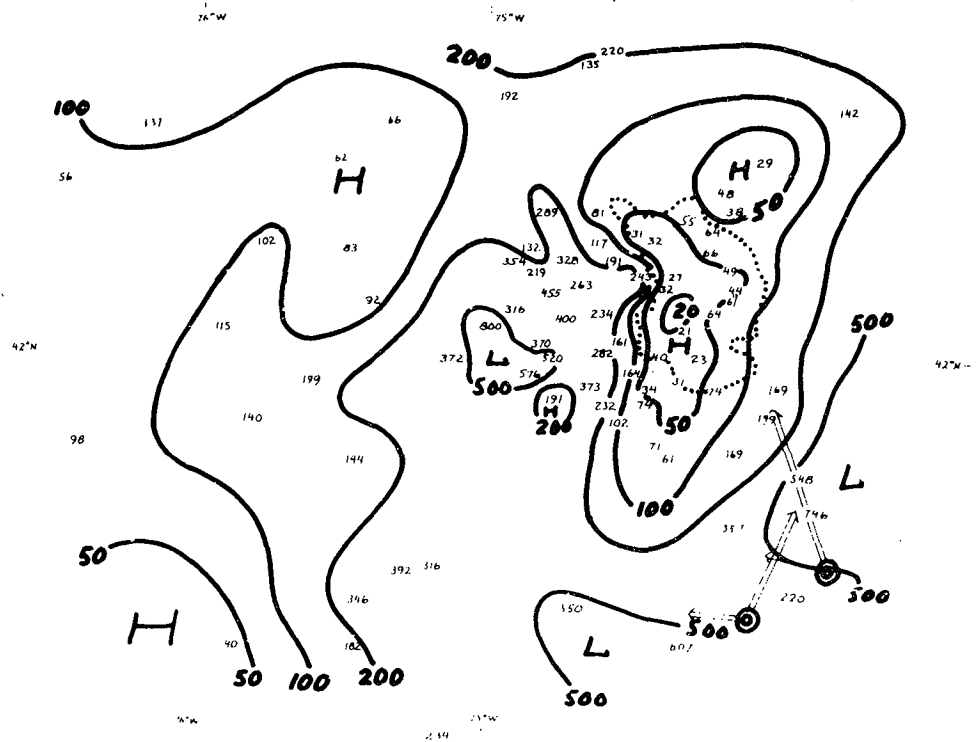


Fig. 3. Rankings of precipitation, Oct. 9-10, 1950

This, then was a storm of extraordinary magnitude, one that at many stations toppled records that had stood for decades, both within the Catskill watersheds and in places that were entirely outside the zone of possible influence of the cloud seeding.

The center of the storm passed northwestward near the southwest corner of the map, figure 2. Immediately to the right of the path lies a region of very heavy rainfall (low rank numbers) undoubtedly associated with the region of strongest dynamic convergence in the storm. Another area of very low rank numbers lies in the eastern portion of the Catskills, with a small region in the Schoharie watershed where the rainfall exceeded the maximum observed during the 13-year base period. This region lay almost exactly in the path of the silver iodide smoke as carried by the wind aloft between 10,000 and 14,000 feet above the sea level (long arrow), while the southern end of the region of very heavy rainfalls coincides almost exactly with the carry of the wind near the ground (short arrow) from the point of seeding (bull's eye).

The rain that fell in the Catskill regions conforms closely to a pattern that might have been expected to result from the influence of the mountains in causing the air to rise in its flow over them; the heaviest amounts are in the region of highest terrain. The fact that this mountain effect seems to have found such a large degree of expression in the seeded area as compared with its magnitude elsewhere raises but does not answer the question whether the seeding may have stimulated the precipitation of water from clouds that might otherwise have carried their burden onward until it would have been at least partially reevaporated as the wind blew down the farther slope of the mountain region. A contribution to the answer would be a comparison with the rainfall pattern of this storm with those of other storms of the same general character. The limitations of time did not permit this comparison to be carried out.

The storm of November 25th, together with those of October 9-10 and April 19-20, which will be described in a later paragraph, constitute the only reported seedings of clouds in the frontal rain system of extratropical cyclones, although it is understood that other such seedings have been accomplished but not reported. It has been the consensus of professional meteorologists that cloud seeding would not materially stimulate rainfall in a region of the atmosphere such as the frontal rain area of a cyclone, where rain was already falling. Nevertheless, a study by means of radar of the formation of precipitation in the upper portions of frontal cloud systems revealed that the precipitation process, rather than being continuous, begins over and over anew in the form of many small showers that tend to merge as they fall toward the ground and finally forming the

more or less even rainfall or snowfall observed there. This observation suggested that cloud seeding, after all, might have an influence in stimulating the more energetic formation of these showerlets. Occasion was, therefore, sought to seed cyclonic disturbances during the course of the experiments. Since in most cases frontal zones cannot be effectively seeded from the ground, and suitable aircraft for airborne seeding were not available, there was little opportunity to carry out this type of seeding.

October 9-10, 1950. - The storm associated with the rainfall pattern shown in figure 3 passed northward across Ohio during the early morning of October 9th, stagnated near Detroit until the 10th, then moved north-eastward, passing close to Buffalo late on the 10th. The belt of heavy rainfalls through central New York State appears to be associated with the path of this center. In contrast to the general decrease of rainfall farther to the eastward, an area of low rank numbers appears over the eastern Catskills, in the area where the cloud seeding would be expected to have its maximum influence. Once again, the pattern strongly suggests an influence of cloud seeding, especially since there is very little evidence of any orographic effect of the high ridges south of the East Branch of the Delaware River.

In the evening of October 9th, when the seeding began, there was a well-marked frontal inversion that inhibited vertical motion and probably prevented the smoke from reaching an elevation where it could become effective. However, as convergence continued the inversion weakened rapidly during the early hours of October 10th, and by the evening of that day had disappeared completely and had been replaced by a steep lapse rate, indicative of conditions favorable to vertical transport of the smoke by turbulent airmotion. Since the seeding was done at first from the summit of a mountain ridge near Bear

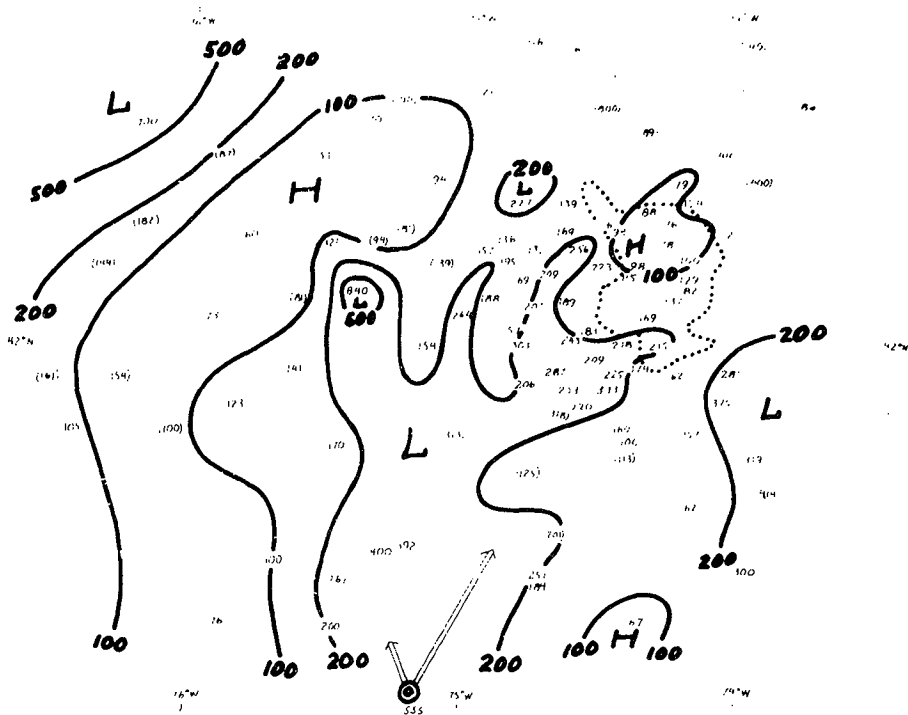


Fig. 4. Rankings of precipitation, Apr. 19-20, 1950

Mountain, above the base of the frontal inversion, it is highly probable that the smoke was carried aloft during the active portion of the storm to the region where it could become effective.

April 19-20, 1950. - The rainfall pattern shown in figure 4 was associated with the point of occlusion of frontal systems that sprang from a storm far to the northwestward, over the southeastern part of Hudson Bay. The air remained stable near the ground throughout the episode of

heavy rainfall; and since the smoke generator was located in the floor of a valley at Stroudsburg, Pennsylvania, there is presumably little likelihood that the smoke was carried high enough to become effective.

The precipitation pattern is relatively flat. The region of relatively low rank numbers in the vicinity of Binghamton corresponds to the path of a slight wave disturbance along the cold front. The path of the seeded air is, in general, a region of light rainfall except in the extreme northern part of the Schoharie watershed, where an island of heavy rainfall appears that corresponds well in position to the expected influence of the orography. By comparison with figures 2 and 3, the pattern is singularly devoid of any big indication of either seeding or orographic effect.

July 12, 1950. - The rainfall pattern of figure 5 resulted from a day of thunderstorm activity that was associated with an indistinct

region of convergence not characterized by frontal activity. It shows that one or more heavy showers developed in the vicinity of Balsam Lake and moved east-northeastward in the direction of the wind near the freezing level (about 13,000 foot elevation). The location of the showers coincides well with the expected location of the seeding effect, although the more southerly generator appears to have had no influence. No other showers of comparable magnitude occurred nearby. Unfortunately, the showers did not pass over any recording rain gauges, so that the hour of their occurrence could not be determined.

June 10, 1950. - The rainfall of this day was associated with the passage of a squall line that reached the watersheds in the evening. Figure 6 shows that a shower developed in the hour preceding 7 p.m. in the vicinity of Downsville, directly downwind from the more southerly silver iodide smoke generator at Thompson, Pennsylvania, and moved eastward across the southern part of the Schoharie watershed, reaching Hudson during the hour ending at 9 p.m. A second, smaller shower developed near Relay, downwind from the smoke generator at Deposit, passing Prattsville during the hour ending at 8 p.m. A third shower of considerable magnitude was reported at only a single station, West Shokan, probably outside the influence of the seeding. One or more of these showers regenerated after reaching the highlands east of the Hudson Valley, yielding heavy rain at Spencertown. The speed and direction of motion of the showers coincide well with the wind travel at the freezing level, about 13,000 feet.

June 1, 1950. - Cloud seeding on this date was done following the



Fig. 5. Rankings of Precipitation, July 11-12, 1950

passage of a slow-moving cold front, and the winds aloft showed that colder air was flowing in from the northwest and west at the time. Only scattered light showers occurred in the mountains (figure 7), one near Andes being perhaps attributable to the generator near Walton. Seeding had been done on the preceding evening, May 31, near Port Jervis, and may have allowed the air that settled near the ground during the night to remain contaminated with silver iodide until the front approached on June 1, since the winds near the ground were nearly calm. Heavy rain developed in the Hudson Valley, along the part of the front behind which the generators were seeding, and where silver iodide may have remained from the previous day. The rain affected the southeastern portions of the watersheds. The coverage of the map is not sufficient to indicate whether these showers in any way were distinguishable from others that may have formed elsewhere along the front. It may be noted that heavy showers developed along the front in the forenoon as it passed the vicinity of Binghamton and Sidney, but that the front then became inactive during its passage over the mountains, a somewhat unexpected circumstance. It is interesting to speculate that this inactivity may have been the result of overseeding of the clouds, and that stimulation may have taken place over the Hudson Valley at a distance such that the smoke was more dilute and its activity more greatly diminished. For this speculation the narrow neck of light rainfall a short distance south of Kingston is of interest, since it lies where the smoke clouds from the two generators, as carried by the winds near the ground, would have overlapped and reinforced one another.

April 29-30, 1950. - The seeding of this date was done in relatively calm air beneath a warm front that was associated with a wave moving eastward some distance south of the watershed. Throughout nearly the whole period of rainfall, the watersheds lay near the northern boundary of the rain area. The nearly stagnant air near the ground was characterized by moderate instability up to an altitude of about 5,000 feet, topped by a very stable layer about 2,000 feet thick, above which was the unstable tropical air from which the precipitation came. Because of the presence of the stable air beneath the warm front, it is quite probable that very little of the silver iodide reached the region where it could become effective, even though the stagnant condition of the lower air favored accumulation of a relatively high concentration of silver iodide over the area in the lower levels.

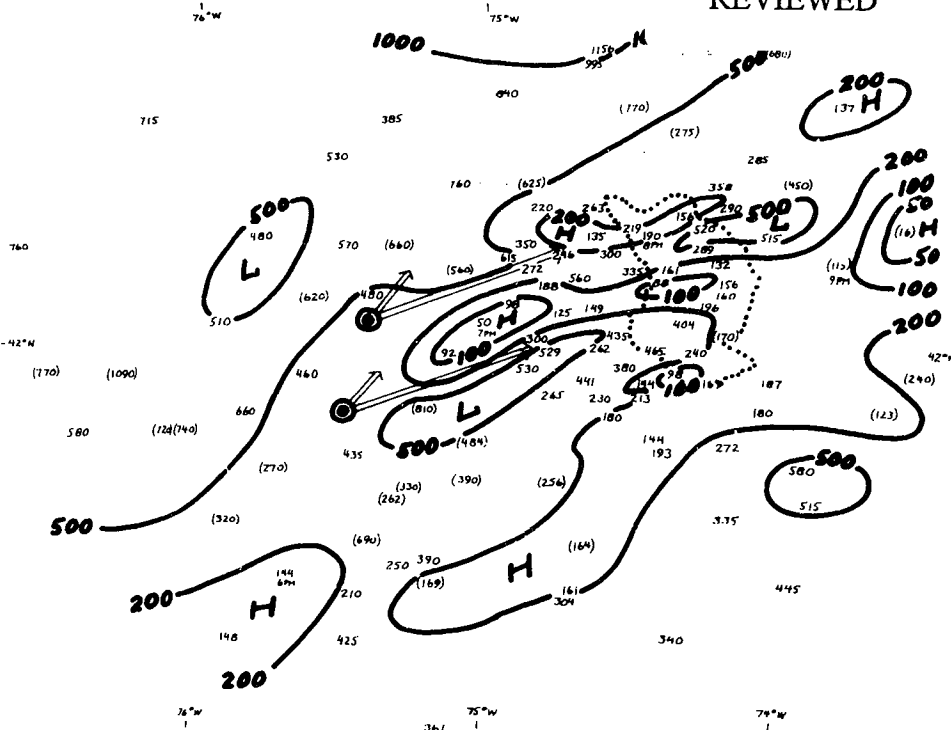


Fig. 6. Rankings of precipitation, June 10, 1950

The rainfall pattern shown in figure 8 shows a broad band of somewhat heavier rainfall extending from southwest to northeastward. Close inspection of the figure shows that there is a center of rain activity over the higher Catskills surrounded by a narrow band of decidedly lighter rainfall (ranks 300 or greater) that bounds it on the south, west, and northwest. This band appears as if convective activity in the warm air aloft had been enhanced over the higher Catskills, the rising air currents there causing compensatory descending currents

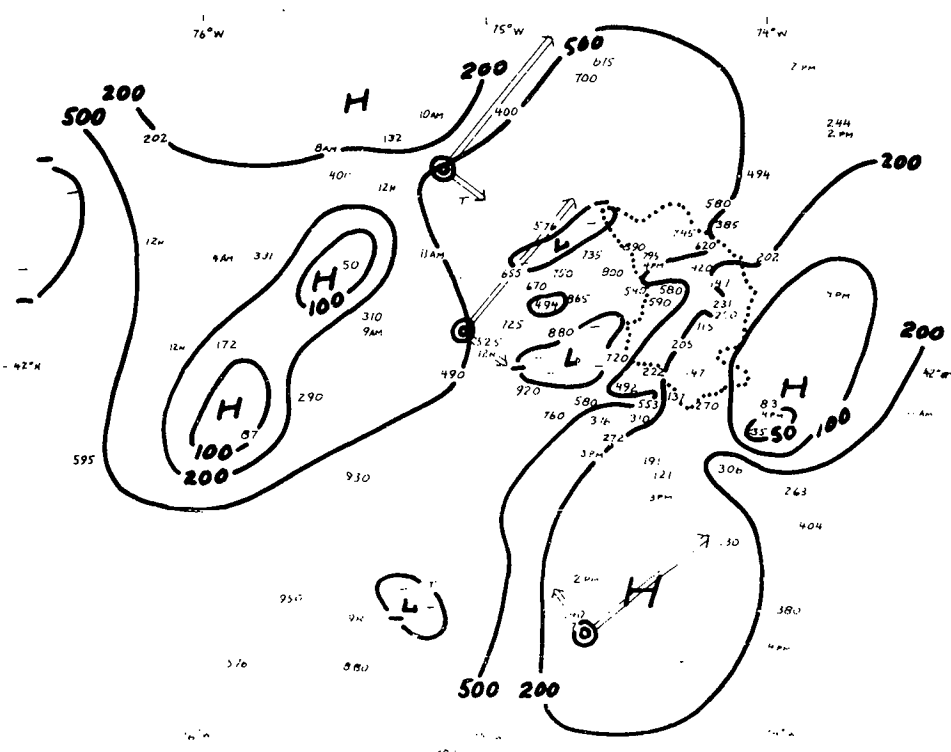


Fig. 7. Rankings of precipitation, June 1-2, 1950

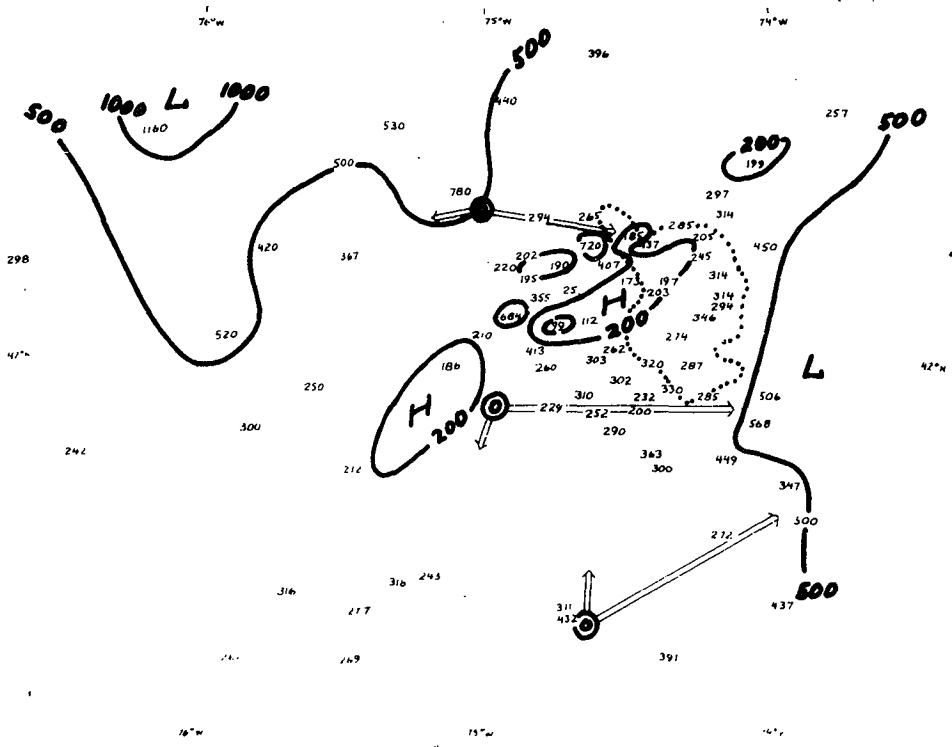


Fig. 8. Rankings of precipitation, Apr. 29 - May 2, 1950

that diminished the rainfall in the immediately surrounding zone. Whether this additional rainfall may have been the result of silver iodide carried aloft by the turbulence engendered where the wind passed over the higher mountains is a question that cannot yet be adequately answered, but the rainfall pattern is at least highly suggestive in view of the fact that the average orographic effect is eliminated by the method of presentation.

June 3, 1950. - The rainfall on this occasion accompanied the passage of a slow-moving cold front which passed the watersheds in the late evening of the 3rd. Areas of heavy rainfall, as shown in figure 9, developed at about midnight near Downsville and moved east-northeastward. Their

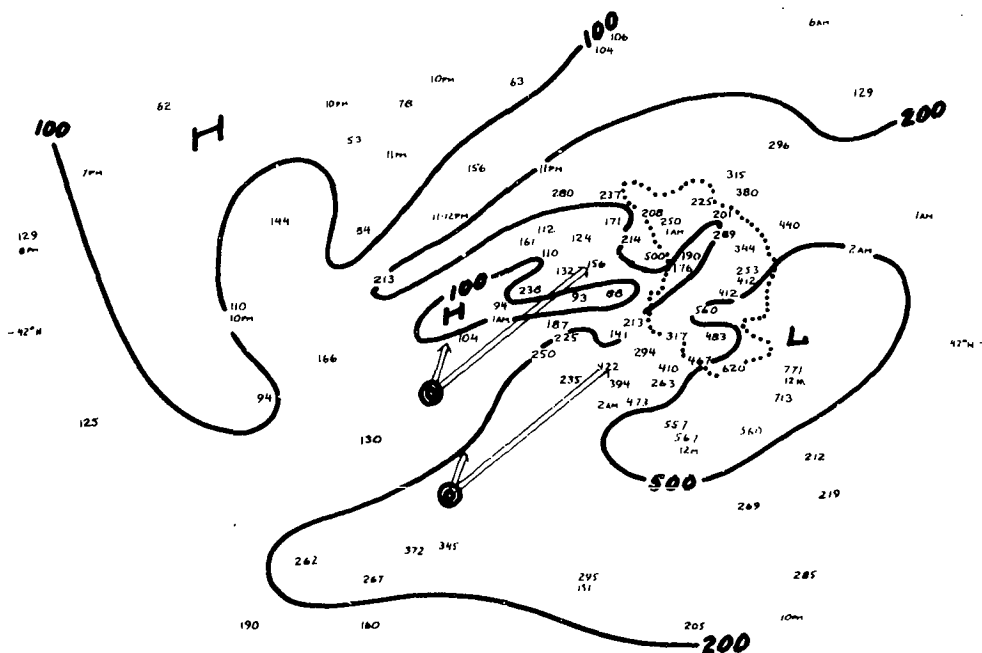


Fig. 9. Rankings of precipitation, June 3-4, 1950

location coincides well with the expected area of influence of the silver iodide.

July 13, 1950. - Figure 10 shows the distribution of rainfall that accompanied the passage of a rapidly moving cold front in the evening. Small areas of locally heavy rainfall appear in the western portion of the Catskills that may have had a connection with the seeding. Although operation ceased an hour before the showers began, the relatively light winds probably permitted much of the smoke to remain for at least that long a period in the vicinity of the mountains.

June 24, 1950. - The passage of a rapidly moving squall line that reached the watersheds in midafternoon caused the precipitation pattern shown in figure 11. Heavy thunderstorms had occurred in central New York State early the same morning, the last holdover from the activity of the previous day in Ohio, but only a few sprinkles had reached the Catskills before the

renewed activity began in the afternoon. The figure shows that a narrow tongue of heavy rainfall developed that coincides exactly with the downwind direction from one of the two smoke generators. It passed south of the Esopus and Schoharie watersheds, however. It is noteworthy that the line of heavy rainfall, although exactly aligned with the smoke cloud, does not bear any discernible relationship to the principal mountain ridges, indicating that the latter apparently exerted no influence on the development of the shower. A later shower at Poughkeepsie may be traceable to one or the other of the generators.

July 5, 1950. - Thundershowers developed on this day in scattered areas, in the warm sector of a weak disturbance, causing the patches of rainfall indicated on figure 12. Seeding was done from Grossinger Airport, near Liberty, for a short time in the late afternoon. The heaviest rainfall in the Catskills ensued at Balsam Lake, directly in the line of drift of the smoke cloud. However, this shower did not pass over any recording gauge, so there is no indication of the hour of its occurrence.

Other occasions. - Because of limitations of time, only the storms described in the paragraphs above were evaluated, these being the occasions when the ensuing rainfall in the Esopus and Schoharie watersheds had been greatest. Although many of the remaining occasions of seeding were not followed by more than very light rainfall anywhere in the region of the seeding, several of them were followed by heavy showers that either were so limited in area within the watersheds that they did not result in an average rainfall as heavy as those analyzed

or else fell outside these watersheds entirely.

No matter how impressive or how dubious may be the results of a few occasions, as illustrated by the evaluations described above, their value for the purpose of increasing the water supply depends upon the accumulated results throughout the period of the experiment. For that reason, in addition to studies of individual occasions of cloud seeding, an analysis was made of the rainfall for the entire period that was available for cloud seeding, even though by no means all the storms during that period were seeded. If the rainfall stimulation increased the precipitation in the Catskills, this increase should be discernible as a local feature in the general pattern of the rainfall distribution for the period. To test for the presence of a feature in that pattern, the amount of rain falling during the entire experimental period (figure 13) was compared with the mean annual rainfall of the 13-year base period (figure 14), and the result, reduced to the appropriate fraction of a year, was mapped as percentages of mean expected rainfall.

The resulting pattern of actual rainfall is shown in figure 15. It is so burdened with confusing details, however, that in order to separate out the salient features of the pattern, it was smoothed by 10-mile squares, a single value being plotted at the center of each 10-mile square representing the mean of the four values at its corners obtained from figure 15. The resulting pattern is shown as figure 16. Its most prominent features are a tongue of high percentages extending from a small center in extreme northeastern Pennsylvania northeastward to the highest part of the Catskills, with isolated centers of high percentage near Slide Mountain and near Prattsville; a trough of low percentages over the Hudson Valley; and a second tongue of high values over the southern Berkshires and Taconic Mountains.

Before these features can be given any interpretation, it is necessary to compare them with the general precipitation pattern in a larger frame for the same period. Figure 17 shows the rainfall anomalies, as published by the U.S. Weather Bureau, summed for the months from April through November 1950 (omitting August, since nearly all of that month was interdicted as far as seeding was concerned). The anomaly chart shows that the general trend of the rainfall marched from a region of deficit in northern New Hampshire and western Maine to a region of surplus near extreme southern Ohio, with the gradient trending more or less smoothly in the region between. One would not expect, from this large-scale pattern, to find either of the

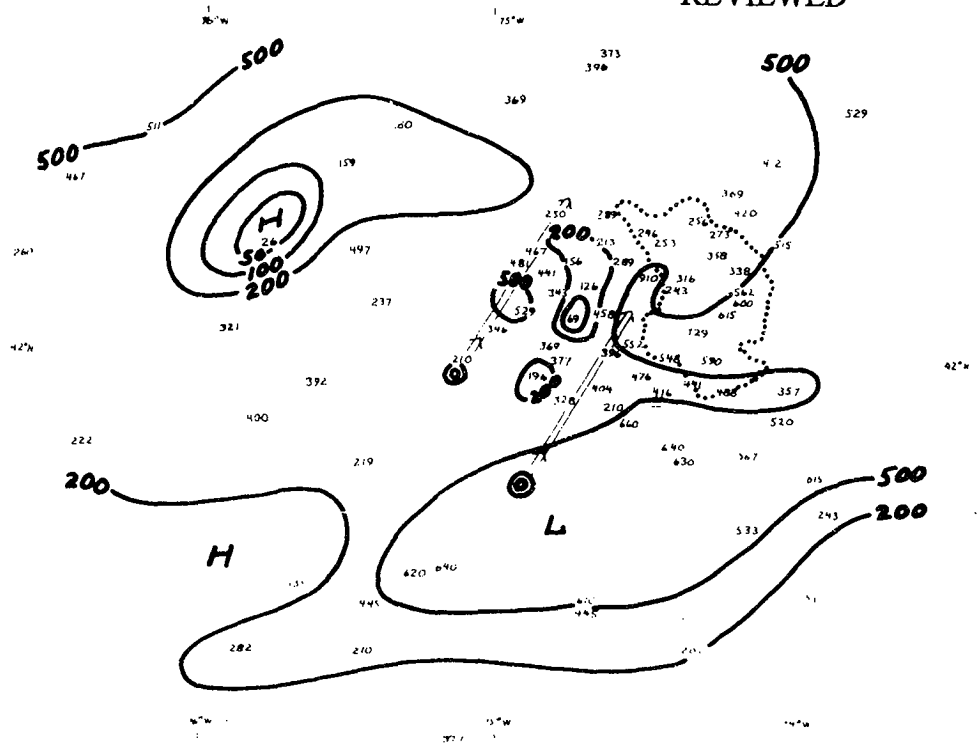


Fig. 10. Rankings of precipitation, July 13-14, 1950

two tongues of heavy rainfall shown on figure 16. It is also clear from figure 17 that the tongue over the Taconic Mountains, incompletely shown on figure 16, must be closely bounded on its eastern side. It is not unreasonable, on the basis of this comparison, to assume that the tongue of high rainfall over the Catskills may be the result of rainfall stimulation, and that the tongue over the Taconics is a secondary effect derived from the regeneration of storms such as that of June 10, which formed over the Catskills apparently as a result of seeding, skipped over the Hudson Valley, and regenerated in the Berkshires.

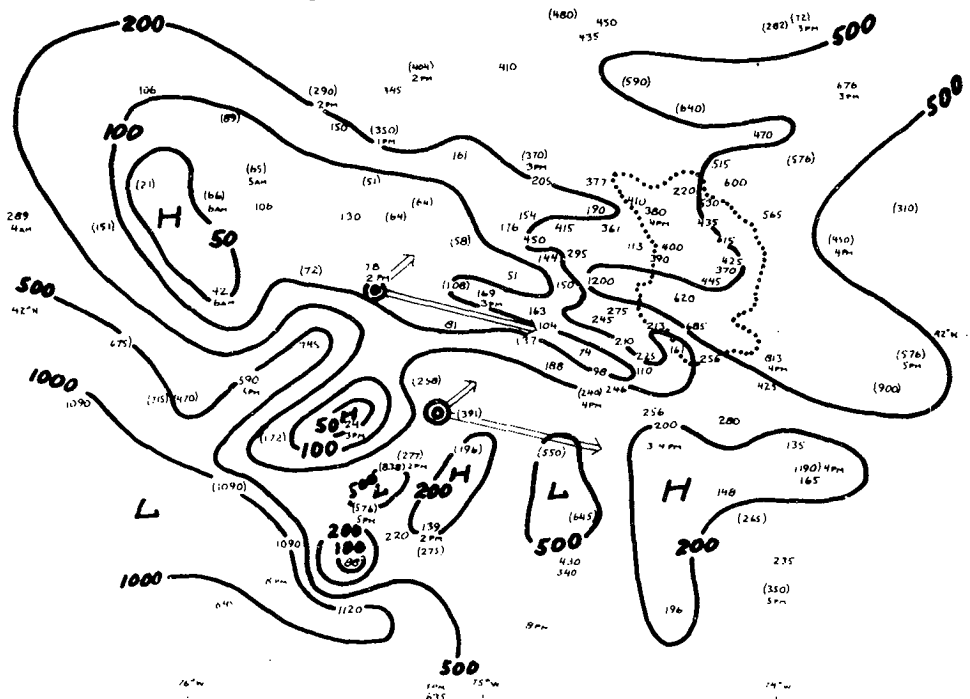


Fig. 11. Rankings of precipitation, June 24-25, 1950

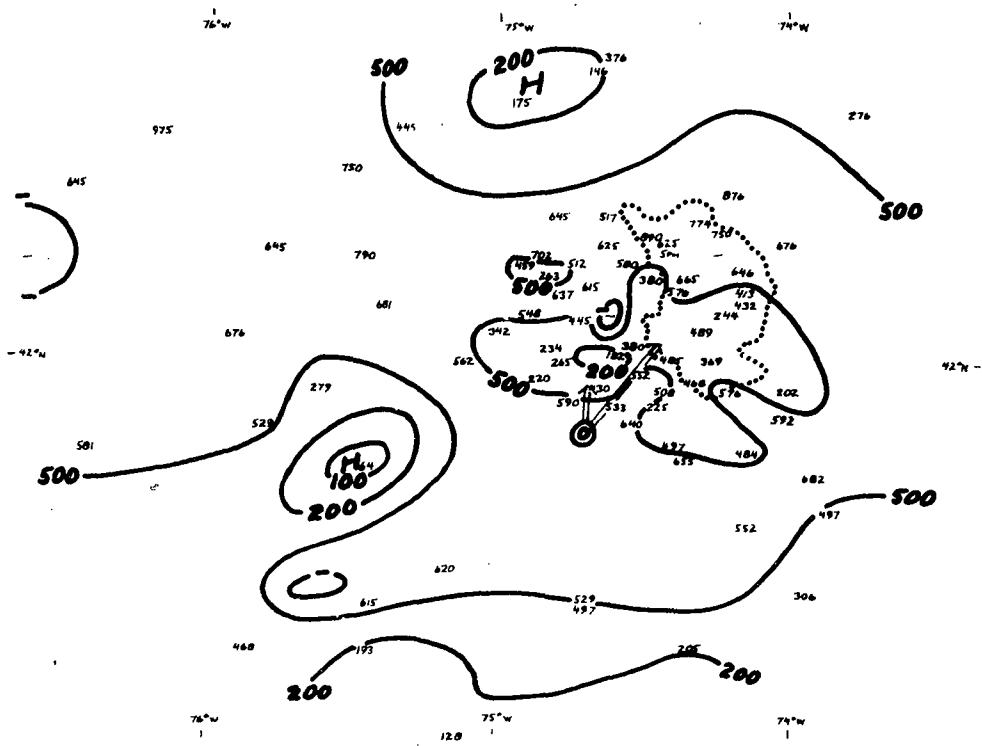


Fig. 12. Rankings of precipitation, July 5-7, 1950

In order to obtain an estimate of the degree of rainfall stimulation, based on the assumption that without seeding the pattern of figure 16 would have conformed with that of figure 17, the former was redrawn (see figure 18), omitting the two tongues that are presumably due to the stimulation, and new percentage values were interpolated in the region of the watershed. In comparison with the mean value of 90 percent derived from figure 16 for the watershed area as a whole, the mean value of the estimated percentage of normal rainfall obtained from figure 18 is 77 percent,

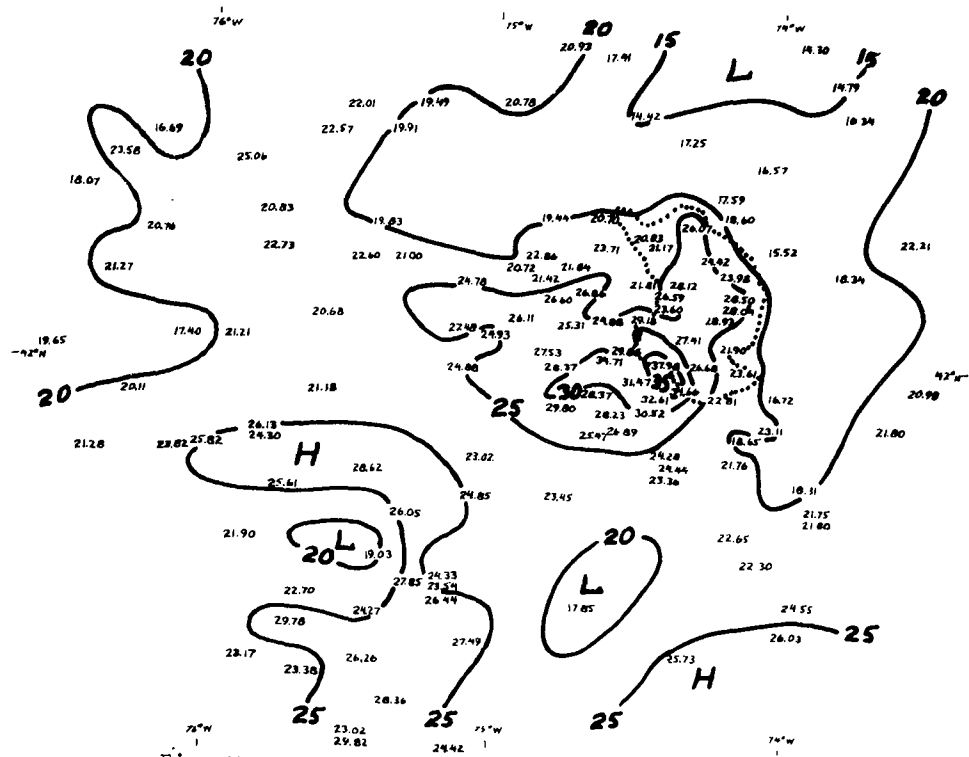


Fig. 13. Precipitation in inches during period of tests

indicating estimated stimulation of 17 percent above the unstimulated precipitation. Since the total precipitation during the experimental period was 28.89 inches, of which 14.93 inches fell from seeded storms, and if all the stimulation is presumed to come from the seeded storms, then these must have been stimulated by about 39 percent.

Because of the approximations that have been used at various stages in the evaluation, particularly in the estimation of the precipitation that would have fallen if seeding had not been done, the results presented must be considered as tentative, subject to confirmation by refinement of the procedures of evaluation and by additional experimentation. It is believed, however, that they indicate reasonably well the general scale of magnitude of the results that are to be expected from cloud seeding.

VI. DISCUSSION

General

During the first season of experimentation, attempts to stimulate rainfall were limited to the Catskill watersheds, for a number of reasons. In the sparsely settled Catskills, there is less likelihood of interference with normal activities than in the thickly populated Croton and Long Island watersheds; and for anticipated airborne operations, the freedom from commercial air traffic over the Catskill area was an important consideration, while only a very small portion of the Croton and Long Island areas lay outside of the civil airways. Furthermore, it was expected that the mountains themselves would tend to intensify and localize the effects of cloud seeding, and would increase the frequency with which favorable weather situations would be encountered. While, in general, these latter expectations were fulfilled, nevertheless it was found that stimulation appeared to be effected on several occasions in the western Catskills where the terrain is scarcely more rugged than that of the Croton watershed, although at a somewhat higher elevation. It is likely, therefore, that rainfall stimulation may be effectively carried out over the Croton watershed if the need should arise.

As a pioneering investigation, undertaken in a newly developing field of science without a background of previous experience, the program had as its primary objective to gather data and attempt to establish the salient facts about the effectiveness of rainfall stimulation. For this purpose it was necessary to accept the risk that

cloud seeding might on some occasions cause heavy rains and possibly damage property, and that on other occasions seeding might be done and storm damage might later occur without any causal relationship that could be proven or disproven. Now that even tentative indications have been obtained of the degree of rainfall stimulation that may be expected, it will be possible to avoid seeding operations in the great majority of occasions when damage might ensue, either causally or by chance. The risk of damage, therefore, may be expected to diminish sharply with the growth of experience.

Interpretation of Individual Seedings

Interpretation of the results of individual cloud seedings presents an extremely difficult problem because of the enormous variability of natural rainfall from one place to another and from one storm to another. This natural variability creates bold patterns such as those that appear on the rainfall distribution maps of the preceding section, patterns in which it is perhaps too easy to see a wishful connection with the cloud seeding. It is well known that cloudiness and rainfall, especially showers, are accentuated over mountainous terrain; and it was this same terrain at which the silver iodide smoke was aimed. The shower of July 11 1950 (figure 5), to take an example, began over some of the highest terrain in the region, the most favored by nature for shower activity; whether this shower was initiated or intensified by silver iodide from the smoke generator favorably located to influence that same area is a question that cannot be resolved on the basis of this single occasion, or any other single occasion. Nevertheless, repeated observation of accentuated rainfall in the seeded areas creates at least a presumption that there may be a real effect. If such accentuation of the rainfall could not have been observed on individual occasions, serious doubt would have been cast on any other indications of success.

Further substantiation of the effect of seeding may be sought by attempting to determine whether a relationship exists between the location of the smoke generators and the areas of accentuated rainfall, other than that created by the terrain or other natural influence. For instance, if it can be shown that the region of heaviest rainfall lies, with significant frequency, in a direction from the smoke generator determined by the winds aloft, or at a distance determined by the amount of vertical air motion and the height of the freezing level,

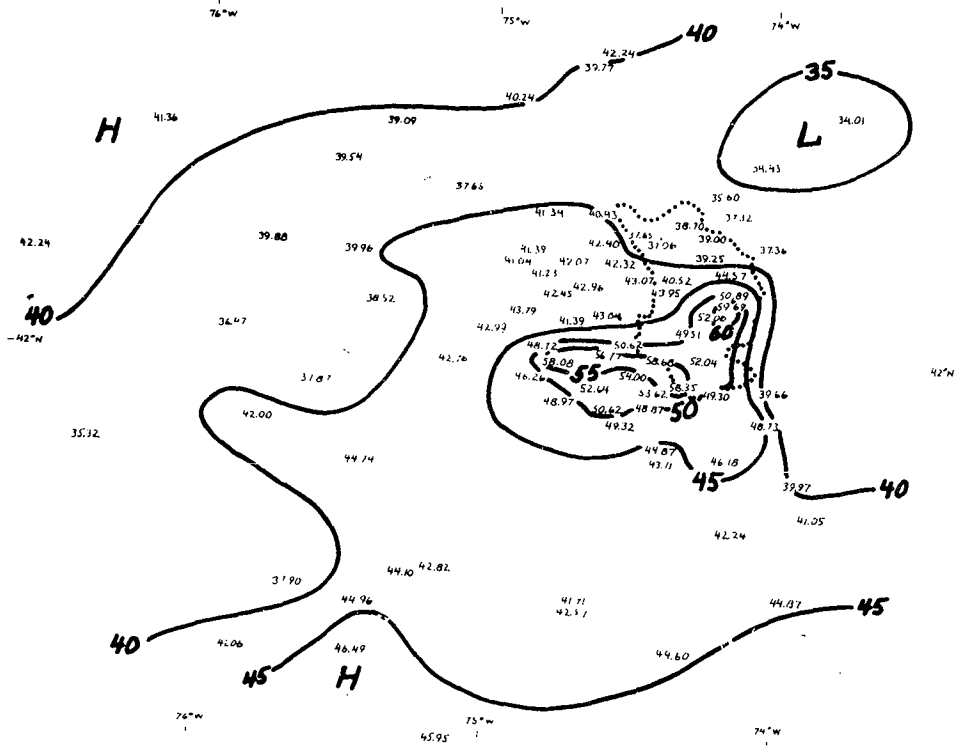


Fig. 14. Mean annual precipitation, 1937-1949

the influence will be substantiated. Figure 19, which shows the position of first occurrence of accentuated rainfall, as related to the position of the generators and the wind directions at the ground and at the freezing level, offers many instances of apparent confirmation of these hypotheses; but the body of data is too small to determine whether or not the instances are due to chance.

The three occasions of seeding of cyclonic storms (figs. 2, 3, and 4) deserve especial mention, since the normal distribution of rainfall

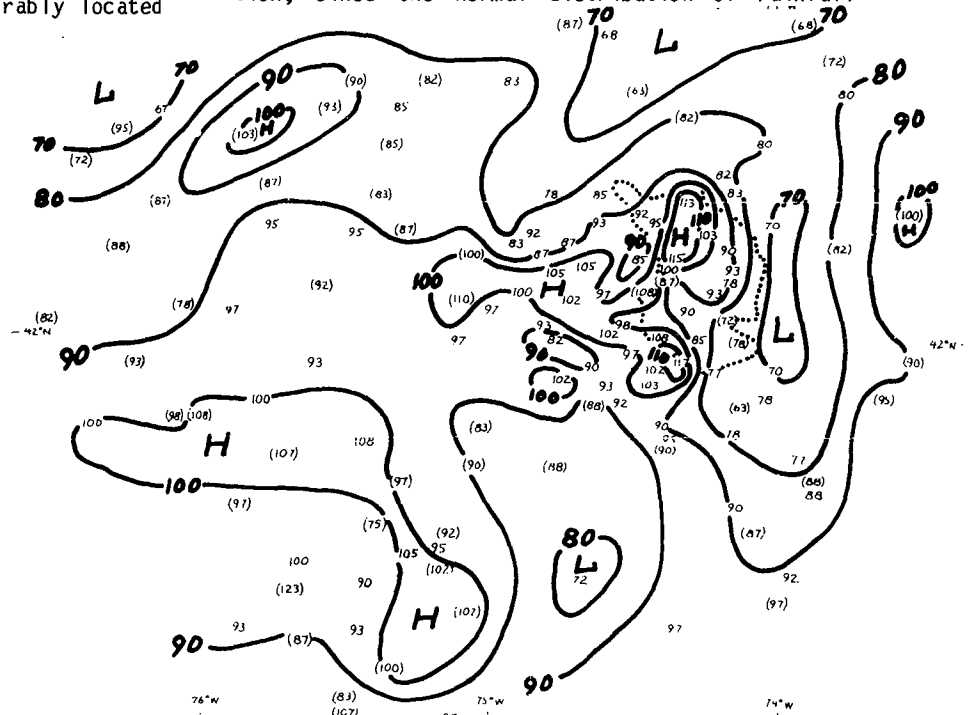


Fig. 15. Percent of normal precipitation during test period

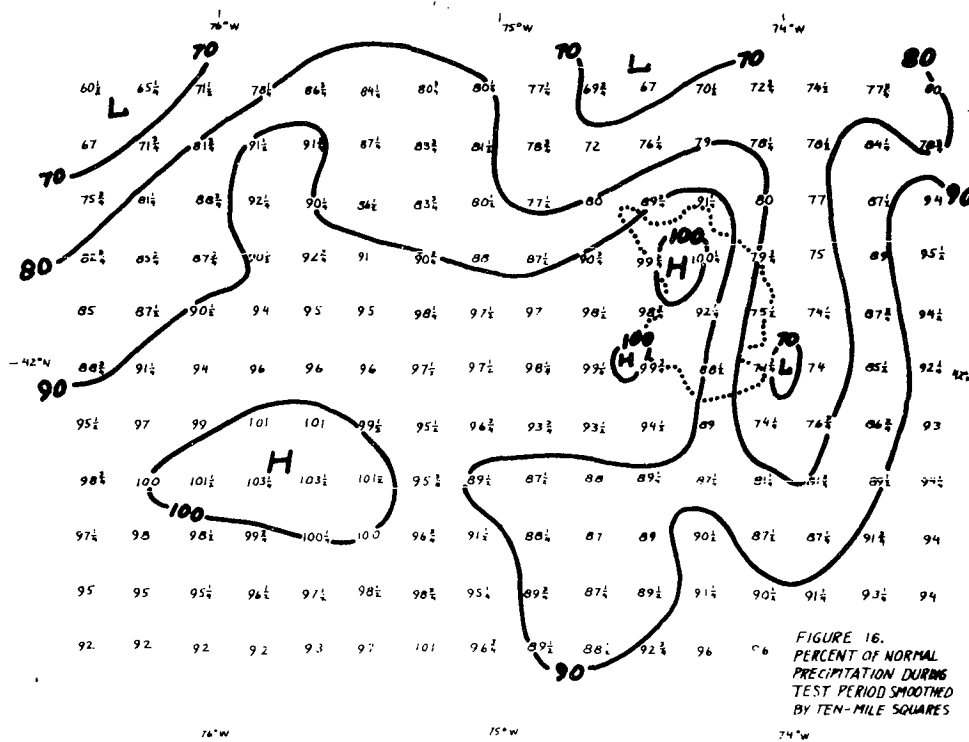


Fig. 16. Percent of precipitation during test period smoothed by 10-mile squares

from cyclonic storms is quite different in character from that due to showery conditions. One would expect the map for such storm to represent mostly the track of the storm itself, without particular regard for the type of terrain over which it passes, especially in view of the fact that the method of representation cancels out the mean influence of terrain on the rainfall. It is quite surprising and suggestive, therefore, to find that such pronounced areas of local rainfall accentuation exist at all, aside from the fact of their location in the most likely area of seeding influence. Because a large proportion of the rainfall reaching the Catskill watersheds originates from cyclonic storms, the question of the susceptibility of these storms to stimulation is an important one. It will therefore be worthwhile to undertake a detailed study of other storms that have brought heavy rainfall to the Catskills, in order to determine whether similar patterns are

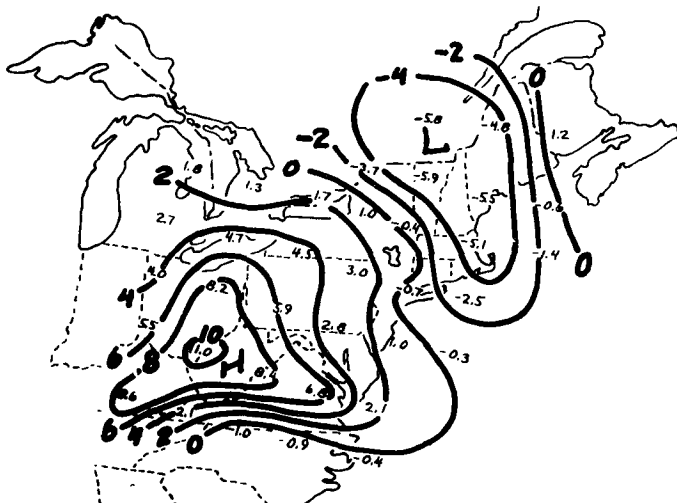


Fig. 17. Precipitation anomaly in inches during test period, after U.S. Weather Bureau maps

observable in them.

While no specific attention has yet been given to the possibility of widespread effects due to seeding in the watershed areas, the apparent regeneration of rainshowers over the Berkshires after crossing the Hudson Valley, such as that of June 10, 1950, seems to substantiate the idea that rainfall at a greater distance will be, if anything, increased rather than decreased by the seeding. The anomaly patterns to be discussed in a later paragraph appear to confirm the evidence of an effect over the Berkshires but reveal no influence at any more remote point.

Interpretation of Average Results

Another way of seeking to substantiate the reality of the seeding influence is to suppose that, if some of the accentuation of rainfall is due to initiation or intensification of showers by the seeding, the region of seeding

influence will stand out, by comparison with surrounding regions, in its deviation from the normal rainfall. This test is, furthermore, the final proof of the pudding insofar as effectiveness of the seeding is concerned for the purpose of increasing water supply, since it involves not only the effectiveness of individual occasions of seeding but also the frequency with which effective seeding can be carried out. However, it cannot avoid, on the one hand, dilution of the data with occasions of unseeded unseeded rainfall without, on the other hand, involving a selection of the data that might falsely bias the results. Dilution must be accepted as the lesser evil.

The fact that the seeding of a portion of the storms during the experimental period did apparently create a local feature in the rainfall anomaly pattern is an encouraging indication of a real influence, but it cannot be regarded as proof; for there is still the possibility that this feature may have occurred by chance. The probability of its chance occurrence can be established only by statistical methods that have been beyond the scope of the evaluation so far undertaken, and it is for this reason that the results so far obtained must be regarded as tentative. In view of the close correspondence between the observed anomaly and the expected effect of the seeding, however, it seems very likely that a more refined analysis will confirm the tentative findings.

Estimate of Yield Increase

Before the effect of the rainfall stimulation on the actual yield of the watersheds can be estimated, losses in the form of evaporation and transpiration must be considered. The losses are expressed in the statistics of the Department of Water Supply by listing the yield of each watershed for each month as a percentage of the no-loss yield, the difference between this percentage and 100 percent being considered the loss. However, the losses are not, in actuality, proportional to the precipitation; for they proceed at a rate determined largely by the temperature, whether or not there is precipitation. The additional

precipitation that may be produced by stimulation therefore increases the yield without proportionally increasing the losses, although the latter are somewhat increased thereby. Especially in the case of the warmer months, then, the actual increase of yield by stimulation of the precipitation is underestimated if the overall "percentage yield" coefficient is applied to it as a multiplier. Nevertheless, lacking data in any other form regarding the losses, these percentages of yield were used in the present instance to gain a conservative estimate of the increase of yield due to stimulation. The results are shown in table II. Since the data are insufficient to permit individual evaluations of the rainfall anomaly patterns for the separate months, the overall estimated percentages of stimulation are applied to the precipitation amounts of each month in this tabulation, and the results thereby suffer from an additional degree of approximation. The estimated total additional yield due to stimulation of 2.19 inches is equivalent to approximately 24 billion gallons of water, of which 1.18 inches or about 13 billion gallons was realized before August 1, 1950. It is likely that the program of artificial rainfall stimulation made at least this much contribution to the timely easing of the water shortage and the lifting of restrictions on water use, even though the tide of later events brought such an oversupply that a far greater quantity of water has since flowed to waste over the spillways. The estimate is conservative in that it takes no account of the quantity of stimulated rainfall that may have been recovered through the emergency intake on Rondout Creek, the watershed of which was within the region of seeding influence, and to some extent also, possibly, through the Croton system, since a few of the showers apparently caused by the seeding moved in the direction of the Croton watershed.

Table II. - Precipitation, percentage yield, and estimated stimulation for individual months during experimental seeding period

Month	Mean precipitation from seeded storms Esopus, Schoharie	Estimated stimulation by seeding	Mean percent yield	Estimated increase of yield
April	2.16	0.61	75.7	0.61
May	0.63	0.18	72.0	0.13
June	2.98	0.84	42.0	0.35
July	2.15	0.60	15.4	0.09
August	0.16	0.04	7.0	0.00
September	0.10	0.03	24.4	0.01
October	2.05	0.58	21.4	0.12
November	4.51	1.26	66.0	0.83
December	0.18	0.05	96.0	0.05
Total	14.93 inches	4.19		2.19

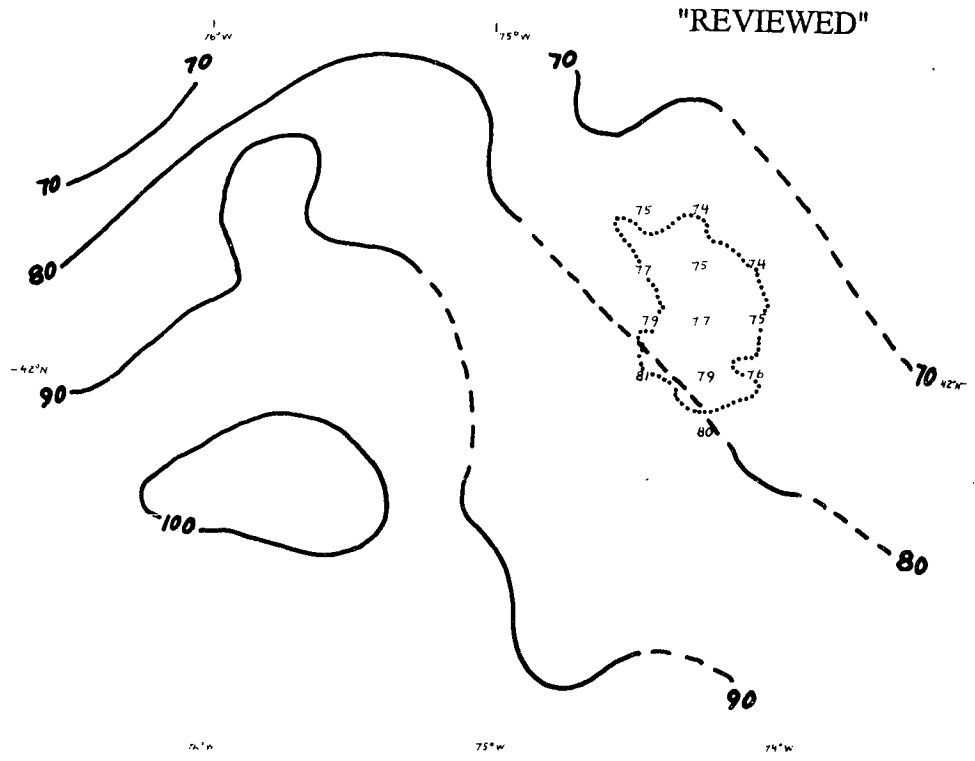


Fig. 18. Estimated percent of normal precipitation without seeding during test period

Applications

In the 7 months of its operation, according to this estimate, the rainfall stimulation project produced about as much additional water as the water-conservation campaign saved in a little over 2 months. In making this comparison, however, it is essential to note that there is a fundamental difference between abstention from the consumption of water and the provision of a more adequate supply. The consumption of water is productive of value, both in the form of revenue for the city and in the course of purposive use, industrially or domestically. Water conservation decreases this purposive use, and hence diminishes the realization of value from the water supply system as a whole, while augmentation of the supply by artificial stimulation tends to maintain purposive use unrestricted. It is highly probable that in a repetition of the shortage of 1949-50, timely renewal of rainfall stimulation activities would greatly shorten the period when conservation measures would be necessary and avert the necessity for the more drastic restrictions on water use.

Of perhaps greater significance in the long run is the use to which artificial stimulation of precipitation may be put for increasing the efficiency of the watersheds now in use or under construction. If the tentative results obtained in the first year of experimentation are confirmed by further study and experimentation, the prospect for full development of artificial rainfall stimulation as a means of increasing the dependable yield of existing watersheds before additional ones must be developed is most inviting. In order to realize the benefits of increased dependable yield, it is only necessary to stimulate the rainfall during the one or two driest seasons in 10 years or so, with correspondingly low cost for operations and compensation for possible damage. The rainfall stimulation carried on in 1950 appears to have been as effective in increasing the yield of the Esopus and Schoharie watersheds as if the Rondout and half of the Neversink watersheds had been added to the former two.

To gain an idea of the financial significance of this increase in yield, let us compare the expense of rainfall stimulation with the expense of an equal increase of dependable yield by the development of new watersheds. A generous estimate for the cost of a rainfall stimulation program is \$50,000 per year. Applied to the nearly 800 square miles of watershed now developed or under construction in the Catskills, it appears capable of increasing the dependable yield as much as the addition of 135 square miles of new watershed. Assuming the cost of development is approximately one million dollars per square mile and that taxes, interest, depreciation, and operating costs together amount to 6 percent of the capital valuation, the new watersheds would cost \$8 million annually, a hundred and 60 times as much as the rainfall stimulation. Even if the tentative estimates of stimulation were a hundred percent too high and damage claims cost the city a million dollars during each of the few dry seasons when seeding was done, the comparison would still be overwhelmingly in favor of rainfall stimulation.

The potential usefulness of rainfall stimulation, and the long-range economies that may be realized by its use, justify the most thorough study of the experimental results so far achieved and confirmation of them by further experimentation.

The power to stimulate rainfall will introduce a new complication into management and operation of the watershed system. Up to the present time, it has been possible for the Department of Water Supply to operate efficiently with a minimum of attention to the hydrological aspects of the problem, simply by going on the assumption that every gallon of water falling on the watershed will eventually, subject to normal losses, end up in one reservoir or another. Since rainfall stimulation raises complex questions of public convenience and necessity and exposes the city to claims for damages, it will become necessary to base decisions authorizing rainfall stimulation activities on the most complete information possible regarding available water supplies, including ground water. Furthermore, since the Catskill system will take on the characteristics of a multiple-use hydrological development when present plans are fulfilled, involving considerations of power generation and the fulfillment of interstate commitments regarding streamflow, other complex considerations for the management of the watersheds are to be anticipated, considerations on which the hydrology of ground-water storage, evaporation, etc., will have a direct bearing. In planning to meet these needs for specialized hydrologic information, it may be well to consider the establishment of a hydrometeorological office in the Department that would be in a position to keep track of the current hydrological situation of the watersheds, to make operational analyses of watershed management problems, and to carry out rainfall stimulation when required. An example of the type of operational analysis that might be undertaken is a study of the relative advantages, at different levels of storage and different seasons of the year, of minimizing evaporation by completely emptying as many reservoirs as possible and concentrating storage in the deepest one (thereby minimizing the area of exposed water surface), or of minimizing the possibility of spillage by adjusting the voids in each reservoir according to the drainage area and mean rainfall.

VII. FINDINGS

The most important findings resulting from the rainfall stimulation experiments may be stated briefly as follows, subject to the limitation that the findings are tentative, subject to substantiation by further experimentation and study.

1. Artificial stimulation of rainfall, almost entirely through ground-based operations, stimulated precipitation during the experimental period (including both seeded and unseeded storms) by about 17 percent.

2. This artificial stimulation increased the precipitation from seeded storms by about 39 percent, on the average.

3. Artificial stimulation was effective both for showery rainfall and for cyclonic rainfall, when vertical air motion was insufficient to carry the silver iodide smoke aloft.

4. Artificial stimulation was chiefly effective over mountainous regions but was not limited to them.

5. Secondary stimulation of rainfall over the Berkshires was observed, but effects at a greater distance from the Catskills were not noted.

6. On most occasions in summer, and on a few occasions in winter, cloud-seeding missions can be effectively carried out from the ground by small crews using mobile equipment.

7. Airborne cloud-seeding missions, under the conditions of climate and air traffic prevailing in the vicinity of New York City, require full-equipped, long-range aircraft capable of sustained instrument flight and radio navigation for periods up to 8 hours. The most favorable base for airborne operations is northeast of the watersheds, in the direction of Albany.

VIII. RECOMMENDATIONS

The tentative conclusions obtained from the rainfall stimulation project indicate that rainfall stimulation, undertaken during periods of rainfall deficit, can at very small expense increase the minimum safe yield of existing watersheds by an important amount. Further investigation for the purpose of establishing the conclusions on a more substantial basis, and thorough consideration of their significance for water supply plans and operations, are therefore in order, and the following recommendations are made accordingly.

1. It is recommended that the data obtained during the 1950 experiments be subjected to further analysis in order to refine the tentative conclusions:

- a. By extension of the rank method of rainfall representation to all seeding occasions;

- b. By application of the rank method of rainfall representation to a number of rainfall occasions when seeding was not

done, particularly to occasions meteorologically similar to the outstanding occasions of seeded rainfall;

c. By statistical analysis of the relation between the position of seeding and the position of accentuated rainfall.

2. It is recommended that an experimental rainfall stimulation program should be established to be conducted over a period of 10 years, for the following purposes:

a. To protect the city of New York against recurrence of a critical water shortage during the period before completion of the East Branch watershed development;

b. To provide additional data and experience upon which to base decisions regarding long-range plans for the utilization of rainfall stimulation as a means of increasing the dependable yield of the watersheds during seasons of deficient rainfall.

This program should include the following features:

a. Cloud-seeding should be limited to periods when the total supply is below 90 percent of capacity and the Catskill reservoirs are below 100 percent of capacity;

b. Cloud-seeding should be limited to occasions when unusually heavy precipitation, that might cause floods, is not expected to ensue;

c. Cloud-seeding should be limited, for the time being, to ground-based operations;

d. A radar observing station operating in the three-centimeter band should be established having the best possible coverage of the Catskills and the area immediately to the southwest;

e. If a radar observing station cannot be established, then the present network of precipitation gauging stations should be supplemented by the addition of 24 recording precipitation gauges at the following stations:

Arena	Neversink
Balsam Lake	New Kingston
Brown Station	Oak Hill
High Falls	Parkston
Cairo	Phoenicia
Highmount	Relay
Kortright	Slide Mountain
Lackawack	Sundown
Lake Delaware	Tannersville
Lake Hill	Walton
Lewbeach	Westerlo
Lexington	Windham

f. Using the observations obtained by radar and from the recording rain gauges, the behavior of a large number of precipitation-forming convective cells in the atmosphere should be studied, and preferred locations for the first formation of convective cells should be mapped

g. Information obtained from the study of the behavior of convective cells should be applied to the experimental results of cloud seeding as an additional means of evaluating the effectiveness of the cloud seeding.

3. It is recommended that consideration should be given to the integration and operation of plans for artificial stimulation with other planning and operational aspects of water supply.

a. By study of artificial stimulation as an alternative to enlargement of existing watersheds.

b. By establishment within the Department of Water Supply a Bureau of Hydrometeorology.

4. It is recommended the work of the past year be reviewed by the Mayor's Advisory Committee on Precipitation Stimulation, and by the New York City Board of Water Supply, as well as by the Department of Water Supply.

IX. ACKNOWLEDGEMENTS

So many persons have contributed to the success of the precipitation stimulation project that a complete listing of their names is beyond the scope of this report. Particular recognition is due to Commissioner Stephen J. Carney, under whose auspices the project was initiated and, in large measure, carried out. Others within the Department of Water Supply, Gas, and Electricity who contributed signally to the project include Chief Engineer Edward J. Clark, Deputy Chief Engineer Francis X. Elder, Division Engineer Johan A. Aalto, and Maintenance Shop Chief R. W. Harvey.

The assistance of the Commissioner of Police for the provision of flight and communication services is deeply appreciated. Particular thanks are due to Captain Gustav Crawford and the flight crews of the Police Aviation Bureau.

Invaluable advice and technical assistance was given the project by Dr. Irving Langmuir, Dr. Vincent J. Schaefer, and Dr. Bernard Vonnegut of the General Electric Research Laboratory, by Mr. Robert W. Miller of the Airborne Instruments Laboratory, Inc., Mr. Glenn Stout of the Illinois State Water Commission, and by many others.

Special assistance in the way of forecasts and technical studies was given by the U.S. Weather Bureau. Thanks are especially due to Dr. F. W. Reichelderfer, Chief of the Bureau, Mr. Louis C. Harmantas, Official in Charge of the Weather Bureau Airport Station at LaGuardia Airport, and Mr. H.C.S. Thom of the Scientific Services Division.

Acknowledgement is due to Mr. Roland J. Boucher and Mr. John H. Conover for their contribution to the typing of the storms affecting the New York watersheds and preparation of a catalogue of storms according to type.

Thanks are extended to the Mayor's Advisory Scientific Committee, and to its Chairman, Prof. Victor K. La Mer, for its encouragement and assistance in the performance of the project.

APPENDIX 1

March 2, 1950

MEMORANDUM TO: Mr. Stephen J. Carney
Commissioner of Water Supply, Gas
and Electricity
New York City, N.Y.

SUBJECT: Proposals for rain-stimulation project

THE PROSPECT FOR RAIN-MAKING

In my opinion, based on all the reports on the subject so far published, on discussion with scientists who have worked on the problem, and on my own studies of cloud physics, the prospect that the natural rainfall and snowfall over the Catskill watersheds might be increased by a significant amount - a few inches in the course of a year - by artificial means is good enough to justify a concerted and sustained attempt to do so. If successful, it would not only help to relieve the present water shortage but would also increase the dependable yield of the water supply system. It is not possible, however, to give assurance that the outcome of the experiment will be successful. It is quite probable that no positive conclusion could be reached unless the experiment is carried on for 6 months at least, and preferably for a full year.

Limited operation of the program proposed below could be ready within a week of the time it is authorized. Full operation can be reached within 6 to 8 weeks.

THE SCOPE OF THE PROPOSED EXPERIMENT

The art of rainfall and snowfall stimulation is by no means a perfected one. Experimentation with new techniques and thorough study of the physical changes brought about in clouds promise quite as much, and maybe more contribution to a successful outcome than application of techniques so far developed. Provision should therefore be made for fundamental studies of the physics of the process, to be carried on in connection with the actual operations.

Natural rainfall and snowfall are very variable. The variations that can be produced artificially will probably be smaller than the natural variation, and will be significant only if they trend persistently in the desired direction. The value of the effort can be judged only by distinguishing between natural and induced variations. To do so will require careful sifting of the climatological evidence.

An adequate program must therefore include:

a. Operations, in the air and on the ground, aimed at stimulating rainfall and snowfall over the Catskill watersheds;

b. Efforts, by theoretical and experimental studies, to perfect the art of rain- and snowfall stimulation;

c. Comprehensive observation of the effects of the operations on clouds and on the rainfall and snowfall from them;

d. Evaluation of the climatic trend, if any, resulting from the operations;

e. Interpretation of the results achieved in terms of the climate and hydrology of the Catskill region and the utilization of the watersheds.

POSSIBLE SECONDARY EFFECTS OF THE EXPERIMENT

If the experiment is successful in stimulating rainfall in the Catskills, a certain amount of additional rain and snow will fall over outlying regions, despite the fact that the mountains themselves will to a considerable degree limit the effects of cloud modification to that region. However, any effect felt outside the region will in all probability be hard to distinguish from the ordinary year-to-year variations of rainfall.

Although fears have been expressed in various quarters that stimulation of precipitation over the Catskills will cause deficient rainfall over adjacent areas where rain may be needed, there is as yet no evidence of such an effect; in fact, evidence has been adduced which, it is claimed, shows that artificial stimulation of showers tends to make further showers out of the same air mass more rather than less likely. The question is by no means definitely settled, however.

PROPOSED OPERATIONS

It is recommended that the experiment be carried out by a team composed of a control group, an operating group, an observing group, and a statistical group. The control group would comprise the project director and a full-time meteorological assistant, with the help of certain special assistants from time to time. In order to free the project staff from the necessity for doing a large amount of routine work connected with weather forecasting, forecasts would be obtained from a suitable weather service.

The operating group would comprise four mobile units, two on the ground and two in the air. The two ground units would be motor vehicles manned by Water Supply Department employees, operating silver iodide smoke generators. The generators may be mounted on light trucks or on light trailers towed behind passenger cars. The two air units would be light twin-engined airplanes equipped to dispense either silver iodide smoke or dry ice. Suitable airplanes and flight crews can be made available by the City Police Department.

The observing group would comprise the Water Supply Department employees who regularly make rainfall observations (they would be equipped and trained to make more elaborate observations than now), volunteer observers in and around the Catskills, and a mobile radar unit operated by a qualified electrical engineer with one assistant. The radar is capable of "seeing" the development of rain within a cloud where it is hidden from view, and can be used to guide aircraft so that they may operate to best advantage.

The statistical group would be organized within the Water Supply Department, staffed for the most part by regular Department employees, and charged with the task of assembling and analysing data in connection with the operations.

A constant watch on the weather would be kept by the meteorological service. When the weather is forecast to be favorable for operation, the project director would be notified. He would decide whether an operation would be undertaken and, if so, make a plan of operation directing what units should be used, where, and when. The

control group would then set the plan in operation, ordering the operating and observing units into service and coordinating their activities. Records of the operation would be transmitted to the statistical unit for processing.

During the periods between operations, the control group would be occupied with theoretical and experimental studies, climatological studies, etc.

PLANT AND EQUIPMENT

The control group should be located in quarters in the Catskill region as well located as possible for radio communication with the mobile units. It should be equipped for meteorological observation and radio and telephone communication. In addition, an office and a small laboratory should be provided there for the project director and his meteorological assistant.

Most of the operating equipment, including silver iodide smoke generators, dry ice dispensers, and some of the instruments, may be built in the shops of the Department of Water Supply at very reasonable cost. It is recommended that certain instruments, such as recording rain gauges, nephoscopes, and certain equipment for the laboratory, be acquired by purchase.

It is understood that suitable aircraft can be made available by the Police Department. In addition to smoke and dry ice dispensing equipment, these planes should be equipped with additional instruments, including one to measure the concentration of sublimation nuclei in the air, true air temperature in clouds, etc.

The mobile radar unit should be a three-centimeter set, APQ-13 or similar, and should be equipped to make a continuous photographic record of the plan-position indication.

ESTIMATED EXPENSES FOR AN INITIAL 6-MONTH PERIOD

Salaries	
Consultant fee, at \$100/day	
Consultant's expenses	\$1,080
Meteorological assistant	2,500
Radio operator, lab assistant	1,800
Radar engineer*	2,100
Radar assistant*	<u>1,200</u>
Services	
Weather forecasts	1,800
Special assistants	1,000
Telephone, telegraph, etc.	<u>700</u>
	\$ 3,500
Equipment	
Radar set and truck*	\$8,500
Radio equipment	2,500
Smoke generators	650
Weather instruments	<u>4,800</u>
	\$15,000
Supplies	
Dry ice, chemicals, etc.	1,500
Miscellaneous supplies	<u></u>
	\$ 2,000

* Not needed if the Armed Services will furnish radar observations.

Sincerely yours,

WALLACE E. HOWELL
Meteorological Consultant

DERIVATION OF RANK STANDINGS OF STORM RAINFALL*

To evaluate the rain stimulation, the best possible comparison of rain at one station was desired with rain at others nearby, or with previous records at the same station, in a way that suppresses differences caused other than by stimulation. Precipitation at each station is affected by gauge location relative to terrain, trees, etc. These effects are often large, causing annual mean precipitation within the region studied to range from about 35 to nearly 60 inches.

For the evaluation, precipitation at each of six stations in every storm from 1937 through 1949 was listed in decreasing order, and the amounts were numbered from heaviest to lightest. The stations used were:

<u>Station</u>	<u>Inches mean annual precipitation</u>	<u>Number of storms listed</u>
Westerlo	34.43	1092
Lexington	40.52	1170
Lackawack	44.87	910
Claryville	50.62	1144
Frost Valley	54.00	1100
Elka Park	59.69	1172

From this list, each observed precipitation amount was assigned a number that ranked that storm in comparison to all storms during the base period. These rank numbers have two desirable properties. First, they measure the intensity of each storm independently of local terrain and exposure effects insofar as these are constant during the base and experimental periods. Second, with a minor restriction due to chance deviations, each rank number has an equal probability of recurring in a given storm, so that the very skew distribution of natural storm amounts is avoided.

Limitations of time and cost prevented listing of all storm amounts at each of the more than 100 stations in the study area. A graphical scheme was therefore set up to interpolate between the six stations tabulated. From each rank list, cumulative totals were formed from the lightest up, and these were plotted against the square root of the corresponding ranks. The resulting curves lay nearly parallel and equidistant from one another, so interpolation on the basis of mean annual rainfall could be done with relatively high confidence. A second graph of ranks smoothed for each 5 inches of mean annual precipitation was used to obtain the rank standings plotted in figures 2-12.

In spite of the interpolation and smoothing, the rank numbers thus obtained retain in essence the two important properties: they may be compared directly from one station to another as a measure of the intensity of a storm; and they have equal probabilities of recurrence.

* This is the first known use of nonparametric statistics in evaluation of weather modification.

THE ISRAELI RAINFALL ENHANCEMENT EXPERIMENT

A PHYSICAL OVERVIEW

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Abstract

This paper will attempt to give a summary of the findings obtained during the period in which the two Israeli (I and II) cloud seeding experiments were conducted. It includes a synthesis of all the information obtained through extensive measurements of cloud and cloud system properties ranging from mesoscale characteristics of the cloud systems to the microphysical structure of the cloud elements that form these systems.

It is suggested that the positive effects on rainfall, under seeding, obtained in the course of these two experiments can be attributed to the following:

1. The organized winter cloud systems responsible for most of the rain in Israel almost always form in the cold sector of the prevailing low pressure systems. They consist of cumulus cloud elements which are typically continental in nature with a fairly high degree of colloidal stability.
2. The modal values of the cloud top temperature distributions on rain days are in the range of -15 to -22°C . Cloud temperatures are fairly uniformly distributed around 5 to 8°C .
3. The nature of the cloud droplet spectra in these clouds is such that ice crystal formation and its subsequent growth by riming seems to be the major rainforming process rather than that of the collision-coalescence mechanism.
4. On the average, the chain of events from initial ice crystal formation through graupel formation to the arrival of raindrops on the ground, can be described on a quantitative basis to suggest that seeding for "static" effects can increase the precipitation efficiency of the clouds in the range of top temperatures of -10 to -20°C and particularly in the range of -15 to -20°C .

Statistical analyses of the rainfall data taking into account physical measurements lend the Israeli experiments the strongest support, namely that of physical plausibility. They suggest that:

1. The positive effects of seeding on all days can be stratified according to the daily mode of the cloud top temperature distributions to indicate a gradual and systematic increase of detectable seeding effects (and their statistical significance) in clouds converging from both ends of the cloud top temperature spectrum towards the most amenable range of clouds with tops between -15 to -21°C . Thus, confirming both our field studies and microphysical predictions.
2. The area of maximum seeding effect, at a distance of 35 - 50 km downwind from the line of seeding, which has consistently been found to exist, can be attributed to the known patterns of turbulent diffusion of the seeding material released at cloud base altitudes.

While far from being complete the above studies and analyses provide a fair basis for understanding and accepting the statistical results and thus also indicate which criteria should be used to transfer this knowledge.

1. INTRODUCTION

This paper offers a summary of the findings obtained during the two Israeli cloud seeding experiments, I (1961-67), and II (1969-75). The cloud physics research component of these experiments was fairly extensive. As early as 1960, it was decided that, while randomization and statistical analyses would play a major role in the process of assessment of the results, a strong emphasis would be put on outlining an extensive program of cloud physics research which was expected to provide the necessary physical plausibility to the statistical results. We now realize that the transferability of knowledge, results and techniques can only be accomplished on the basis of factual information obtained through extensive measurements of cloud and cloud system properties ranging from the mesoscale characteristics of the cloud systems to the microphysical structure of the cloud elements that form these systems.

While our cloud physics research is incomplete and still under way, we will attempt to describe what are thought to be at this time, some of the major findings that may enhance understanding of the statistical analyses. The concluding paragraphs will also outline the gaps in our knowledge as well as the areas of uncertainty which we hope to clarify during the course of Israeli III, the current experiment, begun in 1977. As a result of the general recognition in Israel, and perhaps also abroad, of the validity of the results indicating highly significant positive effects due to seeding, it has been decided that, in parallel with Israeli III after 15 years of experimentation, a program of operational seeding should be initiated in the north of Israel applying the techniques which were tested during the experiments to fully realize the effects of seeding on all days.

2. SUMMARY OF STATISTICAL ANALYSES

Before outlining the physical aspects, we summarize some of the major statistical findings relating to the two Israeli experiments (Gagin and Neumann 1981):

a. The earlier overall results of Experiment I, namely those indicating rainfall increases of the order 15%, significant at the 2% level, have been confirmed in Experiment II, i.e., 13% increase at a 2.8% significance level.

b. The larger increases due to seeding in the "interior" areas of Experiment I, some 35 to 50 km downwind from the seeding line (Gabriel, 1970, Gagin and Neumann, 1974) of the order of 22% significant at 1.3%, have been confirmed again in Experiment II, i.e.: increases of 18 to 27% at corresponding significances of 2.4 and 0.6% respectively. In Experiment II the line of seeding was shifted eastwards to realize these maximum effects in the more eastern catchment area of Lake Kinneret. Despite this shift, the pattern of maximum increases was conserved.

c. Stratification of data indicates that increases in daily rainfall vary systematically with the modal value of the daily distribution of cloud top temperatures. Thus, Gagin and Neumann (1976, 1981) found that seeding effects peak up from both ends of the top temperature distribution for those days when the modal value of the daily distribution is between -15 and -21°C . Under such conditions the effects are indeed very large, i.e., +46% at 0.5% significance, or increases within the confidence interval of 13 to 173% and 10 to 243% at confidence bounds of 90% and 95% respectively. On days when the modal value of these distributions is either warmer than -10°C or colder than -21°C , overall seeding effects are either nonsignificant or nil, respectively.

d. Stratification of the data according to daily precipitation in the control area shows that the days with large natural precipitation contributed much less to the end result. Rather, the effect of seeding is most pronounced and consistent on most days (82%) when the daily rainfall is equal to or less than 15 mm, the mean daily rainfall being 8.8 mm. Gagin and Neumann (1976, 1981) suggest that this result reflects the relation between cloud top height and temperature distributions and rainfall, associating heavier rainfall days with cloud top distributions with modal values colder than -24°C .

e. Statistical analyses (Gagin and Neumann, 1976) of data from our recording rain gage network led us to conclude that the positive increases in rainfall probably can be attributed to effect of seeding on the duration of rainfall, which also may be due partly to an increase under seeding of the number of rain periods. These effects were significant at the 1.7% and 4.2% levels, respectively.

Recently analysis by Sharon (1977) indicated that seeding effects enlarge the area covered by rainfall. More specifically, he indicated an average increase of about 10 km in the linear dimensions of rainfall areas on seeded days. This work also suggested that the expanded rainfall areas have a twofold effect on the augmentation of the total rainfall yield of individual storms:

- i. an increase in point rainfall resulting from prolonged exposure to the moving cloud systems and,
- ii. an increase in the total area affected.

We now describe the physical studies accompanying these experiments.

3. PHYSICAL ASPECTS OF CLOUDS AND CLOUD SYSTEMS

At the outset of Israeli I, in 1960, general guidelines were drawn for the cloud physics research that was to accompany the seeding project. These guidelines were directed mainly to testing the hypotheses underlying the theory of seeding with ice forming nuclei. In short, these studies had to answer a few basic questions and clarify five problems (Gagin and Neumann, 1974):

- i. To define the predominant mechanism for the formation of precipitation in local clouds; more specifically, are ice crystals and their subsequent growth essential factors in initiating the rain-forming mechanisms and determining their efficiency?
- ii. Is heterogeneous nucleation solely responsible for ice formation in the local clouds? Are there conditions when a deficiency of such nuclei responsible for a delay, or even a failure, in the initiation of precipitation?
- iii. Will introduction of artificial ice nuclei having higher threshold temperatures of activity, and the associated increases in concentrations of ice crystals, lead to precipitation increase?
- iv. Can we reach a better understanding of the quantitative aspects of seeding?
- v. Could overall positive results be a superposition of strongly positive, negative and nil effects? Can we identify the conditions when seeding effects are most favorable?

The most logical way to obtain the necessary answers outlined above would be by computational evaluations applied to a realistic cloud model. The latter, we thought, could be obtained only through an initial extensive program of actual measurements

of cloud properties, which would then be used to form and test the required mathematical model of precipitating clouds.

Therefore, we now turn to a summary describing the rain producing clouds and cloud systems. Following this description, we summarize the studies, and conclusions emerging from them, which we think could support some of the statistical findings.

3-a. Clouds and cloud system characteristics

The rain-producing cloud systems in Israel are predominantly those associated with cold, winter, low pressure systems affecting the Eastern Mediterranean region. Description of 8 types of such cloud systems with details about their frequencies, relative contribution to rainfall, duration, orientations, movements and dimensional characteristics, has been prepared by D. Rosenfeld of our department (Table 1). Except for the very rare warm front (one occurrence in two years) all systems consist of bands or clusters of cumuliform elements.

These cloud systems as observed by satellites are shown in Figs. 1, 2, 3, and 4 and as observed from our research aircraft flying above cloud tops in Figs. 5 and 6. Distributions of cloud-top heights and temperatures of these cumuliform clouds are shown in Fig. 7.

Recent studies utilizing a computerized system consisting of a remotely located C-band radar, a vertically pointing X-band radar and a disdrometer collocated under the clouds yielded information on the relation between depth and rainfall rates of these cumuliform clouds. Fig. 8 displays the relationship from Gagin (1981). Cloud base altitudes have been reported by Gagin (1974) to be around 800 m (5 to 8°C).

Most, if not all, of these systems occur in the post cold-front regions of the cold sector of the closed low pressure systems affecting the Eastern Mediterranean. The air masses, as will be pointed out below, are continental air masses originating predominantly in either Central or East Europe or Western Asia.

3-b. Microstructure of local cumuliform clouds

Cloud condensation nuclei (CCN) (Terlius and Gagin 1971) have been shown to be typically continental in nature. The average spectrum for rain days being $C = 1178 S^{0.9}$ where C is the number per cm^3 and S the supersaturation in %. Air mass trajectory analyses indicated that the air masses which originate in the continents of Europe or Asia spend a very short time over the rather narrow (N-S) Mediterranean and hence do not appreciably change their continental aerosol properties. Furthermore, quite often these air masses, after crossing the Mediterranean Sea, north to south, are changed again with CCN particles as they move from the southwest. Consequently, droplet size spectra measured at various elevations above the bases of the prevailing clouds have been shown to be fairly narrow, with almost no drops larger than 20 μm . Examples of droplet spectra and their variations with height are given by Gagin and Neumann (1974) and Gagin (1975). Both the absence of such large drops, even at the highest elevation in clouds

TABLE 1
Types of Cloud Systems and Their Characteristics Responsible for Rain in Israel

Type of Cloud System	Relative Frequency of Occurrence (%)	Relative Contribution To Overall Rainfall (%)	Relative Duration (%)	Average Duration Per Event. (hrs.)	Average Orientation (degs.)	Motion of Clouds Within Cloud System		Direction of Movement minus Orientation (degs.)	Band Characteristics		
						Speed (km/hr.)	Direction (deg.)		No. of Bands	Width (km)	Separation (km)
Cold Fronts	23.3	30.2	20.0	6.7*	235	45	260	10-50	1-2	20-120	40-50
Open Benard Cells	21.1	20.1	31.7	16.3	-	36	283	-	-	-	-
Coastal Fronts	7.8	18.2	12.6	17.6	260	46	260	-5+10	1	10-40	-
Vertical Bands	10.0	10.6	7.5	8.1	-	45	260	-	1-5	10-100	50-80
Scattered Cells	6.7	10.6	3.6	5.9	-	42	265	-	-	-	-
Post-Frontal Bands	27.8	9.9	22.3	8.2	235	29	270	0-55	1-5	10-30	30-100
Longitudinal Bands	2.2	0.4	1.7	8.1	300	29	310	0+20	2-3	10-20	60-100
Warm Fronts	1.1	negligible	0.6	6.3	-	25	235	-	-	-	-

* Excluding Stationary Fronts.

with tops $> -16C$, and calculations indicating that the observed limited broadening of spectrum can be solely attributed to condensational growth, (Gagin and Neumann, 1974), led us to the conclusion that the collision-coalescence process is probably ineffective in the local clouds when the latter have tops that are lower than about 5 km or warmer than about $-20C$.

Supercooled liquid water contents (LWC) of these clouds have been reported by Gagin and Neumann (1974) and Gagin and Steinhorn (1974) to be dependent on cloud depth increasing to an average maximum of about 0.75 g m^{-3} for clouds having tops at about 5 to 6 km. Rarely did clouds reach values of 3 gm^{-3} . Averaging LWC for the whole width of the clouds, rather than taking the maximum values for each cloud traverse and plotting the vertical profiles of LWC in clouds of various depths (Gagin and Steinhorn, 1974), would yield an average variation with height from about 0.2 gm^{-3} at cloud base topping at 0.75 gm^{-3} for the deepest clouds studied, i.e., 5 km.

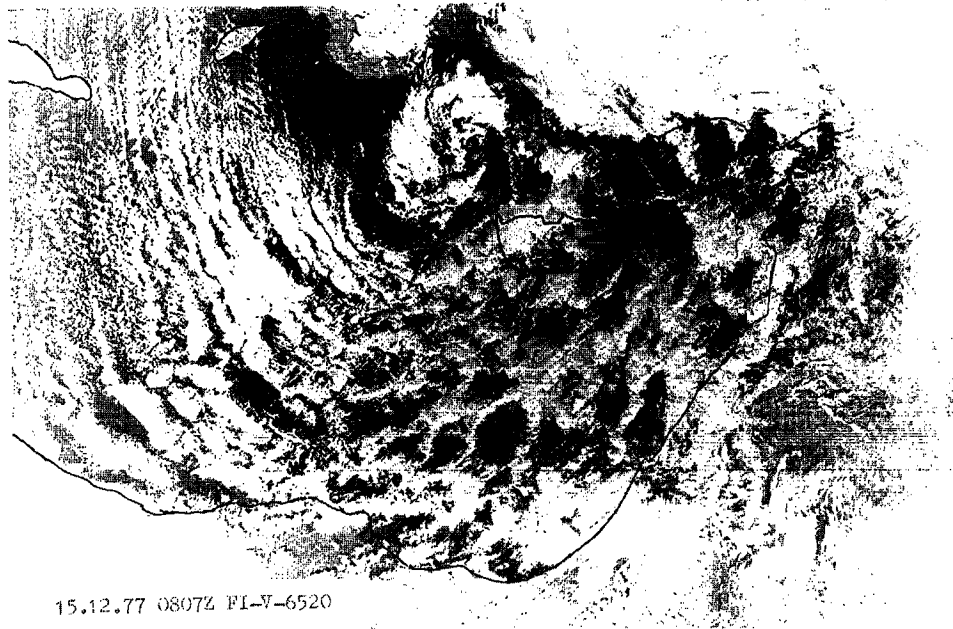
The variation of ice crystal and graupel particle concentrations about 300m below cloud top, as a function of cloud top temperature, has been studied quite extensively (Gagin, 1975). Concentrations of both these ice forms have been shown to be temperature dependent.

Concentrations of ice crystals and of ice nuclei correspond within about an order of magnitude. This limited discrepancy could be attributed partly to insufficient secondary production of ice crystals and partly to our inability to account, instrumentally, for the activation of nuclei through such mechanisms as contact nucleation. Therefore, we suggested that continental cumuli at $-5 C \pm 2$ do not provide conditions for strongly effective ice

multiplication mechanisms. In particular, as also briefly discussed above, the characteristics of cloud droplet spectra at about $-5C$ in such clouds are also the key factor in determining the ice budget of the clouds as it affects the timing and the nature of the riming processes that lead to ice crystal multiplication by the Hallett-Mossop effect (Hallett and Mossop, 1974).

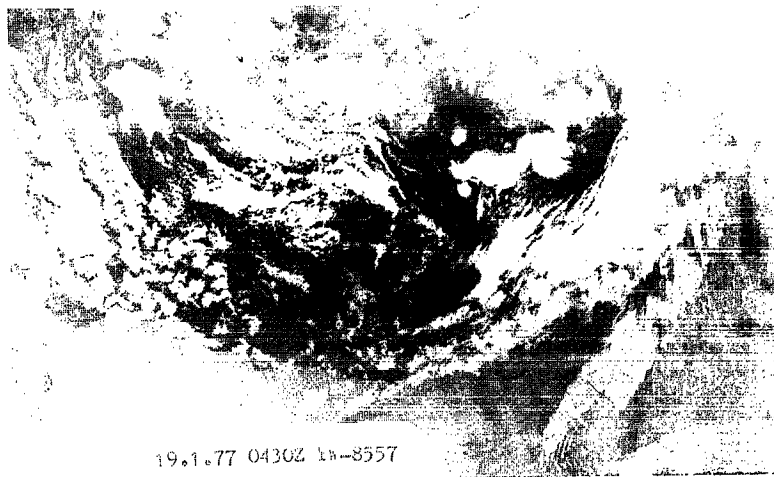
While, as stated above, graupel concentrations seem also to depend on temperature, they were always lower by about one order of magnitude than those of ice crystals at the same temperature. Thus, no graupel particles were detected 300 m below cloud tops $-10C$ or warmer. This important deficiency has also been attributed to the inability of cold continental clouds to generate large drops at such low and warm levels. The onset of riming by columnar crystals, typical of the ice crystal growth domain of -3 to $-10C$ is known to depend on two major factors: the minor axis of such crystals should be longer than $60 \mu\text{m}$, and droplets should have diameters larger than $20 \mu\text{m}$, preferably 30 to $40 \mu\text{m}$. These two conditions are not met in the local cold cumuliform clouds with top temperatures in this range (Gagin 1975). Indeed, rain is detected in clouds with tops 3 km (Fig. 8).

Graupel concentrations are roughly always lower by one order of magnitude than ice crystal concentrations, and their observed concentrations increase by about a factor of ten for a temperature drop of about $5 C$ (as is also the case for ice crystal concentrations). Hence, the transformation of crystals to graupel particles under microstructural characteristics of the local clouds stated above, with top temperatures -12 to $-20C$, takes place along a cloud depth with a temperature span of about $5C$ or 0.8 to 1 km.



15.12.77 0807Z FI-V-6520

Fig. 1. A coastal front north of Egypt and central Israel. Open Benard cells over the east Mediterranean. Longitudinal bands in the central Mediterranean and a vertical band over Rhodes.



19.1.77 0430Z IN-8557

Fig. 2. A cold front over Israel and post-frontal bands behind it.

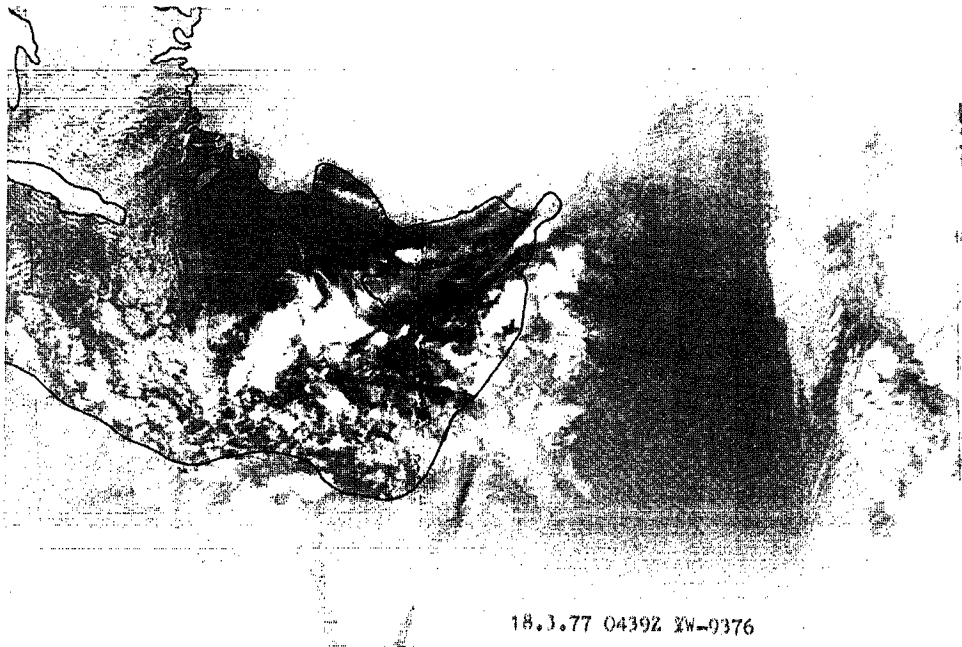


Fig. 3. Scattered cells over Israel and the east Mediterranean Sea.



Fig. 4. Weak post-frontal bands following the passage of a cold front.

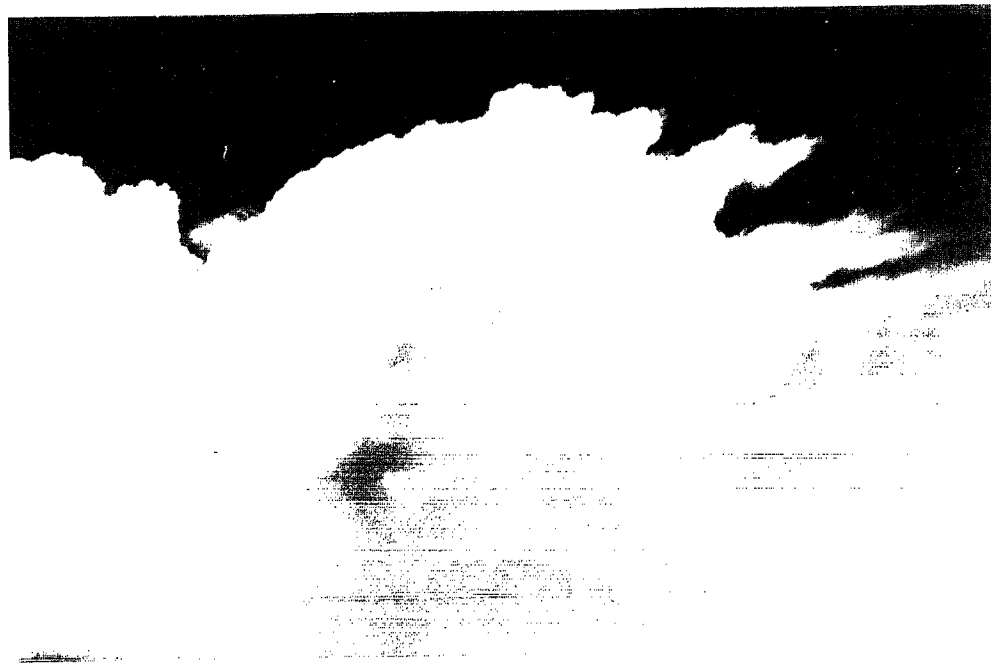


Fig. 5 & 6. Typical appearance of cloud tops as observed from our research aircraft.

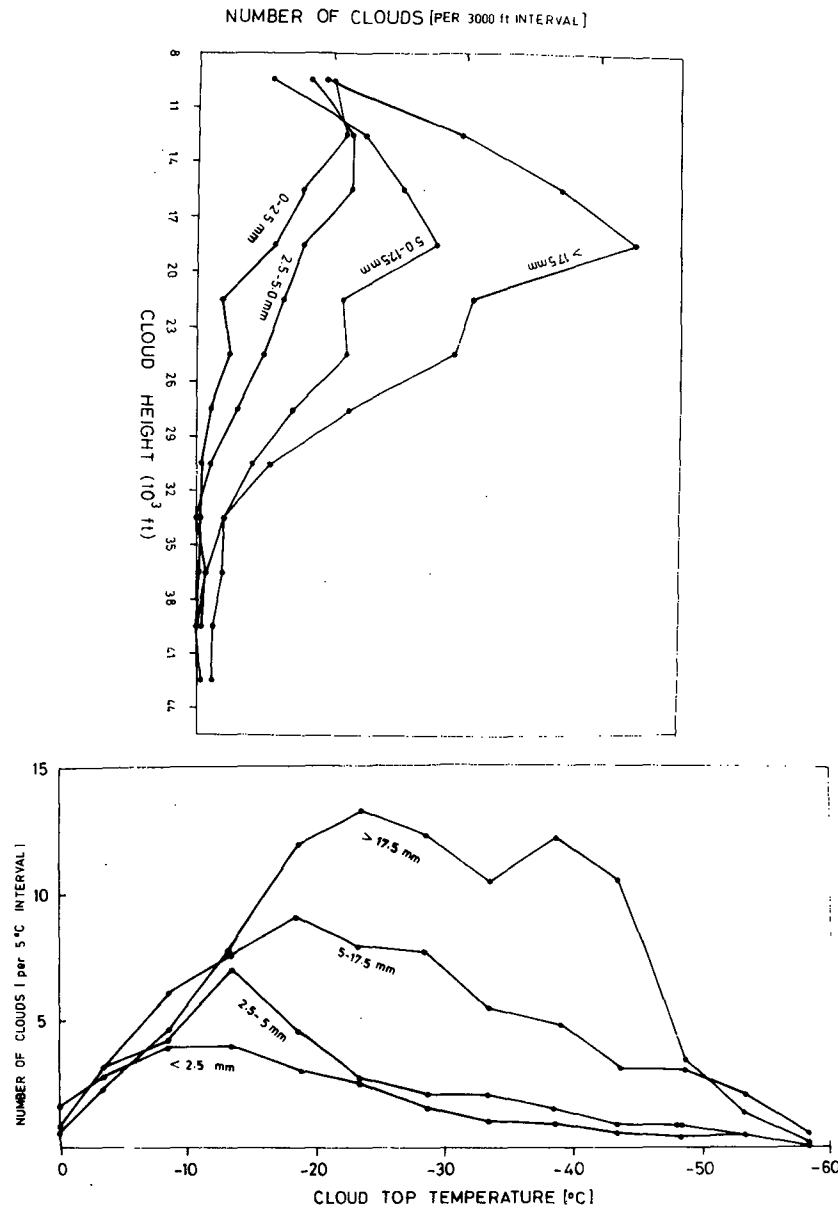


Fig. 7. Frequency distributions of cloud top height and top temperatures on days with different amounts of rainfall.

Another important feature of such clouds (Fig. 9) is the clear relationship between raindrop concentrations on the ground and cloud top height (Gagin, 1981). This relationship was interpreted as an indicating one-to-one relationship between graupel particle numbers in clouds and concentrations at the ground of raindrops produced by these clouds.

4. IMPLICATIONS ON "SEEDABILITY"

Considering the efficiency of the collision-coalescence theory, Houghton (1950), Squires (1958) and Squires and Twomey (1958) have defined continental clouds, distinguished from clouds with maritime microstructures, as colloidally stable entities. In cold continental clouds, lacking "larger" drop-

lets, apparently ice plays a major role in formation of precipitation elements. Taking this conclusion in account and the observations mentioned above on the limitations imposed on both the formation of ice crystals through secondary processes and their inability to subsequently form graupel particles, Gagin (1971, 1975) proposed that such clouds are rendered even more colloidally stable so that their precipitation likelihood is reduced significantly compared to that of maritime clouds. These differences are clearly manifested (Fig. 8) and by the observations of Pepler (1940) and Battan and Braham (1956), relating to the similarly colloidally stable continental clouds of central Europe and New Mexico. In this connection, Gagin (1975) postulated that warm, summer continental convective clouds are not colloidally stable, because conditions caused by their warmer cloud bases will promote formation by condensation-

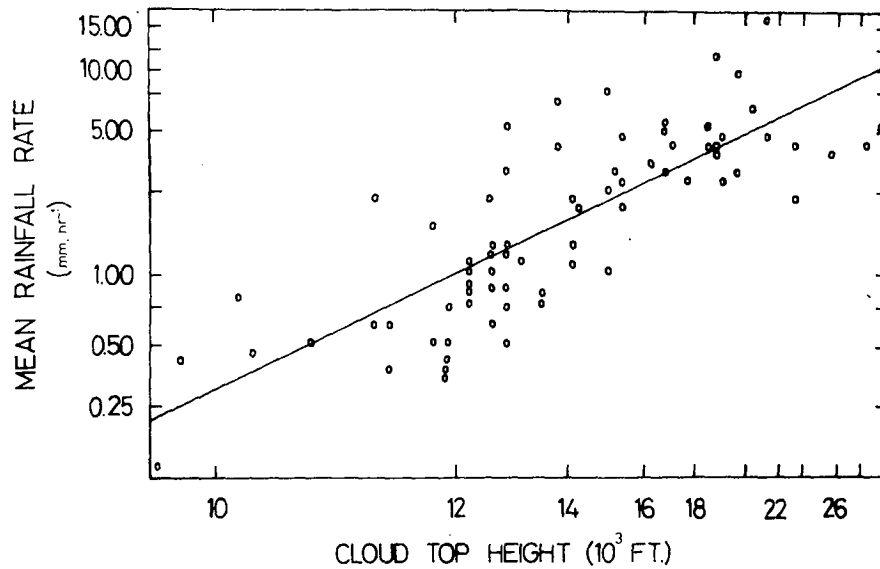


Fig. 8. The relationship between cloud-top height and mean rainfall rates.

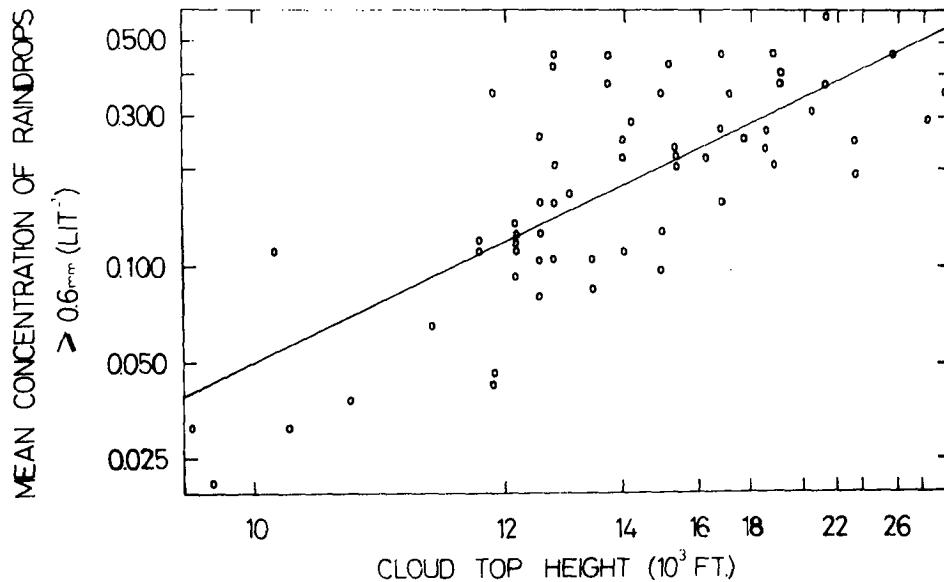


Fig. 9. The relationship between cloud top height and raindrop concentration on the ground.

collision and coalescence of larger drops which will either increase the rate of ice formation or generate precipitation particles rather efficiently.

Thus, cold continental clouds may be more amenable to static-seeding than all-season maritime clouds or summer continental cumuli. The observations about graupel formation, given above, suggest that cold-based cumuli with tops warmer than -10°C will not be favorable to static seeding, even though they may have a relative deficiency of ice crystals

and an ineffective collision-coalescence process. The time element in such clouds is so short that even artificially induced ice crystals, formed at, say -5°C , will not grow to the size of columnar crystals, typical of this temperature domain, which are capable of riming. Furthermore, even if this were possible, the colder bases and the shorter times available for particle growth in such shallow clouds do not allow condensational growth to produce droplets large enough for riming by such crystals.

In conclusion, we tend to postulate that, since collision coalescence mechanisms are very efficient once initiated, and since clouds capable of promoting such mechanism will also, if supercooled to about -8°C , produce secondary ice crystals, maritime-like clouds or summer continental cumuli are much less amenable to seeding aimed at augmenting rainfall by static effects. We also tend to conclude that, by the virtue of their microstructure and top temperature distributions, Israeli clouds are basically more amenable to seeding of this type. These criteria constitute the necessary conditions for a successful seeding operation.

4-a. Static Seeding Conditions

We now suggest some conditions that should be met to apply static-seeding on safer grounds. A low precipitation efficiency of a cloud or a cloud system would suggest that the processes of nucleation and particle growth rates, throughout the lifetime of the cloud, are less than the rates at which moisture is released by vertical motion.

This precipitation efficiency can be increased in either of two ways. One is static seeding to increase the autoconversion rates through increases in nucleation rates, which subsequently use the naturally available conditions for more efficient growth rates of these nucleated particles. Or, cloud growth can be enhanced by dynamic-seeding which leads to an increase in cloud dimensions and hence to an increase in moisture release rates. The latter effect would then be a result also of the increases in nucleation rates and growth of particles for a prolonged period of time.

Statistical analyses have shown that, in Israel's clouds, static-seeding is probably ineffective in clouds with tops warmer than -10°C or colder than -21°C . This result is explained by modelling hydrometeor growth in clouds with a wide variety of depths and top temperatures and known stratifications of LWC, temperature, ice crystals and graupel contents (Gagin and Steinhorn, 1974). These models account for the interactive processes resulting from the effects produced by nonlinear processes of crystal growth rates, which are operative on different time scales determined by the clouds' updraft vertical profiles. Because both these factors determine the rates by which moisture is removed by precipitation, we found that:

1. In the absence of an alternative rain-forming process, normal ice crystal formation and its subsequent growth by accretion can produce precipitation sized particles in only those convective clouds that have top temperatures colder than -10 to -12°C (equivalent to a cloud 3.25 km thick).

2. The size and concentration of precipitation elements in various clouds are proportional to cloud thickness and top temperature. The shallowest cumulus cloud that is capable of producing precipitation sized elements will produce 1.6mm diameter raindrops at concentrations of only 0.02 lit^{-1} , whereas a cloud having a top temperature of -14°C will produce 1.8mm raindrops at concentrations of about 0.1 lit^{-1} . These studies suggest that graupel concentrations and subsequently raindrop concentrations, at cloud base, are determined at a lower level (and hence at a warmer temperature) than those of cloud top, thus confirming the above mentioned relationship between crystal and graupel

numbers. These theoretical estimates agree well with the observations of graupel aloft (Gagin 1975) and raindrop concentrations at the ground (Fig. 9).

3. Clouds having top temperatures warmer than -10 to -12°C are unlikely to be affected by seeding with AgI particles having a threshold activation temperature of -5°C .

4. If a concentration of precipitation elements of the order of 1 lit^{-1} is assumed to be a necessary minimum for an efficient rain process, then convective clouds having top temperatures in the range of -12 to -20°C seem most favorable to the type of seeding discussed above. In fact, within this temperature range, seeding can be allowed to produce even higher concentrations than 1 lit^{-1} without completely glaciating the clouds.

As mentioned earlier, on a typical rain day in Israel a substantial fraction at the total daily cloud population is within the -12 to -20°C temperature range (Fig. 7). Gagin and Neumann (1976) also showed on the basis of physical-statistical analyses, that seeding seems to be exceptionally positive when cloud top temperatures were -15 to -21°C . For clouds in the warmer range of top temperatures of -12 to -15°C , they suggest that although the "natural" rate of water consumption by the growing elements is far less than that of the rate of condensate formation, the lower output of our AgI generators at -5 to -10°C , the temperature level in such clouds at which embryonic crystals form a concentration that later determines the graupel concentrations, prevents the realization of potential seeding effects.

4-b. Radar Studies

To improve previous studies on the quantitative relationship between ice crystals and graupel particles in clouds of various depths, we have applied (Gagin, 1981) a computerized observation system. This consists of a remotely located (50 km) C-band radar, an X-band vertically pointing radar, and an adjacently located ground-based distrometer. This system can provide real-time cross-sections of clouds passing overhead together with their raindrop characteristics at the ground, such as rain rates, rain liquid water content raindrop concentrations and their respective mean volume diameters, at a 60-sec. temporal resolution. Some of the major findings of these studies are:

1. Both maximum and mean rain rates depend quite clearly on cloud-top height. Correlation coefficients were 0.84 and 0.81, respectively.

2. Clouds with tops lower than about 3 km MSL rarely produce any rain which can be detected at the ground, about 100 m below cloud base.

3. Both mean rain liquid water content and raindrop mean volume diameters in the clouds of different thicknesses show similar positive correlation coefficients with cloud-top height 0.77 and 0.73, respectively.

4. The correlation between the concentration of raindrops at the ground and the height of the top of the clouds producing them is 0.75.

5. Raindrop concentration ($>0.6 \text{ mm}$) roughly

corresponds, on the average, to graupel concentrations 300 m below cloud top for clouds in the range of top heights of 3 to 6 km or in the top temperature range -10 to -22C.

Tentative conclusions are drawn to suggest that:

1. In winter continental cumuliform clouds of the Eastern Mediterranean, the chain of events from ice crystals via graupel particles to raindrops at the ground can be described quantitatively.

2. Comparisons of observed raindrop concentrations with the calculations and observations mentioned above, as related to clouds with various top temperatures, lend support to our earlier conclusions of the "seedability" of local winter continental cumuli. In another type of clouds, those that experience ice crystal multiplication, riming by graupel particles precede multiplication. (Mossop, 1970). Under such mechanism, rain embryos form prior to cloud glaciation. Therefore, we propose that, in the absence of such alternative rainforming process as collision-coalescence in the clouds, the initial ice crystal formation is of crucial importance in determining the rain embryos content of the clouds. Consequently we also conclude that introduction of "artificial" ice nuclei can play a positively important role in the initiation of an efficient rain mechanism, if applied at the early stages of the life of such clouds.

3. The highly correlated relationship between cloud depth and rain rates was used to determine, by comparisons with one dimensional model prediction of rainfall, the adequate autoconversion rates for such highly colludal clouds. The best fit between the computed and observed rate rates was obtained for autoconversion constants of $k = 10^{-4}$ and $a = 1.5$, compared to $k = 10^{-3}$ and $a = 0.5$ used for Florida cumuli.

This last result indicates that the local winter continental cumuliform clouds release their rainfall at relatively low precipitation efficiencies.

5. AREA SEEDING FOR STATIC EFFECTS AND TURBULENT DIFFUSION OF AGI FROM AIRBORNE GENERATORS

Twenty years ago, at the outset of the Israeli experiments, we realized that understanding the quantitative aspects of seeding should be given due attention. The findings in Israeli I of increased effects in the "interior areas" (Gagin, 1970), and subsequently the replication of this pattern in Israeli II (Gagin and Neumann, 1976), where the eastward shift in the location of the seeding line resulted in a parallel shift of the area of maximum effect, led us to initiate some theoretical and experimental studies in order to shed some light on this rather complicated problem.

Dispersal from ground generators was studied by Aroyo and Gagin (1971). The more difficult matter of diffusion from airborne generators will now be described briefly. The calculations assume a "smooth" windfield whose turbulence characteristics are homogeneous both in space and time. A point source (the seeding aircraft's burners) is assumed to travel at about 800 m msl, the usual height of the bases of our winter cumulus clouds, along a line forming an angle of 70° with the mean wind. In the

first calculations the length of that line was taken to be 54 km, the speed of the airplane 50 m sec^{-1} , the rate of release of AgI 500 g hr^{-1} and the mean wind 10 m sec^{-1} . The starting point for the computations, from Slade (1968), represents a Gaussian model for the nuclei dispersal. In the numerical calculation the line of seeding flight is also assumed to consist of a succession of 2.7 long segments of instantaneous line sources. The percentage of time in which the concentration of AgI particles is 10 liter^{-1} in the horizontal flight level plane is shown in Fig. 9. The value of 10 liter^{-1} was adopted as an adequate concentration, but now a concentration perhaps 3 times higher might be more desirable.

Under the above mentioned assumptions, we predict a concentration of 10 liter^{-1} about 50% of the time, approximately 20 km from the line of seeding (Fig. 10). This location of the "time coverage" maximum relates rather closely to the location of the maximum apparent increase under seeding in the "interior" sectors of the experiment areas, i.e., 25 to 50 km downwind from the seeding line, if in addition to these calculations allowance is made for cloud movement eastwards with the winds at the 700 mb level.

If we assume two seeding aircraft flying opposite each other, at minimal vertical separation, along the same seeding line, the same assumptions adopted in connection with Fig. 10 indicate a 100% coverage in time of concentrations of 10 liter^{-1} at about the same distance from the line of seeding as from a single aircraft. (Fig. 11). In view of these results we now plan to examine the possibility of letting two airplanes do the seeding and also increase the output of the aircraft generators to increase the concentrations of AgI nuclei, active at temperature warmer than -10°C , by applying AgI-NH₄I solutions instead of the previously used AgI-NaI solutions.

Increasing the AgI smoke output of a single plane by a factor of 2 has not at all the same effect as letting two planes fly in opposite direction, each releasing AgI smoke at the rate assumed in connection with Figs. 10 and 11. If we increase the output of a single plane by a factor of two, the maximum time coverage of AgI particle of about 10 liter^{-1} increases from the present figure of 50% in Fig. 10 to 70%, but not to the 100% of Fig. 11.

Before describing some observational work concerning the diffusion of particles, we must point out that the various assumptions underlying the theoretical calculations take no note of the probably extremely complicated flow fields to be found under cloudy conditions. Clouds, at times, large clouds, develop, modify the flow field and then die, often causing development or intensification of other clouds. These processes are so involved and our knowledge of their effects on the flow field is so incomplete, that we cannot consider them at this time.

As indicated above, ice-crystal concentrations have been measured at tops of clouds, using our instrumented research aircraft (Aerocommander 680 FL) flying downwind from the seeding line. The small number of hours of such measurements show appreciable fluctuations in concentrations. Clouds close (20 km or less) to the seeding line rarely

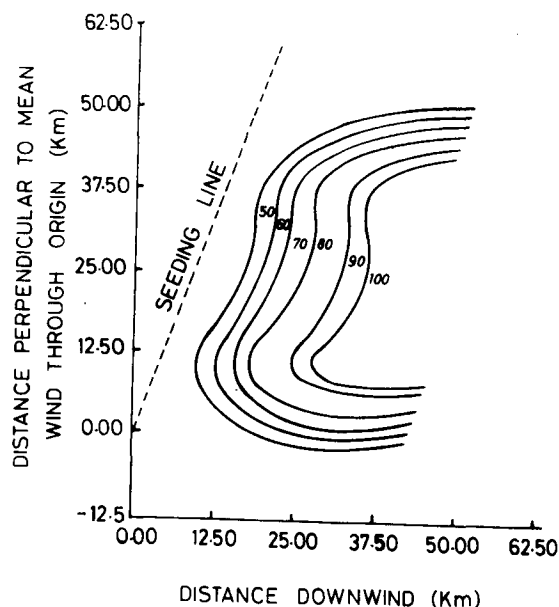


Fig. 10. Calculated percentage of time that the concentration of Silver Iodide particles is 10 liter^{-1} . The diffusion computations assume that a single seeding plane flies back and forth at cloud-base height. The mean wind at cloud-base level is taken to be parallel with the abscissa and is directed from left to right. Note the maximum time coverage at distances from about 20 to 40 km from the line of seeding.

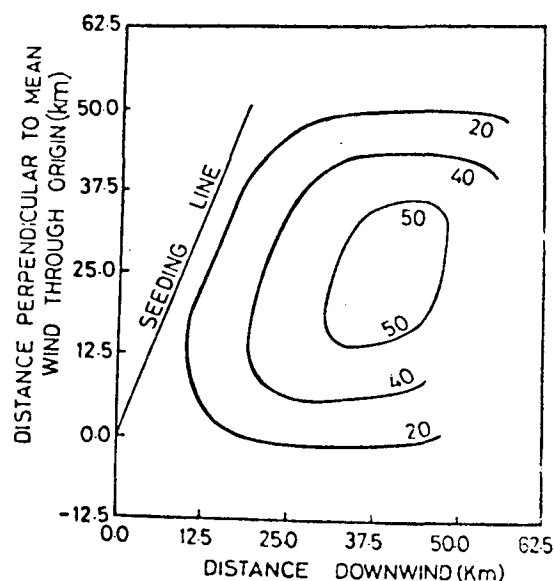


Fig. 11. As Fig. 10, but not the calculation assumes that two planes do the seeding flying in opposite directions, along the line of seeding, releasing silver iodide particles. Each plane releases at the same rate as the single plane of Fig. 9. The maximum time coverage, from a distance of about 25 km from the seeding line is 100% in contrast to the 50% maximum in Fig. 9.

exhibited higher concentrations than those of unseeded clouds. However, at larger distances, i.e., 35 to 50 km, and at the same temperatures (-15°C), clouds with concentrations of 30 to 50 crystals per liter were more frequent, in fair agreement with the location of the maximum time coverage (Fig. 10 and 11). These preliminary results suggest that perhaps seeding was only partly effective, areawise, in the Israeli experiments I and II and that the results presented above, significant both statistically and economically as they are, relate to such a seeding efficiency. Only now, when operational seeding is being applied in Israel, can attempts be made to supplement the seeding in a manner suggested by these studies.

6. CONCLUDING REMARKS

The Israeli I experiment was initiated, as were many others at the time, on the basis of some working hypotheses. Its final exploratory results formed the basis of the confirmatory Israeli II experiment. The evolutionary nature of the physical research that accompanied these experiments has now provided the basic knowledge and recognition of the general validity of these assumptions. Thus, we tend to

believe that the overall positive results are due to a rather uniform cloud regime, basically and predominantly one of cumuliform bands of clouds with a high degree of colloidal stability. Their modal depths and top temperatures make these clouds and cloud systems particularly amenable to seeding.

Perhaps the most physically significant result of these experiments is the statistical stratification analysis of the data according to cloud top temperatures. The gradual and systematic increase of detectable seeding effects (and their statistical significance) in clouds converging from both ends of the cloud top temperature spectrum towards the most amenable range of clouds, with tops between -15 to -21°C , lends the Israeli experiments the strongest support, namely that of physical plausibility. The relative predominance of such clouds on practically all experimented days, is yet another factor contributing to the repeatability of positive results. On 82% of all experimented days of Experiment II having rainfalls smaller than or equal to 15mm, the overall effect of seeding was +23%, significant at the 0.5% level; the mean daily rainfall was 8.8 mm. The heavier rainfall days associated with colder cloud tops contributed much less to the end result. The two Israeli experiments have given us a fair basis,

supported by theoretical and experimental studies, for estimating the area of maximum effect due to seeding.

The immediate and most complicated problem facing the present Israeli rain augmentation project is to optimize the effects of seeding within the framework of operational seeding, started after 15 years of experimentation. The above studies and analyses, while far from being complete, provide a fair basis for understanding and accepting the statistical results. They also indicate which criteria should be used to transfer this knowledge.

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WEATHER RESOURCES MANAGEMENT

ON

THE KINGS RIVER WATERSHED

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In 1954 a cloud seeding program designed to increase precipitation in the form of rain and snow was initiated over the watershed of the Kings River in the Sierra Range of California. The project has been funded by the Kings River Conservation District, Fresno, California, and operated continuously each season during the seven-month October-April period. In recent years, operations have been expanded to include the total annual period except in those years when riverflow forecasts indicate annual flows will exceed about 135% of normal. At the end of the first three-year period, a multiple regression analysis was developed utilizing the unregulated historic flow of the Kings River and the flow of adjacent rivers presumed to be unaltered by cloud seeding activities. This statistical analysis has been applied to the flow of the rivers. During the 25-year seeded period 1954-1979, the analysis shows an apparent increase in flow amounting to 6% of the total predicted by the regression analysis. This apparent increase is significant at the 0.001 level.

1. INTRODUCTION

The Kings River is one of the several streams which originates in the high snowfields along the western slope of the Sierra Range in California and flows from its 1600 mi² (4144 km²) watershed to the rich San Joaquin Valley. Emerging from the foothills east of Fresno, the total annual flow has ranged from a minimum of less than 400,000 acre feet (4.934×10^8 m³) to a maximum of more than 4,000,000 acre feet (4.934×10^9 m³). The average for the past 50 years has been near 1,500,000 acre feet (1.85×10^9 m³).

Irrigation development on the Kings River has been extensive which explains, in part, why Fresno County remains the richest agricultural county in the United States and probably one of the richest farming areas in the world. There are presently about 1,200,000 acres of irrigated land in the area served by the Kings River. In years of normal runoff, no water from the river reaches the ocean. Present estimates indicate it takes nearly 140% of normal runoff before surplus water would reach the coast. Of course, this depends on the condition of the watershed, the amount of carry-over storage, the manner in which the water runs out of the basin and other hydrologic and meteorological factors governing the flow of the river.

There are three main dams in the watershed. Two of these, Wishon and Courtright, are storage reservoirs for power generation, built and operated by the Pacific Gas and Electric Company. The other is Pine Flat, a five million cubic yard concrete dam built by the Corps of Engineers. The dam itself is 440 ft. high, providing a reservoir storage of about 1,000,000 acre feet.

The Kings River Conservation District (KRCD) is a political subdivision of the State of California. The District was formed by the California legislature in 1951 with the passage of the "Kings River Conservation District Act" (Stats. 1951, c.

931, p. 2463). In general, the administrative structure and method of operation of the KRCD are similar to those of irrigation districts. In the 1954-55 water year, the KRCD initiated an operational research weather resources management program designed to increase the annual flow of the Kings River into Pine Flat Reservoir. The program has been operated continuously since that time during the winter seasonal periods from October through April. In 1971, as a result of a three-year summer cloud seeding research experiment, the District authorized expansion of the cloud seeding program to include the remaining months of May through September. The entire weather modification program is conducted by Atmospherics Incorporated, Fresno, California, under contract with the District.

This report summarizes in some detail the operation of the weather resources management program and presents the results of the evaluation for the total 25-year period. The location of the Kings River operational area is shown in Figure 1.

2. GENERAL OPERATIONS

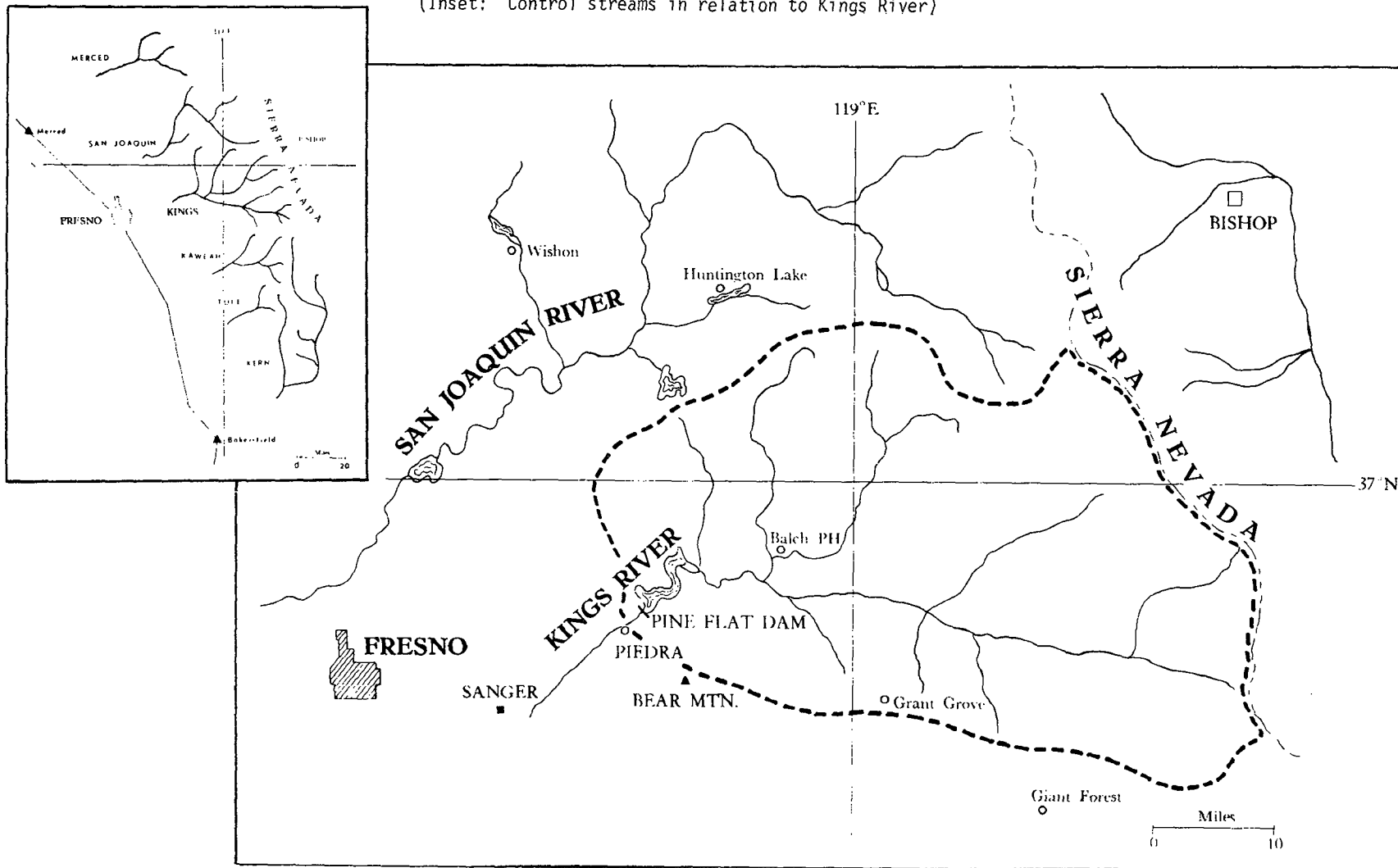
2.1 Meteorology

The normal winter storm meteorology, if there really is any such thing along the western slopes of the Sierra, involves a low pressure center positioned off the Washington coast with an associated frontal system trailing southwestward into the Pacific. As the system moves southeastward over Oregon and California the activity in the frontal zone diminishes. The Kings River watershed usually marks the southern boundary of any intense weather activity. Precipitation amounts usually diminish rapidly south of this area.

A second weather pattern, one which is less common but produces very large amounts of precipi-

FIGURE 1.

TARGET AREA - KINGS RIVER CLOUD SEEDING PROJECT
(Inset: Control streams in relation to Kings River)



tation in the southern Sierra, is associated with a high pressure center in British Columbia which shunts the low center further south off the coast of northern or central California. In this situation the freezing levels move upward from the usual 4,000 ft. level to around 8,000 ft. asl.

A third and rather unusual weather pattern in the southern Sierra is associated with the low pressure center located off the southern California coast. This produces easterly to southeasterly flow along the Sierra crest with the eastern slopes being favored for the larger precipitation amounts. This pattern usually produces large amounts of precipitation in the Los Angeles Basin and far lesser amounts in the downslope regions along the western portions of the Sierra.

Troughs at the 500 mb level are usually associated with all these weather patterns and exert a variety of influences on the total precipitation amounts resulting from each system. However, in each precipitation period there is a tendency toward "bands" of precipitation to move across the valley area and seldom does the radar show long periods of unbroken continuous precipitation. These "bands" are most evident up to the foothill areas but usually merge into areas of solid cloud cover and more homogeneous precipitation areas at the higher altitudes throughout the higher mountain areas.

Through the years, storm typing has been a fashionable exercise with 10 or 12 different types now accepted as reasonably identifiable. The numbers of storm types in these sub-sets seem to increase as additional forecasting uncertainties are expressed with each "newly discovered storm type".

At the moment, a feeling still persists on the operational level that the most pronounced seeding effects can be found during storm periods when supercooled liquid water is high and ice crystal concentrations are low. Radar photographs and aircraft penetrations within the general storm systems continue to support this view. By these same observations, there is further indication that seeding is ineffective or may even produce negative results when 500-mb temperatures are colder than about -24°C . However, the 500 mb temperature is only a guide to seedability because there are extreme variations in the ratio of supercooled liquid water to ice crystals even when the 500 mb temperature is colder than any specific number.

2.2 Ground Generators

During the early years of the project, the silver iodide ground generator progressed from the use of a chemical-propane mixture dispersed through a standard paint spray nozzle to a modified Wells Fuquay aspirator type in which the solution was drawn from a 10-gallon storage reservoir by the passage of a propane jet across the tip of a hypodermic needle. This finely divided mixture was burned in a three-inch diameter flame chamber at a temperature of about 980°C which produced some 5×10^{15} nuclei per gram of silver iodide effective at -20°C . In recent years the ground generator configuration has returned to the more sophisticated stainless steel spray nozzle and the flame chamber temperature reduced to about 850°C .

The silver iodide chemical solution strength has ranged between 1½% and 4% silver iodide by weight in acetone. Each generator consumes about 15 grams of silver iodide per hour depending upon solution use rate. Propane use rate is 2.0 liters per hour when the pressure is regulated at 10 psi.

The total number of silver iodide ground generators installed each season during the past 25 year period has ranged from as few as 15 to the present level of 25 units. From year to year the actual locations of the individual generators have been shifted in a number of cases. These modifications have resulted from studies of wind-flow characteristics throughout the watershed and from ground and airborne silver iodide plume tracking during operational periods. In general, the present silver iodide ground generator network is reasonably well fixed. The main line of units is along the southwest border of the target boundary with additional units scattered in certain sections of the western and northwestern areas for use during changing wind directions.

The total number of ground generators used during any individual storm period has ranged between 2 and 24. The number is dependent upon the intensity and duration of the particular storm. Insofar as possible, the general method of operation involves ignition of units located along a path perpendicular to the surface windflow. Every storm period is seeded provided certain public safety criteria are fulfilled and supercooled liquid water is present. No ground generators are used during the summer months of May through September.

In the 24-year operational period a total of 3512 generators have been operated during the 607 storm periods. Total time logged as 40,913 hrs. Total amounts of silver iodide consumed during this period was 574,382 gms (1265 lbs.) an average of about 14 grams hr^{-1} .

Silver iodide ground generator operations during the individual seasons are shown in Table 1.

2.3 Aircraft

In the past 25 years of operation there have been nine types of seeding aircraft used on the Kings River Project: P-40 (War Hawk), F-51 (Mustang), F8F (Bear Cat), T-28 (trainer), Cessna 180, Piper Twin Comanche, Piper Apache, Piper Aztec, and Piper Navajo. Since 1970 the Aztec PA23-250T and the Navajo (PA31-310) have been the primary seeding aircraft. These aircraft are equipped with turbochargers, complete deicing equipment, and all normal navigational aids. Under flight configuration the altitude capability is in excess of 25,000 ft. msl. These aircraft have performed well and have served as reasonably good platforms for both nuclei dispensing equipment and research instruments.

The seeding aircraft has two main functions. It has first served as supplemental equipment to the overall ground generator network. Secondly, it has provided a platform for certain research equipment provided within the structure of the total program. Terrain features, locations of National Park boundaries, and specific windflow patterns make it impossible to place silver iodide ground generators in locations suitable for com-

TABLE 1.

SUMMARY OF SILVER IODIDE GROUND GENERATOR OPERATIONS

- 25-year Period 1954/55 through 1978/79 -

Year	Storm Periods	Number Generators Operated	Total Hrs.	Silver Iodide dispensed (gm)
1954-55	16	87	783	9,788
1955-56	23	277	2694	30,981
1956-57	18	241	1715	25,725
1957-58	23	258	2064	26,832
1958-59	15	145	1276	17,226
1959-60	26	275	3221	35,431
1960-61	26	225	2677	26,770
1961-62	23	195	3212	32,120
1962-63	24	184	2401	24,010
1963-64	18	120	1597	22,360
1964-65	21	145	1964	26,202
1965-66	21	111	1710	20,521
1966-67	21	103	1561	20,080
1967-68	22	81	281	6,730
1968-69	29	70	1012	15,488
1969-70	23	84	1145	17,187
1970-71	29	94	1311	19,666
1971-72	25	94	1242	19,125
1972-73	37	128	1969	29,658
1973-74	38	146	1659	33,208
1974-75	32	141	1807	36,138
1975-76	28	89	782	13,646
1976-77	26	67	573	11,708
1977-78	23	107	1654	33,080
1978-79	20	45	603	20,702
TOTAL	607	3512	40,913	574,382
AVERAGE	24	140	1,637	22,975

plete nuclei coverage in all areas of the Kings River watershed. Silver iodide plume tracking, under a program funded by the National Science Foundation, indicates the seeding capability of the aircraft is essential on this particular program.

In most winter storm situations, both aircraft and ground generators are operated. In these cases it is difficult, and no attempt has been made, to separate the effects from the individual sources. However, there have been a number of cases throughout the period when the aircraft was used on cumulus clouds (post frontal and summer orographic) which were not producing precipitation. In some of these cases the only clouds which produced precipitation were those which were seeded. These continue to be substantial evidence that the aircraft is essential for any full-scale efficient cloud seeding program in this particular mountain area.

Silver iodide seeding is accomplished from the aircraft by ignition of flare devices each containing 20 grams of AgI. Burning time of each

unit is about 10 minutes and 24 are carried on racks mounted aft of the wings. The flares can be ignited individually or in groups. The efficiency of these pyrotechnic seeding devices has been checked at Colorado State University and found to be about 2.5×10^{15} nuclei per gram of silver iodide effective at -20°C .

Auger type dry ice equipment has been carried on the aircraft with dispensing rates available in the range of 1-30 lbs. per minute. Silver iodide seeding is accomplished at the -5°C level and dry ice is dispensed at cloud tops or near -15°C .

A total of 987 aircraft seeding flights have been made during the 25 years of operation. Total silver iodide dispensed from the aircraft during the 25-year period has been 92,846 grams (205 lbs.). During the four year period 1961-1965 a total of 8,393 lbs. of dry ice was dispensed mainly in post-frontal cumulus clouds over the upper portions of the Kings River watershed. In addition to the flights conducted primarily for cloud seeding purposes, a total of about 80 additional flights have

been conducted as part of basic research efforts.

A summary of aircraft operations during each year may be found in Table 2. Total nucleating agents dispensed each year from all sources is shown in Table 3.

2.4 Radar

The original radar system used on the Kings River Project was a modified APS-15 military surplus system. It operated on a frequency of 9375 MHz and a peak power of 50 Kw. The antenna was a 30-inch parabola with 3^o pencil beam radiation. The system had a maximum range of 200 miles and a scope presentation of the 7-inch Plan Position Indicator type.

In 1960 a new radar system was designed and built by Atmospheric Incorporated for use on the Kings River Project. This 3.2 cm system also operated in the 9375-9400 MHz range, producing a peak power of 50 Kw. The system included two indicator presentations of the 7-inch PPI type. One of the indicators was used for general viewing and data procurement as necessary for the direction of both ground generator and aircraft operations. A second indicator was used exclusively for 16mm time-lapse scope photography of precipitation echoes. The installation site for this system was moved westward to a point about 14 miles NNE of Fresno at an elevation of 350 ft. msl. The site provided an unobstructed view of the total Kings River watershed and made it possible to view in considerable detail precipitation echoes as the storms moved

TABLE 2.

SUMMARY OF AIRCRAFT SEEDING OPERATIONS

- 25-Year Period 1954/55 through 1978/79 -

Year	Aircraft Operations (winter)					Aircraft Operations (summer)			
	Storm Periods	Total Flts.	Total Hrs.	AgI Dispensed (gm)	CO ₂ Dispensed (lb.)	Storm Days	Total Flts.	Total Hrs.	AgI Dispensed (gm)
1954-55	16	9	16	450	-	-	-	-	-
1955-56	23	41	58	1300	-	-	-	-	-
1956-57	18	66	153	3750	-	-	-	-	-
1957-58	23	49	118	2950	-	-	-	-	-
1958-59	15	31	68	1750	-	-	-	-	-
1959-60	26	29	56	1430	-	-	-	-	-
1960-61	26	46	69	-	2065	-	-	-	-
1961-62	23	34	70	-	2234	-	-	-	-
1962-63	24	44	52	37	2658	-	-	-	-
1963-64	18	32	27	387	1109	-	-	-	-
1964-65	21	54	52	948	300	-	-	-	-
1965-66	21	24	25	695	-	-	-	-	-
1966-67	21	21	30	1290	-	-	-	-	-
1967-68	22	23	45	3210	-	-	-	-	-
1968-69	29	21	41	3156	-	-	-	-	-
1969-70	23	15	32	2385	-	-	-	-	-
1970-71	29	27	38	3008	-	40	40	104	24,602
1971-72	25	21	33	2505	-	52	62	82	5,239
1972-73	37	36	59	3376	-	-	-	-	-
1973-74	38	34	67	3678	-	-	-	-	-
1974-75	32	35	81	6631	-	29	54	98	1,334
1975-76	28	25	40	2963	-	25	27	63	4,631
1976-77	26	24	39	2841	-	27	27	32	2,280
1977-78	23	29	38	3240	-	-	-	-	-
1978-79	20	7	12	2780	-	-	-	-	-
TOTAL	607	777	1319	54760	8393	173	210	379	38,086
*AVERAGE	24	31	53	2381	1679	35	42	76	7,617

*Averages are based on the actual number of years in which an entry is made.

TABLE 3.

SUMMARY OF TOTAL NUCLEATING AGENTS

- 25-Year Period 1954/55 through 1978/79 -

Year	Storm Periods	Silver Iodide (gm)	Carbon Dioxide (lb)
1954-55	16	10,238	-
1955-56	23	32,281	-
1956-57	18	29,475	-
1957-58	23	29,782	-
1958-59	15	18,976	-
1959-60	26	36,861	-
1960-61	26	26,770	2065
1961-62	23	32,120	2234
1962-63	24	24,047	2635
1963-64	18	22,747	1109
1964-65	21	27,150*	300
1965-66	21	21,216*	-
1966-67	21	21,370*	-
1967-68	22	9,940*	-
1968-69	29	18,644	-
1969-70	23	19,572	-
1970-71**	69	47,276	-
1971-72**	77	26,869	-
1972-73	37	33,034	-
1973-74	38	36,886	-
1974-75**	61	44,103	-
1975-76**	53	21,240	-
1976-77**	53	16,829	-
1977-78	23	36,320	-
1978-79	20	23,482	-
TOTAL	780	667,228	8,393
AVERAGE	31	26,689	1,679

* Includes ignition of pyrotechnic units utilized on the ground as a supplement to the liquid fuel ground generators.

** Includes summer aircraft seeding operations.

eastward across the San Joaquin Valley and into the higher mountain areas.

In 1971 a Decca II Weather Radar System was added to the program and all radar equipment was moved a few miles further west to the Atmospherics Incorporated headquarters building near the Fresno Air Terminal. This Decca system operated on a frequency of 9380 MHz with a peak power of 40 Kw and a range of approximately 144 nautical miles.

In 1973 the first 5-cm type radar built by Enterprise Electronics was installed for the Kings River Project. This system operated on a frequency of 5,550 MHz, a peak power of 250 Kw and a range of 250 nautical miles. An L-band interrogator/transponder unit also became a part of the radar system.

Throughout the history of the Kings River Project the radar systems have provided two important functions within the application of the total cloud seeding program. As an operational tool, they have provided the meteorological information necessary for proper direction of aircraft and ground generators. Routine weather forecasting procedures by individuals and agencies have not been sufficient for direction of a full-scale cloud seeding operation and the radar has provided the necessary supplemental information. Secondly, the radar systems have provided a significant input to the various basic research and evaluation efforts which have played an important part in this total weather resources management program.

2.5 Research

Beginning in 1960 the National Science Foundation provided modest funding for supplemental instrumentation considered essential to the total Kings River Program. The actual equipment procured in this research effort, such as time-lapse cameras, temperature measurement devices, calibrated portable cold boxes, microscopes, potential gradient recorders, small particle detectors, and miscellaneous laboratory equipment, permitted a more definitive examination of storms and seeding effects within and beyond the boundaries of the Kings River watershed.

In 1964, a continuing cost-sharing contract between Atmospherics Incorporated and the National Science Foundation provided another three-year period for "Physical Studies of Winter Storms Mechanisms as Related to Cloud Seeding Efforts in the Sierra Range of California". Under this research activity particular emphasis was placed on an expanded area of interest including the watersheds of the Kern, Tule, Kaweah, Kings, San Joaquin and Merced Rivers. Of particular importance was the inclusion of certain watersheds along the eastern slopes of the Sierra for purposes of determining some of the downwind effects¹ of cloud seeding activities further to the west.

During the eleven year period 1966 through 1977, Atmospherics Incorporated conducted a number of research efforts sponsored by the Naval Weapons Center, China Lake, California. These investigations were largely related to the field application of pyrotechnic nuclei generators and measurements of related parameters. Additionally, certain airborne investigations were conducted on the distribution of small particulates which act as freezing and condensation nuclei in precipitation mechanisms. These research programs focused on the development and use of pyrotechnic seeding devices as sponsored by the Naval Weapons Center were instrumental in major modifications to the manner in which silver iodide nuclei were generated and dispensed by aircraft over the Kings River area.

In 1966 Atmospherics Incorporated became part of a weather modification research program conducted by Atmospheric Water Resources Research, Fresno State College Foundation, under a contract with the Bureau of Reclamation. This particular research effort, referred to as Sierra Cumulus I, II and III, was designed to investigate the possible initiation and enhancement of precipitation from summer orographic cumuli which develop over the Southern Sierra Range in California and to measure the resultant effects. The Atmospherics Incorporated input to this research program involved the aerial application of silver iodide to single randomly chosen cumulus within a pair of selected cells, the identification of any possible seeding effects with high altitude sub-basins in the Sierra, and the operational seeding of portions of the upper Kings River watershed in order to supply supplemental water during a very low water year. The results from this particular summer orographic cumulus research effort led the Kings River Conservation District to expand their program over the summer months of May through September.

The numerous historic research efforts over the Kings River and adjacent watersheds as sponsored by the National Science Foundation, Department of the Interior (WPRS) and the Naval Weapons Center, have produced an enormous amount of information used to enhance our overall understanding of precipitation mechanisms and the application of cloud seeding technology to both winter and summer cloud systems over the Sierra Range of California.

3. STATISTICAL EVALUATIONS

The 1978-79 season completed the 25th consecutive year of weather modification operations on the Kings River watershed. During this period, many months have been spent attempting to identify a "most significant" evaluation procedure.

One of the early attempts at evaluation dealt with the comparison of raingauge figures. As in many cases using raingauge data, particularly in mountain areas, the figures did not produce relationships with high significance levels. In addition, the network of established raingauges over the Kings River and adjacent areas is too small to provide adequate sampling of the areas inside and beyond the target boundaries.

In the early stages of the program an investigation of all snow survey courses and compiled data was initiated. These investigations indicated a more significant relationship between seeded and non-seeded areas and the precipitation comparisons. However, even though these analyses produced rather high positive indications of the success of cloud seeding on the Kings River, the confidence levels were considered inadequate. It is important to note that many of these snow survey data comparisons served as strong clues pertaining to the effects of seeding operations within certain areas of the program and were not ignored during the investigations of specific local effects.

An examination of the streamflow records along the western slopes of the Sierra Range yielded additional basic data which were considerably more meaningful than either the snow survey data or precipitation figures. Furthermore, it seemed more appropriate at the time to deal directly with the amount of water available for irrigation, and the numbers dealing with acre feet of water were more meaningful to the actual water users.

Applications of statistical methods have been applied to many of the streamflow figures from rivers along both the western and eastern slopes of the Sierra. The results of these analyses indicate a very high confidence level may be placed on results from comparisons between the flow of the Kings River and combinations of flows from the Merced River to the north and the Kern River to the south. The use of control streams from areas both north and south of the target area seemed appropriate in any search for methods of eliminating bias from years which contain a predominance of either northerly or southerly type storms.

The possible bias from persistent storm directions was not the only item investigated in these original analyses. For example, the total numbers of acre covered by forest fires in

¹Cost-sharing contracts NSF C-206, C-402.

both control and target areas was tabulated, methods of streamflow measurements were checked, types of measuring devices and locations of measuring points were investigated, and the historic record of streamflow itself was repeatedly checked. All of the possible items which may have had some abnormal effect on the flows of either the control or target streams were eventually considered insignificant.

It was thought desirable to keep any statistical analysis as simple as possible without resorting to complex transformations of the basic data or to controversial methodology. Consequently, a straightforward multiple regression analysis was used to indicate any possible change in the flow of the Kings River. No peculiar manipulation of these data has been made during the evaluation period nor has there been any change in methodology since the initial choice was made in 1957.

Combinations of possible control streams were examined and these included the Merced, San Joaquin, Kern, Kaweah, Tule and Owens. The combination of streams which resulted in the highest correlation with the Kings River was found to be the Merced River measured at Pohono Bridge and the Kern River measured at Kernville. Mathematical analysis tells us the combination of these control streams which best minimizes the departure during the base period prior to any cloud seeding activity. The analysis also gives us the correlation coefficient between the target stream and this best combination of the two control streams.

A study of this analysis follows:

- Let X = flow of the Kings River for any water year
- C₁ = flow of the Merced River for any water year
- C₂ = flow of the Kern River for any water year

Averages over the base period were denoted by bars and standard deviations by S. Thus:

\bar{X} = mean annual flow (unregulated) of the Kings River at Piedra during the base period and

S₁ = standard deviation of the annual flow of the Merced River during the base period, etc.

The correlation coefficients were denoted by R. Thus,

R_{X1} = correlation coefficient between the annual runoff of the Kings and Merced Rivers for the base period, etc.

R₁₂ = correlation coefficient between the annual runoff of the Merced and Kern Rivers for the base period.

The correlation coefficients were defined by the standard formula,

$$R_{X1} = \frac{\overline{XC_1} - \bar{X}\bar{C}_1}{S_X S_1}$$

where $\overline{XC_1}$ is computed by averaging the products of the streamflow of the Kings and Merced Rivers over the base period.

The result of the computations are as follows where all values except the correlation coefficients are expressed in thousands of acre feet.

$$\begin{array}{lll} \bar{X} & = & 1509.4 \quad S_X = 662.0 \quad R_{X1} = 0.947 \\ \bar{C}_1 & = & 421.1 \quad S_1 = 153.7 \quad R_{X2} = 0.967 \\ \bar{C}_2 & = & 497.0 \quad S_2 = 226.6 \quad R_{12} = 0.876 \end{array}$$

These results indicated that the chosen control streams have a very high relationship to the flow of the Kings River and will produce a formula which will predict the Kings River flow with a high degree of confidence.

According to statistical theory, the correlation coefficients between the best possible combination of the two control streams and the Kings River runoff is given by:

$$R^2 = \frac{R_{X1}^2 + R_{X2}^2 - 2R_{X1}R_{X2}R_{12}}{1 - R_{12}^2}$$

Substitution of numerical values leads to:

$$R^2 = 0.978$$

To see what improvement this represents over the better of the individual controls, we computed the standard error for each case. For the Kern River alone, the standard error (thousands of acre feet) is given by:

$$S_E = S_X \sqrt{1 - R_{X2}^2} = 661.9 \times 0.255 = 168.8$$

For the combination control figure,

$$S_E = S_X \sqrt{1 - R^2} = 661.9 \times 0.15 = 99.3$$

The use of the combination control figure reduces the standard error by approximately 70,000 acre feet.

The control figure calculated from the Merced and Kern Rivers can be denoted by X_E. Then,

$$X_E = b_0 + b_1 C_1 + b_2 C_2$$

$$\text{where } b_0 = \bar{X} - b_1 \bar{C}_1 - b_2 \bar{C}_2$$

$$b_1 = \frac{S_X}{S_1} \left[\frac{R_{X1} - R_{X2} R_{12}}{1 - R_{12}^2} \right]$$

$$b_2 = \frac{S_X}{S_2} \left[\frac{R_{X2} - R_{X1} R_{12}}{1 - R_{12}^2} \right]$$

Substituting numerical values we found

$$X_E = 1.85C_1 (\text{Merced}) + 1.72 C_2 (\text{Kern}) - 124.4$$

Using the proportions of the Merced and Kern control streams as indicated, a formula was re-solved which gave us a relatively high confidence prediction of the flow of the Kings River in any

single year. A tabulation of all streamflow figures during the base period 1925-26 through 1949-50 is presented in Table 4. A tabulation of all streamflow figures during the cloud seeding operational period 1954-55 through 1978-79 is shown in Table 5.

TABLE 4
STREAMFLOWS IN ACRE FEET*

- 25-Year Historic Record 1925/26 through 1949/50 -

WATER YEAR	KINGS RIVER	MERCED RIVER	KERN RIVER + #3
1925-26	1,036,200	343,700	299,000
27	1,984,200	537,800	616,000
28	970,900	370,600	303,000
29	849,400	255,600	287,000
30	862,800	277,800	299,000
1930-31	465,800	144,700	177,000
32	2,083,500	506,700	585,000
33	1,180,900	289,900	390,000
34	658,800	187,300	220,000
35	1,621,300	527,200	421,200
1935-36	1,876,500	504,400	634,100
37	2,340,800	493,200	858,500
38	3,275,100	849,300	1,015,000
39	974,400	252,600	388,900
40	1,790,400	499,500	608,400
1940-41	2,542,800	616,800	946,000
42	2,005,300	599,300	618,600
43	2,026,600	537,800	802,500
44	1,168,200	327,700	443,500
45	2,062,400	478,300	665,700
1945-46	1,612,000	497,900	528,200
47	1,107,300	309,700	355,500
48	996,200	387,700	301,400
49	960,700	332,600	271,800
50	1,281,000	399,700	399,100
TOTAL	37,734,500	10,527,800	12,425,500
AVERAGE	1,509,400	421,100	497,000

* From Surface Water Records -- Annual Reports, U.S. Dept. of Interior, Geological Survey, Sacramento, California.

TABLE 5.

STREAMFLOW RECORDS IN ACRE FEET*

- 25-year Cloud Seeding Period 1954/55 through 1978/79 -

Water Year	Kings River (incl. Mill & Hughes)	Merced River (Pohono Bridge)	Kern River +#3 (near Kernville)
1954-55	1,143,000	296,200	331,400
1955-56	2,695,000	783,700	766,000
1956-57	1,259,000	361,700	387,200
1957-58	2,615,000	613,100	810,700
1958-59	823,700	241,700	246,000
1959-60	718,900	252,000	246,400
1960-61	571,500	186,900	165,300
1961-62	1,871,850	461,700	550,400
1962-63	1,902,000	501,200	628,500
1963-64	877,900	254,900	273,800
1964-65	1,980,000	640,500	575,100
1965-66	1,219,430	328,900	335,100
1966-67	3,332,000	758,600	1,192,600
1967-68	843,200	230,900	388,300
1968-69	4,386,200	882,800	1,547,000
1969-70	1,330,600	422,200	491,500
1970-71	1,175,000	402,500	359,600
1971-72	859,600	325,200	235,000
1972-73	2,135,400	519,600	740,300
1973-74	2,095,900	566,800	638,100
1974-75	1,583,300	492,300	447,800
1975-76	540,700	157,000	209,100
1976-77	396,000	91,700	171,500
1977-78	3,453,800	724,600	1,138,000
1978-79	1,729,820	468,500	504,800
TOTAL	41,539,700	11,689,800	14,517,500
AVERAGE	1,661,588	467,592	580,700

*From Surface Water Records -- Annual Reports, U.S. Dept. of Interior, Geological Survey, Sacramento, California.

4. CONCLUSIONS -- 25 YEAR PERIOD

The details of many investigations, oriented toward the measurement of the flows of rivers both along the eastern and western slopes of the Sierra, will not be covered in this paper. These investigations have established that the figures, as submitted by the U.S. Geological Survey are reasonably accurate and do reflect a true picture of the unregulated flow of all streams used in this analysis.

The flow of the Kings River, as published by the U.S.G.S. is the result of measurements at their gaging station below Pine Flat Dam, plus the gain and loss in the upstream reservoirs, plus an evaporation factor applied to the surface of these reservoirs. Two streams, Mill and Hughes Creek, enter the Kings River between the dam and Piedra. These streams are measured by the Kings River Water Association and their flows added to the U.S.G.S. figures. A sound reconstruction of the historic and unregulated flow is obtained.

If these unregulated flow figures of the Kings River are used in the statistical formula, then the apparent change in Kings River flow during the 25-year cloud seeding period is noted as shown in Table 6.

The figures appearing in the last column are the probability that the observed departure is a chance fluctuation as given by application of the standard statistical t-test to the observed departures. The one-tailed t-test has been employed.

The indicated total increase in Kings River flow from those years which have indicated a positive departure is 1,884,930 acre feet over the 25-year period representing an overall increase of approximately 6%. The probability that this total increase was due to chance is 0.001.

TABLE 6.

SUMMARY OF APPARENT CHANGES IN KINGS RIVER FLOW

- 25-Year Cloud Seeding Period 1954/55 through 1978/79 -

Water Year	Unregulated Flow in A.F.	Predicted Flow from Formula	Apparent Change		Flow Change In Standard Errors	Probability of Increase
			A.F.	%		
1954-55	1,143,000	993,600	+149,400	+15.0%	+1.50	93.3%
1955-56	2,695,000	2,643,000	+ 52,000	+ 2.0%	+0.50	69.9%
1956-57	1,259,000	1,210,700	+ 48,300	+ 4.0%	+0.49	68.8%
1957-58	2,615,000	2,404,200	+210,800	+ 8.8%	+2.12	98.3%
1958-59	823,700	745,800	+ 77,900	+10.4%	+0.78	78.2%
1959-60	718,900	765,600	- 46,700	- 6.1	-0.47	31.9%
1960-61	571,500	505,700	+ 65,800	+13.0%	+0.66	74.5%
1961-62	1,871,850	1,676,450	+195,400	+11.7%	+1.97	97.6%
1962-63	1,902,000	1,883,800	+ 18,200	+ 1.0%	+0.18	57.1%
1963-64	877,900	818,100	+ 59,800	+ 7.3%	+0.60	72.6%
1964-65	1,980,000	2,049,700	- 68,800	- 3.5%	-0.69	25.0%
1965-66	1,219,430	1,060,400	+159,030	+13.0%	+1.60	94.5%
1966-67	3,332,000	3,330,300	+ 1,700	+ 0.5%	+0.02	50.8%
1967-68	843,200	970,600	-127,400	-15.1%	-1.28	10.0%
1968-69	4,386,200	4,169,600	+216,600	+ 4.9%	+2.18	98.5%
1969-70	1,330,600	1,502,100	-171,500	-12.9%	-1.72	4.3%
1970-71	1,175,000	1,238,700	- 63,700	- 5.4%	-0.64	26.1%
1971-72	859,600	881,400	- 21,800	- 2.5%	-0.22	41.2%
1972-73	2,135,400	2,110,200	+ 25,200	+ 1.2%	+0.25	59.9%
1973-74	2,095,900	2,021,700	+ 74,000	+ 3.5%	+0.75	77.3%
1974-75	1,583,300	1,556,570	+ 26,730	+ 1.7%	+0.27	61.3%
1975-76	540,700	531,975	+ 8,725	+ 1.6%	+0.09	53.6%
1976-77	396,000	340,225	+ 55,775	+16.4%	+0.56	71.2%
1977-78	3,453,800	3,173,470	+280,330	+ 8.8%	+2.83	99.8%
1978-79	1,729,820	1,610,580	+119,240	+ 7.4%	+1.20	88.5%
TOTAL	41,539,700	40,194,470				
AVERAGE	1,661,588	1,607,780				

5. ACKNOWLEDGEMENTS

A sincere note of appreciation must go to the Kings River Conservation District of Fresno, Calif. for its continued support of the total cloud seeding program. The early Board of Directors, under President Philip A. Gordon, and Cloud Seeding Chairman Edward E. Harper, displayed an unusual understanding of the uncertainties connected with this effort. The philosophy underlying the operation of this program has been continued under the current direction of the Board President Edward H. Howe and Cloud Seeding Committee Chairman Raymond W. Lambrecht. The District is to be commended for its insistence that the project be operated on a professional level and that the resultant data be made public information.

Notes of appreciation must also go to Dr. Earl Droessler during his earlier tenure with the National Science Foundation; Dr. Archie M. Kahan, who was Chief of the earlier Bureau of Reclamation's Atmospheric Water Resources Management group, and to both Dr. Pierre St.-Amand and Dr. William G. Finnegan of the Naval Weapons Center during that

period when the Earth and Planetary Sciences Division provided such a strong insight to the fundamentals of applied cloud seeding and the useful devices which have become the foundation of our operations program.

Of course, a special note of thanks must go to Dr. Vincent J. Schaefer who started all of us along this path and during the ensuing years provided much of the strong enthusiastic support and knowledgeable advice for the continuing Kings River Program.

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ASSESSMENT OF SUMMER 1979 WEATHER MODIFICATION EFFORT IN SOUTHEASTERN ILLINOIS

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Abstract. An operational cloud seeding project took place in southeastern Illinois during a 40-day period in the summer of 1979. A historical target-control evaluation design, using NWS raingage data, indicated an estimated rainfall increase of 39.5% in the target. Three statistical evaluation techniques - principal component regression, multiple regressions and double ratio, were employed and compared. The (randomization) significance levels were .10, .26, and .26, respectively. The possibility of the east control being contaminated was studied and found rather unlikely. Investigation of the 1979 isohyetal pattern, based on a 92-raingage network data revealed that within the target there were wide extremes, from very low to very heavy, and a localized high existed in the target on seeded rain occasions which was not present on no-seed rain occasions.

1. INTRODUCTION

During the dry summer of 1978, a group of citizens in southeastern Illinois became interested in the possibility of obtaining additional rainfall through the use of a weather modification program. By the latter part of the summer, they had formed a corporation called Southeastern Rain Incorporated; raised funds, and launched a cloud seeding project carried out by a weather modification firm in August and early September. No scientific assessment of this hurriedly assembled effort was attempted. The regional interest in this endeavor, and the potential for agricultural benefits deriving from additional summer rainfall in this area of Illinois, led the group to plan for a second summer season project in 1979. During the spring of 1979, a local fund raising program was conducted.

Interactions between the local county cooperative extension advisors and staff of the Illinois State Water Survey, which was providing scientific and technical information on weather modification, led to the decision that the State Water Survey would plan and perform an assessment of the rainfall during the 1979 project. This would provide information to local groups and state officials, and also test evaluation techniques and concepts being evolved on an NSF-sponsored project concerned with operational projects.

Survey officials discussed the needs for rainfall data with county extension advisors. This led to the establishment of a network of 92 raingages in a 6-county area embracing the 1979 "target area" (Figure 1) of about 2600 sq km. The Target Area was defined as that area in which funds were raised and was identified as the site for cloud seeding operations, based upon the contract between Southeastern Rain Inc., and Atmospheric Incorporated, the company contracted to do the 1979 cloud seeding project. The Target Area embraced most of Saline and Gallatin Counties, and parts of Franklin, Hamilton, White, and Williamson Counties. Plastic raingages were obtained, and given to farmers who were to serve as observers of daily rainfall amounts.

Results from this 1979 cloud seeding effort are presented and assessed. It is *important* to appreciate that the assessment of the 1979 summer rainfall, which involved comparisons of the rainfall pattern and amounts in the Target (seeded) area with those in the surrounding (non-seeded) areas, is not to *infer conclusively* that the rainfall in the Target was either increased or decreased because of seeding. We *stress* that it is very unlikely due to the great natural variability of summer rainfall in southern Illinois, that one could decide whether cloud seeding during a period of a few weeks altered the rainfall.

Rather, these statistics are presented with these *cautions* to achieve our objectives which are: 1) to describe the rainfall in and around the Target Area, and 2) to compare three of many statistical evaluation techniques being investigated by the authors (Changnon et al., 1980). The second objective is emphasized here in interpreting the subsequent analyses. From a scientific standpoint, these data will hopefully become a part of a larger bank of data, including radar echo data and cloud seeding operational data for 1979 (and subsequent years and other projects), which ultimately may provide sufficient information to allow some assessment of whether cloud seeding in Illinois actually 1) altered clouds and their behavior, and 2) altered rainfall *with some high degree of certainty*.

2. DATA

By the middle of June 1979, a reasonably dense network of 92 non-recording raingages had been installed, largely within the Target Area, Figure 1. Although the 92 raingages in the raingage network were *not* evenly distributed, the network represents a much denser sampling of rainfall than would be obtained without the network.

The official raingages of the National Weather Service in the area are shown on Figure 1,

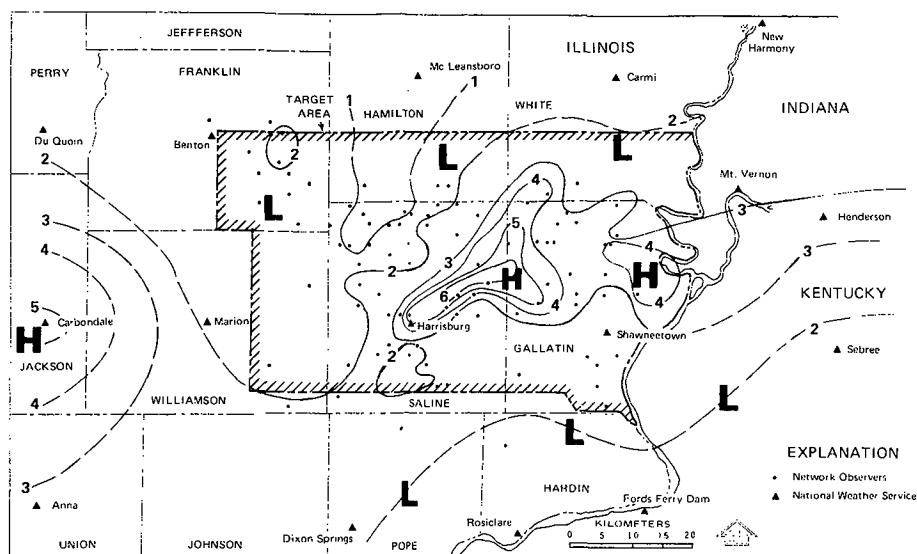


Figure 1. Rainfall (inches) from rains when cloud seeding occurred.

each denoted by a small triangle. Typically, there is only one such station per county in this region of Illinois and Kentucky.

Rainfall at these National Weather Service stations and at the 92 raingages operated by the local volunteer observers in the special network was measured once daily, typically at 0700 or 0800 CDT. Data were collected from the middle of June (prior to the start of cloud seeding) until late August (several days after operations terminated). Daily rainfall observations of the cooperative observers were entered on postcards, mailed to the county extension advisors, who in turn transmitted the data to the Illinois State Water Survey. The daily rainfall data of the National Weather Service observers in the area of interest were available in the published records of that agency. These two data sets were used for assessing the summer 1979 rainfall distribution in the Target.

The cloud seeding company was available and ready to seed clouds from 23 June through 26 July 1979, and then, after a pause because local conditions were too wet with lowland flooding, the operations were available again from 10 August through 15 August 1979. Thus, cloud seeding could have been conducted, if suitable weather conditions were available, for a period of 40 days within this 23 June-15 August period. This period of 23 June-26 July and 10 August-15 August was called the operational period.

3. ANALYSIS

In the following, we first looked at the 1979 isohyetal patterns based on the network of observer gages as well as the National Weather Service stations during the operational period. The purpose of this initial analysis was to reveal any unusual rainfall patterns on an exploratory-data-analysis sense. Subsequently, we conducted historical target-control comparison using only the National Weather Service station data from 1949 to 1979 in and around the Target Area. All NWS stations used possess continuous rainfall records during the 31-year period.

3.1 The 1979 Isohyetal Patterns Based on Dense Raingage Network

Daily rainfall values were classified according to three types of operational decisions by the weather modification group which operated its radar and seeding aircraft at the Marion Airport. Rainfall data from days when cloud seeding occurred during all or a portion of the rain in the Target Area, became the "seeded" rainfall amounts. These included six occasions: 23-24 June, 29 June, 30 June, 8-9 July, 10 July, and 12-13 July. The rainfall at each of the observer gages and at the National Weather Service gages for these six occasions were totaled and identified as the "seeded rains only."

It is important to realize that it rained on other occasions during the operational period. There were 17 rain occasions identified that classified as "non-seeded rains." The reporting forms from the cloud seeding operations indicated that these could be further subdivided into two classes. First were those when there were no cloud seeding but when the seeding airplanes flew to observe and measure clouds to see if they were amenable to seeding. This inferred that the project meteorologists believed atmospheric conditions suitable for successful seeding existed, and had the pilots go aloft to monitor conditions. However, the pilots concluded in these cases that the clouds were not right. The second class comprised eight rain occasions when there was no flying. These were situations in which the project meteorologists considered the conditions were totally unsuitable for rainfall modification.

These three categories of the rainfall during the 1979 operational period were further developed into five classifications:

- 1) Rainfall from these rain occasions when cloud seeding occurred (6 rain occasions).
- 2) Rainfall from the non-seeded rain occasions but when aircraft cloud observations occurred (9 rain occasions).
- 3) Rainfall from the non-seeded rain occasions with no cloud observations (8 rain occasions).

- 4) Rainfall from both of non-seeded rain occasions (a total of 17 rain occasions).
- 5) Rainfall from all rain occasions (a total of 23 rain occasions).

The pattern from the total rainfall in the six occasions with cloud seeding is shown in Figure 1. A small but well-defined high rainfall area occurred in the center of the Target Area. Low rainfall values fell in the northern and western parts of the Target Area, rainfall almost as high as in the center of the Target is found to the west, centered at Carbondale. The area embraced by the 3-inch isohyetal line extends from near Harrisburg eastward well beyond the Target Area into southwestern Indiana and western Kentucky.

The isohyetal map of the rains when no cloud seeding occurred *but* when aircraft cloud observations were made (Figure 2), shows a rain pattern similar to that of the seeded rainfall (Figure 1).

A rainfall high is in the center of the Target Area and extends eastward beyond the Target. However, greater rainfall highs are found to the southwest of the Target. In general, the pattern is remarkably similar to the seeded-occasion pattern, and the rainfall totals, in general, are comparable at many locations to those for the seeded occasions.

Figure 3 presents the pattern of rainfall on the eight non-seed occasions without airborne cloud measurements. These reflect atmospheric conditions that were considered totally unsuitable for cloud seeding well before the rain began and during the rain. The pattern of these non-seed rainfall occasions is somewhat similar to those of the seed and the other non-seed occasions with cloud observations. A generalized west-east high crosses the Target Area, but farther south. Rainfall in the center of the Target Area is much lower than in the seed category, although rainfall values in the northern part of the Target

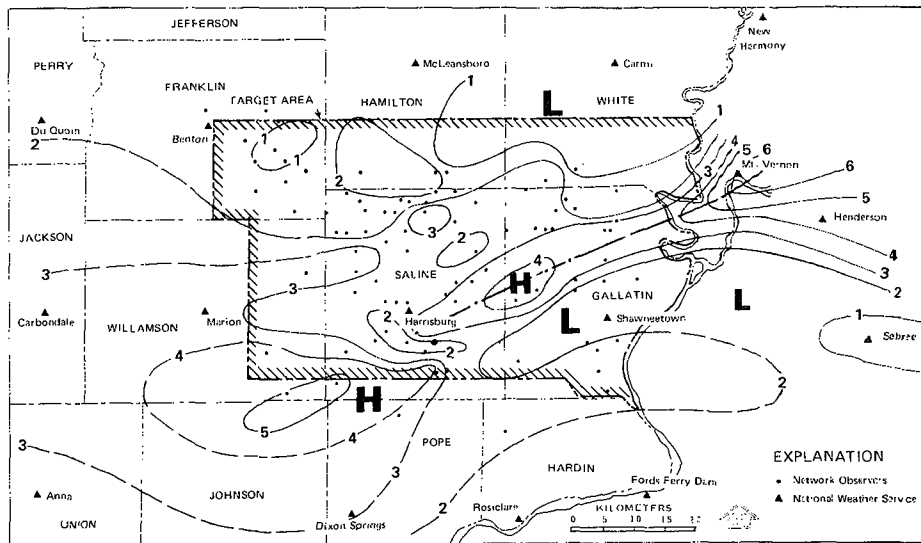


Figure 2. Rainfall (inches) from rains without cloud seeding but with aircraft cloud observations.

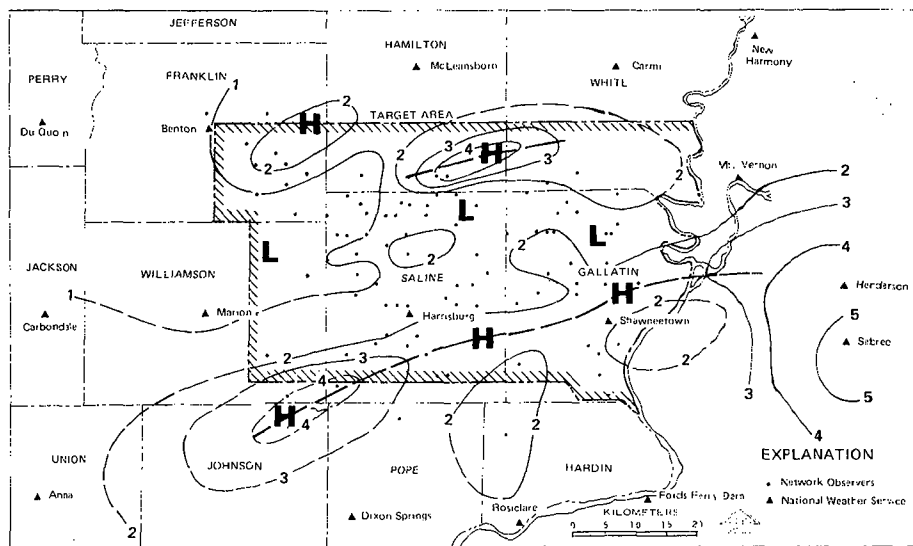


Figure 3. Rainfall (inches) from rains without cloud seeding or cloud measurement.

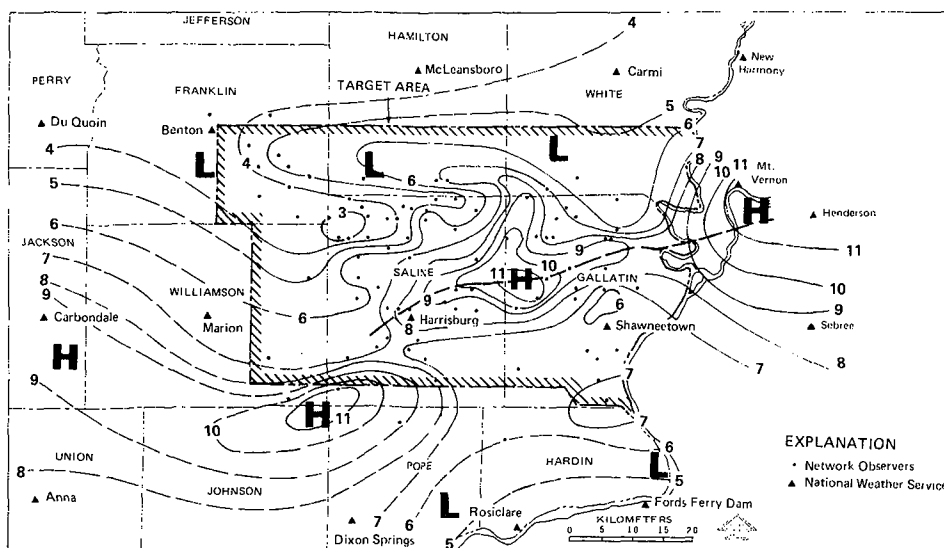


Figure 4. Total rainfall (inches) in 1979 period of weather modification.

Area (Franklin, Hamilton, and White Counties) are higher in this non-seed category than in the seed category or in the non-seed/cloud observation category.

Combining the values from the three categories of rain occasions gives the total rainfall for the 40-day operational period (Figure 4). A west-east oriented ridge of heavy rainfall runs from Carbondale to the southwest corner of the Target Area and then ENE across the center of the Target. It reaches a maximum of 11 inches (280 mm) between Harrisburg and Shawneetown and then extends eastward into Indiana and Kentucky, where amounts greater than 11 inches (280 mm) also occurred. Rainfall values in the Target Area ranged from less than 3 inches (76 mm) in one locale between Benton and Harrisburg, to as much as 11.22 inches (285 mm).

The danger of making claims for cloud seeding from inspection of rainfall patterns alone is easily demonstrated by Figure 4. One might wish to claim that the heavy rainfall centered in the Target Area was a result of cloud seeding. However, rainfall totals as high or higher outside of the Target were found to the southwest and east. Within the Target Area, in the northwest, the northern, and southeastern portions, rainfall was as low or lower than those anywhere else in the area surrounding the Target.

3.2 National Weather Service Gages

One of the problems in assessing the rainfall data for seeding effects utilizing the excellent, dense raingage network established for the Target Area relates to the fact that there was *not* a comparable raingage network and rainfall data from the surrounding areas. This becomes a problem when one wishes to evaluate the Target Area rainfall by comparing it with that in surrounding areas to derive conclusions as to its relative magnitude. That is, was the Target rain higher or lower than one might have expected? A time-honored approach to rainfall evaluation of a specific area has been to compare the rainfall in a Target Area with that in climatologically homogeneous regions nearby. The nearby regions

are typically called "control areas" for comparison with the "Target Area."

In order to make a fair comparison considering different raingage densities, the rainfall data from only the available National Weather Service (NWS) raingages in and around the Target Area were used. The only NWS gages in the Target Area were at Harrisburg and Shawneetown. Prior to the seeding project (in early June 1979), control areas to the north, west, south, and east of the Target Area were defined and each included two or three National Weather Service gages. The groupings of these gages according to the various controls are shown in Table 1. For example, the North Control Area comprised the rainfall values from the station gages at McLeansboro and Carmi. In essence, the four control areas surrounding the Target Area are shaped, at least conceptually, as shown by the four boxes in Figure 5. They are areas of a size equivalent to the Target Area, and each has the same general raingage density of approximately one gage per 1300 sq km.

3.2.1 1979 Target-Control Comparisons. Rainfall totals were defined to be that total during the operational period (June 23 to July 26 and August 8-15). Table 1 shows the total rainfall values at each of these stations for the five classifications of rainfall. The station values (under the five rain categories), in the Target and in the four control areas, were combined to form areal averages. The areal averages are plotted in the map portrayals (Figure 5) to permit easier comparison and reveal differences between regions. For example, on the seed occasions (Figure 5a), one finds the Target areal average of 3.50 inches (89 mm) with lesser area averages in all of the 4 surrounding control areas. The average of all 4 control areas was 1.91 inches (49 mm), and the difference between target and control average, labeled T-C (or target minus control), is equal to 1.59 inches (40 mm). This difference, expressed as a percent of the control average, represents 83.2% more rainfall in the Target than in the Controls.

Similar comparisons for the two non-seed rain categories appear as Figure 5b and 5c. Both

show that the Target Area received less rainfall, than did the average of the four control areas. It was 11.4% less in the cloud observation/non-seed category, and 28.3% less in the non-seed rains with no cloud observations.

Figure 5d presents the areal average rainfall values combined for both categories of non-seed conditions. One sees here that the Target Area received more rainfall than did the North, West, and South Control Areas, but noticeably less than did the East Control Area. The difference between the four control areas and the Target represents 0.90 inch less, or 19.4% less rainfall in the Target than in the surrounding control areas. It is important to note that rainfall in the East Control Area in both of the non-seed categories (Figures 5a and 5c) were higher than in the Target Area.

The combination of all the 1979 rains in the operational period is shown in Figure 5e. The Target Area rain of 7.24 inches (184 mm) easily exceeds the averages of the North, West, and South Control Areas but is considerably less than the East Control Area. The four control areas had an average rain of 6.20 inches (157 mm). The target/control ratio is thus 1.17, a crude indication of more rainfall in the Target Area than the control areas. (For all gages the ratio is $7.24/6.55 = 1.11$.) However, this ratio cannot be used alone as indication of any seeding effect, as certain "selection bias" may have been introduced by

the seeding operator in favor of more natural rainfall on days chosen for seeding. More reliable and more bias-free evaluation involves use of the historical target-control comparison.

3.2.2 Historical Target-Control Comparison, All Controls. The area precipitation values from 1949 to 1978 were used as historical observations. Three statistical evaluation techniques were chosen before the actual evaluation efforts were undertaken, namely, the principal component regression (PCR), multiple regression (MR), and double ratio (DR). The choice of evaluation techniques were largely based upon findings from an NSF-funded research, which investigated performance of various statistical-physical techniques in evaluating operational weather modification projects (Changnon et al., 1980; Hsu, 1979). The decision to use three techniques undoubtedly will raise the question of multiplicity, but the evaluation efforts are basically exploratory, rather than to confirm the effectiveness of cloud seeding over southeastern Illinois.

1. Principal Component Regression. First, a principal component analysis for the four control areas using 1949-1978 historical data was performed and the first three components were retained, which were used in turn as independent variables to run a regression on the Target Area value. The principal component regression equation thus derived was used to

Table 1. Rainfall Totals at National Weather Service Raingages, Operational Period, Southeastern Illinois 1979 Cloud Seeding Project.

	Seeded	Cloud Flights	No Cloud Flights	Both	Total Rainfall
Occasions	6	9	8	17	23
<u>Target Area</u>					
Harrisburg	4.35	2.79	1.13	3.92	8.27
Shawneetown	2.65	1.54	2.02	3.56	6.21
Average	3.50	2.17	1.57	3.74	7.24
<u>North Control Area</u>					
McLeansboro	0.63	1.47	1.21	2.68	3.31
Carmi	1.95	0.90	1.55	2.45	4.40
Average	1.29	1.19	1.38	2.57	3.86
<u>West Control Area</u>					
Benton	1.51	1.19	1.00	2.19	3.70
Marion	1.87	3.57	0.87	4.44	6.31
Average	1.69	2.38	0.94	3.32	5.01
<u>South Control Area</u>					
Dixon Springs	2.13	3.11	2.32	5.43	7.56
Rosiclare	1.30	1.06	2.03	3.09	4.39
Fords Ferry	1.80	1.34	1.22	2.56	4.37
Average	1.74	1.84	1.86	3.69	5.44
<u>East Control Area</u>					
Mt. Vernon	2.96	6.89	1.84	8.73	11.69
Henderson	3.09	4.09	4.40	8.49	11.58
Sebree	1.90	0.85	5.45	6.30	8.20
Average	2.65	3.94	3.90	7.84	10.49

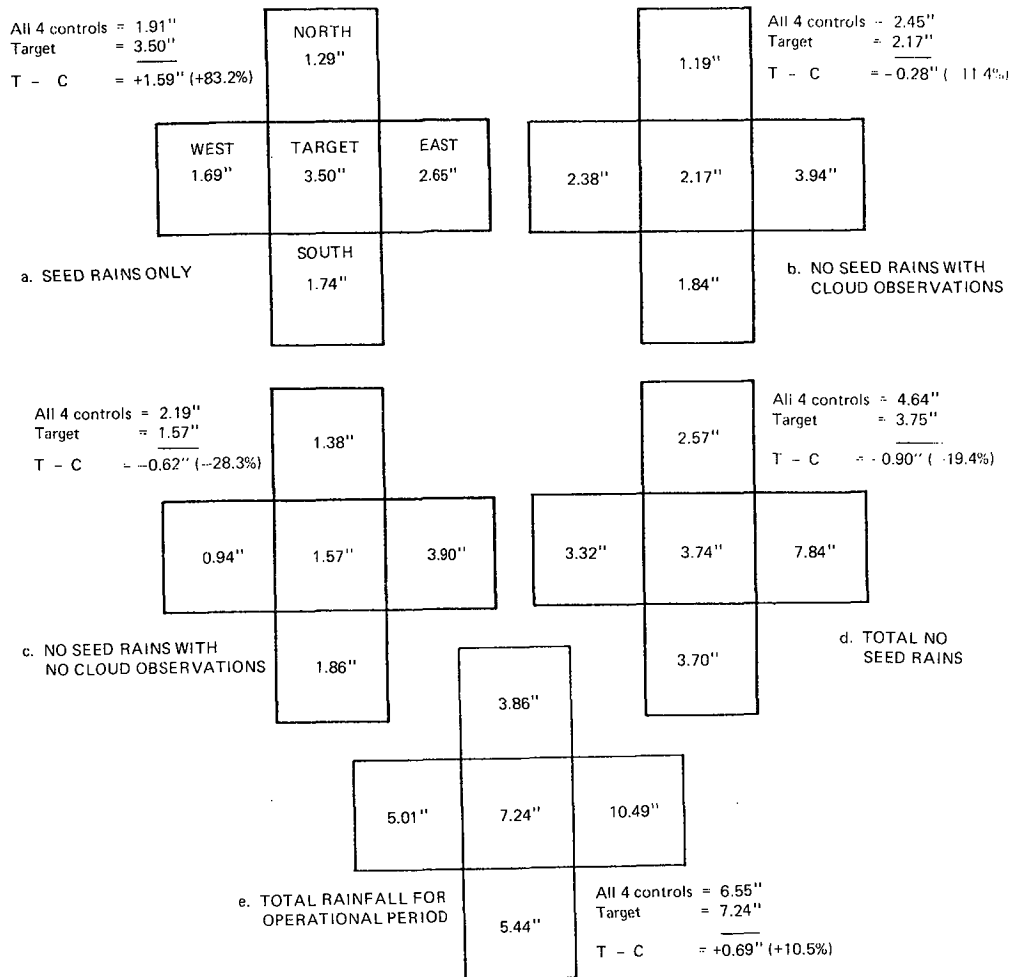


Figure 5. Area mean rainfall in target and control areas during the South-eastern Illinois Cloud Seeding Project in 1979. Values are based on NWS data.

predict 1979 Target Area rainfall, which was then compared to the actual 1979 Target Area rain. The use of three components in the regression is also due to findings from the same research. The resulting predicted rain for the 1979 Target Area by using 1949-1978 PCR equation is 5.19 inches (132 mm). The difference between this and the actual rain value, (7.24-5.19), gives an estimated rainfall increase of 2.05 inches (52 mm), or 39.5%.

To assess the significance of this rainfall increase, a randomization principal component regression was performed. One year from 1949 to 1978 was selected as a hypothetical "seeded" year, and all other years (including 1979) as historical "control" years. Then a principal component regression was performed on this seeded-historical setting, a predicted precipitation was obtained, and a rainfall increase was computed.

This process was repeated by selecting another year as "seeded" and so on, until a distribution of rainfall increases was obtained. A distribution of 31 estimated rainfall increases was obtained and shown in a "stem-and-leaves" display (Table 2a). Two rainfall increases are larger than the 1979 rainfall increase (indicated by an asterisk in the table);

the corresponding significance level is 3/31 = 0.10. That is, the chance is about one out of ten that this sizeable increase is due to nature, rather than to cloud seeding. Although the 1979 rainfall increase is not statistically significant at the usual .05 level, due to the very short duration (one summer) of the present project, the seeding effect is usually difficult to detect than longer project, even using more powerful evaluation techniques. Therefore, this marginal significance of 0.10 reveals that the 1979 rainfall increase may not have been completely due to natural variation, but whether this is due to cloud seeding or not is far from certain.

2. Multiple Regression. The four control areas values were used as independent variables to regress on the Target Area values using 1949-1978 data. The resulting (historical) regression equation was used to predict 1979 Target rainfall. The predicted value, 6.15 inches (156 mm), and the actual 1979 Target rainfall, 7.24 inches (184 mm), give an estimated rainfall increase of 1.09 inches (28 mm), or 17.7%. A randomization multiple regression was performed similarly to that using principal component regression. Table 2b shows a "stem-and-leaves" display of the randomization dis-

Table 2. Randomization Distributions of Estimated Rainfall Increases, All Control Areas.

2a PRINCIPAL COMPONENT REGRESSION

Stem	Leaves	Cumulative	
		No.	%
-2.00	00,04,09	3	9.7
-1.00	08,09,19,60,67,70	9	29.0
-0.00	11,23,42,47,57,58,74,95	17	54.8
0.00	10,19,23,43,48,48,68,69,88	26	83.9
1.00	55,75	28	90.3
2.00	05*	29	93.5
3.00	03	30	96.8
4.00	12	31	100.0

2b MULTIPLE REGRESSION

Stem	Leaves	Cumulative	
		No.	%
-2.00	02,07	2	6.5
-1.00	00,08,08,11,40,45,54,66	10	32.3
-0.00	02,28,33,36,41,57,82,97	18	58.1
0.00	03,10,38,50,72	23	74.2
1.00	09*,19,36,47,92	28	90.3
2.00	07,69	30	96.8
3.00	63	31	100.0

2c DOUBLE RATIO

Stem	Leaves	Cumulative	
		No.	%
.500	94	1	3.2
.600	49	2	6.5
.700	13,16,19,48,77,91	8	25.8
.800	32,32,76,93,95	13	41.9
.900	49,87	15	48.4
1.000	06,12,24,34,43,67,79	23	74.2
1.100	41*	24	77.4
1.200	06,70	26	83.9
1.300	17,81	28	90.3
1.400	02	29	93.5
1.500	37	30	96.8
1.600	44	31	100.0

*1979 value

tribution of estimated rainfall increases using MR; the significance level is found as 0.26.

3. Double Ratio. For the 1979 seeded year, a double ratio is calculated as follows:

$$DR = TsCns/TnsCs$$

where Ts is the rainfall total of the Target Area in the year 1979, Tns is the averaged rainfall total of the Target Area in the non-seeded years (1949-1979), and similarly Cs and Cns. A randomization double ratio was performed, and a "stem-and-leaves" display of the randomization distribution is shown in Table 2c. The double ratio corresponding to 1979 is 1.141, or an estimated rainfall increase of 0.89 inches (23 mm), and the significance level is 0.26, the same as that of MR.

These three evaluation techniques give non-identical significance levels to their respective 1979 estimated rainfall increases. Only the estimated rainfall increase using PCR is marginally significant at the 0.10 level; whereas the estimated rainfall increases using MR or DR are not as significant. In other

words, the technique of principal component regression indicates that the 1979 Target Area rainfall increases was more unusual than do the techniques of MR or DR. This result partially supports findings obtained by Hsu (1979) that PCR is more powerful than MR or DR in evaluating cloud seeding under weather regimes similar to the present one.

3.2.3 Historical Target-Control Comparisons, Excluding East Control Area. The Target Area had more rain than the control areas except the East Control Area (Figure 5e), where the average of 10.49 inches (266 mm) in 1979 was much above the other area rainfall values. To find out whether this large value occurred naturally or extremely (in other words, was this an outlier?), frequency distributions of the rainfall for each area are shown in Table 3 with the 1979 rainfall values marked by asterisk. The 1979 rainfall values in the North and South Control Areas were close to their respective medians; whereas the 1979 rainfall values in the West and East Control Areas were above normal (compared to their medians).

The deviation was unusually large in the East Control Area, whose 1979 rainfall value was the second largest in the 31-year period studied. This raises a question of possible extra-area seeding effects there. Some information regarding seeding operations and the meteorological conditions of the present project are available

Table 3. Ranked Distribution of Areal Precipitation, 1949-1979.

	Target	North	West	South	East
1	1.70	1.57	1.60	1.21	2.93
2	1.91	1.83	1.86	1.24	3.23
3	2.33	1.96	1.90	2.66	3.34
4	2.44	1.97	2.47	3.07	3.37
5	2.97	2.58	2.61	3.69	3.46
6	3.23	2.81	2.87	3.69	3.49
7	3.77	2.83	2.97	3.76	3.53
8	3.80	2.88	3.20	3.81	3.61
9	3.88	2.98	3.48	4.21	3.74
10	4.19	3.06	3.63	4.30	3.82
11	4.23	3.51	3.67	4.57	4.15
12	4.39	3.55	4.00	4.72	4.18
13	4.73	3.66	4.05	4.81	4.33
14	4.82	3.82	4.18	4.92	4.56
15	4.88	3.83	4.25	5.08	4.58
16	4.92	3.86*	4.28	5.42	4.87
17	4.93	4.01	4.49	5.43	5.00
18	5.06	4.18	4.54	5.44*	5.20
19	5.21	4.24	4.60	5.61	5.32
20	5.38	4.27	4.89	5.75	5.85
21	5.57	4.72	5.01*	5.78	6.32
22	5.61	4.95	5.05	6.22	7.11
23	5.71	5.13	5.08	6.61	7.31
24	6.49	5.13	5.13	6.69	7.88
25	7.01	5.64	6.08	6.89	7.94
26	7.24*	5.67	6.64	6.91	8.34
27	7.80	6.15	6.84	7.19	8.46
28	8.08	6.19	7.23	7.99	8.53
29	8.86	7.89	7.32	8.28	9.43
30	10.20	10.83	11.86	9.10	10.49*
31	10.62	12.37	12.01	13.08	11.30

*1979 value

from the operator, but they do not contain enough details. Attempts to identify any extra-area effect by examining this information is discussed later; whereas here, it was decided to exclude the East Control Area to perform another historical Target-Control evaluation. This second evaluation does not render the first evaluation invalid, rather it only serves as an auxiliary piece of information to complement the first evaluation in regard to the question of extra-area seeding effect.

Only the techniques of multiple regression and double ratio were used. (Principal component regression with three components is identical to the multiple regression in this case.) Table 4 shows the randomization distributions of estimated rainfall increases using multiple regression as well as using double ratio. The significance levels of both techniques are 0.10. The estimated 1979 rainfall increase using multiple regression is 1.94 inches (49 mm), or 36.6%. The 1979 double ratio is 1.437, or an estimated rainfall increase of 2.20 inches (56 mm).

Overall, the significant estimated rainfall increases using either all four surrounding control areas (39.5%, PCR), or using three control areas excluding the East Control Area (36.6%, MR; 43.7%, DR) were fairly close. This suggests little likelihood that the East Control Area was contaminated during the 1979 cloud seeding period. The unusually large amount of the 1979 rainfall value in the East Control Area was probably due more to natural variation than to cloud seeding.

Indeed, the radar echo overlay (provided by the seeding operator) on the seeded days were examined to discern where seeded echoes and

echo complexes moved beyond the Target. The results shown in Table 5 reveal that there is little possibility of East Control Area being contaminated. It is surprising, however, to note that the West and South Control Areas appeared to be potential areas of contamination, which suggests that the previous estimation of 1979 T-C differences as well as the statistical significance of historical T-C comparisons might be conservative than they actually were.

Table 5. Seeded Echo Motion.

Date	Seeded Echo Motion	Control Areas Possibly Affected
June 20	Unclear	W, S
June 22	Stationary	S
June 23	From Northwest	W, S
June 29	Stationary	None
June 30	From West	E
July 9	Stationary	W
July 10	Stationary	None
July 12	From East	W

Table 4. Randomization Distributions of Estimated Rainfall Increases, Surrounding Control Areas Except East.

4a MULTIPLE REGRESSION			
Stem	Leaves	Cumulative No.	Cumulative %
-2.00	26	1	3.2
-1.00	05,12,19,62,65,69,92	8	25.8
-0.00	04,58,63,65,66,82,86,95,98	17	54.8
0.00	02,05,05,29,73,73,87,88	25	80.6
1.00	43,58,79,94*	29	93.5
2.00	53	30	96.8
3.00	95	31	100.0

4b DOUBLE RATIO			
Stem	Leaves	Cumulative No.	Cumulative %
.600	16,71	2	6.5
.700	26,85,96	5	16.1
.800	06,14,19,25,52,65,91	12	38.7
.900	00,02,22,33,42,56,97	19	61.3
1.000	54,56	21	67.7
1.100	05,80,87	24	77.4
1.200	65,78,90	27	87.1
1.300	82	28	90.3
1.400	37*	29	93.5
1.500	79,93	31	100.0

*1979 value

4. SUMMARY

The Target Area received more rainfall (based on only two gages to determine an area average) during the 1979 40-day operational period than did the surrounding areas. This was particularly true when one compared the Target rainfall with the surrounding control rainfall based solely on the seed rain occasions. Investigation of the 1979 rainfall (isohyetal) pattern within the Target, based on the detailed 92-raingage network data, showed that there were wide extremes, from very low to very heavy rainfall in the Target Area.

The 1979 rainfall data alone cannot be construed as evidence of any cloud seeding effect. However, the differences between seeded and non-seed values, particularly as revealed in Figure 5, do suggest that a localized high existed in the Target on seeded occasions which was not present on non-seed occasions. As one final caution, one expects that cloud seeding in the Target Area would be attempted under conditions that were locally favorable for heavier rainfall there, and a "selection bias" might have occurred.

A more bias-free evaluation using surrounding control areas and historical data shows a marginally significant 39.5% estimated rainfall increase during 1979 cloud seeding period. If the question of the East Control (extra-area effect) is concerned, evaluation using the other control areas shows marginally significant rainfall increase of 43.7% using DR and 36.6% rainfall increase using MR. In both comparisons, the probability that this is due to chance is 1 in 10.

As an evaluation technique principal component regression indicated that the 1979 Target rainfall was more unusual than do the MR or DR results indicated when all the four control areas were used. The MR (or equivalently PCR) and DR also indicated that the 1979 Target rainfall was unusually high when only three control areas were used.

5. ACKNOWLEDGMENT

This assessment of rainfall could not have been possible without the considerable efforts of the Cooperative Extension Advisors in the six counties of the Target Area. We wish to thank the 92 persons who served faithfully as rainfall observers during the summer of 1979. We wish to acknowledge the considerable assistance of Kathy Eckstein and Phyllis Stone who meticulously and carefully compiled the rain data and segregated it into discrete rain occasions. John Brother aided with drafting of the rainfall figures. We also wish to acknowledge the interest and cooperation of the members of Southeastern Rain Inc. who supported the cloud seeding program

and the concept of a rainfall evaluation effort. The comments made by K. R. Gabriel are also appreciated. A portion of this research was done as a part of NSF grant ATM 79-05007.

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SEVEN YEARS OF WEATHER MODIFICATION IN
CENTRAL AND SOUTHERN UTAH

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Abstract. A post-hoc statistical evaluation of an operational cloud seeding project, designed to enhance winter snowfall in the mountainous sections of central and southern Utah, was based on comparison between several control areas and multiple target areas. Linear regression equations were developed for each control-target area combination based on average January-March precipitation, 1956-1973; from 1974 through 1980 the target was seeded consistently during these months. Ratios of observed to calculated precipitation are presented for the target areas and several sub-target areas based on the predictions using the control area precipitation as predictor for the seeded years. Significance of the results was determined using a one-tailed Wilcoxon-Mann-Whitney ranking test.

On the basis of this evaluation it is concluded that seeding has been successful in increasing the January-March precipitation within the intended target areas over the seven year seeded period. The results vary depending on the control area, but all are positive. Indicated increases range from about eight percent to twenty-eight percent within the various target sub-sectors. Over the total Primary Target precipitation increases of between 13 and 20 percent are indicated. These results appear to be highly significant in most of the target areas. Some evidence of positive extra-area effects are noted "downwind" from the target, but with less statistical significance than the target areas.

1. INTRODUCTION

Utah is one of the driest of the 50 states; much of the precipitation that does fall accumulates as high elevation snowpack from October to April. For irrigated agriculture, important in the state, streamflow from these accumulated snowpacks is necessary, and any additional runoff that can be acquired is valuable. An operational weather modification program in central and southern Utah began in the 1973-74 winter and has continued each winter through the present. Sponsors of the program are the Utah Water Resources Development Corporation (formerly Southern Utah Water Resources Development Corporation) and the State of Utah, Division of Water Resources (DWR), an active participant since 1975.

The program goal has been to increase winter snowpack at higher elevations of participating counties in central and southern Utah. North American Weather Consultants (NAWC), the weather modification contractor since the program's inception, has evaluated the effectiveness of the program for both five and seven years of operation. The more recent 7-year evaluation of seeding of winter-spring seeding 1974-1980, is reported here.

2. BACKGROUND

The intended target areas of the program, as defined in an earlier design study (Thompson et al., 1978), encompasses some 19,000 sq km (12,000 sq mi)

of mountains in central and southern Utah. Commissioners or water conservancy districts of counties potentially involved in the program vote annually whether to participate. The DWR then shares the cost of the program. On the average, 12 counties have participated annually since the state involvement began in 1975 (Figure 1).

Both silver iodide (AgI) ground generators and seeding aircraft were used in selected storm periods until 1979, after which only ground generators were used. Manually operated units are supplemented by remotely controlled units at higher elevations. For the current 1980-81 season, 75 manual and 4 remote generators were installed.

The program is strictly an operational program designed to optimize any benefits, without any randomization. Portions of naturally occurring storms deemed seedable by established seedability criteria (Thompson et al., 1978) are seeded. Consequently, evaluation has relied upon comparisons of target and control precipitation.

The earlier evaluation of five years of seeding (Thompson, 1979) also was based upon comparisons of target control precipitation, but only from January to March. This was the only period consistently seeded during the five years. This five-year evaluation work was independently verified by the

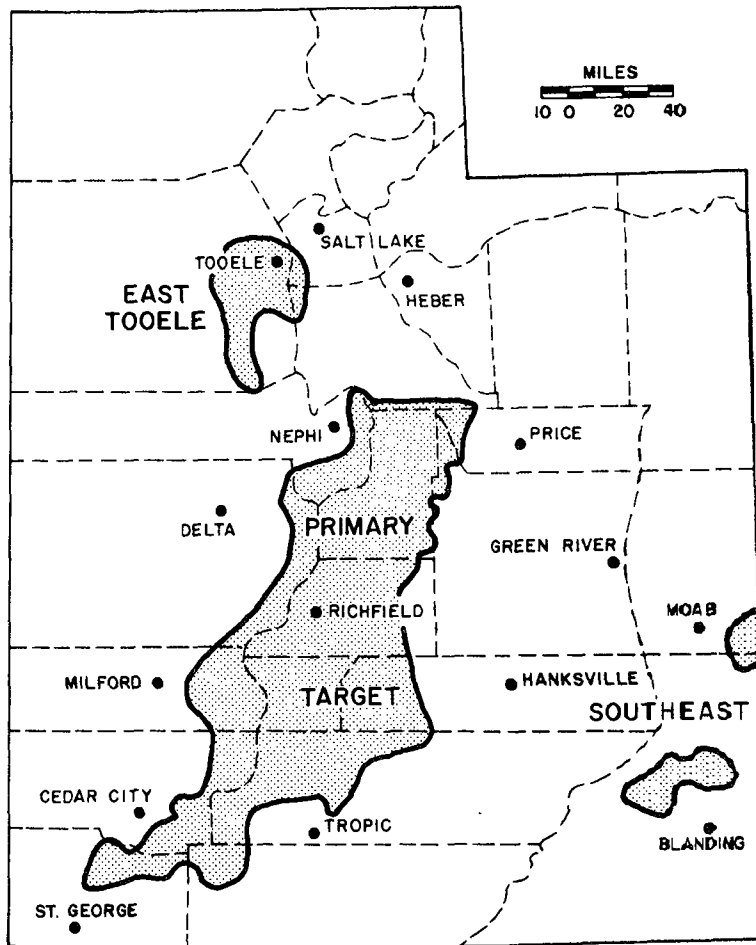


Fig. 1. County seats of Utah counties involved in weather modification program and project target areas (hatched), 1974-1980.

Division of Water Resources (Div. of Water Resources, 1981).

Thompson (1979) found that the 1974-78 January-March precipitation in the Primary Target was greater than that predicted by the regression equations. Some differences between observed and calculated values were highly significant, particularly in the southern half of the target. For the total target, the indicated increase due to seeding was approximately 18 percent, highly significant at the .018 level by the Wilcoxon-Mann-Whitney rank test.

Both this evaluation and that of the DWR were reviewed by a Technical Advisory Board organized by the DWR to provide guidance and expertise. Dr. Ruben Gabriel, Univ. of Rochester statistician, reviewed the five-year evaluation as part of a National Oceanic and Atmospheric Administration (NOAA) program to design a comprehensive evaluation of both the Utah and North Dakota state/local seeding programs.

The major recommendation of both the Technical Advisory Board and Dr. Gabriel was for additional analyses using other stations as control areas, since the evaluation used control stations selected *post hoc*. The new analyses were suggested to confirm that comparable results could be achieved with different controls. In addition, Dr. Gabriel recommended elimination of four of the stations in the original ten station control due to their proximity to the target.

These recommendations have been followed; the results of the evaluation, updated to cover seven years of seeding, 1974-1980 follows.

3. EVALUATION APPROACH

To cover seven years of seeding the evaluation approach is the same as that of the five-year evaluation; e.g., statistical, using the correlation between a control area and a target area to determine the apparent effectiveness of seeding. Like the previous

five-year evaluation, the basic data consist of January through March precipitation.

The control in the five-year evaluation consisted of ten precipitation measuring stations in west-central Utah (one station was actually just over the state line in Nevada). As suggested by Dr. Gabriel, four stations in the eastern part of the control, near the western edge of the target, were eliminated, leaving a six station control (C_1 in Fig. 2). A second control (C_2) included six precipitation stations located in Nevada, Arizona, and Utah. Few stations in eastern Nevada and northern Arizona have long-term stable records of precipitation so Lehman Cave National Monument, Nevada was included in both controls. Otherwise, C_2 stations were much farther removed from the target than C_1 . Combining the average precipitation at each of the 11 individual stations of C_1 and C_2 produced yet another control (C_3) extending from eastern Nevada and western Utah to northwestern Arizona. Table 1 provides a listing of all the precipitation stations. All three of the controls were used to develop regression equations for the various targets (Table 2); ratios of observed target precipitation to calculated precipitation were determined for each target-control relationship (Table 3).

Four target areas, e.g., Central, South Central, Dixie and the east Tooele County target area (not included in the five-year evaluation), and two supplemental areas (Eastern and North Central) were used. The Eastern area is not in the intended target area, but was included to investigate potential extra area effects. The North Central area was selected to seek seeding effects in an area not expected to be directly affected by the seeding. In this manner, some assessment could be made of whether there was some bias in the seeded years favoring the likelihood of detecting a "seeding effect".

The isolated target areas in southeastern Utah were not evaluated in the five-year evaluation and have also been excluded from this evaluation due to lack of long-term precipitation stations. Precipitation gage locations are indicated in Fig. 2 by a circle and storage gage locations are shown by an "X". Most precipitation gages are in valleys at lower elevations, with storage gages at elevations above 3360 m (8000 ft MSL). Seeding in the east Tooele area did not begin until 1975-76, so the evaluation for that section is for January-March, 1976-1980.

Precipitation stations with reliable long-term records were sought in the Climatological Data for Arizona,

Nevada and Utah, published by the National Climatic Center, NOAA, Storage-Gage Precipitation Data for western United States, also published by the National Climatic Center, and the Water Supply Outlook for Utah, published by the Soil Conservation Service, USDA. Except for some storage gages, data were available back to about 1950. However, another seeding project had been conducted in southern Utah from 1951 to 1955 (Hales et al, 1955). To eliminate any possible effect from that seeding these years were excluded and the historical data base was formed from January-March precipitation 1956-1973.

3.1 Data Quality

The control area stations had consistent data, although occasional monthly totals were reported as estimated. Precipitation data were available in the Central target for 17 low elevation stations and 17 storage gages at higher elevations. Less than five percent of the data were missing but, on those occasions when they were, estimates were made from surrounding locations by plotting the available data on charts and drawing isohyets around the missing data areas. For the eight storage gages installed during 1956 and the one in 1957, data were estimated from surrounding data in a similar manner. The storage gages normally were read at or near the end of each month. When two or more months were combined, an interpolated value for the desired period was computed from the known percentage of precipitation which fell at the surrounding sites.

In the South Central target area, the 12 low elevation precipitation gages all have consistent records. Data were available from five storage gages, although 1956 data were estimated at two. Less than three percent of the historical data were missing from the storage gages, and all was available in the seeded years.

The Dixie target area has five lower elevation precipitation stations, and two storage gages, at lower elevations than the ones in the Central and South Central target areas. These sites were not activated until 1959 and the data for the first three years have been estimated from surrounding locations.

The six precipitation gages in the Eastern supplementary area, just east of the Wasatch Plateau all had good data. The North Central supplementary area had ten stations at both low and high elevations, three of which were storage gage sites at intermediate levels between 2250 and 2450 meters. To select stations less likely to be affected by the seeding generator sites to the west and northwest (i.e., generator locations used to seed the Stansbury and Oquirrh Mountains in east Tooele

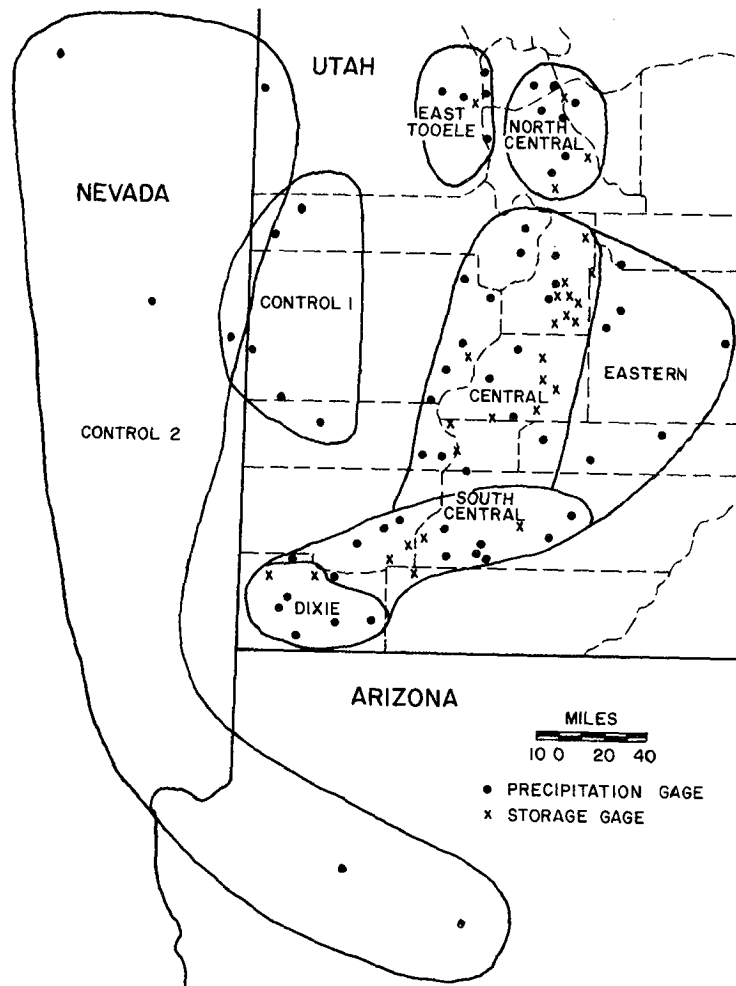


Fig. 2. Control, target, and supplemental areas.

County), precipitation gages in the Salt Lake and Provo areas were not chosen.

3.2 Data Compilation

Precipitation for each station within a group, either the controls or the various target groups, was summed for three months, January through March, for each individual year. These three monthly totals were then summed for all the stations within the group and averaged to obtain a "yearly" average.

Station histories of the precipitation gages indicate that many have been moved from a few to several hundred meters; elevation changes were generally less than 30 meters, but occasionally as much as 120 meters. A few gages have been moved one to as much as five kilometers, but records at the nearest gages suggest no appreciable changes have occurred.

The storage gages' histories indicate a more stable pattern with little

movement. Minor elevation changes (generally less than 60 meters) occurred at about half the sites. None of the moves was significant enough to change the station precipitation pattern and thereby affect the regression computations.

4. RESULTS

Separate linear regressions were developed relating average January-March precipitation, (1956-1973), in each of the target areas to that in the three control groups (C_1 , C_2 , and C_3). These equations were then applied to 1974-1980 control area precipitation to estimate the target area precipitation if it had not been seeded.

Ratios of the observed target precipitation (Y_o) to the calculated precipitation (Y_c) were computed and tested by the Wilcoxon-Mann-Whitney ranking test (onetailed). Where appropriate, target groups were stratified by elevation (valley precipitation gages and mountain storage gages).

Table 1. Precipitation stations.

Index No.	Name	Lat.	Long.	Elev (ft)	Group	Avg. Jan-Mar Precip. (inches)	
						1956-73	1974-80
<u>Arizona</u>							
6328	Peach Springs	35-32	113-25	4810	C2	2.63	4.17
9359	Williams	35-15	112-11	6750	C2	5.00	7.04
<u>Nevada</u>							
2573	Elko FAA AP	40-50	115-47	5075	C2	2.65	3.15
2631	Ely WSO AP	39-17	114-51	6257	C2	2.14	2.71
4514	Lehman Cave N.M.	39-00	114-13	6825	C1,2	3.17	3.35
<u>Utah</u>							
0449	Bartholomew PH	40-10	111-30	5140	NC	7.67	9.35
0519	Beaver	38-17	112-38	5920	CE	2.40	3.51
0527	Beaver Canyon PH	38-16	112-29	7275	CE	5.15	8.03
0534	*Beaver Dams	39-08	111-33	8000	CE	7.99	9.92
0684	*Big Flat	38-18	112-21	10290	CE	9.32	13.23
0700	Bingham Canyon 2NE	40-34	112-08	5620	ET	6.05	6.13
0733	*Blacks Fl. UM Ck.	38-41	111-36	9400	CE	6.86	8.79
0849	Boulder	37-55	111-25	6700	SC	2.01	3.93
0892	*Box Creek	38-30	112-02	9800	CE	7.79	10.72
1002	Bryce Canyon FAA AP	37-42	112-09	7585	SC	2.32	4.83
1008	Bryce Canyon NP Hdq.	37-39	112-10	7915	SC	3.13	4.98
1012	*Buck Flats	39-08	111-27	9400	CE	9.64	12.42
1144	Callao	39-54	113-43	4330	CI	1.00	1.06
1171	Capitol Reef NP	38-17	111-16	5500	EA	.65	1.70
1214	Castle Dale	39-13	111-01	5660	EA	1.22	2.33
1239	*Castle Valley	37-40	112-44	9580	SC	7.82	10.55
1267	Cedar City FAA AP	37-42	113-06	5620	SC	2.17	3.73
1432	Circleville	38-10	112-16	6060	CE	1.83	2.09
1759	Cottonwood Weir	40-37	111-27	4960	NC	6.14	7.10
1792	Cove Fort	38-36	112-35	5990	CE	3.35	4.80
2057	Deer Creek Dam	40-24	111-32	5270	NC	6.39	9.94
2116	Desert Exp. Range	38-36	113-45	5252	CI	.97	1.73
2255	*Duck Creek RS	37-31	112-42	8700	SC	9.87	14.51
2279	*Dutchman GS	40-32	111-36	7560	NC	11.65	15.14
2558	Enterprise	37-34	113-43	5340	SC	3.87	6.72
2565	*Ephraim Alpine Meadows	39-18	111-27	10000	CE	12.54	15.25
2573	*Ephraim Hdq. GBRC	39-19	111-29	8700	CE	9.89	12.13
2574	*Ephraim Majors Flat	39-20	111-31	6880	CE	5.37	6.69
2576	*Ephraim Oaks	39-21	111-31	7655	CE	6.61	8.31
2578	Ephraim Sorensen fld.	39-21	111-35	5670	CE	2.76	3.90
2592	Escalante	37-46	111-36	5810	SC	1.73	3.50
2696	Fairfield	40-16	112-05	4876	ET	2.47	4.54
2752	*Farnsworth Lake	38-46	111-40	9600	CE	11.22	12.41
2798	Ferron	39-05	111-08	5930	EA	1.53	2.69
2828	Fillmore	38-57	112-19	5120	CE	4.41	5.18
2847	*Fish Lake RS	38-33	111-43	8700	CE	4.65	6.68
3097	Garfield	40-43	112-12	4300	ET	3.68	5.35
3138	Garrison	38-56	114-02	5275	CI	1.41	2.22
3298	*Gooseberry RS	38-48	111-41	8000	CE	7.66	8.80
3301	*Gooseberry Res.	39-41	111-19	8700	CE	10.37	13.85
3348	Grantsville	40-36	112-27	4290	ET	2.77	3.04
3418	Green River Avn.	39-00	110-10	4070	EA	.95	2.02
3506	Cunlock PH	37-17	113-43	4060	DX	3.70	6.56
3611	Hanksville	38-22	110-43	4308	EA	.67	1.62
3776	Hatch	37-39	112-26	6910	SC	1.66	4.17
3809	Heber	40-30	111-25	5630	NC	4.37	5.97
3896	Hiawatha	39-29	111-01	7220	EA	2.82	4.15
4005	*Hobble Ck. Sum.	40-11	111-22	7420	NC	9.56	11.90
4527	Kanosh	38-48	112-46	5050	CE	3.57	4.92
4668	*Kimberly Mine	38-29	112-23	9100	CE	10.36	12.67
4764	Koosharem	38-31	111-53	6950	CE	1.57	2.60
4968	La Verkin	37-12	113-16	3200	DX	3.73	6.07
5065	Levan	39-33	111-52	5315	CE	4.07	4.53
5131	*Little Grassy Ck.	37-29	113-51	6100	DX	7.15	13.10
5148	Loa	38-24	111-39	7080	CE	.97	1.29

Table 1 (Cont'd.)

Index No.	Name	Lat.	Long.	Elev (ft)	Group	Avg. Jan-Mar Precip. (inches)	
						1956-73	1974-80
<u>Utah</u>							
5197	*Long Flat	37-30	113-25	8000	DX	6.25	9.59
5402	Manti	39-15	111-38	5740	CE	3.33	4.49
5603	*Middle Canyon	40-29	112-12	7000	ET	9.40	13.30
5837	Moroni	39-32	111-35	5525	CE	2.45	3.34
5906	*Mount Baldy RS	39-08	111-30	9500	CE	10.14	13.01
6135	Nephi	39-43	111-50	5133	CE	3.75	4.59
6181	New Harmony	37-29	113-18	5290	SC	5.50	9.56
6357	Oak City	39-23	112-20	5070	CE	3.16	4.70
6601	Panguitch	37-49	112-27	6720	SC	1.70	2.49
6606	*Panguitch Lake RS	37-43	112-38	8320	SC	3.68	5.99
6686	Parowan Apt.	37-51	112-50	5930	SC	3.57	3.10
6708	Partoun	39-39	113-53	4750	C1	1.09	1.50
6729	*Payson RS	39-56	1-1-38	8050	NC	9.89	11.37
6840	*Pine Creek	38-53	112-15	8780	CE	12.83	15.56
7230	*Red Pine Ridge	39-27	111-16	9000	CE	11.17	13.28
7260	Richfield Radio KSVC	38-46	112-05	5270	CE	1.78	2.37
7516	Saint George	37-07	113-34	2760	DX	2.49	4.52
7557	Salina	38-37	111-52	5190	CE	2.50	3.13
7714	Scipio	39-15	112-06	5306	CE	3.36	4.97
7846	Silver Lake Brighton	40-36	111-35	8740	NC	15.00	16.01
8119	Spanish Fk. PH	40-05	111-36	4720	NC	5.04	6.28
8456	Summit	37-48	112-56	5950	SC	3.03	3.72
8733	Timpanogos Cave	40-27	111-42	5640	NC	6.94	9.02
8771	Tooele	40-32	112-18	5070	ET	4.09	5.55
8847	Tropic	37-38	112-05	6280	SC	2.72	4.47
9136	Veyo Power House	37-21	113-39	4600	DX	3.94	6.66
9152	Wah Wah Ranch	38-29	113-25	4960	C1	1.27	1.34
9352	*Webster Flat	37-35	112-54	9200	SC	11.27	18.49
9382	Wendover Autob.	40-44	114-02	4237	C2	.98	1.31
9512	*Widtsoe Esc. #3	37-50	111-53	9640	SC	6.39	9.65
9717	Zion National Park	37-13	112-59	4050	DX	4.66	7.46

* - Storage gage

Group

C1 - Control 1	SC - South Central
C2 - Control 2	DX - Dixie
CE - Central target	EA - Eastern
NC - North Central	ET - East Tooele

In general, the correlation coefficients (Table 2) were good to very good ($> .80$) for most of the target-control relationships, although a few were .73 to .79. They were poorest with the six station control in western Utah (C_1) and improved with both the expanded six station control (C_2) and the combined eleven station control (C_3).

Differences between observed and predicted precipitation increased from north to south in the three sections of the Primary Target area (i.e., Central, South Central and Dixie), and become correspondingly more significant statistically in the southern regions. In general, C_1 provides the greatest and C_2 the least indication of differences. C_3 (the combined control) typically provides an estimate between these two

controls, and often provides the highest statistical significance of the three.

While the indicated results of seeding for each of the sub-sections are important, perhaps the most important aspect is the apparent effect of seeding for the total Primary Target (Table 3, Group 4). The ratio of seeded precipitation to that calculated using C_1 indicates an increase of approximately 20% during the seeded seven year period (January-March from 1974-80). Results could be attributed to chance alone in less than 3 cases out of 100. The ratio determined from C_2 indicates approximately a 13% increase, but the level of significance remains high (.032). The results from the combined eleven station control (C_3) indicate a 16% increase significant at the .01 level.

Table 2. Linear regression equations developed for target areas.

Target Group	Linear Regression Equations		
<u>1) Central</u>			
Low elevation	$Y_c = 1.2 C_1 + 1.19$	$Y_c = .78 C_2 + .8$	$Y_c = 1.08 C_3 + .78$
High elevation	$Y_c = 2.56 C_1 + 5.28$	$Y_c = 1.69 C_2 + 4.41$	$Y_c = 2.3 C_3 + 4.4$
Combined	$Y_c = 1.88 C_1 = 3.24$	$Y_c = 1.24 C_2 + 2.61$	$Y_c = 1.69 C_3 + 2.59$
<u>2) South Central</u>			
Low elevation	$Y_c = 1.86 C_1 - .02$	$Y_c = 1.18 C_2 - .48$	$Y_c = 1.61 C_3 - .99$
High elevation	$Y_c = 4.21 C_1 + 1.55$	$Y_c = 2.66 C_2 + .46$	$Y_c = 3.64 C_3 + .41$
Combined	$Y_c = 2.55 C_1 + .47$	$Y_c = 1.62 C_2 - .21$	$Y_c = 2.21 C_3 - .22$
<u>3) Dixie</u>	$Y_c = 3.28 C_1 - .3$	$Y_c = 2.03 C_2 - 1.07$	$Y_c = 2.8 C_3 - 1.12$
<u>4) Primary Target (Σ1,2,3)</u>			
Low elevation	$Y_c = 1.84 C_1 + .48$	$Y_c = 1.17 C_2 - .02$	$Y_c = 1.61 C_3 - .04$
High elevation	$Y_c = 2.93 C_1 + 4.44$	$Y_c = 1.91 C_2 + 3.52$	$Y_c = 2.61 C_3 + 3.5$
Combined	$Y_c = 2.26 C_1 + 1.98$	$Y_c = 1.45 C_2 + 1.32$	$Y_c = 1.99 C_3 + 1.3$
<u>5) Eastern Tooele</u>	$Y_c = 1.11 C_1 + 3.1$	$Y_c = .65 C_2 + 2.94$	$Y_c = 1.00 C_3 + 2.72$
<u>6) Eastern Supplemental</u>	$Y_c = .74 C_1 + .21$	$Y_c = .48 C_2 - .01$	$Y_c = .64 C_3$
<u>7) North Central Supplemental</u>	$Y_c = 2.07 C_1 + 5.2$	$Y_c = 1.26 C_2 + 4.77$	$Y_c = 1.75 C_3 + 4.71$

where:

- Y_c = Target group calculated precipitation (inches)
- C_1 = Revised control group precipitation (inches)
- C_2 = Expanded control group precipitation (inches)
- C_3 = Combined ($C_1 + C_2$) control group precipitation (inches)

In eastern Tooele county results of five years of seeding were very similar for each control. Computations from both C_1 and C_2 indicated a precipitation increase of approximately 17% in the target during the seeded period, while the results utilizing C_3 were 15%. The significance levels were .04 to .055.

In the Eastern supplemental area ratios of observed to calculated precipitation were high, with reasonably high statistical significance, suggesting a rather strong possibility of a positive extra-area effect in an area normally "downwind" of the primary target area during storm periods. Although indicated seeding effects yield large percentages in this Eastern region, the absolute magnitudes are relatively

small since the normal wintertime precipitation is low.

In the North Central supplemental area ratios of observed to calculated precipitation are greater than one, although they do not approach statistical significance. This region could be affected intermittently by the seeding in either the Eastern Tooele County or northern portion of the Primary Target area.

As indicated in Fig. 3, most of the apparent effects of seeding seem to have occurred during the last three years, although a sizable increase in observed over calculated precipitation is indicated also in 1974. In all, five

Table 3. Summary of correlations, ratios and significance for various sub-sectors of target

Target Group	Correlation Coefficient (r)			Ratio (Yo/Yc)			Statistical Significance (P)		
	C ₁	C ₂	C ₃	C ₁	C ₂	C ₃	C ₁	C ₂	C ₃
<u>1. Central</u>									
Low elevation	.760	.829	.832	1.178	1.113	1.132	.234	.194	.122
High elevation	.730	.804	.798	1.135	1.083	1.106	.070	.178	.055
Combined	.755	.829	.825	1.144	1.086	1.113	.079	.110	.079
<u>2. South Central</u>									
Low elevation	.846	.896	.889	1.360	1.235	1.282	.028	.010	.017
High elevation	.891	.937	.935	1.262	1.173	1.213	.007	.004	.002
Combined	.874	.922	.918	1.303	1.202	1.244	.012	.007	.002
<u>3. Dixie</u>									
	.885	.917	.918	1.329	1.228	1.268	.089	.028	.055
<u>4. Primary Target (Σ1,2,3)</u>									
Low elevation	.883	.935	.934	1.272	1.176	1.210	.055	.032	.015
High elevation	.799	.867	.862	1.162	1.102	1.125	.032	.062	.024
Combined	.852	.913	.910	1.204	1.132	1.161	.028	.024	.010
<u>5. Eastern Tooele</u>									
	.813	.796	.806	1.175*	1.175*	1.155*	.055	.055	.049
<u>6. Eastern (supplemental)</u>									
	.785	.847	.830	1.522	1.399	1.476	.163	.070	.070
<u>7. North Central (supplemental)</u>									
	.758	.774	.780	1.137	1.103	1.117	.314	.273	.272

* Eastern Tooele for five-year period, 1976-80.

of the seven seeded years indicate increases over expected values. Little seeding effect is suggested in the drought years of 1976 and 1977, which had few seeding opportunities due to lack of storminess. The year 1975 also indicates that little seeding effect, for reasons that are not as apparent.

5. CONCLUSIONS

Post hoc analyses using three separate controls to predict target precipitation from three sets of regression equations, while differing in indicated percentage increase, generally agree qualitatively. All indicate that the January-March target area precipitation, 1974-1980 (1976-80 for East Tooele), was greater than that predicted by the regression equations. Some differences between observed and calculated (expected) values were highly significant. In the five-year evaluation, Thompson (1979) noted that the southern portion of the Primary Target had higher ratios which

achieved greater significance than those in the northern portion. This trend has continued through the seven-year evaluation; the indicated increases in the south are about twice those in the north. The southern area indicates statistical significance about one order of magnitude greater than the northern portion, except for Dixie where several seeding suspensions during the last two years, might account for the lower significance level.

Evidence of positive extra area effects continues to appear to the east of the target, but the results are not highly significant. North of the target, an indication of a minor seeding effect, is even less statistically significant than east of the target where carryover effects could be occurring for the last five years, from seeding in Tooele County.

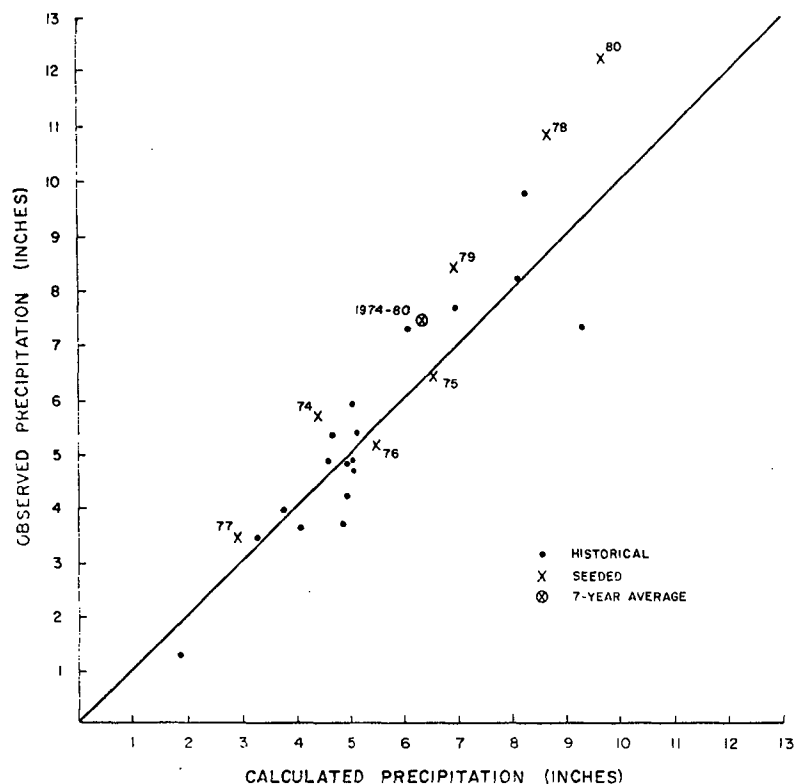


Fig. 3. Comparison of calculated precipitation (based on combined controls, C₁ and C₂) vs. observed January-March precipitation for unseeded and seeded periods, primary target area (low and high elevations combined).

The five-year evaluation (Thompson, 1979) concluded that seeding had increased January-March precipitation within the intended target area of the Utah seeding program. This seven-year evaluation utilizing the revised control and extended area controls corroborates the previous results.

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VARIATIONS IN RAINFALL AND INSURED CROP-HAIL LOSSES ASSOCIATED
WITH OPERATIONAL CLOUD SEEDING IN SOUTH DAKOTA

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Abstract. A brief review of operational cloud seeding programs in South Dakota is given, followed by an evaluation on the basis of rainfall data and insured crop-hail loss data for the years 1948-1978.

All of the projects used silver iodide as the seeding agent, but a wide variety of generator types, seeding rates, and delivery methods was used.

In years with aircraft seeding over small areas, both rainfall and hail damage tended to be larger in target than in non-target counties. The data available do not show such a trend for years when ground-based generators were employed.

In years when 40% or more of the state was seeded, the results for target and non-target counties became indistinguishable in terms of both rainfall and crop hail damage. However, increases in the area included in cloud seeding programs, using either ground based or airborne generators, were associated with an apparent net hail suppression effect, extending over the entire state. The rainfall data do not display such a trend.

1. INTRODUCTION AND HISTORICAL BACKGROUND

This paper summarizes the results of a 3-year investigation into the statistics of summer rainfall and crop-hail losses in South Dakota before, during, and after extensive operational cloud seeding programs in that state. Portions of the work have been reported previously at two scientific meetings (Brown et al., 1979; Dennis et al., 1980).

The investigation has been motivated in part by repeated inquiries from government agencies and private parties about the effects of operational cloud seeding programs in South Dakota. In addition, the data related to the operational seeding appeared to be a potential source of information about seeding effects and the relative merits of different seeding methods.

Cloud seeding in South Dakota has been intended generally to increase agricultural production by moderating certain aspects of the state's harsh continental climate. Crop yields are nearly always limited by available moisture, and are sometimes reduced by hailstorms. The average annual rainfall ranges from over 600 mm (24 in) in the southeast corner of the state to about 300 mm (12 in) in the northwest corner. The Black Hills at the extreme west end of the state have an average annual rainfall of up to 750 mm (30 in) and are forested. Hailstorms are frequent and crop damage (in 1980 prices) averages over \$50,000,000 per year.

There have been a few winter projects in South Dakota, but nearly all of the operational projects

have involved attempts to increase rainfall, suppress hail, or both, during the growing season by seeding cumulus and cumulonimbus clouds with silver iodide (AgI). Information on each project is given in Schock's (1977) summary of weather modification activities in Minnesota, North Dakota, and South Dakota. Project reports, newspaper clippings, and correspondence about the projects are available in the Bruce Collection, which was donated to the Devereaux Library, South Dakota School of Mines and Technology, by the family of the late M. N. Bruce, first chairman of the South Dakota Weather Control Commission.

All of the operational seeding in the 1950's was by ground based AgI generators. Most of the projects were conducted by the Water Resources Development Corporation (WRDC) using generators burning coke pellets impregnated with AgI (e.g., Krick, 1952). Each generator consumed only a few grams of AgI per hour. The WRDC generators were widely scattered. For example, newspaper accounts indicate that one project covering several counties in the west central part of the state was served by a network of about 25 generators located throughout western South Dakota and adjacent parts of North Dakota, Montana, Wyoming, and Nebraska. A competing firm used acetone generators charged with AgI-NaI solutions on one project in northwestern South Dakota in 1952 and 1953 (e.g., Battle et al., 1952). From personal knowledge gained subsequently as an employee of that company, the senior author estimates AgI consumption on that project at 10-20 g per generator hour.

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Nearly all of the operational projects after 1960 used aircraft seeding. The first seeding aircraft were equipped with acetone generators, AgI-NaI solution was used in many, if not all, of the early projects. Some of the operators switched to AgI-NH₄I solution about 1970 in the hope of obtaining higher ice nucleating efficiency at temperatures just below 0°C. Consumption rates varied from perhaps 100 to 400 g per generator hour. Many aircraft were equipped with two wing-tip mounted generators, and it became a common practice to operate both simultaneously for hail suppression.

Some of the earliest aircraft seeding missions involved cloud penetrations around the -5C to -10C levels. There seems to have been an impression among the seeding pilots that in-cloud seeding was more effective than seeding below cloud base. However, safety considerations caused most seeding of intense convective storms, especially seeding for hail suppression, to be conducted from below cloud base.

A state-supported program was operated from 1972 through 1975. The seeding was conducted entirely from aircraft. The seeding pilots were guided by radioed instructions from radar equipped field offices. The aircraft carried generators charged with AgI-NH₄I solution; AgI consumption rate varied from 150 to 300 g per generator hour (e.g., Williams, 1973). Pyrotechnic devices capable of consuming 200 g or more of AgI per minute were also provided for hail suppression attempts. A detailed strategy evolved to guide the seeding operations (e.g., Williams, 1974). Hail suppression was the primary objective whenever a hail threat was considered to exist. At other times, promising cloud formations were seeded to increase rainfall. Seeding was generally done from below cloud base, but cumulus congestus and stratiform clouds were sometimes seeded near the -5C level to initiate precipitation.

Individual counties had the option of participating or not participating in the state-supported program on a cost-share basis. Figure 1 shows the participating counties in 1972, the first year, and in 1974, the year of maximum participation.

The state program was not renewed for 1976, but two projects were operated by groups of counties with some state support. Mewes (1977) has described the history of cloud seeding in South Dakota from a sociological point of view, with particular reference to the organized opposition which caused the state legislature to withdraw financial support from the state program in 1976.

Seeding in 1977 and 1978 was conducted only in Harding County, which is in the northwestern corner of the state. It was conducted by aircraft operating with guidance from radar meteorologists at the Bowman field office of the North Dakota Cloud Modification Project.

In addition to the operational projects, South Dakota has been the site of several experimental cloud seeding projects. Most of the experimental seeding occurred in the western part of the state from 1964 through 1972 as part of the U.S. Department of the Interior's Project Skywater. It involved a variety of seeding agents, but AgI was by far the most commonly used (Dennis *et al.*, 1974). The only experimental seeding after 1972 was the seeding of a few heavy cumulus over the Black Hills with an organic agent, 1,5 dihydroxynaphthalene, in the summer of 1974 (Fukuta *et al.*, 1975).

2. PREVIOUS EVALUATION ATTEMPTS

There have been a number of attempts at evaluation of operational cloud seeding projects in South Dakota.

In the 1950's, the Water Resources Development Corporation distributed reports showing rainfall accumulations during ground-generator operational periods as percentages of monthly normals. They also made some use of control areas and historical analogues of seeded storms in an attempt to sharpen the evaluation of WRDC projects (Krick, 1952). Todd used the historical target-control regression method to evaluate a 1952 project using ground-based acetone generators in the northwestern part of the state (Battle *et al.*, 1952). The Final Report of the Advisory Committee on Weather Control contains "An Evaluation of Commercial Cloud

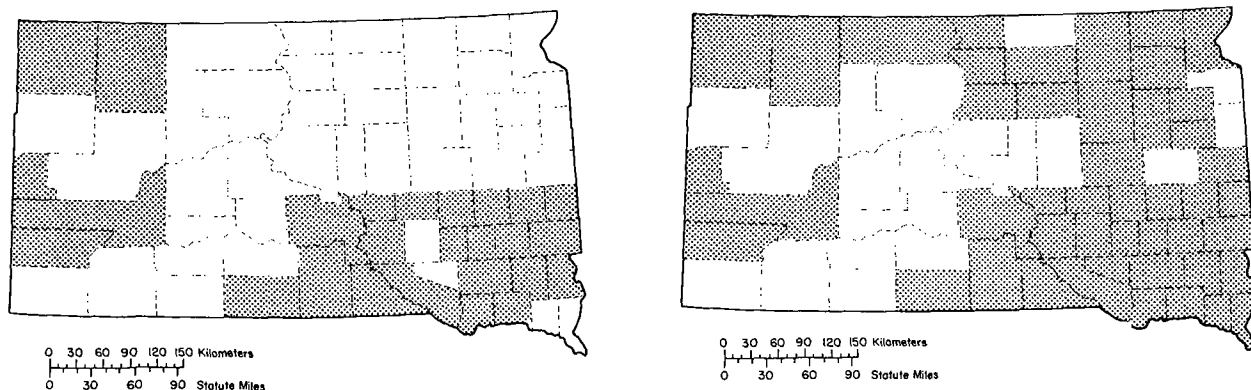


Fig. 1: South Dakota counties participating in state supported cloud seeding program, shaded; (a) 1972; (b) 1974.

Seeding Operations Conducted During the Summer Months in South Dakota," (Berndt, 1957). However, it presents proposed methods for determining changes in rainfall and possible associated economic benefits, rather than an actual evaluation, because Berndt believed that the data available to him were too scanty to sustain any conclusion about seeding effects.

Bruce performed some unpublished evaluations, mostly involving target-control comparisons, of early seeding projects.² Boyd (1972) examined a sample of seven aircraft seeding projects. Two of them were designed to suppress hail as well as stimulate rainfall; the other five were for rain increase only. Boyd found tentative indications of substantial rainfall increases, but no evidence of effects upon hailfall in the two hail suppression projects.

Brown *et al.* (1969) examined rainfall downwind of several projects in both North Dakota and South Dakota in a search for large-scale seeding effects. They found inconclusive evidence that rainfall per storm increased with the advent of seeding programs.

Staff members of the state Division of Weather Modification made some use of target-control evaluations. In one study, Donnan (1973) evaluated the effects of individual seeding flights with floating targets immediately downwind and controls immediately upwind of seeding tracks. The present authors consider that method subject to bias, because cloud systems were selected for seeding only if they looked promising and, in any event, were generally moving eastward toward regions with larger natural rainfall.

Miller *et al.* (1976) and Pellett *et al.* (1977) compared the insured hail loss data and the rainfall data, respectively, for the target and non-target counties for the period 1972-1975. Both groups of authors considered the years prior to 1972 as essentially unseeded years. They used data from those years in permutation tests to establish p-values for differences between target and non-target counties for the years 1972-75. Recognition of the need to overcome this shortcoming of the analysis by Miller *et al.* (1976) was one of the reasons for undertaking the present study.

3. DATA BASE FOR PRESENT STUDY

3.1 General Remarks

The evaluation required data pertaining to the seeding, to the rainfall, and to crop-hail damage, which were obtained from, respectively, the report by Schock (1977), the National Climate Center (NCC), and the Crop-Hail Insurance Actuarial Association (CHIAA). The hail reports are therefore weighted by those townships within each county that had the most insured crops; a few townships in the western end of the state never had any insured crops at all during the period under investigation. Although factors other than hail intensity affect hail insurance payouts, the usual climatological data are completely inadequate to characterize hail occurrences on an annual basis.

As most of the operational projects ran during the spring and summer, the analysis was limited to

data for the months of May through August only (hereinafter called the growing season). For reasons to be discussed below, the study was further limited to data from the 31-year period of 1948 to 1978, inclusive. Because most of the seeding projects were organized by counties, the data for the evaluation were organized in the same way.

3.2 Seeding

The fraction of the area of South Dakota covered by both operational and experimental cloud seeding each year during the growing seasons of 1948 through 1978 is shown in Table 1, which is from Dennis *et al.* (1980).

The fractional coverage was estimated taking into account, with appropriate weighting, such factors as the inclusion of a county in a project for only a part of a season. The peculiarities of each experimental project, for instance, the limitation of seeding to daylight hours only, or to days selected in accordance with a randomization scheme were also considered.

The operational projects were classified initially according to stated objective (rain increase or hail suppression), number of Ag1 generators per unit area, availability of weather radar, and so on. Preliminary analyses of the resulting data sets led nowhere. The only classification retained was the distinction between ground-based and aircraft operations (Table 1). The "Type of Seeding" listed in Table 1 applies to operational seeding only, even though the "Fraction of State Seeded" reflects all types of seeding. Only one year (1968) had operational projects of both types. It is represented in Table 1 and in some figures below by two entries (Dennis *et al.*, 1980).

3.3 Rainfall and Hailfall Data

As noted above, rainfall and hail damage data were obtained from NCC and CHIAA, respectively. The analysis was limited to years from 1948 onward to avoid the extreme drought years of the 1930's, and because of apparent improvements in the compilation of hail statistics just after World War II.

The county-year was adopted as the basic unit for study. As South Dakota has 67 counties and the period under study was 31 years, the decision implied that there would be 2077 sample values for each variable chosen for study. However, counties that were only partly seeded or were seeded experimentally in a given year were dropped from the analysis, which reduced the basic data set to 1990 values for each variable studied. Some other data were missing due to a county not having a rain gage operating in a given year or due to a lack of CHIAA insurance records.

The basic rainfall statistic for each county year is the average growing season rainfall, which is the arithmetic average of the rainfall recorded at the climatic stations in the county during May through August.

The basic hail damage statistic chosen for analysis was the loss-cost ratio, which is the

²Available in the Bruce Collection, Devereaux Library, South Dakota School of Mines and Technology.

TABLE 1: Type of seeding, fraction of state seeded, and mean ranks for non-target and target counties by years

Year	Type of Seeding*	Fraction of State Seeded (%)	Mean Rainfall Rank		Mean Loss-Cost Rank	
			Non-target	Target	Non-target	Target
1948		0	24.1		15.3	
1949		0	8.9		12.3	
1950		0	8.5		14.3	
1951	G	38	24.1	21.4	12.0	12.2
1952	G	36	12.5	16.0	12.8	12.8
1953	G	33	21.9	23.6	14.6	12.4
1954	G	26	16.8	18.5	11.8	7.4
1955		0	14.6		18.3	
1956	G	6	20.1	14.2	24.8	24.0
1957	G	6	20.9	18.9	17.4	18.7
1958		0	12.4		14.6	
1959	G	8	7.7	4.4	17.2	22.5
1960		0	17.8		17.2	
1961		0	11.4		17.3	
1962	A	11	26.1	27.9	18.2	19.3
1963	A	8	23.1	28.2	18.6	23.6
1964	A	8	18.1	19.0	16.8	20.9
1965	A	8	13.9	22.8	16.3	19.4
1966	A	12	20.8	26.0	15.3	18.0
1967	A	18	18.7	19.0	16.9	21.7
1968	G	20	21.5	13.2	19.6	16.0
1968	A	20	21.5	25.0	19.6	24.8
1969	A	9	17.5	14.1	21.4	22.3
1970	A	11	7.3	4.7	19.7	11.6
1971	A	14	12.9	9.5	13.4	18.5
1972	A	35	14.8	17.9	17.4	11.6
1973	A	56	4.5	4.7	11.6	11.3
1974	A	63	9.6	8.2	11.9	13.7
1975	A	58	17.7	17.9	12.2	11.0
1976	A	21	8.3	10.9	13.6	15.0
1977	A	4	17.2	18.5	18.3	31.0
1978	A	4	18.9	25.5	16.0	18.0

*G = ground

A = aircraft

arithmetic average of the rainfall recorded at the climatic stations in the county during May through August.

The basic hail damage statistic chosen for analysis was the loss-cost ratio, which is the ratio of losses paid out throughout the county each year to the total insured liability. We compared it to other possible response variables, such as the fraction of the townships in a county reporting hail damage, and found them to be closely correlated. The need for a response variable other than the actual hail damage claims paid is obvious from Fig. 2, which shows the total insured liability as well as the loss-cost ratio calculated for the state as a whole. The loss-cost ratio suppresses variations due to changes in cropping patterns, prices, and insurance-buying practices, although some uncontrolled variations due to these factors may well remain.

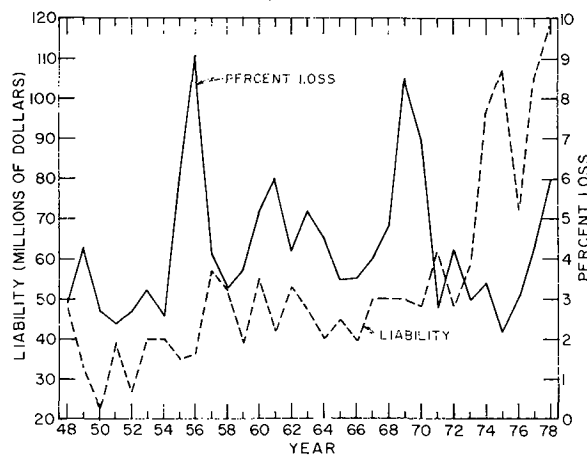


Fig. 2: Insurance liability (dashed line) and loss-cost ratio in percent (solid line) for the State of South Dakota, 1948-1978, inclusive.

3.4 Use of Ranks

The western part of South Dakota is drier and more prone to hail than is the eastern part. Miller *et al.* (1976) had to divide the state into five regions to obtain statistical homogeneity of hail loss-cost ratios.

One part of the analysis given below compares events in target and non-target counties. The climatological variations could lead to erroneous indications of seeding effects due simply to a concentration of target counties at one end of the state or the other. For that reason, the actual rainfall and loss-cost ratio for each county year have been replaced by ranks, which are a measure of how wet (or how hail-prone) the year in question was in that county compared to the other 30 years in the data sample. The ranks thus obtained are referred to below as rainfall and hail loss ranks, respectively. Increasing ranks are indicative of increasing average rainfall and of increasing loss-cost ratio.

4. EXAMINATION OF STATEWIDE TRENDS

The designs of the operational programs did not specify any evaluation methods. Therefore one is free to choose any reasonable approach. Each statistical approach implies the acceptance, perhaps unconsciously, of a corresponding model of how seeding changes precipitation, and is a test of whether or not that model was applicable to the particular situation under investigation. Failure to detect a seeding effect according to one model does not prove that no effect exists, so curiosity leads one to analyze the data again and again, assuming a different model each time. In doing so, one must remain alert to the hazards associated with multiplicity in statistical approaches to a data set.

A very simple approach is to consider the response of the state as a whole to the presence of cloud seeding projects. Figure 3 shows the mean of the rainfall ranks and the mean of the hail loss ranks for the individual counties for each year from

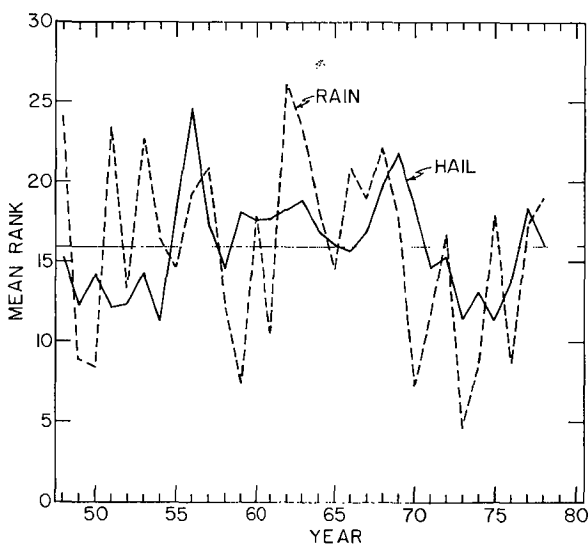


Fig. 3: Mean rainfall rank and mean hail loss rank, 1948-1978, inclusive. A rank of 16 is the expected value in both cases.

1948 through 1978. The mean rainfall rank and mean hail loss rank are independent of each other for this data sample. The correlation coefficient for the two variables is 0.3, which is not significantly different from zero at the 95% confidence level. Hail losses were low during the early 1950's and the middle 1970's, two periods with extensive operational projects. The question immediately arises whether the low hail losses were due to seeding or to natural climatological variations.

The mean rainfall rank and mean hail loss rank for each year are plotted against the fractional coverage by cloud seeding projects in Fig. 4 and Fig. 5, respectively. There is no significant correlation between mean rainfall rank and fractional coverage by seeding projects. The significant negative correlation ($r = -0.72$) between mean hail loss rank and fractional seeding coverage leads us to draw a regression line as shown on Fig. 5. While the regression line of Fig. 5 shows the mean hail loss rank decreasing as cloud seeding projects become more widespread, the points at the left show that the mean hail loss rank was higher for years when a small part of the state was seeded than when

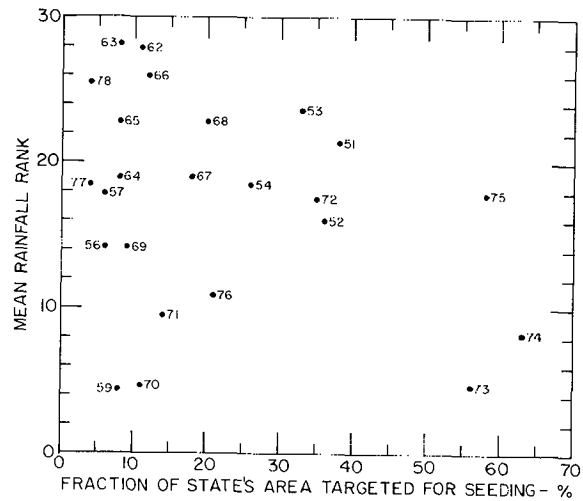


Fig. 4: Mean rainfall rank vs. fraction of the state's area targeted for seeding, 1948-78.

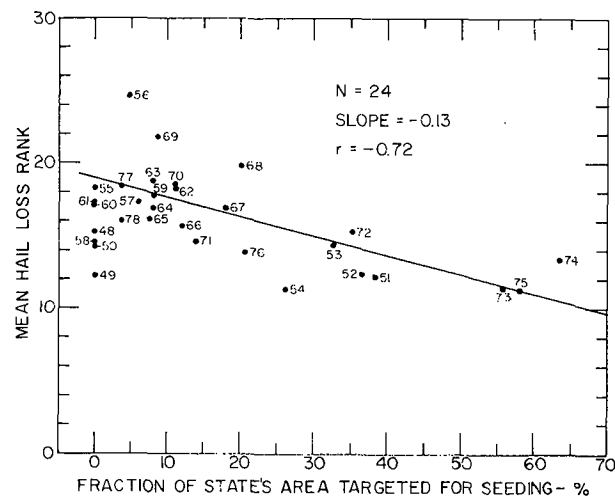


Fig. 5: Mean hail loss rank vs. fraction of the state's area targeted for seeding, 1948-78.

no seeding was done at all. [The correlation coefficient and regression line of Fig. 5 were calculated with the non-seeded years omitted.] This point is discussed in Sec. 5.

In the present study, we have not used control areas from outside South Dakota to evaluate state-wide trends. This is a possibility for future investigations of seeding effects upon rainfall, but not as likely for determining effects of seeding upon hail. Wang (1976) found the correlation between hail losses in South Dakota and large parts of neighboring states to be generally small; the best correlations, around 0.7, were found between parts of northeastern South Dakota and parts of southwestern Minnesota, and between southeastern South Dakota and northwestern Iowa.

5. COMPARISON OF EVENTS IN TARGET AND NON-TARGET COUNTIES

A comparison of events in target and non-target counties is meaningful if one assumes that:

- 1) the effects of seeding are limited to (or at least concentrated in) the target counties; and
- 2) there are significant correlations between precipitation in target and non-target counties.

For this study, we have ignored county-years involving partial seeding or experimental seeding. The mean rainfall ranks and mean hail loss ranks for years with operational seeding are shown for target counties (with full operational projects) and non-target counties (with no seeding whatever) in Table 1. Years without operational seeding have no entries under target counties, but entries are provided for non-target counties.

The rain and hail loss ranks for target and non-target counties during years with operational projects are compared in Figs. 6 and 7, respectively.

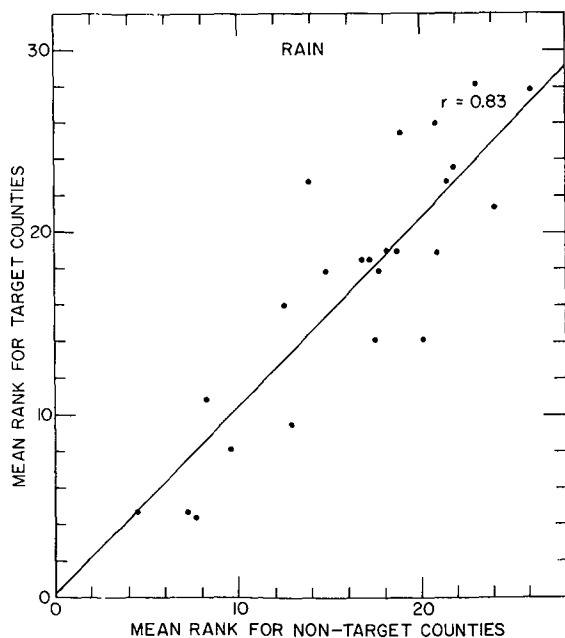


Fig. 6: Scatter diagram of mean rainfall rank for target counties vs. mean rainfall rank for non-target counties.

The correlation coefficient of the mean rainfall ranks is 0.83, while that for the mean hail loss ranks is 0.64. Both coefficients are statistically significant and justify use of ranks in non-target counties as controls or predictors of the corresponding ranks in target counties. However, because the target counties shifted about from year to year, there is no obvious way to apply the historical regression method. We have therefore adopted simple comparisons, in which a mean rank for non-target counties is accepted as a first estimate of what the corresponding mean rank for the target counties would have been without seeding.

The mean ranks shown in Table 1 for target and non-target counties have been compared to yield the counts shown in Table 2. In 16 of the 25 operational seasons, the average rainfall rank in the target counties exceeded that in the non-target counties. The hail loss ranks were in nearly the same proportion. Assuming a 50% probability that a mean rank for the target counties would exceed the corresponding mean rank for the non-target counties, a draw of 16 to 9 or greater could easily happen by chance. That is, there is no evidence of a net seeding effect under this model.

Distinguishing between ground generator and aircraft seeding leads to a different result (Table 2). The eight ground seasons show no evidence of differences in rainfall or hail losses between target and non-target counties. However, for both rain and hail, 13 of the 17 aircraft seasons yielded a higher average rank in the target counties than in the non-target counties. [The sets of years involved are not identical.] The probability of drawing 13 or more positive results out of 17 is 0.025. This analysis suggests that operational aircraft seeding in South Dakota from 1962 to 1978 tended to increase both rainfall and hail losses. One should not assume that that was the net result, because the analysis gives equal weight to years like 1963 (8% of state seeded) and 1974 (63% seeded). However, the indication of

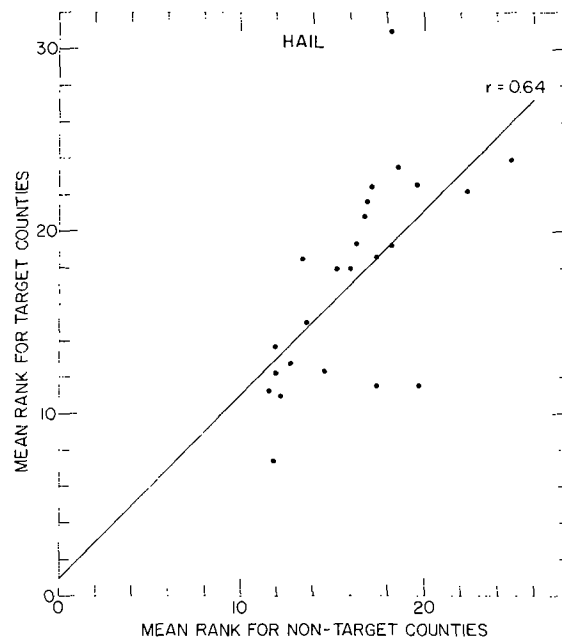


Fig. 7: Scatter diagram of mean hail loss rank for target counties vs. mean hail loss rank for non-target counties.

TABLE 2: Distribution of operational seasons in terms of whether mean ranks for target counties were higher or lower than mean ranks for non-target counties

	Rainfall			Hail Loss Cost		
	Ground	Aircraft	Total	*Ground	Aircraft	Total
Mean Target Rank Higher	3	13	16	3	13	16
Mean Target Rank Lower	5	4	9	4	4	8
Total	8	17	25	7	17	24

*One season (1952) was a tie.

increased hailfall in target counties on certain years merits a closer look, especially as it is consistent with the indication in Fig. 5 that seeding of small areas might have led to increased hail for the state as a whole.³

When mean ranks are computed with reference to the target counties only, the regression line on the scatter diagram relating mean hail loss rank to fractional seeding coverage for the state (Fig. 8) has a more negative slope than in the case where non-target counties were included (Fig. 5). The indication of increased hail associated with seeding of small areas is accentuated by limiting attention to the target counties.

Figures 9 and 10, which combine essentially all of the data presented to this point, indicate

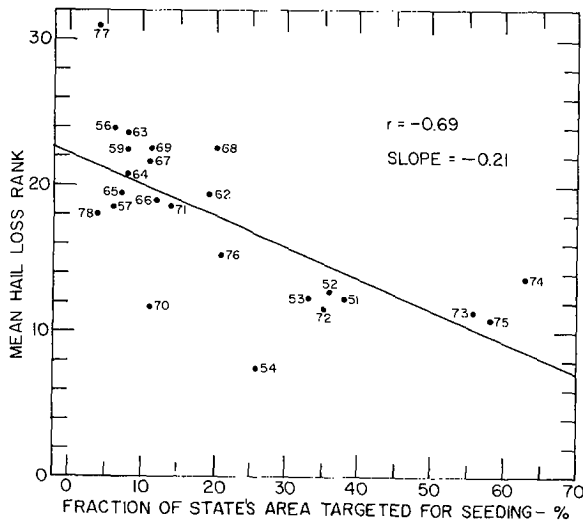


Fig. 8: Mean hail loss rank for target counties vs. fraction of state's area targeted for seeding.

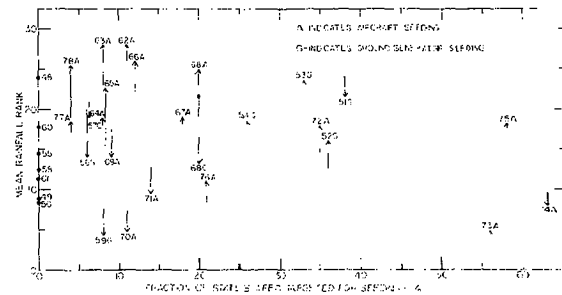


Fig. 9: Mean rainfall ranks in target and non-target counties. [Head of arrow shows mean rank in target counties; tail shows mean rank in non-target counties; G indicates ground generator seeding; A indicates aircraft seeding.]

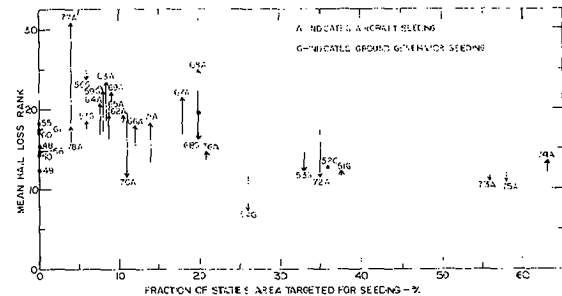


Fig. 10: Mean hail loss ranks in target and non-target counties. [Head of arrow shows mean rank in target counties; tail shows mean rank in non-target counties; G indicates ground generator seeding; A indicates aircraft seeding.]

³The analysis includes projects for which hail suppression was not the announced goal. However, it seems that results of all projects should be evaluated in terms of both rain and hail.

that little or no difference in average ranks for target and non-target counties can be demonstrated once the fraction of the state targeted for seeding reaches 40%. Of course, the longer arrows on the left side of Figs. 9 and 10 reflect the greater natural variability of precipitation in small areas, as well as the possibility of differences between seeding effects in target and non-target counties. However, this variability does not account for the fact that most of the arrows on the left side point upward (as they must, to agree with results given above).

We conducted one more study, a permutation test on the hail data in which results were compiled for individual counties, and the years 1972-75 inclusive (the state program) were identified as a special subset of the years with aircraft projects. The procedure for comparing hail damage in a given county (A) to that in any other county (B) was as follows:

- 1) Calculate the hail loss rank difference (A-B) for each year when County B was not in a seeding program. The years when County B was seeded are considered as missing.
- 2) Using the Mann-Whitney two-sample rank test, compare the differences for years when County A was in a seeding program (of specified type) to the differences for years when County A was not in a seeding program of any type. Calculate the resultant p-value, using the convention that the p-value increases as the results shift in a direction favorable to County A when it is seeded.

The steps were repeated until County A had been compared to all other counties, at which point an average p-value was computed for County A. The entire process was repeated for all counties that had ever been included in a seeding project of the type under investigation.

The average p-values for individual counties vary widely, but their median holds close to its expected value of 0.50 (Table 3 and Fig. 11). The binomial probabilities for the observed departures of the medians from 0.50 (assuming the average p-values to be independent) are included in Table 3. That for the "Air 1972-1975" category (0.003) indicates a systematic difference between the hail loss tendencies in the target and non-target counties

during the years 1972-75 [Fig. 11(b)], but the binomial probability of 0.003 should not be taken at face value as a test of statistical significance because the events in neighboring counties are not completely independent. There are no significant differences for the other categories.

The statistical analyses described above are, in general, rather unusual and have not been subjected to rigorous theoretical inquiry. Certain assumptions may pose problems. While the non-parametric nature of the analyses and the use of permutations should minimize such problems, the possibility of problems should still be kept in mind while interpreting the results.

6. SUMMARY AND INTERPRETATION OF RESULTS

The results of the various tests described to this point can be summarized as follows:

- 1) For the state as a whole, hail loss decreased as the fraction of the state targeted for seeding increased. However, when small areas were seeded, hail was worse there and, hence, for the state as a whole than on years when no seeding was done at all.
- 2) Aircraft seeding was associated with increased rainfall and hail loss in target counties as compared to non-target counties.
- 3) Seeding with ground generators has not produced a detectable difference between target and non-target counties.
- 4) During the state program of 1972-75, hail losses in target counties tended to be less than in non-target counties.
- 5) Results for target and non-target counties were not distinguishable in years when the fraction of the state targeted for seeding exceeded 40%.

The overlap among the various data sets makes it impossible to sort out the various effects in an unequivocal fashion. Further subdivision of the data sets, for example, to consider the effect of ground generator seeding directed at small target areas, is not feasible because of sample size limitations. However, by considering these results in the light of those from other cloud seeding operations and experiments on convective clouds, both in South Dakota and elsewhere, some tentative conclusions can be drawn.

TABLE 3
Summary Statistics for Average P-value Samples

Type of Program	Number of Counties	Mean	Standard Deviation	Median	Binomial Probability
Air + Ground	59	0.50	0.18	0.504	0.30
Ground	33	0.50	0.17	0.526	0.15
Air (All)	51	0.52	0.18	0.504	0.29
Air (1972-1975)	50	0.57	0.15	0.557	0.003

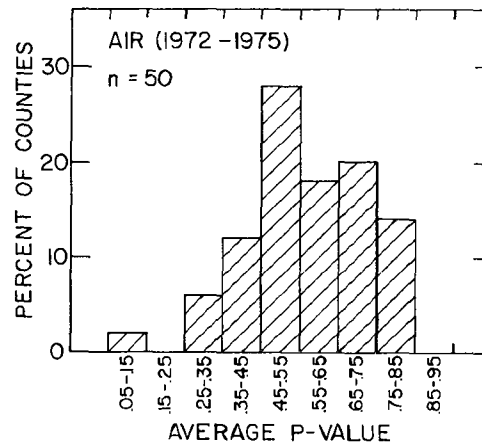
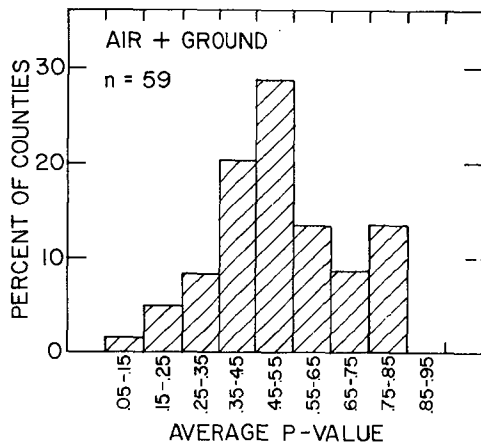


Fig. 11: Distribution of average p-value from comparison of each target county with all non-target counties individually.

Examination of the points in Fig. 9 shows that the generally favorable rainfall result for aircraft seeding (Table 3) is in fact due to projects involving small target areas. The indication that aircraft seeding increases rainfall from convective clouds in small target areas is in line with observations from randomized experiments in South Dakota (e.g., Dennis et al., 1974) and elsewhere, and with the expectations of the project sponsors. It therefore requires no additional comment here.

The rather clear-cut indication that aircraft seeding over small areas has been associated with more hail rather than less in the target counties is surprising. An apparent increase in hail has been observed before in aircraft seeding of single storms or of all storms over small areas (Schleusener and Sand, 1964; Atlas, 1977; Wong and Chidambaram, 1979), but has never been considered statistically significant.

Seeding over larger areas has not given a clear signal on rainfall but appears to have suppressed hail, primarily in the target counties, but in non-target counties as well. The indication that results in target counties become indistinguishable from those in non-target counties once seeding projects expand to cover about half of the state is very reasonable. Especially in 1973-75, the non-target counties constituted isolated pockets (Fig. 1b). As the seeding aircraft often intercepted and seeded approaching storms over non-target counties (Mewes, 1977), and seeding effects are commonly believed to extend some tens of miles downwind from the point where seeding is stopped (e.g., Brown et al., 1969), it is reasonable to think that, for practical purposes, the whole state was seeded during those three years. It was only in 1972, when the northern half of the state was mostly unseeded (Fig. 1a), that a clear-cut distinction between target and non-target counties appeared (Figs. 9 and 10). Therefore the analysis presented in Table 3 appears to have been "carried" by the 1972 results. A rerun of the permutation program for the years 1973-75 only showed no significant difference between target and non-target counties ($P(H_0) = .53$), although the small sample size would have made it hard to demonstrate an effect in any case.

The spreading of seeding effects into non-target counties may explain why ground-generator seeding programs did not produce detectable differences between target and non-target counties. Presumably, targeting is more difficult in the case of ground generator programs than in aircraft seeding programs. This would be especially important as four of the eight seasons with ground generator programs had extensive target areas covering about one-third of the state's total area.

The data provide no indication of seeding effects upon rainfall when a large part of the state is seeded. The low mean rainfall ranks of 1973 and 1974 cannot be attributed to seeding because a large-scale drought affected much of the Great Plains during the mid-1970's. In view of the spread of seeding effects into non-target counties, only the selection of control areas outside South Dakota could provide an analysis with the necessary sensitivity to detect and evaluate the possible effect.

The mean hail loss rank stabilized around 12 in target counties when seeding coverage exceeded 25%, and around the same value over the whole state when seeding coverage exceeded 40%. Computer simulations indicate that a uniform 10% reduction in hail loss reduces the mean hail rank by approximately one unit. Therefore, a reduction in mean hail loss rank to 12 from the expected value of 16 could be due to a uniform reduction of roughly 40% in hail losses. It is not likely, though, that a hail loss reduction would occur in such a uniform fashion. The apparently favorable hail experiences of the early 1950's and mid-1970's could also be due to natural causes, but the lack of any correlation between mean hail loss rank and mean rainfall rank for each year argues against attributing the relatively low hail losses of 1973-75 to the dry conditions prevailing in those years.

7. COULD TARGET SIZE AFFECT RESULTS OF HAIL SUPPRESSION?

The most puzzling aspect of the whole study is the indication that seeding over large areas tends to suppress hail, even though aircraft seeding in small areas was associated with local increases in hail.

The difference in results between the small-scale aircraft projects of the 1960's and the state program of the 1970's could be due to the use of better equipment and seeding techniques during the state-run program. However, this hypothesis does not explain either the apparently favorable hail results from ground generator seeding in the 1950's or the evidence of hailfall increases associated with radar-directed aircraft seeding for hail suppression over a single county in 1977 and 1978. We should be alert to the possibility that the size of the target area matters, perhaps through its impact on the conduct of an operation, or perhaps for more fundamental reasons.

There are precedents for thinking that seeding effects could vary with the size of the target area. Randomized trials to test hail suppression methods on single clouds or small areas have nearly always suggested increases in hail, rather than the anticipated decreases (e.g., Schleusener and Sand, 1964; Schmid, 1967; Atlas, 1977; Wong and Chidambaram, 1979). On the other hand, Changnon (1977) assembled data from several large-area projects, including one randomized project and several operational ones, that provided evidence of net hail suppression effects from AgI seeding from aircraft. Dennis and Schock (1971) noted a general tendency for hail in the vicinity of the randomized crossover Rapid Project to be lighter on days when the project was operational than on days when it was not, even though on each operational day the seed target area tended to receive more hail than the no-seed one. The South Dakota situation bears a resemblance to that in Alberta, where randomized trials have failed to show any reduction in hailfalls from storms seeded by aircraft but where, nevertheless, loss-cost ratios have been consistently smaller throughout the seeded areas during years with seeding than during years without it (Wong and Chidambaram, 1979). The scientists responsible for evaluating the Alberta seeding have pointed out that the year-to-year variations might be due to natural causes or industrial pollution (e.g., Goyer and Renick, 1979), but attributing the observed effects to one or the other of those possible causes rather than to cloud seeding is a judgment call.

One can suggest mechanisms by which AgI seeding could increase local rainfall and hail, and simultaneously suppress hail and, possibly, rain some miles away (e.g., Brown et al., 1969; Dennis and Schock, 1971). However, in view of the wide range of combinations of possible effects and the impossibility of sorting them out on the basis of the data in hand, we shall not pursue that topic. We simply note that, until the matter is resolved, the results of small area experiments like the National Hail Research Experiment can hardly be accepted as a reliable guide to the effects of operational programs covering much larger areas.

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WEATHER MODIFICATION ACTIVITIES IN TAIWAN, 1951-1978

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Abstract. Weather modification in Taiwan has been going on for more than 20 years, which makes it one of the longest continuously running operation projects in the world. The three goals of the program are enhancement of precipitation for hydroelectricity, agriculture, and drought-relief. Evaluation efforts using simple least squares regression indicate a 44% increase. Recent aircraft seedings to relieve short droughts aroused considerable public interest.

1. INTRODUCTION

The first modern effort to modify weather in Taiwan occurred on the 22nd of January, 1951, when the Taiwan Power Co. (TPC) began experiments using aircraft to dispense dry ice and a colloidal silver iodide solution into clouds to increase the rainfall over the Sun Moon Lake area, the largest reservoir for hydroelectric power generation in Taiwan. In April, 1952 the Rain Stimulation Research Institute of Taiwan (RSRIT) was established under the auspices of TPC, with support from the Chinese Petroleum Corporation and the Central Weather Bureau. Since then RSRIT has been the major organization responsible for conducting weather modification activities in Taiwan.

Ground generators were the major delivery systems from the winter of 1952 to 1978, except in 1951-1952 when only aircraft were used for seeding experiments (22 flights), and in 1977-1978 when aircraft were used to relieve drought spells temporarily. Balloons carrying dry ice into clouds were used in the springs and summers of 1956, 1959-1967, and 1970 along the western coast, mainly at Tainan (Fig. 1), for a total of 113 station days. Four hundred forty kg of dry ice were used. Ground generators were operated by local people, usually ranchers or power lines maintenance personnel, through telephone or telegraphic instructions from operation head quarters according to the weather conditions. On the average, generators were operated for a duration of 2.0-2.7 hours (Shieh, 1956; Tau, 1958; Lin, 1961; Lin, 1962; Lu, 1966; Lu, 1972; Lu, 1978).

Charcoal impregnated with 1% silver iodide was burned at the rate of 2.5-3.0 kg per hour. The decision to use impregnated charcoal was based on laboratory studies (Shieh, 1956), which compared the effectiveness of various silver iodide and lead iodide in charcoal, acetone solution, colloidal solution and water solution. The original generator was first modified in the spring of 1963, the result being that the smoke outlet was moved from the top to the middle of the three sides so as to reduce the outlet temperature. In 1966, the outlet was placed back on top, this time using better materials (Lu, 1966).

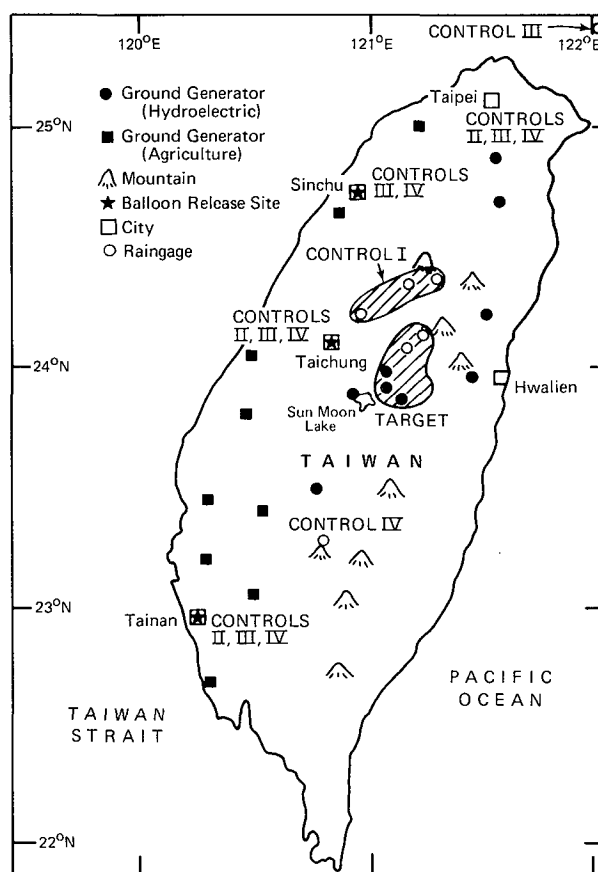


Figure 1. Locations of the Target and Control areas in evaluating the rainfall enhancement project around the Sun Moon Lake area.

2. THREE GOALS

The main goal of weather modification activities in Taiwan has been to increase precipitation for three subgoals: The first and the main thrust has been to increase the rainfall on the upstream areas of rivers which supply the

water for generating hydroelectricity. Cloud seeding has been conducted mainly in the upstream areas of the Ta Chia and Cho Suay Rivers, both in central Taiwan, in the winters (November to March) of 1952-1959 and in all seasons from 1960 to 1979. After 1963, the beginning of the major "operational" phase of weather modification caused a substantial increase in generator operation time (Fig. 2).

The second subgoal has been to increase rainfall for agricultural usage, usually initiated by the Taiwan (Provincial) Food Bureau and conducted by RSRIT. The Taiwan Food Bureau is the main organization in Taiwan responsible for overseeing the production and distribution of grains and rice and has a keen interest in the supply of irrigation water. Ground generators in the western coastal plains (Fig. 1) operated mostly in the spring and summer from 1959 onward. The agriculturally oriented generator operations in this period are also shown in Figure 2. In addition, seeding experiments using balloons to carry dry ice into convective clouds were implemented along the western coast (Fig. 1).

The third subgoal has been to relieve short drought spells, partly for agricultural irrigation water and partly for municipal water supply. The effort devoted to the achievement of this subgoal was relatively sparse, occurring mainly in the spring of 1977 and the summer of 1978. Aircraft were used to deliver dry ice and saturated salt water into clouds from cloud top levels.

3. GEOGRAPHY AND CLIMATE

The island of Taiwan is 200 km southeast of mainland China and 1200 km southwest of Japan. It

is inside the rectangle (120°E, 122°E) x (22°N, 26°N) and has an area of 36,000 km². About 80 mountains with altitudes over 3,000 m: spreading from north to south along the Central Mountain Range exert substantial influence on the movement of weather systems and on local weather conditions. Major rivers flow westward into the Taiwan Strait. The island is surrounded by the Pacific Ocean, East China Sea, and South China Sea, which have tremendous impacts on the climate. The majority of the population resides along a strip of plains on the western coast, where most of the agricultural activities are conducted.

In general, the winter season (November to April) in Taiwan is relatively dry. Nearly continuous light rains fall in the northeastern part of the island, while rainfall on the western coast, where most power plants' reservoirs are located, can be best described as sparse. Steep slopes and the very short lengths of rivers further restrict the available water supply in winter. This dryness is reflected in the typically very low levels of reservoirs maintained by hydroelectric power plants.

When the dominant Mongolian high in the winter moves southeast toward Taiwan, it is intercepted by the Central Mountain Range. Upper air wind direction of this high is forced to switch from northwest to west. The moisture picked up when passing over the oceans is also forced to rise, thus creating favorable conditions for seeding using ground generators in the mountains. Seedings were carried out mainly when high pressure prevailed over mainland China, and when this high's front or upper trough approached Taiwan. The winter average freezing level aloft is 3,700 m (Lu, 1978). Most precipitation is in the form of rain, although the peaks get some snow.

Rainfall brought by typhoons becomes a major source of water supply in July, August, and September, so the need for cloud seeding in summer is not as urgent as in winter. Weather conditions in May and June are rather favorable for seeding, moisture is ample, and wind direction is usually from the southwest; thus, more seedings occurred in May than in any other month, except those of winter. The agricultural need for water in spring for planting and seedling developments also justifies cloud seeding to improve weather conditions.

4. EVALUATION EFFORTS

Efforts to evaluate winter cloud seeding activities by RSRIT from 1952 to 1977 were summarized in eight reports. The aircraft seeding project conducted in 1977 was reported by Lu (1978), Liu (1977), and Chu (1978).

The evaluation effort by RSRIT used a historical target-control approach. The technique used was simple regression, and the statistic used was difference/predicted ratio (see below). For each month, January to December, mean areal rainfalls were calculated for a chosen target in the mountain area (3 stations) and four control areas (3, 3, 5, and 5 stations) (Fig. 1). However, only seeding efforts related to hydroelectric reservoirs were evaluated. Agriculturally oriented seeding efforts (including balloon experiments) in

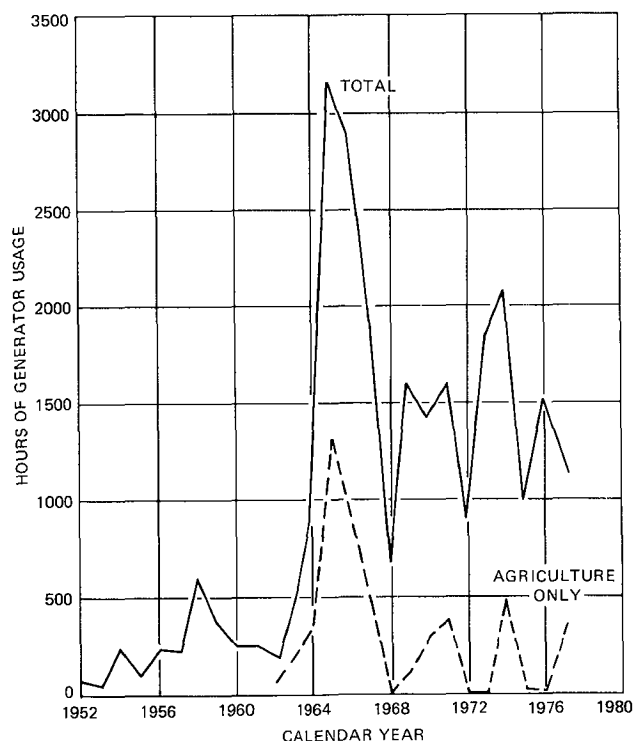


Figure 2. Yearly generator usage (in hours).

the western coastal plains, due to lack of appropriate control areas, were not evaluated.

Simple regression equations were fitted by least squares to each target-control pair for each of the 12 months in 1923-1944. Out of 12 monthly regression equations, five (November to March) were selected in the evaluation effort for the hydroelectric subgoal. The multiple correlation, R, of the 20 regressions ranged from .616 to .966, with the better fits in February and March. For each of these five months, historical regression of each target-control pair was used to compute a predicted rainfall value for the target area, PT, during seeding years. This predicted value was then compared to the observed target rainfall, OT, as in the following difference/predicted ratio:

$$D = 100(OT - PT)/PT.$$

Table 1 shows the 5-month average of D for each year using matching of Target vs. Control I, and Target vs. Control IV. Control I is north of the target and at a similar altitude. Controls II to IV consist of stations widely spread over the western coast, at lower altitudes than the Target. Because Controls II, III, and IV overlap, it is not appropriate to average D values using all four Controls as in the RSRIT reports. Instead, only Control I and Control IV were used, for the following two reasons: First, coefficients of determination, R², of the historical regressions for Control IV are consistently larger than those

of Controls II and III in each winter month. Second, R² of the historical regressions for Control IV are larger than those of Control I in December, January, and February.

The 26 years of seeding activities reported here have 20 positive and 6 negative D values, using comparison with Control I. The mean seeding effect indicates a positive 44% increase in rainfall, the significance level corresponding to the Wilcoxon signed rank test is .000. The individual seeding effects vary from -39% to 349%. On the other hand, 14 positive and 12 negative D values result from the Control IV comparison. The mean seeding effect indicates a positive 12% increase, the corresponding significance level of Wilcoxon signed rank test is .406, and the variation ranges from -62% to 200%. The combined (averaged) D values offset a few negative values (only 5 negative values are left), and the range of variation is reduced to -45% to 216%, with an average effect of +28%, and significance level .002.

The Target and Control I have similar geographic and climatological features, are closer together, and the areas covered by the stations are more nearly equal than those of Target and Control IV. If no contamination can be safely assumed, Control I offers a better comparison than Control IV.

5. AIRCRAFT SEEDING

Severe drought occurred in western and northern Taiwan during March-May of 1977 and the summer of 1978. Urgent needs for irrigation and municipal water supplies led to cooperative efforts between the staff of RSRIT and the Chinese Air Force to seed clouds. The Central Weather Bureau provided weather forecasts for suitable clouds and synoptic weather conditions. Two C-119 aircraft were used to deliver dry ice and saturated salt water at levels between 3500-4500 m, very close to 0°C. Crushed dry ice particles, mostly 1-2 cm in diameter, were shoveled into a funnel-shaped aluminum cylinder and dispensed through the gate (Chu, 1978). Salt water was dispensed using funnel and tube. No precise dispersing rate was available; however, approximate rates were estimated at 100 kg/min for dry ice and 80 liters/min for saturated salt water.

Seeding efforts took place on five occasions (9 flights), mostly in the afternoon -- March 24, April 18, May 7-8, May 13 in 1977 and August 5 in 1978. Total dry ice dispensed was 640, 1000, 3000, 1000, and 1000 kg, respectively; total salt water dispensed was 400, 400, 800, 800, and 800 liters, respectively. Cloudtop heights from 00Z radiosondes closest to seeding for the first four occasions were respectively 3500, 4300, 4600 (3400), and 4300 m; cloudtop temperatures were respectively 0, 1, -3.5 (6.5) and -1°C (Chu, 1978). Reporters from newspapers, as well as from radio and television stations, were aboard seeding aircraft on some occasions and gave the public a rather interesting account of the seeding operations.

There has been no evaluation effort for aircraft seeding comparable to that of the winter seeding. On one occasion, May 7-8, visual observations from the aircraft did show considerable growth of seeded cloudtops to 10,000

Table 1. Difference/Predicted Ratios for Target vs. Control Rainfall Comparisons.

Year	Control Area		Avg.
	I	IV	
1951-1952	-11	12	1
1952-1953	101	2	52
1953-1954	-9	-7	-8
1954-1955	188	62	125
1955-1956	13	-12	1
1956-1957	22	-1	11
1957-1958	66	5	36
1958-1959	-27	-62	-45
1959-1960	-26	200	87
1960-1961	36	-20	8
1961-1962	-31	-44	-38
1962-1963	28	58	43
1963-1964	25	-23	1
1964-1965	2	30	16
1965-1966	78	12	45
1966-1967	66	11	39
1967-1968	63	53	58
1968-1969	-39	15	-12
1969-1970	4	-42	-19
1970-1971	45	-21	12
1971-1972	41	-24	9
1972-1973	53	-15	19
1973-1974	28	7	18
1974-1975	349	83	216
1975-1976	21	5	13
1976-1977	56	-46	5
Mean	44	12	28

m; ground stations also reported a noticeable increase in precipitation. However, cause and effect were not established. The inflow rate of water into Shih Men Reservoir in northern Taiwan increased from 4 to 5 m³s⁻¹ after seeding, and the water level of the city reservoir of Taipei increased from 7 m to 22 m (Chu, 1978). Liu (1977) also reported that, on this occasion, a rain increase of 19% was observed in a northern station inside the target area. However, no statistical evaluation was pursued. The cost for the seeding on 6 August 1978 was estimated to be near \$4,000 (Central Daily News, 6 August 1978, Taipei). Six mm of rainfall was observed near a reservoir which provides water to the city of Taipei.

6. CONCLUSIONS

The lack of reference to these Taiwanese seeding projects in the literature indicates that few scientists are aware of this large scale program. It represents an interesting mix of government, weather service and power company involvement to address water needs for hydroelectric power generation and agriculture. The governmental statistical evaluation suggests precipitation increases in 20 of the 26 years. Interestingly, this project represents one of the longest, continuously operated weather modification projects in the world. More thorough physical and statistical evaluation could provide very useful information on the effectiveness of ground-based silver iodide seeding of winter orographic precipitation.

7. ACKNOWLEDGMENTS

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projects in Taiwan. The comments of the reviewers are appreciated.

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OVERVIEW OF THE WEATHER MODIFICATION RESEARCH
IN INDIA

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A Rain and Cloud Physics Research (RCPR) Centre was set up in 1955 at the National Physical Laboratory, New Delhi for undertaking scientific studies on Cloud Physics and Rainmaking. The RCPR Centre conducted a long series of ground based salt seeding experiments in north India during the southwest monsoon seasons (June-Sept.) of 1957-1966. The results of these experiments showed on the average, an increase of about 20 percent in rainfall on seeded days.

The Institute of Tropical Meteorology (ITM) was established at Poona on 17 November 1962 as a part of the India Meteorological Department. The RCPR Centre at New Delhi was transferred to the ITM on 1 March 1967. The ITM was converted on 1 April 1971 into an autonomous organization and was renamed as the Indian Institute of Tropical Meteorology (IITM) attached to the Ministry of Tourism and Civil Aviation, Government of India. As a National Centre for basic and applied research in Tropical Meteorology, the primary functions of IITM are to promote, guide and conduct research in the field of meteorology in all its aspects, including weather modification, with special reference to tropics and sub-tropics. The research work in the Institute is organized under five research divisions:

1. Forecasting Research
2. Climatology and Hydrometeorology
3. Physical and Aerology
4. Instrument and Observational Techniques
5. Theoretical Studies

A sixth division, Library, Information and Publication, renders necessary facilities. Computer, workshop and laboratories provide research support.

In 1973, the IITM initiated a warm cloud seeding experiment using aircraft in a 3200 sq. km area located 40 km to the east of Poona, in Maharashtra State. The experiment was conducted during 5 southwest monsoon seasons, June-September of 1973, 1974, 1976, 1979, and 1980. Extensive cloud physical studies were undertaken using the in-cloud electrical and microphysical data obtained during this experiment.

A new technique for the computer simulation of cloud seeding experiments was developed at the Institute. The simulation of experiments undertaken using the historic rainfall data of the Poona region suggested that the aircraft salt seeding experiment should continue for a minimum period of 7 years for detecting a 15 percent increase in rainfall due to seeding.

The IITM also conducted a long series of cold cloud seeding experiments at New Delhi using ground-based silver iodide generators during seven winter seasons (1968-1975). The result was evaluated using the rainfall and radar data. It is not statistically significant.

The Institute carried out, in collaboration with the India Meteorological Department, aircraft salt seeding experiment over the catchment area of Rihand ($24^{\circ} 12'N$, $83^{\circ} 03'E$, 310 m MSL) in the State of Uttar Pradesh. The rainfall analysis based on the limited number of raingauges in and around the catchment suggested an increase in rainfall by 17 to 28 percent which is statistically not significant.

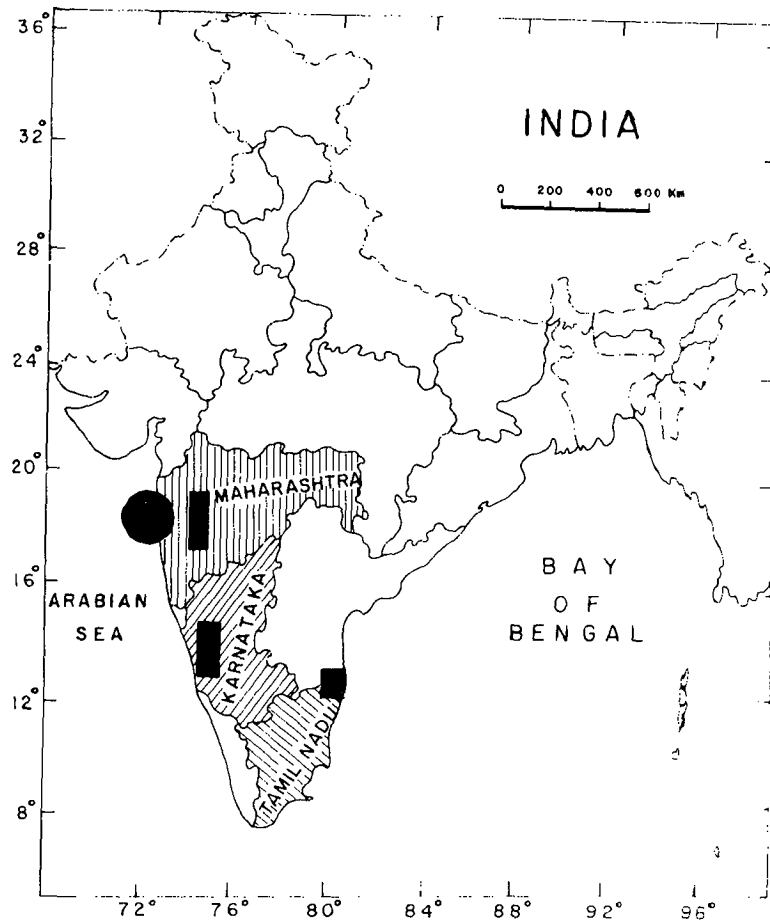
The IITM also conducted (i) ground based salt seeding experiments in Madras ($13^{\circ} 00'N$, $80^{\circ} 11'E$, 16 m ASL) region, Tamil Nadu State, South India, in 1973-77, (ii) aircraft salt seeding experiment over Linganamakki catchment ($14^{\circ} 12'N$, $74^{\circ} 50'E$, 704.3 m ASL), in Karnataka State, in 1975 and (iii) aircraft salt seeding experiment over the Arabian Sea 20-40 km off the coast at Bombay ($18^{\circ} 15'N$, $72^{\circ} 49'E$, 11 m ASL) in Maharashtra State, in 1973, 1974 and 1979. The locations of the experiments in the States of Maharashtra, Karnataka and Tamil Nadu are shown in the following Figure 1.

The four papers which follow provide summaries of work accomplished as part of the overall experiments conducted under the Institute of Tropical Meteorology.

FIGURE 1.

MAP OF INDIA

(Dark areas indicate locations of cloud seeding projects)



SALT SEEDING FROM AIRCRAFT OVER LINGANAMAKKI CATCHMENT, SOUTH INDIA

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1. BACKGROUND

Acute power shortages because of weak monsoons in the summers of 1973, 1974, and 1975 led to several cloud seeding operations over hydroelectric catchments throughout India. One of these involved salt seeding of warm cumulus clouds from aircraft over the Linganamakki catchment in southwest India during the summer of 1975, at the request of the Karnataka State Government. Operational details have been given by the Karnataka State Electricity Board (KSEB, 1975). Rainfall measured in the target area and in adjacent control areas (Fig. 1) is used for the present evaluation.

The project was similar to that conducted in the preceding two years 1300 km to the northeast over the catchment of Rihand reservoir ($24^{\circ} 12'N$, $83^{\circ} 03' E$, 310 m MSL) in the extreme southeast corner of Uttar Pradesh, south of Varanasi (Banaras). A limited number of raingauges in and around the catchment indicated increases on seeded days of 17 to 28 percent, which was not statistically significant (Kapoor et al., 1976). Despite the strong chance of similar inconclusive results from a non-randomized operational project, the Karnataka authorities requested an operational project, to alleviate a critical water shortage.

The 2000 sq. km Linganamakki catchment ($14^{\circ} 12'N$, $74^{\circ} 50'E$, 704 m MSL) is the headwaters of the Sharavati River, which flows northwest and west through the Western Ghats to the Arabian Sea. Three comparison or "control" areas were defined immediately north, east and south of the target (Fig. 2), having respectively 14, 8 and 14 raingauges. Daily rainfalls averaged for 14 target area raingauges during five summer monsoon seasons (June-September, 1970-1974) had correlation coefficients of 0.38, 0.27, and 0.37, with the north, east and south area averages respectively.

The Linganamakki region's rainfall comes mainly during the summer monsoon, with more than 60 percent of annual rainfall in July and August. Westerly airflow in the lower troposphere brings a large influx of moisture. Clouds generally are stratus and cumulus, with bases about 1,500 meters MSL. The western edge of the catchment, along the crest of the Western Ghats, is 600 to 700 meters MSL, the eastern and southern boundary somewhat higher (Fig. 2). Rainfall on the west (windward) slopes of the Ghats is heavy, but decreases sharply inland, to the northwest (Fig. 3). The number of days on which seeding was conducted in different portions of the target varied from 9 in the south-east to 43 and 44 over the central part (Fig. 1).

Aircraft temperature observations were made

in the lower atmosphere up to 10,000 ft. ASL during the cloud seeding operations. The details of the aircraft thermometer were described elsewhere (Ramachandra Murty et al., 1976). The mean lapse rates of temperatures obtained on 47 days of the experiment are shown in Figure 5. The thermodynamical characteristics of the lower atmosphere were examined on the days of the experiment and the mean lapse rates of temperatures on days with rainfall (R) in three categories (i) R \geq 80mm, (ii) R 20-80 mm, and (iii) R \leq 20 mm and the mean lapse rates for the total period of the experiment (47 days) are shown in Figure 6. The lapse rates in the sub-cloud layer (below 3000') were nearly dry adiabatic on all the three categories of the days. Above this level, the lapse rates were steeper, the rate of fall being the largest for Category I. The lapse rate decreased at a slower rate in case of categories II and III.

2. OPERATION

On 48 days between 21 June and 31 August, 1975, a pulverized mixture of salt and soapstone, at a 10:1 ratio with particle modal diameter of 10 μm , was released from a special device in a DC-3 aircraft, about 600 m above bases of warm stratocumulus and cumulus. About 1500 kg of salt mixture were dispersed on each seeded day.

Target area rainfall, as measured by the 14 target area gauges, was 7, 349, and 163 percent greater than expected by comparison with rainfall in the north, east and south control areas, but the increases are not significant statistically (Table 1). Rainfall at the single Linganamakki gauge was greater (by 10 to 1000 percent) than expected from individual comparisons with 30 control gauges, less (by 20 to 30 percent) than predicted by the pre-seeding ratios with 6 other gauges.

The increase of 73.25 feet in reservoir water level during the seeding operation was 25.7 percent greater than the largest increase reported in the preceding 10 years. However, no data were available on reservoir releases, so the significance of the increase in water level could not be established. The apparent precipitation increases must be viewed cautiously because of the limitations in evaluation of operational cloud seeding experiments.

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Meteorological Department for valuable cooperation during the cloud seeding experiments and for supplying rainfall data for the present study. The cloud seeding operations were under the project leadership of Dr. K. Krishna.

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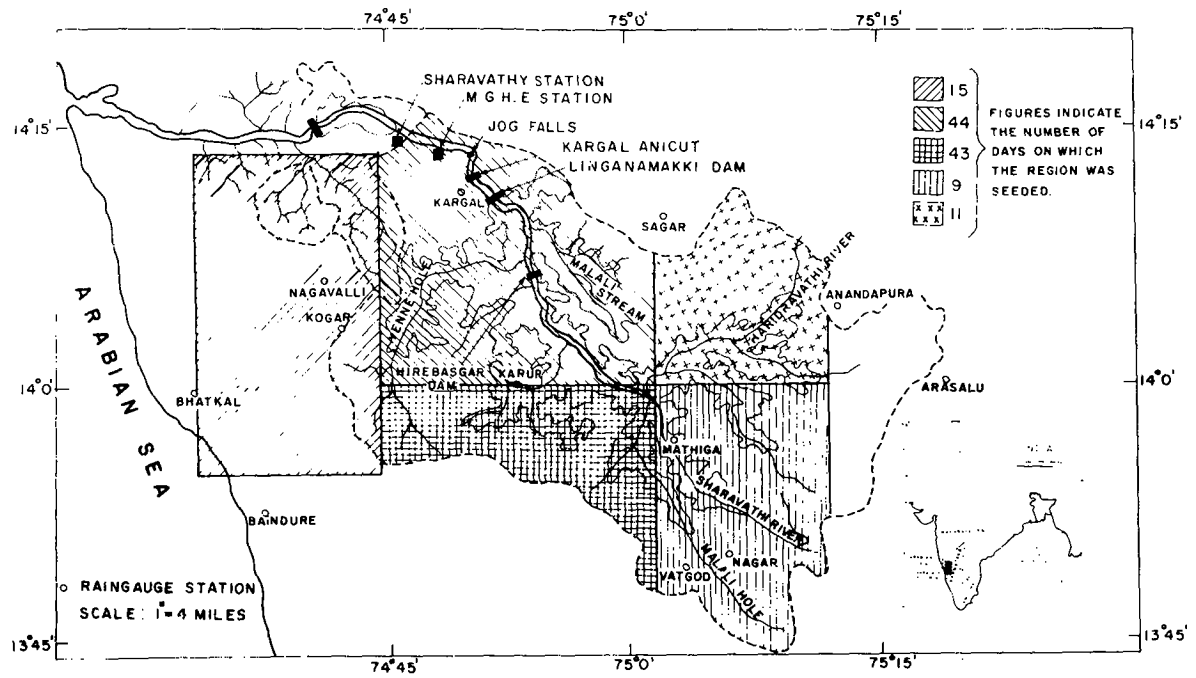
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Table 1. Average rainfall (mm) in Target (T) and North, South, and East Control Areas (C_N , C_S , C_E) on Seeded Days over Linganamakki Catchment.

1975	T	C_N	C_S	C_E	T/ C_N	T/ C_S	T/ C_E
JUN 21	159.5	80.7	144.0	23.4	1.98	1.11	6.82
22	221.4	105.0	183.1	49.7	2.11	1.21	4.45
23	198.7	97.6	161.7	46.7	2.03	1.23	4.25
28	66.4	28.8	53.5	19.3	2.30	1.24	3.44
29	59.8	17.0	58.8	10.5	3.52	1.02	5.69
JUL 02	30.6	14.2	23.0	5.6	2.15	1.33	5.46
03	50.5	30.9	37.0	4.1	1.63	1.36	12.32
04	52.8	27.2	27.0	4.7	1.94	1.95	11.23
06	26.3	8.8	34.2	5.8	2.99	0.77	4.53
10	128.1	78.4	99.4	41.1	1.63	1.29	3.12
12	122.2	30.7	102.2	9.4	3.98	1.19	13.00
13	55.8	12.4	67.1	4.3	4.50	0.83	12.98
14	41.9	11.8	34.8	9.4	3.55	1.20	4.46
15	14.8	5.1	22.0	0.3	2.90	0.67	49.33
16	24.0	6.8	20.6	0.0	3.53	1.16	-
17	34.0	9.3	33.0	1.8	3.65	1.03	18.89
20	12.1	15.5	21.1	8.0	0.78	0.57	1.51
21	3.3	0.7	13.2	9.9	4.71	0.25	0.33
22	6.4	1.3	26.5	8.4	4.92	0.24	0.76
23	2.6	1.7	2.6	7.2	1.53	1.00	0.36
24	6.2	7.6	5.4	19.6	0.81	1.15	0.32
29	51.8	16.5	39.1	9.8	3.14	1.32	5.29
30	27.4	11.3	31.5	10.8	2.42	0.87	2.54
31	19.9	10.1	15.5	12.4	1.97	1.28	1.60
AUG 03	92.4	37.7	70.8	23.1	2.45	1.30	4.00
04	77.1	38.1	71.6	17.5	2.02	1.08	4.40
05	74.5	37.2	75.7	6.4	2.00	0.98	11.64
06	76.6	24.5	56.7	8.6	3.13	1.35	8.91
07	44.5	12.2	30.1	4.4	3.65	1.48	10.11
08	48.3	13.8	43.7	6.3	3.50	1.10	7.67
09	48.4	21.6	53.9	12.2	2.24	0.90	3.97
12	102.0	21.1	99.0	27.2	4.83	1.03	3.75
13	93.4	20.2	95.7	20.8	4.62	0.97	4.49
14	119.4	49.1	115.6	33.9	2.43	1.00	3.52
18	29.1	13.6	36.5	4.5	2.14	0.80	6.47
19	22.5	3.8	27.1	6.4	5.92	0.63	3.51
20	34.9	5.0	28.0	4.2	6.98	1.25	8.30
21	16.0	3.6	16.7	7.1	4.44	0.96	2.25
22	17.7	4.5	15.5	5.9	3.93	1.14	3.00
23	15.5	7.1	15.2	3.3	2.18	1.02	4.70
24	11.3	6.6	4.5	2.6	1.76	2.58	4.46
25	6.8	2.8	10.1	2.8	2.43	0.67	2.43
26	13.4	1.4	26.0	2.0	9.57	0.51	6.70
27	13.7	1.5	20.6	12.5	9.13	0.66	1.10
28	26.5	4.7	59.3	5.1	5.64	0.45	5.20
29	36.4	6.1	41.0	3.3	5.97	0.89	11.00
30	11.9	4.6	24.6	3.3	2.59	0.48	3.60
31	12.5	3.1	14.4	0.7	4.03	0.87	17.86



EXPANDED MAP OF SHARAVATHI BASIN IN KARNATAKA STATE

FIG. 1: Map of Sharavati Basin. Number of days of seeding operations is also shown

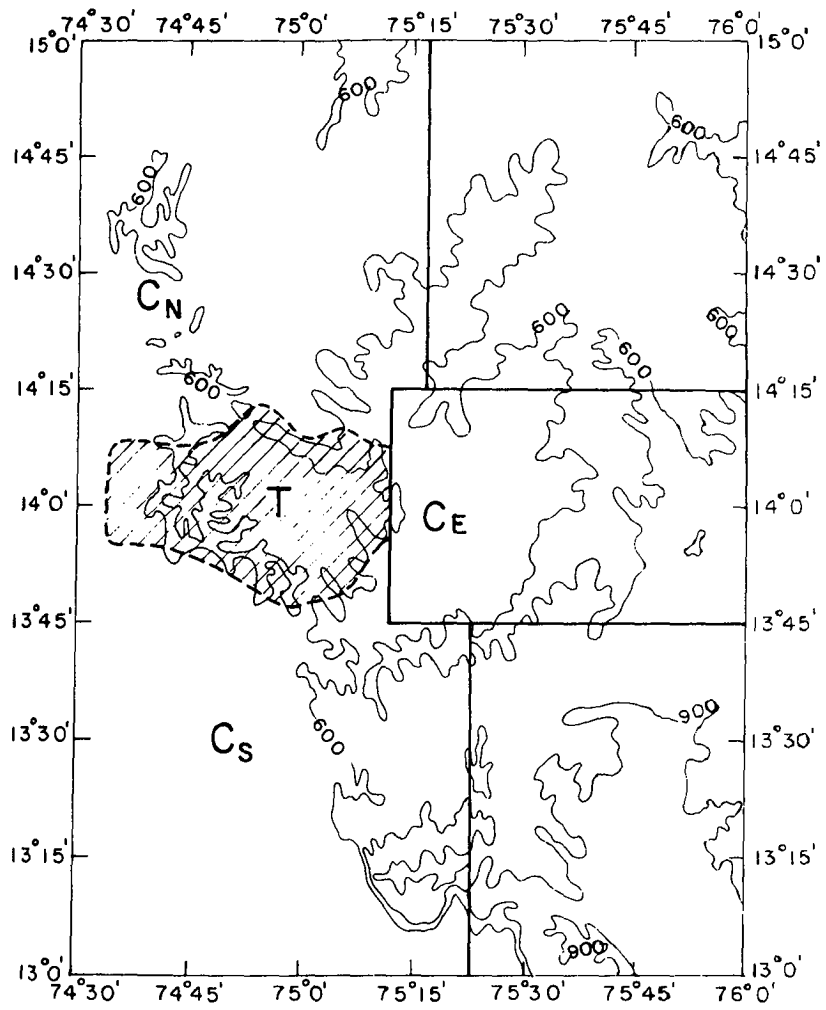


FIG. CONTOUR MAP

FIG. 2: Isolines of station height (metres ASL)

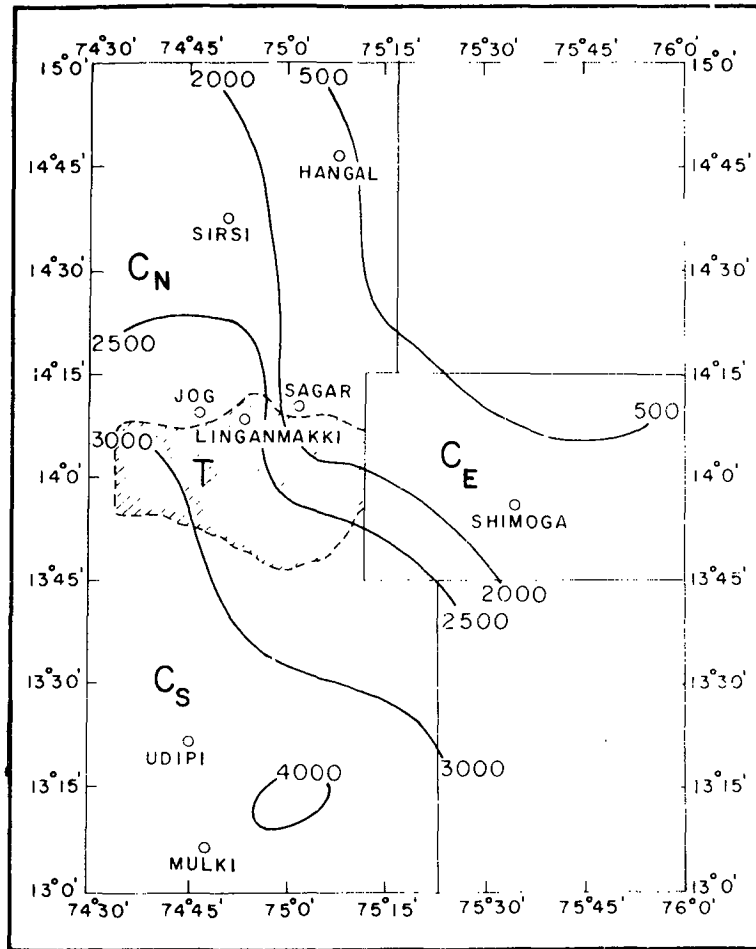


FIG. ISOHYETS OF SEASONAL MEAN RAINFALL (mm)

FIG. 3: Isohyets of seasonal mean rainfall (mm)

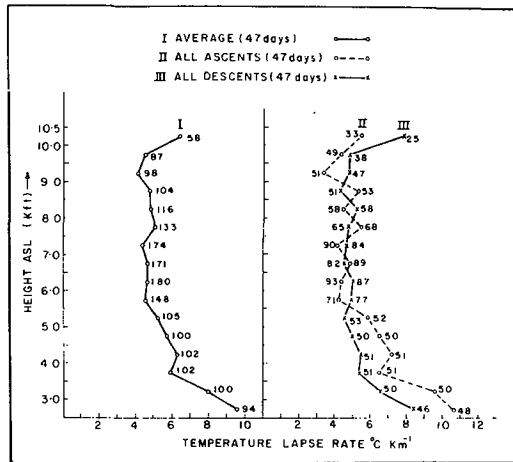


FIG. 4: Mean lapse rates of temperatures based on 47 days aircraft temperature observations.

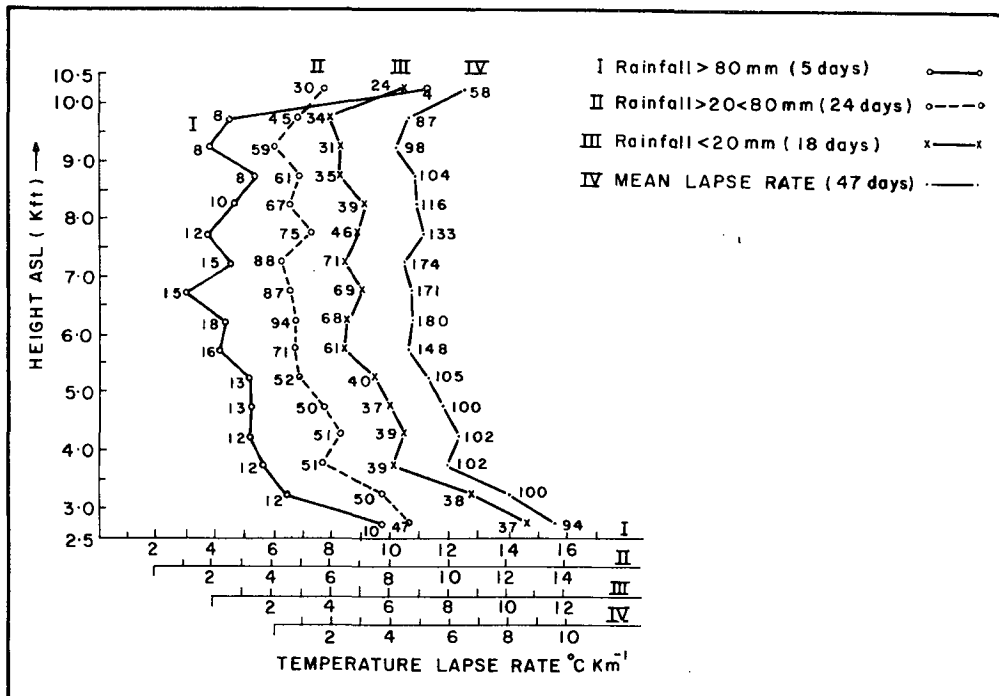


FIG. 5: Mean lapse rates on days with different rainfall amounts. Numbers on the curve indicate the number of observations available for the particular height.

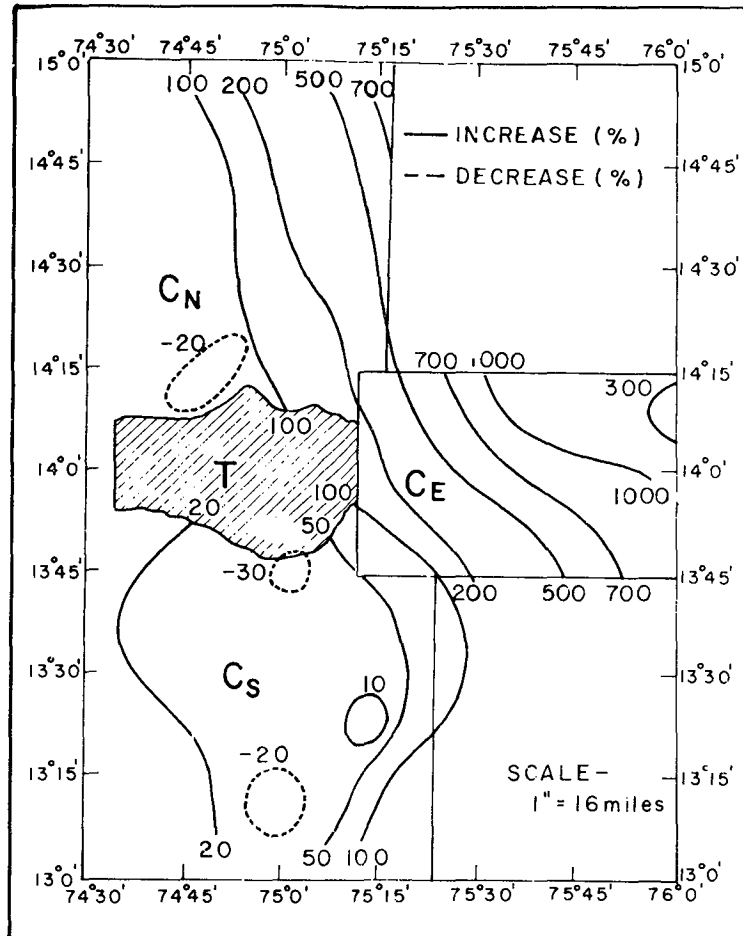


FIG. PERCENTAGE INCREASE/DECREASE IN RAINFALL DUE TO SEEDING.

FIG. 6: Spatial variation of percentage increase/decrease in rainfall due to seeding.

ELECTRICAL AND MICROPHYSICAL RESPONSES TO SALT
SEEDING IN WARM MARITIME CUMULUS CLOUDS

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Electrical, microphysical and dynamical responses to salt seeding have been investigated during cloud seeding experiments in several parts of India. Following massive salt seeding, increases in cloud temperature by 1 to 2 Celsius and cloud liquid water content up to 200 percent were observed in warm cumulus clouds (Ramachandra Murty et al., 1975, 1976). Cloud drop size distributions in seeded warm cumulus clouds increased in mean volume diameter up to 478 percent and computed liquid water content increased upward of 60 percent (Kapoor et al., 1976). In maritime warm cumulus clouds, which developed rain following seeding, the electric field reversed from initial negative to positive, occasionally preceded by intensification (Ramachandra Murty et al., 1976). This field reversal was attributed to the transport of large positive charges, from upper cloud levels to the base, by raindrops which form initially at higher levels in vigorous updraft regions. The prior intensification was attributed to updraft invigoration produced by massive salt seeding, since electrical activity is closely associated with convective activity (Latham and Stow, 1969).

In 1979, measurements on point discharge current, cloud liquid water content, cloud drop size distributions and in-cloud temperature were made at Bombay (18° 15'N, 72° 49'E, 11 m ASL) in warm cumulus clouds before and after their seeding and also in randomly chosen control clouds using a DC-3 instrumented aircraft. All clouds were in the Arabian Sea, 20 to 40 km off the coast of Bombay.

Corona discharge current was measured by a static discharge probe fitted on the tail of the aircraft with a suitable teflon insulator (Selvam et al., 1976). Liquid water content was measured by a JW-hot wire meter (Ramachandra Murty et al., 1976). Cloud drop size distributions were measured using a droplet sampler containing glass slides (Kapoor et al., 1976).

Three to nine traverses were made in each of four pairs of seeded (target) and non-seeded (control) clouds (Table 1). The first three traverses were non-seeded, even in target clouds. Observations in non-seeded traverses of target clouds were compared with those from subsequent seeded traverses.

The corona discharge current in clear air was less than the detection limit of the instrument (± 0.14 A). No corona current was observed in clouds less than 3000 ft. thick. In thicker clouds, a positive corona discharge current was found upon entry; it increased with cloud thickness and liquid water content. Positive electric

fields were found at the bases of warm cumulus clouds (Selvam et al., 1976).

Following seeding, cloud liquid water content increased up to 113 percent and corona discharge current increased up to 400 percent (Fig. 1). In the first three of six cloud traverses on 6 Sept. 1979 no seeding was carried out. In traverses 4 to 7 a salt mixture totalling 300 kg was released into the cloud. The liquid water content and the corona discharge showed marked increases following seeding (traverses 4 to 6 in Fig. 1) compared to the values recorded in the non-seeded traverses 1 to 3. Such marked increases were not observed in any control clouds (Table 1).

In-cloud temperatures increased following seeding in all four target (maximum + 1.2 Celsius), whereas a decrease (maximum -1.4 Celsius) was noted in three of four control clouds, with the fourth warming only 0.1 Celsius. These results are in agreement with those obtained from the clouds in the Poona region (Ramachandra Murty et al., 1975). Following seeding the droplet spectra broadened, with a maximum increase in mean volume diameter of about 250 percent. Such features were absent in control clouds.

CONCLUSIONS

During salt seeding experiments near Bombay during the 1979 summer monsoon:

- 1) corona discharge currents were not found in clouds less than 3000 ft. thick, but were positive in thicker clouds;
- 2) increases in cloud liquid water content up to 113 percent and corona discharge current up to 400 percent followed seeding in target clouds, but no such marked increases were found in control clouds;
- 3) in-cloud temperatures increased up to 1.2 Celsius following seeding in all four target clouds but decreased as much as 1.4 Celsius in three out of four control clouds with the fourth warming only 0.1 Celsius; and
- 4) cloud droplet spectra broadened following seeding, with increases of up to 250 percent in mean volume diameter, but no such increases were found in control clouds.

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Table 1. Radar data of seeded (Target) and non-seeded (Control) clouds.

Cloud Target or Control	T	C	T	C	T	C	T	C
Azimuth (degrees)	280	292	268	297	280	256	315	320
Range (km)	56	77	90	67	95	75	42	59
Time seeding began	1630	-	1716	-	1603	-	1145	-
Time seeding ended	1640	-	1729	-	1620	-	1200	-
Salt used (kgs)	175	-	125	-	300	-	175	-
Total traverses	9	9	7	3	7	4	6	6
Seeding traverses	3-9	-	3-7	-	3-7	-	3-6	-
Areal echo coverage (km ²) at first echo time	10.0	8.2	7.3	9.1	21.8	2.7	8.7	5.8
Time (IST) of first echo	1632	1632	1650	1718	1536	1622	1155	1158
At first traverse	0.0	12.2	21.6	0.5	12.6	8.7	0.0	0.0
At start of seeding	0.0	-	16.4	-	17.4	-	0.0	-
At end of seeding	8.4	-	9.8	-	5.7	-	3.2	-
Maximum	13.7	18.2	32.8	9.1	21.8	20.9	8.7	7.3
Height of echo-top (km)	1.2	2.2	3.5	2.0	4.0	3.0	NA	NA
When first observed (Time IST)	1634	1643	1658	1726	1538	1615		
At commencement of initial traverse	0.0	2.2	3.3	NA	4.1	2.2	NA	NA
At start of seeding	0.0	-	2.9	-	4.6	-	NA	-
At end of seeding	1.6	-	2.0	-	2.7	-	NA	-
Maximum	2.4	2.2	4.2	2.0	5.0	4.5	NA	NA
Total echo duration (min)	64	22	56	18	59	61	16	14

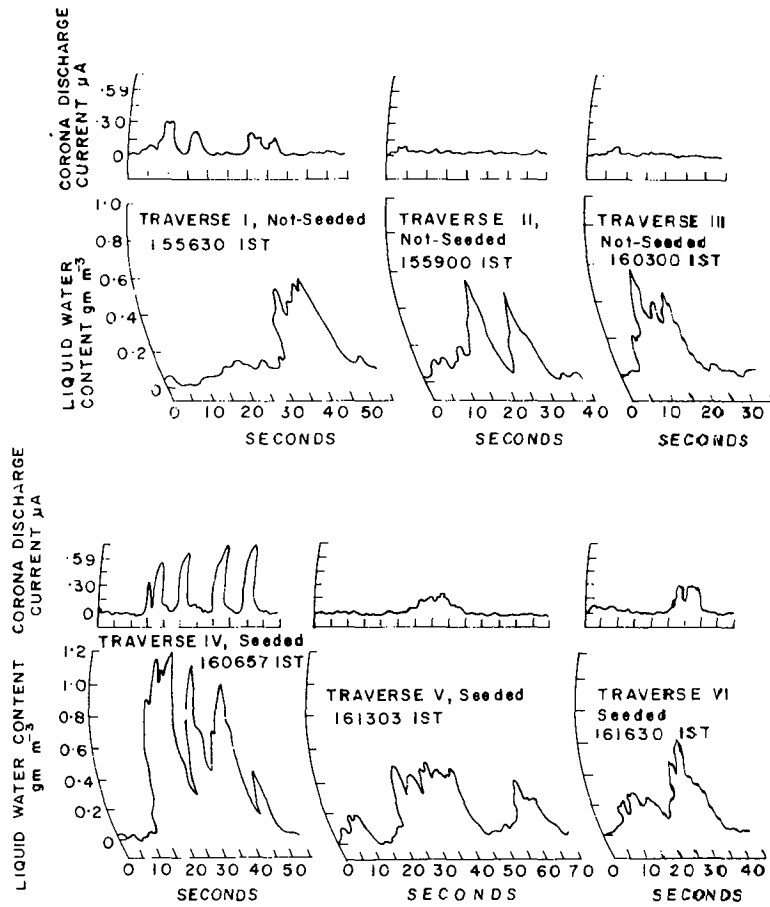


FIGURE 1 : CORONA DISCHARGE CURRENT AND LIQUID WATER CONTENT DURING SIX TRAVERSES (3 NOT-SEEDED, 3 SEEDED) IN AN ISO-LATED CUMULUS CLOUD, 6 SEPT. 1979, NEAR BOMBAY, INDIA.

GROUND-BASED SALT SEEDING IN TAMIL NADU STATE, SOUTH INDIA, 1973-1977

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1. INTRODUCTION

A long series of ground-based salt seeding experiments in north India during the southwest monsoon seasons (June-September) of 1957-66 showed significant increases of about 20 percent in rainfall on seeded days (Ramana Murty and Biswas, 1968). In September of 1974, salt seeding from aircraft on isolated maritime warm cumulus clouds within 50 km off the coast at Bombay (18° 15'N, 72° 49'D, 11 m ASL) was followed by increases in radar echo area coverage in the vertical and in echo intensity (Chatterjee et al., 1978). To seek similar results in a different area, a randomized salt-seeding experiment, using a single ground-based generator, was conducted in 1973 and 1975-77 just west of Madras, on the Bengal coast 1,000 km southeast of Bombay. There in the state of Tamil Nadu, South India, the main rainy season is during the northeast monsoon (Oct-Dec), whereas in most parts of India, about 75 percent of the annual rainfall is received during the southwest monsoon (Ananthakrishnan, 1977).

Precipitable water in the Tamil Nadu region is maximum in July and August, but rainfall is greatest in October and November. Mean daily rainfalls are 9.4 mm and 20.0 mm, respectively, during the southwest and northeast monsoon months. During the northeast monsoon season some of the cyclonic disturbances in the south Bay of Bengal move towards the Tamil Nadu coast and give heavy rainfall over the coastal belt. Since rainfall in Tamil Nadu during the southwest monsoon is low despite the high precipitable water vapour present, the feasibility of increasing rainfall through the modification of cloud microphysical conditions was explored. Aircraft observations made in north India had indicated fewer than one giant condensation nucleus per litre at cloud base under certain meteorological conditions during the southwest monsoon season (Biswas et al., 1968). Correcting this deficiency of giant condensation nuclei may help accelerate rain-formation through collision-coalescence.

A salt seeding experiment using ground based generator was undertaken during the years 1973 and 1975-1977, for exploring the feasibility of increasing rainfall through cloud seeding in the region. For the type of research described above, aircraft seeding would be ideal since it ensures precise targeting of the salt particles into the clouds and also facilitates to make in-cloud microphysical observations. However, the prohibitive cost of the aircraft operations has become the main factor for adopting the ground seeding. During the above experiment surface measurements of the concentration of giant ($r \geq 1 \mu\text{m}$) condensation nuclei (GCN) were also made.

The experimental area with its network of about 1 rain gauge per 30 to 160 km² (Fig. 1) was about 40 km inland (west) from the coast at Madras (13° 00'N, 80° 11'E, 16 m ASL). Target and control areas were 10000 to 12000 km².

During the southwest monsoon season (July-Sept) at Madras, moderate southwesterly to westerly winds prevail in the lower troposphere (Table 1). When the wind is southwesterly or westerly, airmasses travel over land before passing over the experimental area and may have fewer giant condensation nuclei. The average cloud base height is about 5000 ft. ASL.

During the northeast monsoon season (Oct-Dec) winds in the lower troposphere are mostly northeasterly to easterly, and are most gusty - during December. Skies are overcast on 8 to 12 days per month (Table 1). When it is not raining, low clouds are between 1000-3000 feet ASL in most cases. Maximum rainfall is received during November, when maritime airmasses bring giant condensation nuclei traveling over Bay of Bengal before crossing the east coast.

2. EXPERIMENTAL DESIGN AND RESULTS

The fixed target-control design was adopted in the experiment with day randomization. Target and control areas were delineated by the location of the seeding generator and the predominant wind direction in that area. The angular spread of the target area covers the 70 to 90° quadrant opposite to the mean wind direction, as indicated by the analysis. The control and target sectors fixed accordingly for the southwest and northwest monsoon seasons were:

	Target	Control
Southwest (June-Sept)	50° - 120°	230° - 300°
Northeast (Oct-Dec)	180° - 270°	0° - 90°

Correlations between average daily rainfalls of the target and control areas, for the 5-year period 1968-72, were 0.69 for the southwest monsoon and 0.62 for the northeast monsoon seasons. The criteria for seedable day were based on (i) forecast wind at 1.0 and 1.5 km levels, (ii) actual or forecast low cloud amount, and (iii) probability of rain occurrence in the region during the 12 hour period preceding the time of seeding. Days on which intermittent to continuous rain occurred, preceding and during the scheduled period of seeding, were not considered as seedable.

On the afternoons (1400-1700 IST) of seedable days, randomly selected for seeding, a pulverised mixture of salt and soapstone, in the ratio

10:1 with particle mode diameter of about 10 μm , was injected into the atmosphere from a single ground-based generator at Tiruvallur (Madras). Seeding at about 300 kg hr⁻¹ continued for about 3 hours commencing from 1400 IST. The seeding rates adopted should yield about 10¹⁰ giant size hygroscopic particles per second. Cloud bases are about 5000 feet during southwest and 2000 feet during the northeast monsoon seasons. At 25 km downwind particle concentration will be of the order of 20000 m⁻³ (Biswas et al., 1967). Hence only a fraction of the salt particles released at the ground should reach the cloud base levels under favorable meteorological conditions and influence the microphysical state of the cloud.

After the initial year, 1973, with 20 days seeded and 16 not, no experiment could be undertaken during 1974. Thereafter the experiment could be carried out only sporadically (Table 2) which ultimately led to its termination in 1977 before statistically significant results could be obtained.

During the SOUTHWEST MONSOON (Jun-Sept), rainfall on 40 seeded days was compared to that on 34 non-seeded days (Table 2). The result was positive in 2 seasons and negative in 2 seasons, with increases of 7 to 355 percent and decreases of 5 to 8 percent (Table 3). The four seasons showed an increase in rainfall on seeded days of 32 percent, significant at 15 percent level according to Mann-Whitney test (Table 4).

During the southwest monsoon, the air has enough water vapour for cloud formation, but the windflow in the lower troposphere southeasterly to westerly causes the air masses to travel over land. Such air masses may contain few of the hygroscopic nuclei required for rain-formation, and seeding them with giant condensation nuclei may help accelerate rain-formation through collision coalescence process. The surface observations showed fewer giant condensation nuclei during the southwest monsoon season. Numbers per litre of giant nuclei were:

Year:	1973	1975	1976	1977	1978
Southwest monsoon:	10.2	2.6	4.1	5.9	4.4
Northeast monsoon:	23.8	3.2	7.0	7.0	5.5

During the Northeast Monsoon (Oct-Dec) of 1976 and 1977 rainfall on 16 seeded days (Table 2), compared to that on 20 non-seeded days, decreased by 17 percent, significant at 33 percent level (Table 4). The GCN concentrations were higher up to a factor of two during the northeast monsoon.

3. SUMMARY

The ground-based salt seeding experiment, with a fixed control target design and day randomization, on 56 days with 54 days as control during the monsoon seasons of 1973-1977 in Tamil Nadu State, South India showed:

- 1) Rainfall increase of 32 percent, significant at the 15 percent level, during the southwest monsoon;

- 2) A 17 percent rainfall decrease, significant at 33 percent level, during the northwest monsoon;
- 3) Concentrations of giant condensation nuclei at the surface higher up to a factor of two during the northeast monsoon season compared to the southwest monsoon season.

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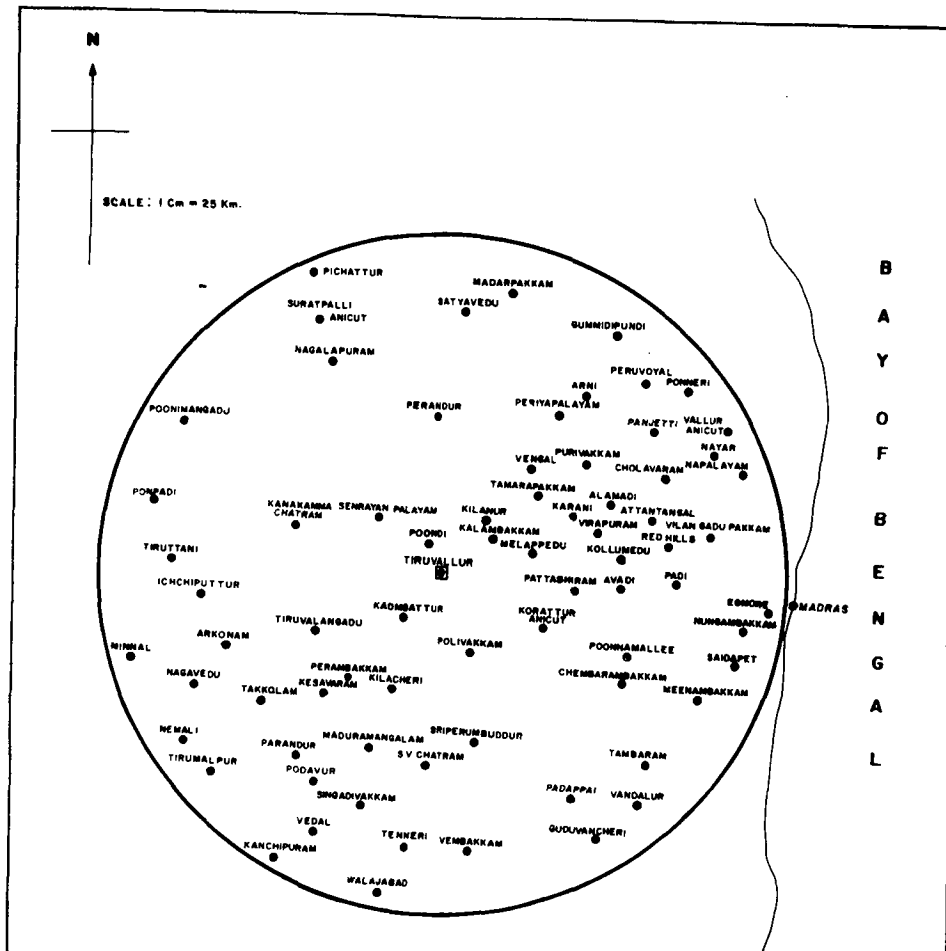


FIG. 1. Location of the experimental area (inside the circle) and the rain gauge network.

Table 1. Meteorological Parameters, 1931-60, at Madras
(13°00'N, 80°11'E, 16 m ASL).

	Southwest monsoon				Northeast monsoon		
	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Relative humidity (%)	59	63	67	71	79	79	77
Days with low cloud > 3 ok	14	15	14	10	8	12	12
No. of rainy days	4.0	6.6	8.4	7.3	10.0	9.8	5.1
Rainfall (mm)	52.6	83.5	124.3	118.0	267.0	308.7	139.1
Mean wind speed (Km/h)	16.4	14.6	13.6	11.1	9.2	11.7	12.6
Percentage number of days with wind at surface from	SW	8	13	9	8	3	0
	W	11	19	13	10	3	1
	NE	1	2	2	2	22	45
	E	8	7	11	17	24	11

Table 2. Seeding details.

Year	Period	Number of days		Seeding material (kilograms)
		Seeded	Not-seeded	
1973	JUN-SEP	20	16	16,050
1974	-	-	-	-
1975	JUN-JUL	3	7	1,825
1976	JUL-SEP	5	4	3,450
"	OCT-DEC	10	10	6,175
1977	JUN-SEP	12	7	10,500
"	OCT-NOV	6	10	4,850
TOTAL		56	54	42,850

Table 3. Total rainfall (mm) per station in Target (T) and Control (C) sectors on seeded and not-seeded days.

Year	Month	Seeded			Not-seeded			$\frac{T}{C}$ / $\frac{C}{T}$	Result
		T	C	T/C	T'	C'	T'/C'		
1973	JUN	6.24	10.05	0.641	3.03	6.83	0.444	1.444	+
	JUL	5.59	4.07	1.373	1.55	5.68	0.273	5.029	+
	AUG	31.02	1.35	22.977	1.32	0.00	-	-	0
	SEP	33.51	27.28	1.228	2.88	9.76	0.295	4.163	+
1974	-	-	-	- No experiments			-	-	
1975	JUN	0.99	0.34	2.912	25.06	9.54	2.627	1.108	+
	JUL	4.08	1.77	2.305	0.00	0.00	-	-	0
1976	JUL	13.63	9.22	1.478	46.46	48.24	0.963	1.535	+
	SEP	0.00	4.02	0.000	0.00	0.00	-	-	0
1977	JUN	1.27	0.26	0.488	1.65	0.00	1.650	0.488	-
	JUL	2.41	10.55	0.228	0.64	0.00	0.640	0.228	-
	AUG	26.57	27.97	0.950	10.16	15.62	0.650	1.462	+
	SEP	0.00	1.82	0.000	0.00	0.23	-	-	0
1976	OCT	5.41	0.82	6.598	1.27	0.13	9.769	0.675	-
	NOV	3.54	4.05	0.874	4.28	10.11	0.423	2.066	+
	DEC	3.11	1.04	2.990	0.32	0.00	-	-	-
1977	OCT	9.54	32.35	0.295	67.25	103.07	0.652	0.452	-
	NOV	3.79	6.62	0.573	15.92	17.05	0.934	0.613	-

Table 4. Average ratio values of total rainfall in Target (T) and Control (C) sectors on seeded and not-seeded days.

Year	Seeded T/C	Not-seeded T'/C'	$\frac{T}{C}$ / $\frac{T'}{C'}$	%
<u>Southwest Monsoon (JUN-SEP)</u>				
1973	1.791	0.394	4.55	+ 355
1974	-	No experiment		-
1975	2.403	2.627	0.92	- 8
1976	1.029	0.963	1.07	+ 7
1977	0.745	0.785	0.95	- 5
Total	1.272	0.967	1.32	+ 32*
<u>Northeast Monsoon (OCT-DEC)</u>				
1976	2.040	0.573	3.56	+ 256
1977	0.295	0.652	0.45	- 55
Total	0.566	0.633	0.83	- 17**

Significance levels by one-tailed Mann-Whitney test : * = 15%
** = 33%

CHLORIDE AND SODIUM ION INCREASES IN RAIN FROM SALT SEEDED CLOUDS

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Chloride and sodium ion concentrations in rainwater from warm clouds seeded with a salt-soapstone mixture were two to three times greater than in rain from non-seeded clouds east of Poona, India, during the 1974 summer monsoon. The warm cloud seeding experiment, begun in 1973 and studied intensively in 1974, 1976, 1979 and 1980, involved two 1600 sq. km experimental areas, each having 40 raingauges and separated by an intervening buffer (Fig. 1). Crossover randomization was used.

A 10:1 mixture of salt and soapstone, with particle model size 10 μ m, was released at cloud base level through a special device fitted to a DC-3 aircraft. The warm stratocumulus and cumulus clouds, with average bases 1.5 km MSL, were seeded during aircraft penetrations about 600 meters above cloud base. An average of 1,500 kg of salt mixture was released in the target sector on each seeded day. Other details are given by Krishna et al. (1976).

At raingage stations at Sirur (north sector) and Baramati (south sector), stainless steel funnels 12 inches in diameter on special stands collected rainwater samples into 1-liter polythene bottles cleaned previously with double-distilled water (Khemani and Ramana Murty, 1968). Concentrations of sodium, potassium and calcium were measured by standard flame photometric methods; chloride, sulfate, nitrate, and ammonium concentrations were measured by standard colorimetric procedures (Khemani and Ramana Murty, 1968; Kapoor et al., 1972).

Of 27 samples collected during the 1974 summer season, five were on seeded days and the remaining 22 on non-seeded days. Rainwater was collected between 1400 and 2000 IST, because seeding was confined to the afternoon. Because the difference of 0.69 mg/l between chloride concentrations in the north and south sectors on non-seeded days (Table 1) is significant, by the Mann-Whitney test, at less than 1 percent level, results were evaluated by sectors.

Table 1. Average concentrations (mg/l) and standard deviations of various chemical constituents of rainwater on seeded and non-seeded days in south and north sectors of warm cloud seeding experimental areas east of Poona, India during 1974 summer monsoon season.

		Cl ⁻	SO ₄ ⁻⁻	NO ₃ ⁻	NH ₄ ⁺	Na ⁺	K ⁺	Ca ⁺⁺
SOUTH (16 samples)								
Seeded	MM	3.96	5.02	1.23	0.16	2.68	1.31	4.84
4 samples	SD	0.74	0.83	0.64	0.13	0.91	0.60	1.32
Not-seeded	MM	1.17	2.48	0.76	0.15	0.93	0.41	2.37
12 samples	SD	0.95	1.16	0.67	0.13	0.67	0.26	1.45
NORTH (21 samples)								
Seeded	MM	4.70	3.70	2.06	0.08	3.00	0.45	3.81
1 sample								
Not-seeded	MM	0.48	1.44	1.01	0.10	0.78	0.56	1.42
10 samples	SD	0.20	0.78	1.14	0.03	0.73	0.22	0.74

In the south sector, concentrations of chloride, sulfate, sodium and calcium are significantly higher on seeded days, the chloride and sodium values about 200 percent, agreeing with rainfall increases on seeded days of 14 to 137 percent (Krishna et al., 1976). Aerosol measurements at cloud base on one seeded day (3 Sept. 1974) suggested an increase of 34 percent in the concentration of giant particles after seeding. Giant particles released at cloud base could help in formation of raindrops through condensation and collision-coalescence processes, facilitating rain development in warm monsoon clouds.

In the north sector, the only rainwater sample available on a seeded day showed a significantly higher concentration of chloride, sulfate, nitrate, sodium and calcium. The sources of nitrate and calcium particles are not clear.

Thus, chemical analyses of rainwater collected on seeded and non-seeded days during the 1974 salt seeding experiment east of Poona suggest that:

- 1) concentrations of chloride and sodium in rainwater on seeded days were significantly higher, by about 200 percent than those on non-seeded days;

- 2) rainfall increases in the target areas varied from 14 to 137 percent;

- 3) concentrations of giant condensation nuclei, measured at cloud base in the target area, increased about 34 percent after seeding, consistent with the increased concentrations of chloride and sodium and suggesting that giant condensation nuclei could induce rain-formation in warm monsoon clouds.

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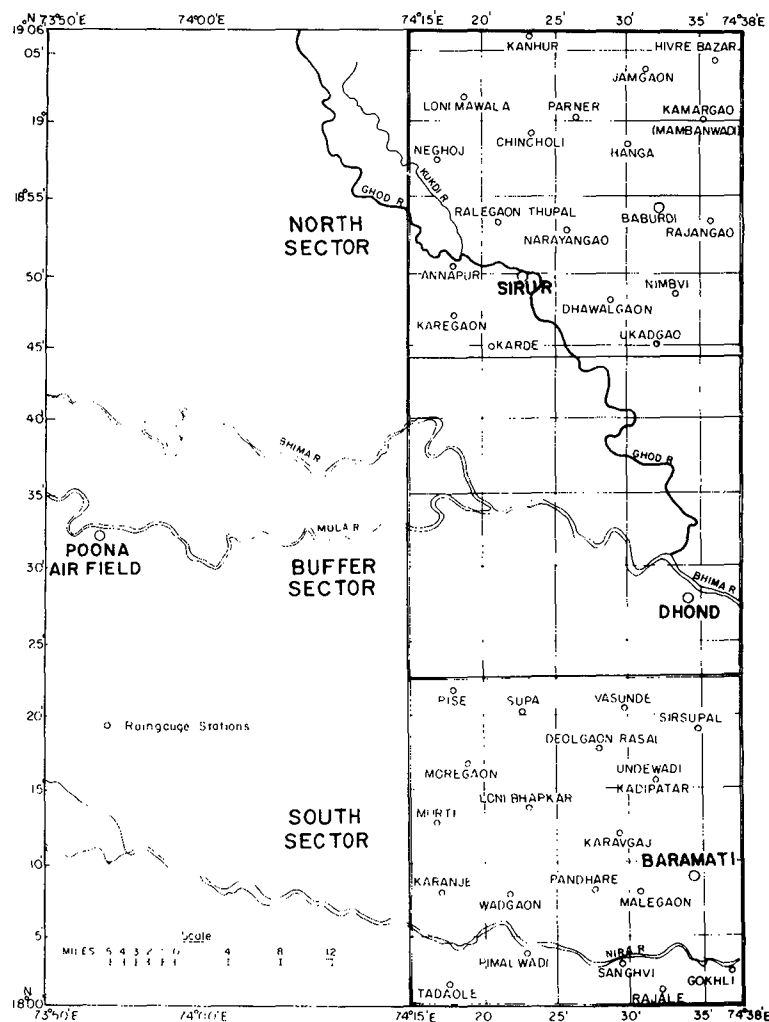


Figure 1: Location of the Experimental Area consisting of North, South and Buffer Sectors.

HAIL SUPPRESSION IN THE HUDSON VALLEY, 1956 AND 1957*

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ABSTRACT. From July to September 1956 and May to September 1957, a hail suppression program was conducted over the Hudson Valley area in New York, sponsored by The Hudson Valley Crop Services Co-op. Voluntary contributions from apple growers throughout the Hudson Valley, and others, supported operations of the Weather Modification Company of San Jose during both seasons. Equipment included one cloud seeding aircraft, a network of 75 to 77 ground generators, and a 3cm radar system. Within these two seasons, a total of 69 storms moved through the Hudson Valley area and 700 individual cells were logged by the radar. Major hail events were produced by cells embedded in frontal associated squall lines in 1956 and mostly from air mass thunderstorms in 1957. Hail damage was reported over some 1% of the total target area in 1956 and about 6% in 1957.

1. BACKGROUND

The first cloud seeding project, intended to reduce hail east of the Mississippi River, was conducted in the Hudson River Valley of New York, just south of Albany, in 1956 and 1957. This was only a decade after the discovery of dry ice and silver iodide as nucleating agents by Drs. Vincent Schaefer and Bernard Vonnegut, working at the General Electric Research Laboratory in Schenectady, NY. The first operational programs, designed to increase precipitation principally in the Catskill Mountains as an aid to the water supplies of New York City, had been conducted in 1950-51.

In May of 1956 a group, composed principally of apple growers, formed the Hudson Valley Crop Services Co-op. Mr. Walter Schreiber and Mr. Elmore Fraleigh, both of Red Hook, were elected President and Secretary-Treasurer. The Weather Modification Company, a commercial cloud seeding group in San Jose, CA, was hired by the Co-op to conduct operations to reduce hail. The designated project area was roughly 21 x 70 miles in Dutchess, Ulster, Columbia and Orange counties (Figure 1).

2. THE WEATHER

The general climate of New York State is of the humid continental type which prevails over most of northeastern United States. However, there is a great diversity within the state itself. The global atmospheric circulation brings a variety of air masses to New York. Cold dry air frequently arrives from the northern interior of the continent, and prevailing clouds from the south and southwest transport warm humid air which has been conditioned by the Gulf of Mexico and adjacent subtropical waters. These two air masses provide the dominant continental characteristics of the climate. A third air mass flows inland from the Atlantic Ocean and produces cool damp weather, but this maritime influence is secondary to the more prevalent air masses from the continent.

Nearly all storm and frontal systems moving eastward across the continent pass through or in close proximity to New York State. Storm systems often move northward along the Atlantic Coast and have an important influence on the weather and climate in the lower Hudson Valley. Frequently, areas deep in the interior of the state feel the effects of such coastal storms. Lengthy periods of abnormally warm weather can result from the movement of great high pressure systems into and through the eastern United States. When a high pressure system moves just off the Atlantic Coast and becomes more or less stagnant for several days, a persistent air flow from the southwest or south affects the state. This circulation brings the very warm, often humid weather of the summer season.

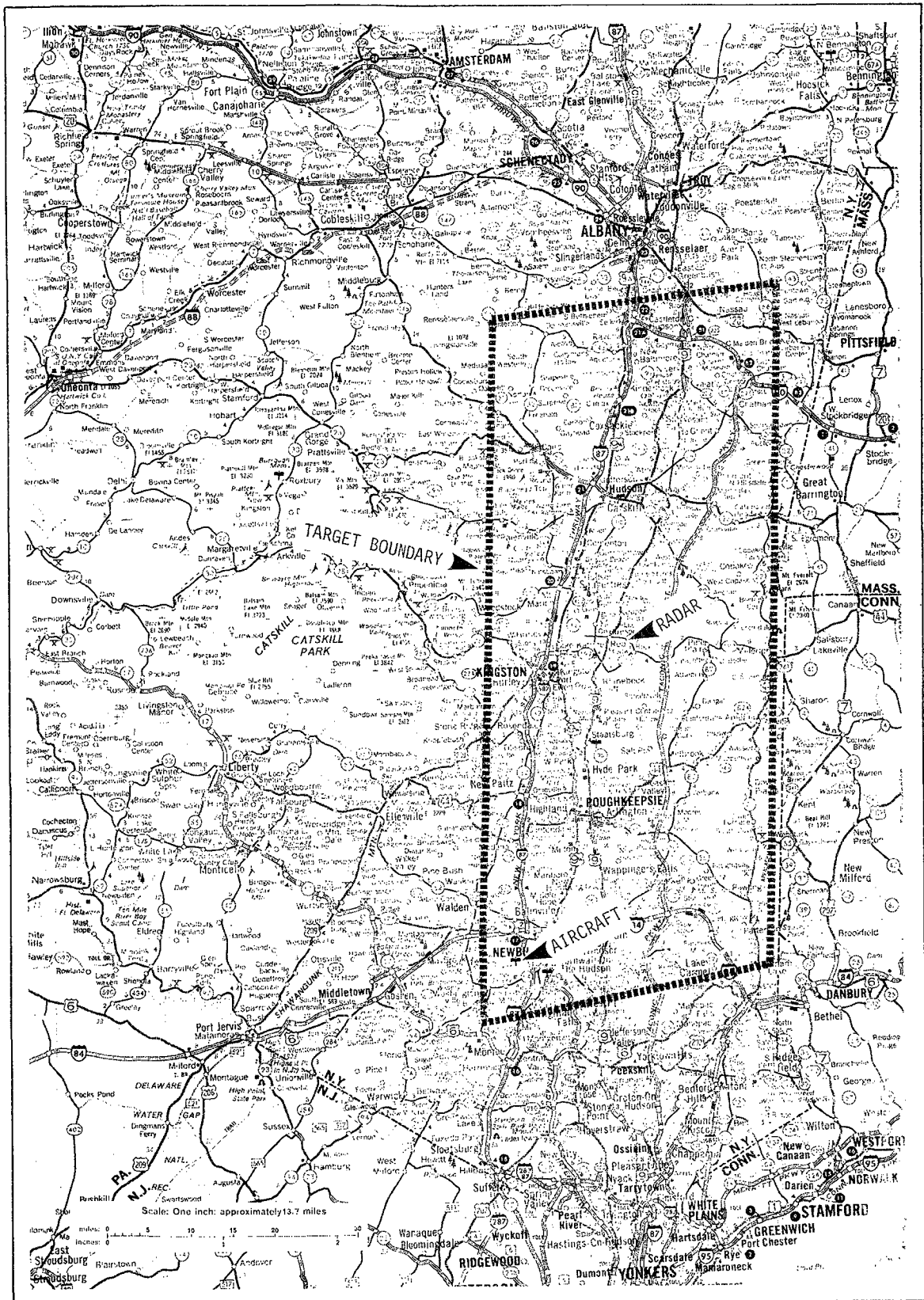
New York State has a fairly uniform distribution of precipitation during the year. No distinctly dry or wet seasons are regularly repeated on an annual basis. Minimum precipitation occurs in winter with an average monthly accumulation of about three inches in the Hudson Valley. Maximum amounts in summer are about four inches. Of course, variations in precipitation amounts from month to month, or in the same month in different years, can be extreme for any individual area. Almost any calendar month has the potential of having the lightest, or heaviest, monthly accumulation of precipitation within a calendar year at a given location.

The prevailing wind is generally from the west in New York State, with southwest component during the warmer months. Occasionally a well-developed storm system moving across the continent or along the Atlantic Coast can produce winds strong enough to cause considerable property damage.

Thunderstorms occur on an average of about 30 days per year throughout most of the Hudson Valley. Destructive winds and lightning strikes in local areas are common with the more vigorous warm season thunderstorm. Locally, hail occurs with more severe thunderstorms, but extensive losses to property and crops are less than the damage found in the hail areas of the Great Plains.

*Presented at the fall meeting, Weather Modification Association, Albany, NY, 2 Oct 1980

FIGURE 1.
Target Boundary
Hudson Valley Hail Suppression Project
- 1956-1957 Season -



Tornadoes are not common, but three or four strike limited, localized areas within the state each year.

The general climate throughout the Hudson Valley supports diversified agriculture including a nationally important production area of apples and other tree fruits. This important Hudson Valley agriculture also includes corn, small grains, grapes and a wide variety of truck crops. Although not a major hail area in the U.S., the Hudson Valley can sustain significant hail damage to crops in some years.

3. PROJECT DESIGN

The original design of the Hudson Valley hail suppression program focused primarily on total operations concepts. No randomization was included because the sponsor desired to minimize hail damage by total application of a technology believed to be effective. However, nothing was implied in this design concept which rejected the desire to acquire data necessary for evaluations and program improvements in future years.

The physical hypothesis for hail suppression was not much different from operational programs as they are conducted throughout the world today; i.e., competition for hail embryo formation and growth through the application of silver iodide as an efficient ice nucleus.

The primary source of silver iodide in both seasons was a network of ground generators established within and adjacent to the lower Hudson Valley area on both sides of the river, essentially from Newburgh on the south to Albany on the north. One P-40 cloud seeding aircraft was based at the airport near Poughkeepsie. A 3 cm weather system (50 kW peak power), with maximum range of 160 statute miles, was located atop Turkey Hill about four miles east of Red Hook and nearly in the geographic center of the target area. Silver iodide nuclei dispensed from both aircraft and ground generators were generated from 5% silver iodide (by weight) in a sodium iodide/acetone solution. Silver iodide use rates were designed for about 50 grams per hour from each ground generator and about 400 grams per hour from an airborne generator.

4. OPERATIONS

4.1 Radar

In 1956 a radar system was considered by some operators as essential to the most effective operation of any weather modification program. Current weather forecasting techniques at that time provided insufficient information for launching cloud seeding aircraft and activating the ground generator network.

The radar system utilized on the Hudson Valley project was a surplus military APS-15 airborne system modified for weather surveillance from a ground level locations. A 30-inch parabolic antenna provided a 3° pencil beam radiation

pattern. The 160-mile range was sufficient to detect precipitation echoes well beyond the target area boundary. During 1957, the most distant precipitation cells were logged southwest of the area around Newton, PA, (south of Port Jervis) and near Saratoga Springs, (north of Albany). These echoes were 25 to 35 miles beyond the target boundary.

In 1956 the radar was operated for a total of 384 hours during the various storm periods, an average of about 13.2 hours per storm. In 1957 the radar was operated for about 251 hours during a longer time period, an average of about 6 hours per storm. This wide variation in radar operation per storm period between the two years is explored in the final Section.

4.2 Ground Generators

All ground generators used during the 1956 and 1957 seasons were standard propane/acetone types which burn a solution of silver iodide/sodium iodide/acetone in a propane flame. This mixture of chemical and gas was burned in flame chambers at about 980 C. During operations, the mixture is combined and both the liquid and gas are forced through a spray nozzle to produce liquid solution droplets about 30 micrometers in diameter.

In 1956 a total of 77 ground generators logged 1,632 hours. In 1957 a total of 75 ground generators logged a total of 2,061 hours. In each season an average of 16 generators was operated per storm.

4.3 Aircraft

During both seasons the Hudson Valley Program used a surplus World War II P-40 fighter aircraft, equipped with two airborne liquid fuel silver iodide generators, each using approximately 8 liters per hour of 5% silver iodide (by weight) in the acetone/sodium iodide solution. Propane was used to pressurize the system and as an additional fuel for combustion, much like the ground generators. All airborne cloud seeding was accomplished near cloud base within the strong inflow areas associated with either the air mass type thunderstorms or embedded cells within squall lines.

In 1956 the aircraft flew a total of 28 hours during 14 seeding flights. In 1957 there were 79 hours logged during a total of 37 seeding flights. At the time this program was designed, an aircraft was considered an indispensable supplement in hail suppression work.

5. SUMMARY AND CONCLUSIONS

Thunderstorms logged during the two operational periods differed significantly. In 1956 almost all of the severe storms developed from embedded cells within squall lines associated with cold or occluded fronts. These fronts extended southwest from low pressure areas in southeast Canada or northeast United States, ultimately moving east or southeast across the Hudson Valley. As

in the case of other hail areas, the Great Plains, cold dry air aloft and warm moist air on the surface were the main ingredients for hail production. In 1957 the weather pattern changed dramatically. Very few hail events came from cells embedded in squall lines. Most of the severe activity occurred from air mass thunderstorms not associated with frontal zones, but rather from the extremely unstable conditions of warm moist air on the surface coupled with steep temperature lapse rates. Often the moisture at 500 mb was in strong support of the overall unstable conditions.

An operational summary of events during 1956 and 1957 (Table 1) shows an average of 13.2 hours of radar operation per storm in 1956, and 6 hours per storm in 1957. This supports the belief that air mass storms with shorter life cycles were the dominant type in 1957, while the longer duration cells embedded in relatively slow moving frontal zones were dominant in 1956. Hail suppression technology in 1956 and 1957 did not recognize that the locations of inflow areas important to the formation of hail are very different in each of the two storm types.

The areas with hail, expressed as a percentage of the total area protected, were 1% in 1956 and 6% in 1957. The figure was established after a liberal analysis of the significant hail damage boundaries. Another investigation of the total area covered by precipitation cells having hail potential indicated that precipitation from hail potential cells passed over about 90% of the total target area in 1956 and about 65% of the total target area during 1957.

The outlook on evaluations of operations during the two seasons can best be summarized in quotations from actual reports prepared at the end of the 1956 and 1957 seasons.

"The evaluation of any weather modification program is always the most difficult portion of the entire operation and necessarily open to the most severe criticism by those directly connected with the program as well as those scientific groups viewing it with more than casual interest from distant points. These evaluation problems are particularly amplified in the case of hail suppression work."

"The major difficulty in any analysis of this type is to determine how much hail or resultant crop damage might have been expected if the program had not been operated. An answer satisfactory to the scientist or statistician is still not possible at this time."

Table 1. Hudson Valley Hail Suppression Program Operations Summary

WEATHER	1956	1957
Total periods of operation	29	40
Hail bearing storms	16	22
Total cells	282	418
Hail in Target (storms)	4	7
Area hit by hail (% of total area)	1%	6%
GROUND GENERATOR OPERATION		
Number in field	77	75
Total hours logged	1632	2061
Average number per storm	16	16
AIRCRAFT OPERATION		
Total flights	14	37
Total hours	28	79
RADAR OPERATION		
Total hours	384	251
Average hours per storm	13	6

"SIDE-SKIM SEEDING" FOR CONVECTIVE CLOUD MODIFICATION*

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Abstract. Ice crystals growing by vapor diffusion at -10 C, primarily as short solid columns, fall faster than those developing dendritically at lower temperatures or those of long columnar shapes at warmer temperatures. To keep artificially induced crystals around -10 C as long as possible and thus cause them to grow and fall faster in order to enter the rapid riming growth regime, cumulus clouds should be seeded at the -10 C level just inside the cloud, rather than at the center, using liquid propane or other nucleant with little temperature dependence.

1. INTRODUCTION

Effective modification of convective clouds requires, first, knowledge of the clouds, seeding materials, seeding methods and microphysics-dynamics interactions in the clouds, and second, the selection and proper combination of these elements so as to maximize the desired effects of seeding. In this paper, we shall re-examine basic factors of cloud seeding in the light of our new finding about ice crystal fall behavior (Fukuta et al., 1979), and formulate a new seeding method which can avoid some previous difficulties. Possible applications of the new method will be discussed for cumuliform cloud modification for precipitation augmentation and hail suppression.

2. RE-EXAMINATION OF FACTORS INVOLVED IN CONVECTIVE CLOUD SEEDING

2.1 Purposes of convective cloud seedings

For precipitation augmentation seeding, maximization of precipitation is naturally the normal intent. Sometimes, in addition, transportation to a more desirable location may be required. Due to the relatively short life time of certain convective clouds, maximization of precipitation formation frequently demands rapid formation of precipitation after seeding. For other occasions where the atmosphere is conditionally unstable, the maximization may require fusing small clouds to induce a much larger cloud development.

Another common goal for seeding convective clouds is to suppress hail. Where hail occurrence is frequent, the total amount of precipitation is normally small. So, hail suppression operations should not lead to a reduction in the amount of precipitation. For these reasons, hail suppression operations should be aimed at the reduction of hail size with an increased number of hail embryos by proper seeding.

2.2 Ice nucleants and ice nucleation

Ice nucleants most frequently used at present are AgI and dry ice, especially the former. One drawback to AgI, apart from the recent quantum jump in price, is the strong temperature dependence in the number of active nuclei. Activity curves of AgI particles from various smoke generators are normally

measured under coexistence of supercooled fog as a function of temperature (Garvey, 1975). When the temperature drops from -10 to -20 C, the number of active nuclei per gram of compound increases by approximately 10^3 . This leads to a serious problem of depleting the available moisture at low temperatures if the number is adjusted for proper seeding at a warm temperature. As a result, ice crystals never grow to desirable sizes.

If a factor of 10^3 increase were assumed in the number of active nuclei as the temperature lowered from -10 to -20 C and if all the ice crystals formed were assumed to be the same size, the mass of each crystal would be smaller by a factor of 10^3 than that without the number increase. In the Stokes regime, this mass reduction corresponds to a fall velocity reduction by a factor of 10^2 , since the fall velocity $v \propto r^2$, where r is the radius. Instead, if the number were adjusted for proper seeding at a high altitude, say at -20 C level, there would be hardly any ice crystals at the -10 C level, wasting the precious time available for ice crystal growth before the nuclei reach high altitude.

The second problem with AgI nuclei concerns the nucleation mechanisms. As Schaller and Fukuta (1979) have identified, the mechanisms of ice nucleation vary a great deal, depending on cloud conditions. Among now commonly accepted processes of heterogeneous ice nucleation, i.e., deposition, condensation-freezing, including immersion-freezing, and contact-freezing, the former two occur relatively quickly even at temperatures near the nucleation thresholds. On the contrary, contact-freezing is slow. Therefore, the values of ice nucleation shown by Garvey (1975) are overestimates to a large extent as far as contact-freezing nucleation is concerned, because developing natural clouds, the kind desired for seeding, do not allow much time for the nucleation mechanism to operate. On the other hand, the condensation-freezing mechanism does operate at warm temperatures without much time delay. However, it depends on the water supersaturations which the cloud process produces, and since the water supersaturation levels vary depending on the microphysics-dynamics interaction of cloud, the ice nucleation rate also varies.

The number of ice crystals generated by dry ice per gram of the compound is nearly independent

* paper presented at the 3rd WMO Scientific Conference on Weather Modification, Clermont-Ferrand, France, 21 - 25 July 1980.

of temperature at a level about $10^{12}g^{-1}$, a marked advantage over AgI nucleants. We believe this number of ice crystal produced per gram dry ice is well within the realm of operation, for reasons discussed below. Other than the well-known awkwardness of availability, storage and crushing as well as need for high flying airplanes, dry ice seeding tends to produce vertical curtains of ice crystal plumes. This, however, results in rapid upward movement of ice crystal plume due to heating by cloud parcel glaciation (Fukuta, 1973), and reduces the number of ice crystals formed at low altitudes as well as increases that at higher altitudes, although the problem is far less serious compared with that of AgI nucleants.

2.3 Growth and fall behaviors of ice crystals

To develop precipitation rapidly, fast growth of ice crystals is naturally desirable. The two basic kinds of ice crystal growth exist, i.e., one by vapor diffusion and the other by riming. After nucleation, ice crystals normally go through the diffusional growth regime with the fastest growth occurring at a temperature around $-17^{\circ}C$, corresponding to plate form. The second peak of vapor diffusion growth occurs at around $-6.5^{\circ}C$ with columnar crystal shape (Fukuta, 1969; Fukuta et al., 1979). The growth rate of an ice crystal by vapor diffusion, disregarding effects due to fall, thermal and mass accommodation on its surface and supercooled fog existence under a given temperature, may be described as

$$\frac{dm}{dt} = 4\pi C(S_i - 1) \left[\frac{L_d^2}{KRT_{\infty}^2} + \frac{1}{\rho_{\infty, sat} D} \right]^{-1}, \quad (1)$$

where m is the ice crystal mass, t the time, C the electrostatic capacitance of ice crystal, S_i the saturation ratio with respect to ice, L_d the latent heat of deposition per gram of water vapor, R the specific gas constant of water vapor, $\rho_{\infty, sat}$ the saturation water vapor density at the environmental temperature T_{∞} , and D the diffusivity of water vapor in air. If we can assume a spherical shape for the crystal,

$$\frac{dm}{dt} = 4\pi r^2 \rho_i \left(\frac{dr}{dt} \right), \quad (2)$$

where ρ_i is the density of ice crystal. From Eqs. (1) and (2) with $C = r$, it is clear that $r dr \propto dt$. After integration, we have $r^2 \propto t$ or $r^3 \propto m \propto t^{1/2}$.

On the other hand, ice crystal growth rate by riming mechanism is given as

$$\frac{dm}{dt} = \pi r^2 \bar{E} W_L v, \quad (3)$$

where \bar{E} is the average riming efficiency, W_L the liquid water content of cloud, and v the fall velocity of ice crystal. For a spherical particle of graupel size, $v \propto r^2$ normally holds. Then,

$$r^{-1/2} dr \propto \bar{E} W_L dt.$$

After integration, we have

$$r^3 \propto m \propto (\bar{E} W_L t)^6. \quad (4)$$

Although these estimations were carried out under highly simplified conditions, they show a drastic change in the growth rate of ice crystal, if the switch-over from vapor diffusion mechanism to riming occurs. Fig. 1 illustrates the diffusional growth regime where $r \propto t^{1/2}$ or $m \propto t^{1.5}$ and the riming growth regime where $r \propto t^2$, or $m \propto t^6$ in the zone where $v \propto r^2$.

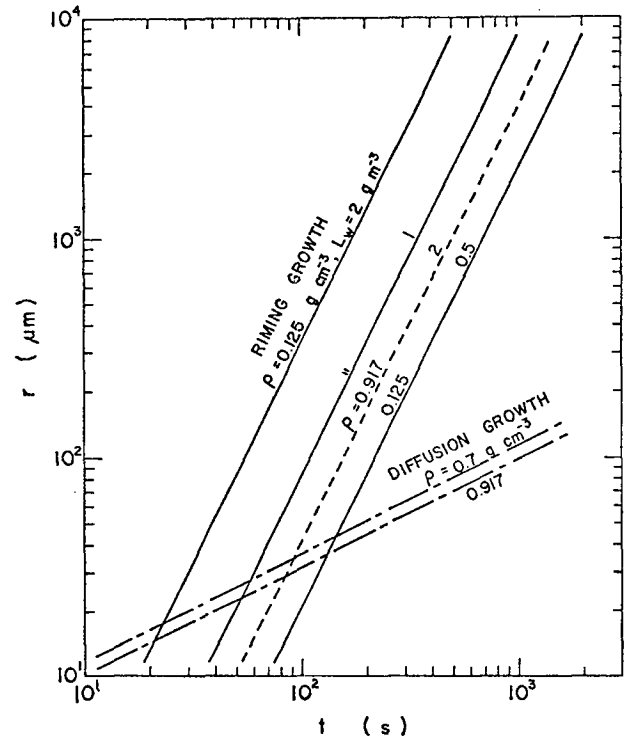


Fig. 1. Relation between ice crystal radius r and time t for vapor diffusion and riming growths at 500 mb and $-10^{\circ}C$. ρ is density of ice crystal and L_w is liquid water content of supercooled cloud. The riming efficiency is assumed to be unity.

Under what conditions does this switch-over happen? Graupel fall fast compared with snow flakes, and fast-falling ice crystals are expected to enter into the riming regime more quickly than others. We recently discovered that ice crystals growing at $-10^{\circ}C$ develop fastest fall velocities although their mass growth rates are at a minimum. Fig. 2 shows development of fall velocities of ice crystals growing under different temperatures. Although the $-10^{\circ}C$ peak continues to increase linearly, the $-15^{\circ}C$ peak, corresponding to the diffusional maximum of mass growth, slows down rapidly apparently due to dendritic form development (Fig. 3).

Crystal habit changes from column to plate at $-10^{\circ}C$ as the temperature lowers, and the crystals at this temperature take a shape near spherical with high apparent density (Fukuta, 1969; Fukuta et al., 1979). Rapid development of precipitation is often required in convective cloud seeding, so $-10^{\circ}C$ is clearly the most advantageous temperature zone where rapidly growing and falling graupel can easily form.

2.4 Seeding modes, nuclei plume diffusion and cloud interactions

A few different methods of seeding are possible. Vertical sheet, horizontal and sometimes vertical line and point seedings have been employed in convective cloud seeding, in addition to broadcast seeding from the ground. As mentioned earlier, a vertically long ice crystal plume tends to develop a premature updraft due to heat generation by phase changes in the supercooled cloud. Different modes

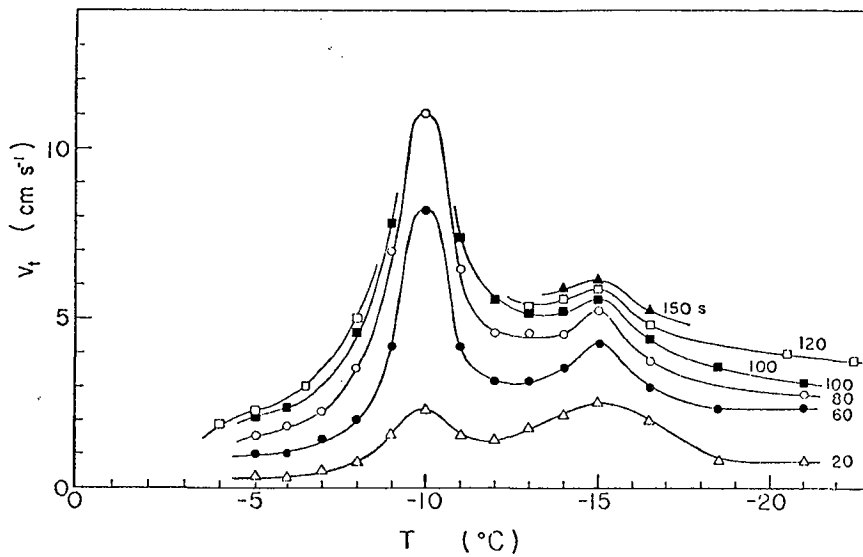


Fig. 2. Fall velocity of ice crystal v_t as a function of temperature T at different time intervals after onset of growth.

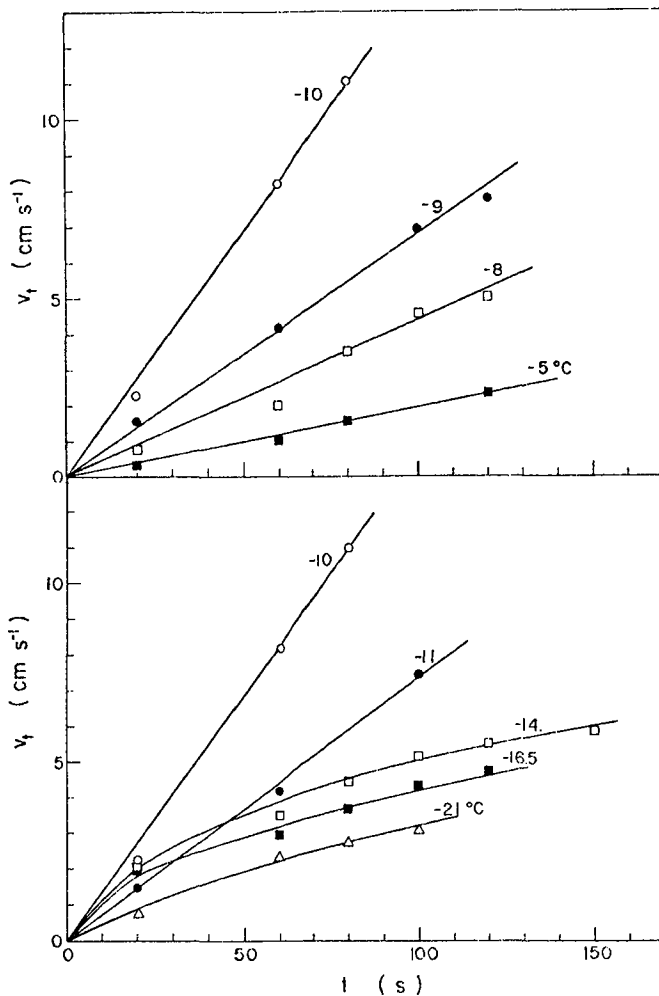


Fig. 3. Fall velocity of ice crystal v_t as a function of time t after seeding at different temperatures.

of seeding lead to different rates of plume diffusion. Ice nuclei and ice crystal diffusion from a point source is the fastest.

Additional buoyancy of cloud parcel due to glaciation depends on the total mass of ice crystals M which can be expressed as

$$M = \int_0^{\infty} n(r)m(r)dr,$$

where $n(r)$ and $m(r)$ are respectively the number and mass of ice crystals with radius r . Therefore, M can be increased in either of two ways, by increasing n or by increasing m . So-called "dynamic seeding" supplies a large amount of seeding material to increase $n(r)$. This overdosage of nucleant, however, induces an overseeding effect, particularly at high altitudes, and does not necessarily produce the best result. Ice crystals thus formed or brought up to high altitudes are too small to fall and form precipitation within the available time period. By allowing sufficient time for molecular diffusion growth with the help of turbulent diffusion of the plume, m can be increased, rather than n , by securing sufficient moisture around growing ice crystals. In this regard, nucleants used should not increase activity at low temperatures.

This problem of n vs. m is also important in hail suppression seeding. Increasing n in the overseeding method of hail suppression, although difficult to achieve at warm temperatures (and if not achieved, the method does not work), is likely to reduce the amount of precipitation. A more desirable method is to increase m so that the artificially formed ice crystals compete with hail embryos, yet they are small enough to melt and not cause any damage on the ground. To achieve the desired effect of seeding, motions of cloud parcels including convection must be utilized carefully.

2.5 Seeding rate

Seeding rate is one of the most poorly defined quantities in cloud seeding and should be adjusted to achieve the best final result, not necessarily to produce dramatic intermediate reactions. For precipitation augmentation seeding, the rate may be estimated roughly from the following parameters; (a) the diffusion volume of ice nuclei plume within the available cloud life time, (b) the mass that ice crystals can attain under free growth during the cloud life time, (c) the liquid water content of the cloud parcel, and (d) the thermodynamic and dynamic status of clouds. Fall velocity consideration for the ice crystals formed is particularly important.

The seeding rate determination becomes complex when the active number of ice nuclei shows temperature dependency such as AgI nucleants. The disadvantage of temperature dependency comes in, so that optimization of the seeding rate has to be done within the restriction of the temperature dependent activity. Nevertheless, if an airborne seeding

were carried out, the diffusing front of the ice crystal plume would receive sufficient moisture to generate a small number of falling ice crystals.

3. SIDE-SKIM SEEDING IN CONVECTIVE CLOUD MODIFICATION

The above discussions show that many of the previous problems in convective cloud seeding relate to increase in number instead of mass. Therefore, considering all factors involved in convective cloud seeding, we propose new methods of seeding for precipitation augmentation and hail suppression.

3.1 Cumuliform cloud modification for precipitation augmentation

Cumuliform clouds normally are quite tall, covering wide ranges of temperature. During the cloud growth stage, which is the best time for seeding, the convective motion has large scale rotations. Updraft velocity is often highest at the center of convective cell. The convective cell enlarges by entrainment along a cone with a semivertical angle of about 15° . In an active cell with a high liquid water content, which is often worth seeding, the central updraft is so fast that even ice crystals formed at warm temperatures pass quickly through the zone of columnar crystal habit and enter into the plate zone of low temperatures. Once ice crystals are carried to high altitudes, unless in hail clouds, they tend to become slow falling dendrites. This trend becomes stronger if more ice crystals form at high altitudes.

To avoid these problems, we propose "Side-Skim Seeding" of convective clouds for precipitation augmentation. Fig. 4 shows the principle of this seeding. At low level, the convective cell is

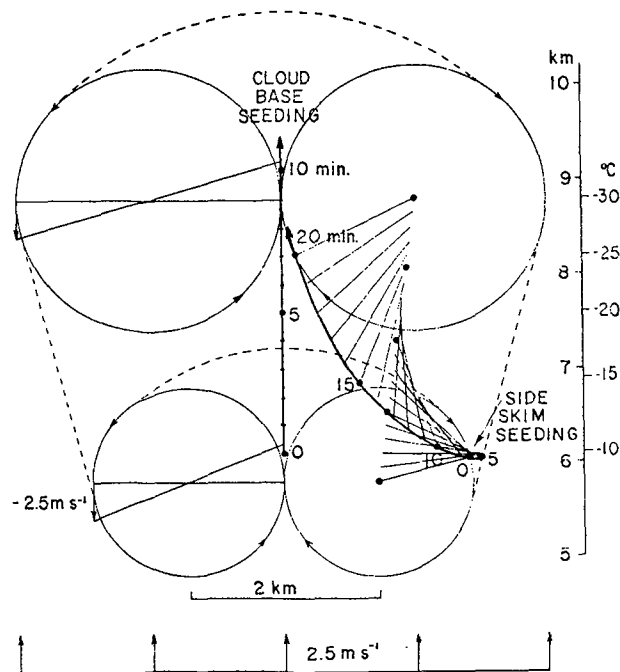


Fig. 4. "Side-Skim Seeding" concept of convective cloud modification. The updraft velocity of cloud is 5 m s^{-1} at the center and 0 at the sides. Trajectories of ice nuclei plume centers are shown for cloud base seeding as well as for Side-Skim Seeding.

assumed to be 4 km wide with the updraft velocity 5 m s^{-1} at its center and 0 at the sides. This motion has two components, a uniform vertical motion of 2.5 m s^{-1} and rotation with a tangential velocity of 2.5 m s^{-1} . The centers of rotation move upward at a vertical velocity of 2.5 m s^{-1} . The centers of cloud rotation are placed at -8 C level, slightly lower than the 6 km level.

Side-Skim Seeding assumes horizontal seeding at the -10 C level along the inside edge of the cloud with ice nuclei (or ice crystals) having little or no temperature dependence, such as liquid propane. In this manner, the seeding aircraft is unlikely to hit a strong updraft and can easily leave the cloud at any time. The center of the nuclei plume remains at the same altitude for about 10 minutes after seeding, and takes about 15 minutes to reach the -15 C level without the help of added buoyancy from seeding. Beyond this temperature, the tendency for dendritic growth becomes strong, if the riming process has not yet been achieved. During this 15 minute period, the ice crystal plume will spread in the eddy field and the ice crystals, in the form of graupel with a density of about 0.13 g cm^{-3} , will be about 2 mm in radius and fall at 1 m s^{-1} or more, if the cloud liquid water content is more than 0.5 g m^{-3} , because this is the temperature zone where ice crystals of the fastest fall velocity develop (Fukuta et al., 1979).

If the cloud center were seeded at the same altitude, the center of nuclei plume would take only 3 minutes to pass the -15 C level, even without the help of added buoyancy by seeding. Most of the ice crystals probably would start to develop dendritic forms, which do not enter readily into the riming regime of fast growth, and the crystals fall much more slowly than the graupel produced with the Side-Skim Seeding at -10 C.

The dynamic effect of Side-Skim Seeding is also expected to be better, due to wider coverage of cloud space by turbulent diffusion of ice crystals formed, utilizing the ample available time. Although slow at the beginning, uniform lifting over wider regions of the cloud will develop. This is more likely to bring a larger amount of moist air from below into the cloud and thereby enhance further cloud development.

3.2 Hail cloud modification

The rapid development of fast growing and fast falling graupel at -10 C may be utilized in hail suppression. When multicell storms are seeded by the Side-Skim Seeding procedure, the graupel formed should be efficient in reducing the liquid water available for hail growth in the clouds. In addition, a precipitation augmentation effect may be expected because the method avoids overseeding.

"Competing hail embryos" possibly may be introduced into supercell hail storms, by creating fast falling ice crystals in the -10 C zone, although the chance is slimmer compared with that in multicell storms. Side-Skim Seeding at around the -10 C level of small convective tower in front of the main updraft shaft of a supercell storm may possibly permit the fast falling ice crystals to enter the main updraft. Then they will be carried upward following the trajectory of the natural hail embryos as suggested by Browning and Ludlam (Mason, 1971, p. 360), provided that the embryos originated

at around -10 C. A large number of hail embryos thus introduced should compete with natural ones for available moisture, thereby reducing hail size. Hail embryos are either frozen drops or snow pellets, and the latter formation should be easiest at around -10 C, provided that other necessary conditions are satisfied.

The effects of these new seeding methods for precipitation augmentation in convective clouds and for suppressing hail without reducing precipitation in multicell as well as supercell storms should be studied.

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DESIGN FOR EVALUATION*

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Abstract. Non-randomized operational weather modification projects can be evaluated meaningfully only if they have been thoroughly planned in advance, stating precise intentions or goals in form amenable to later verification by procedures which also are specified in detail and use observations likewise fully specified, up to alternative actions in case objectives change or desired data are not available.

Designing an operational weather modification project so that its results can be determined is considered impossible by many at either end of the problem: the operating meteorologist who runs the program day-to-day and even hour-to-hour, and the practicing statistician who is asked to evaluate it when it's over. The meteorologist may say that he can't design the project because he doesn't know how it will develop, that goals and methods for attaining them will change as the weather unfolds, and so on. The statistician may insist that no valid conclusions can be drawn, with any sort of probabilistic confidence statement, unless the project is strictly randomized. But randomization, which requires that a substantial fraction of the apparently favorable opportunities be left untreated, usually is opposed by the meteorologist, and especially his client, who wants as much snow or water -- or as little hail -- as he can have.

While each of these attitudes is not without merit, the problem isn't hopeless. To obtain the best possible assessment of his degree of success, the meteorologist must plan carefully, in collaboration with his client and his statistician. First, he must think like a lawyer, who is (among many other things) a specialist in enumerating all possible eventualities and arranging accordingly. He must agree with his client as to the precise purpose of the project, without, of course, promising to accomplish it. For snowpack augmentation, 50 inches of water equivalent on 1 April, without blocking roads, might be specified. For a spring and summer rain increasing effort, the goal might be 10 inches in each of three months, but no more than 3 inches in any one day or 6 inches in three consecutive days.

These goals are then translated twice. The first is to the actual intent of the operation, often expressed not in actual amounts but as percentage increases of what would otherwise occur. The second translation is into a procedure for estimating these increases, positive or negative. This is where the statistician becomes involved, before the project starts.

Statistics provides perfectly precise answers to questions that weren't asked, and may be of no interest. This can happen unless advance planning properly expresses in statistical terms the physical questions of interest. Beginning students often are mystified by the basic concept of statistical testing, the null hypothesis: Why assume no effect, when the real question is how big it is. They soon learn that the null hypothesis can be rejected with greater precision than the increase can be estimated, and that a null hypothesis needn't specify equality: it can be that A does not exceed B by more than two inches, or 20 percent, or some such criterion. So the operator's intentions must be phrased in terms amenable to statistical test.

Measurement of the results also requires careful planning, the most detailed of all. If the goal is areal precipitation, its method of computation must be specified, down to alternate procedures if a precipitation gage or snow course is moved, lost, or abandoned. Changes in purpose, such as curtailing or extending the target area, must also be considered, and proper plans made.

Without randomization, the most crucial part of any weather modification evaluation is the method for estimating what would have happened if treatment had not been applied. Usually this is by regression, using predictors from outside the target, far enough away that the treatment doesn't affect them.

"Upwind control areas" aren't necessarily unaffected: winds at the surface, or near the tropopause, may be opposite to those at cloud level. Pre-treatment conditions, on the ground or in the atmosphere, are less suspect, but may be inappropriate for an operation lasting several days. Furthermore, they may have figured in the decision to initiate treatment.

Any regression procedure for estimating untreated conditions in the target should be based only on prior situations which would have been suitable for treatment: operational success can't be judged in comparison to all previous circumstances, many of which weren't treatable.

However, an entire month or season, part or all of which was treated, can be compared with

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corresponding untreated months, if general similarity is indicated by correspondence in storm types, air masses, circulation indices, etc. Again, such criteria for equivalence should have been specified before the project started, and certainly before its results have been examined in detail. The best and simplest way to avoid any bias, or even appearance of bias, is to specify in full detail the precise procedures to be used in acquiring and averaging data, inside and outside the target, and the statistical tests and criteria for the evaluation.

These complications are among the many reasons that randomization is the preferred method of evaluation: errors in the procedure for estimating area precipitation, or other criteria, tend to be the same for treated as control situations. When randomization is precluded, much more care must be taken to minimize these possible sources of error. Whether they can all be eliminated, or rendered

insignificant, depends on the particular operation. Any intentional rain increase on an isolated island, without comparable control areas nearby, and without frequent radiosonde observations, may be completely undetectable. The same program over a single Iowa county, without other activities nearby, may, with proper advance planning, be amenable to rather stringent evaluation.

Unfortunately, most operational projects begin without adequate planning, and usually have barely enough funds even for proper operation, none for advance planning and careful evaluation. In such circumstances, all the operator can say is that he did essentially what he was paid to do--the best he could. If the customer wants a thorough evaluation of the results of the non-randomized project, he must pay for it substantially, in money for the detailed plan of analysis that must be prepared in advance, and in lead time for such proper experimental design.

STATISTICAL TECHNIQUES AND KEY ISSUES FOR THE EVALUATION OF OPERATIONAL WEATHER MODIFICATION

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Abstract. A major factor calling for evaluation of operational cloud seeding projects concerns the growth of its usage. A number of statistical techniques were selected and tested on simulated weather changes in western Kansas, and it was found that principal component regression is consistently one of the more powerful evaluation techniques. Key issues affecting statistical evaluations were identified, they were better comparison, uniform definition of sampling unit, uniform measurement of response, choice of statistical technique, bias-consciousness, starting and stopping effects, and validity of historical comparison.

1. INTRODUCTION

A feature of weather modification in the United States is the existence of operational, or commercial, weather modification projects. Operational projects are generally based on a premise that weather modification works and no proof is needed. Whether these projects can or should be evaluated to gain proof of their efficacy, or to gather scientific knowledge, has been debated for more than 25 years. Certainly, their evaluation has not always been addressed properly or believably. Evaluation of operational weather modification efforts is sufficiently difficult to require a sizeable scientific effort. Not only is atmospheric research needed, but statistical expertise must be involved in the evaluation issue (Changnon *et al.*, 1979).

The key stakeholders in weather modification — the scientists, the weather modification industry, and the user public in the United States — have all come to realize that this issue must be faced. A major assessment of the national program in weather modification completed in 1978 recommended that considerable attention be given to the evaluation of selected future operational projects (Weather Modification Advisory Board, 1978 and Statistical Task Force, 1978).

Well-designed seeding projects offer unique opportunities for learning about the effects of cloud seeding, for testing concepts developed in exploratory research, for transferring technology to user groups, and for encouraging sound weather modification practices. Carefully controlled and randomized projects could help serve as "confirmatory type" experiments, as distinct from exploratory type experimentation.

Such evaluations face a variety of challenges, including: 1) the development of statistical-physical techniques for evaluation, 2) the evaluation of operational projects to test the techniques, and 3) the planning and control of future operational projects to make them easier to evaluate. A major factor calling for evaluation

of operational weather modification concerns the growth of its usage. Figure 1 reveals the extent and number of operational projects in recent years. There were 88 commercial projects in the United States in 1977, with weather modification being applied over 676,000 km², 7% of the total area of the United States. Techniques and procedures to evaluate operational projects are being developed, partially as a result of this growing usage.

We have been studying approaches for evaluating operational weather modification projects. The extensive assessment of inadvertent precipitation modification induced by the city of St. Louis (Changnon *et al.*, 1977) has helped illustrate how evaluations of nonrandomized influences can be achieved. Our primary objective now is to develop statistical-physical evaluation techniques for operational projects, including both the usual non-randomized operations and those of the future which might employ some degree of randomization ("piggy-back type," as recommended by the Weather Modification Advisory Board, 1978). Weather data have been collected for several areas where studies of projects are likely (either simulations or actual operational projects), and potentially useful statistical techniques have been determined (Hsu, 1979a, b; Gabriel, 1979). The statistical techniques are being applied to simulated convective precipitation changes in three areas (Fig. 1) Kansas — warm season rainfall; Montana — seasonal hail; and Illinois — summer rainfall. Because of the experience derived in our research, at Illinois and Rochester, we have also been involved in the statistical assessment of the North Dakota and Utah programs, a part of a NOAA funded, CSU managed effort to address past and future evaluation of these two state projects.

The study of predictor variables (covariates) for simulated project areas is also being pursued (Achtemeier and Schickedanz, 1980; Achtemeier and Westcott, 1979; Westcott, 1979). A third project objective of our research is to establish operational criteria for future operational projects so as to allow more meaningful scientific evaluations. We also aim to assess past problems in

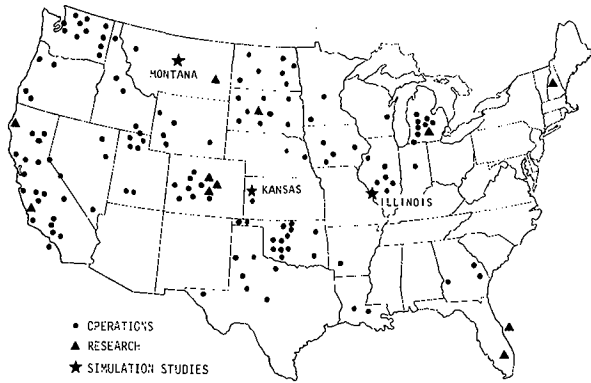


Figure 1. Locations of research and operational weather modification projects in the United States, 1973-1977. Two operational projects were in South-Central Alaska and no projects in Hawaii (from WMAB, 1978a).

evaluations of operational projects and to use these and the project research to set forth recommendations as to the performance of evaluations.

Once we have tested some 20 techniques on simulated weather changes in Montana, Kansas, and Illinois, we will apply the better techniques against a series of past operational projects.

This paper focuses on available results from the simulation testing of techniques and on related issues that introduce bias that affect meaningful statistical assessments.

2. STATISTICAL TECHNIQUES

A number of statistical techniques were selected to undergo Monte Carlo investigation. Techniques for comparing a seeded sample with an unseeded sample on target area data and data for several control areas were considered. They were in the forms of double ratio, target regressions on controls, target regression on first principal component of controls, two target regressions (one to the seeded sample and one to the unseeded sample) and a number of non-parametric rank power statistics.

In the study of 35 years of Kansas rainfall data (see Table 1), the Monte Carlo investigation was carried out by several hundred random choices of 5 "seeded" years with the other 30 years designated as "unseeded." The results obtained from this approach can be applied to both randomized seed/no-seed comparisons and to operational/historical comparisons under the following two premises: (1) the operational years are to be thought of as outcome of natural randomization, and (2) randomization tests are to be performed on the actual data in order for the findings from the simulation testing to be validly applied.

For multiple regressions and principal component regression, the test statistics used were:

- D = average of differences between observed and predicted seeded values;
- W = positive rank sum calculated from differences.

Table 1
DATA AND EVALUATION ELEMENTS USED IN THE MONTE CARLO STUDIES

EVALUATION ELEMENT	KANSAS	MONTANA	ILLINOIS
Type	Rainfall Enhancement	Hail Suppression	Rainfall Enhancement
Data	County Rain May-Sept 1936-1970	County Loss-Cost 1948-1976	Areal Rain June-August 1971-1975
Unit	Month	Year	Storm/48-hr
Design*	TC-CH	TC-CH	TCM-R/T-R/TC-CH
No. Seed/Unseeded	5/30 ---	3/26 6/23	24/122 26/132
Covariate	No	No	Yes/No
Target (sq mi)	750/1500	2000/6000/10,000	300/2000
No. of Targets	1/2	1/2/3	1
Control(sq mi)	800/2000/8000	2000/7000/25,000	300/700/1500/0
No. of Controls	1/3/8	1/3/13	1/3/5/0
Effect	Constant Multiplicative	Constant Multiplicative	Constant/Varying Multiplicative
Run:			
Null	500	1000	500
Each Altern.	100	1000	500

*Acronyms for design: TC-CH = continuous historical target-control design
TCM-R = random moving target-control design
T-R = random target-only design

Double ratio was computed as follows:

$$DR = T_S C_N S / T_N S C_S, \text{ where } T_S(C_S) \text{ denotes the average of seeded values in the target (control); } T_N S \text{ and } C_N S \text{ are similarly defined for non-seeded values.}$$

For two regressions, several statistics were used:

- T_1 = test statistic for slope parameter (Bernier, 1965);
- T_2 = test statistic for intercept with same slope (Mielke *et al.*, 1977);
- T_3 = test statistic for intercept and slope (Bernier, 1965);
- TP = non-parametric statistic for slope (Potthoff, 1974);
- VCOS = non-parametric variance ratio similar to F-statistic (Quade, 1967);
- VBRS = Bross test (Bross, 1964).

For sum of rank power test, the test statistics used were:

$$A_r = \sum (R_i)^r, \text{ for } r = 1, 2, 3;$$

$$B_r = \sum |D_i|^r, \text{ for } r = 1, 3;$$

$$C_r = \sum \text{SIGN}(D_i) |D_i|^r, \text{ for } r = 2, 3;$$

where summation is over the seeded sample; R_i is the rank of the i -th seeded target-control ratio; $D_i = R_i - (N+1)/2$, with N the total number of observations; and $\text{SIGN}(a) = 1, 0, \text{ or } -1$, according to whether a is $>0, =0, \text{ or } <0$.

3. MONTE CARLO STUDIES

Test statistics were computed to form the null and alternative distributions for positive 10%, 20%, 30%, and 40% seeding effects. Power curves were then derived by comparing the null and the alternative distributions. Table 2 shows powers of several statistics at the 5% level using average target and control values. Test statistics were ranked by their powers at the 5% nominal significance level for each seeding effect imposed.

Table 2
POWER (IN %) OF SELECTED STATISTICAL TECHNIQUES AT 5%
NOMINAL SIGNIFICANCE LEVEL, AVERAGED TARGET,
WEST-CENTRAL KANSAS, 100: 500 SAMPLES

	δ	DR		MR		PCR		2 REG		SRP	
		W	D	W	D	W	D	T ₂	T ₃	ANR(1)	ANR(2)
May	1.1	16	17	20	17	17	17	17	18	11	11
	1.2	44	26	33	30	40	37	42	23	23	26
	1.3	66	36	53	43	65	65	66	42	43	43
	1.4	85	47	71	55	86	84	86	56	60	60
June	1.1	22	20	23	17	18	18	18	10	10	10
	1.2	52	46	38	53	34	48	39	35	26	26
	1.3	81	66	54	73	65	74	69	53	48	48
	1.4	94	76	75	93	82	91	90	78	74	74
July	1.1	17	20	13	35	16	13	14	17	16	16
	1.2	38	37	24	65	35	37	39	39	27	27
	1.3	64	53	46	82	60	64	63	66	58	58
	1.4	79	63	70	96	80	80	80	81	73	73
Aug	1.1	23	25	24	18	22	16	18	22	18	18
	1.2	51	40	54	28	56	46	48	47	48	48
	1.3	71	55	74	39	78	71	73	62	64	64
	1.4	88	61	83	46	89	83	85	80	85	85
Sept	1.1	16	13	22	16	29	27	29	15	17	17
	1.2	42	20	44	27	52	51	51	38	36	36
	1.3	71	33	60	43	72	70	71	56	59	59
	1.4	82	49	71	57	82	76	79	72	78	78
Season Average	1.1	42	31	45	34	52	50	50	33	31	31
	1.2	89	64	83	80	87	83	85	81	85	85
	1.3	98	88	99	91	98	98	98	97	98	98
	1.4	100	100	100	100	100	100	100	100	99	99

Table 3 summarizes the findings obtained in the simulation study of west central Kansas, using 2 center counties as targets; 8 surrounding counties as the control. Findings indicate that, overall, the principal component regression is uniformly one of the most powerful among the statistical techniques investigated. Target-wise, PCR is one of the most powerful techniques for the target average, and for target 10; whereas it is the most powerful technique for target 9. In most cases, PCR is one of the most powerful techniques. An interesting finding is the case of target average in seasonal average, in which most techniques work equally well. The variation of rainfall becomes smaller and the seeding effect tends to be more easily detectable when the average is used.

Table 3
HIGH POWER STATISTICS FOR SIMULATED RAIN
MODIFICATION PROJECT IN WEST-CENTRAL KANSAS

MONTH	TARGET #1	TARGET #2	AVERAGE
	May	PCR,SRP	PCR,DR
June	PCR	PCR	DR,PCR
July	DR,MR,PCR	SRP	PCR
Aug	PCR, 2 REG	PCR	PCR
Sept	PCR,SRP	PCR,MR	PCR, 2 REG
Season Average	PCR	MR, 2 REG	DR,PCR, SRP,MR, 2 REG
Target-wise	PCR,SRP	PCR,SRP, MR	PCR,DR, 2 REG

Studies using Montana hail data and Illinois raingages data are currently being pursued at the Illinois State Water Survey (see Table 1). They cover a broad range of project types, evaluation designs, and areal sizes. Both constant and varying models of seeding-induced effects are used (Huff and Changnon, 1972). In addition, covariates are used in the Illinois study (Achte-meier and Westcott, 1979).

4. KEY ISSUES AFFECTING STATISTICAL EVALUATIONS

There has been much controversy over the validity of evaluations of operational cloud seeding. Thom's (1957) extensive analyses were subjected to scathing criticism by several statisticians (Brownlee, 1960; Neyman and Scott, 1961), who drew attention to a variety of biases which could affect such evaluations. The opinion seemed to be that reliable evidence could be obtained only from randomized experiments. And yet, 20-odd years later, the evidence from such experiments is still inconclusive and one is loath to ignore altogether the large amount of data available from many commercial or state seeding projects. It therefore is appropriate to offer some principles for such evaluations and to consider the problems encountered with the use of these principles.

The fundamental principle of any evaluation of seeding effect is that of *comparison*: precipitation under seeding must be compared with precipitation without seeding - *other things being equal*. The rub is in the last phrase - how do we ensure that other things are at least close to equal?

Comparison of precipitation in a seeded target area with that in an unseeded area is inadequate. No two areas exist which always have equal natural precipitation. Nor can one reduce variability by increasing sample sizes: It is quite inconceivable that a large sample of seeded areas be available for comparison with another large sample of unseeded areas.

Viable comparisons must be made of *occasions*, be they storms, days, 12-hour periods, weeks, or entire seasons. Of course, such occasions differ from one another even more than areas do, but it is quite feasible to reduce that element of variation by taking sizeable samples of occasions for seeding and for control.

In an experiment, the samples of seeded and control occasions are obtained by randomly allocating each occasion to be seeded or to serve as a control. In an operational project, the seeded occasions are chosen by the operator and/or his client and the *only comparison possible* is with similar occasions prior to the operation, to the extent that historical records of similar occasions are available, i.e., of occasions that would have been chosen for seeding by the operator/client's criteria.

Valid comparisons with "other things being equal" can be obtained only if one avoids certain obvious biases, advertent or inadvertent. We list some precepts that must be adhered to.

Occasions must be *defined in a uniform way*, independently of whether they are seeded or control. Selection biases can result when the operator

defines the occasions that he will seed and the control occasions that will be used for comparison (Brownlee, 1960, discusses this point eloquently). To avoid such biases, some experiments are designed so that neither seeder nor observer can tell which occasions are seeded (High Plains Cooperative Program, 1979). Historical comparisons can avoid selection biases only if the records allow retrospective definition of occasions in a manner equivalent to the definition used during operations. This excludes practically all short term occasions defined on synoptic grounds by the operators and forces one to rely on chronological definitions such as all days or entire months or seasons. Thus, for example, the evaluation of Santa Clara County seeding was done in units of entire seasons -- December through March -- irrespective of the actual amount or timing of seeding (Dennis and Kriege, 1966).

Measurements of responses must also be uniform over all occasions, seeded and unseeded. In an experiment one may arrange for observers to be blind to the seeding and ensure unbiasedness. But historical comparisons must be restricted to standard instrumentation that was available and unchanged during historical and operational years. This may be easier to achieve with precipitation records than with radar data or hail damage reports, but it always has to be checked carefully.

Subtle biases can creep into the choice of the particular measurements e.g., raingages in the target and in a nearby area to be used as a covariate. These choices should obviously not be influenced by the data observed on seeded and control occasions. In an experiment this can be done by making these choices before the experiment is run. In operational/historical comparisons this is only partly possible. Some such biases might be avoided by choosing before the operations begin (if the operators have the foresight to plan for evaluation at that stage - see Dennis and Kriege, 1966). But some biases of this kind are inevitable with such comparisons - though perhaps minor in importance - since the historical data will necessarily be available at the time choices of measurements are made (Gabriel, 1980).

The method of statistical analysis should similarly be decided on as far as possible prior to the occasions. Adapting a technique of analysis to the data at hand is an obvious source of bias, as is concentration on the analyses of special phenomena observed during the seeded and unseeded occasions (Court, 1980). This affects the multiplicity of ex-post analyses of experimental data (e.g., the several breakdowns of Whitetop data) as much as the ex-post decisions on which hail suppression years had been genuinely operational and which had consisted of mere "tooling up" (Peterson, 1975).

The only way to avoid this multiplicity bias completely is to adhere rigorously to a pre-ordained protocol of measurement and evaluation. However, the bias is likely to be much smaller when a very few principal tests are carried out than when an army of students spend years in sifting an experiment's data for possible clues.

Cloud seeding operations are often initiated as a result of several years of drought or bad hail loss. Inclusion of these years among the unseeded occasions would clearly bias comparisons.

One would do well, therefore, to exclude the few years preceding operations. No such "starting biases" can occur with randomized experiments.

Both operations and experiments tend to be discontinued if their initial seasons do not show promising results. Also, they may well be terminated and evaluated when apparently sufficient positive evidence of effects has accumulated. With experimentation, one might hope that there would be some attempt to plan the length beforehand, but funding needs and the wish to publicize findings may violate well-laid plans. As to operations, it is not even conceivable that there should be binding a priori decisions to continue them for exactly so many years, no more and no less. It is difficult to see what one can do to control either of these possible sources of bias, that of discontinuation and that of termination. One can only hope they are minor, both for experiments and for operations.

Another criticism of operational evaluations had addressed the validity of historical comparisons. There is some evidence that meteorological phenomena do not vary independently from day to day, week to week, or even year to year - that long term components of variation may exist in addition to short term occasion-to-occasion variability (Brier and Enger, 1952). It is not clear how grave this matter is and how much it might affect analysis of operations. One would hope for careful studies of time components of variation of precipitation which would tell us how far we might go wrong in analyzing the comparison of a seeded decade with an unseeded decade as though we were comparing two independent samples of 10 years each. As of now, we can only warn of this difficulty with historical/operational comparisons, but not gauge its magnitude.

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CLOUD SEEDING SOUTHEAST OF MEXICO CITY, 1974-76

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Silver iodide was emitted from ten burners from 09 to 13 CST on about half the days, randomly selected before the start of the five-month rainy season, June-October, south and southeast of Mexico City in 1974, 1975 and 1976. Five burners were of voltaic arc type, operating at approximately 2500 C; the other five used butane gas, burning at about 1,000 C. Neither type was calibrated, so no information is available on their output of freezing nuclei. On each seeded day, an average of seven burners operated, consuming 0.24 kg of AgI per day.

The Comision de Aguas del Valle de Mexico referred to its project as in the Sierra de Chichinautzin, a major mountain range southeast of Mexico City, culminating in Popocatepetl and Ixtlaltihuatl two snowcovered volcanoes reaching more than 5 km above sea level and 3 km above the Valley of Mexico. The present evaluation of the project, based on rank sums of precipitation totals, reaches conclusions different from those of the Comision (1979).

The 35,000 km² target area was divided into six zones (Fig. 1). Zone I included the mountains south of Mexico City and contained six of the ten burners. Two each were close by in Zones II, just to the east, and III, to the south. Zones IV, including Mexico City, was to the north, V to the west, and VI to the east, beyond Zone II. The six zones contained 9, 3, 18, 10, 6, and 10 raingages, respectively. The present analysis is based on the daily means of the 9 gages in Zone I, and of all 56 gages, on seeded and unseeded days.

The design and operation of the project involved many hypotheses:

- a. All clouds over the target are supercooled and hence will respond to silver iodide seeding;
- b. Despite the presence of the two snowcovered volcanoes, natural freezing nuclei are very scarce in the target area, so that almost all precipitation comes from a Wegener-Bergeron three-phase process;
- c. Silver iodide ice nuclei, produced at the ground, are dispersed by winds throughout the six target zones in adequate concentrations;
- d. Photolytic decay of the silver iodide nuclei, even in strong sunlight, is unimportant;
- e. Silver iodide nuclei do not persist from a seeded day to the next one, possibly unseeded;
- f. The silver iodide nuclei reach the clouds in adequate concentrations to affect their colloidal structure;
- g. Meteorological conditions are the same on

seeded and unseeded days;

- h. Each of several rainy periods during a seeded day is equally affected by the silver iodide;
- i. Tropical cyclones and hurricanes do not affect the target area, even though it is only 328 km from the Gulf of Mexico and 411 from the Pacific Ocean;
- j. All target area clouds need the same numbers of artificial ice nuclei;
- k. Silver iodide nuclei reach clouds and are effective within the target area, and are not carried outside by winds.

Most of these hypotheses cannot be tested, for lack of data. Only the most available information, the 24-hour catch of each raingage, is used in this report. Effects of ten tropical cyclones did reach the target area, but are not considered specifically here.

Average 24-hour precipitation for all 9 gages in Zone I (Table 1.) and of all 56 gages in all six zones, was obtained for each of the 153 days during each of the three rain seasons. These daily means were then ranked and subjected to the Mann-Whitney U-test (Siegel, 1956) for each year, for pairs of years, and for all three years combined (Table 2). The hypothesis that the distributions of rainfall amounts on seeded days did not differ from that on unseeded days was rejected at the 5% significance level, for 1974 and 1975. In those years the seeded day ranks exceeded those of unseeded days. For further investigation the simple ratio of mean precipitation on seeded and unseeded days in each year was computed. Only in 1976 was the ratio less than unity (Table 1.) but this was not found to be significant at the 5% level for that year.

The ratios were evaluated by permutation ("rerandomization") procedures. All days of a given rainy season were combined into a single sample which was then randomly divided into two parts, arbitrarily called "seeded" and "unseeded", and the ratio taken. After this had been done 100 or more times, the distribution of the resulting ratios were tabulated (Table 3.), and used to evaluate the actual observed ratio. In 1974 and 1975 the positive departures from unity are significant at the 5% level, and in 1976 the ratio difference from unity was so small it could have been accidental.

According to Neyman's criterion (Neyman and Scott, 1967), the power of the ratio test based on all three years combined is only 0.40, and a total of nineteen years would be needed to obtain significant results. Although the results are somewhat conflicting, the significance of the Mann-Whitney test in 1974 and 1975 does suggest positive results

with a ratio of 1.21 for the seeded/unseeded means of all years combined.

Erendira Georgina Estrada V. and Jose Luis Estrada B. assisted materially by drafting the figures and preparing the tables.

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TABLE 1.

RAINFALL AMOUNTS ON SEEDED AND UNSEEDED DAYS IN ZONE I

	1974	1975	1976
Days without rain, JUN-OCT	21	29	19
Days with mean rain > .10 (mm.)	26	19	30
Days with mean rain > .20 (mm.)	5	1	9
Days with mean rain > .30 (mm.)	1	0	2
Tropical cyclones affecting Zone I	5	4	1
Number of days { seeded	70	76	78
{ unseeded	83	77	75
Mean rain at 9 gages { seeded (mm.)	6.72	5.24	5.98
{ unseeded	3.82	3.85	7.22
{ total	5.14	4.54	6.59
Ratio, seeded mean/unseeded mean	1.76	1.36	0.83
Standard deviation { seeded	5.40	4.12	5.52
{ unseeded	4.60	4.27	9.43
{ total	6.06	4.81	8.37

TABLE 2.

RESULTS OF RANK SUM TESTS. (* indicates significance at 5% level)

YEARS	Z O N E I				A L L Z O N E S			
	Rank Sums		Results		Rank Sums		Results	
	Seed	Not	U	Z	Seed	Not	U	Z
1974	6 235.0	5 546.0	2 060.0	-3.09*	5 812.0	5 969.0	2 364.0	-1.95*
1975	6 124.5	5 556.5	2 653.5	-1.00	5 898.5	5 882.5	2 879.5	-0.171
1976	5 904.0	5 877.0	2 785.0	-0.51	5 990.5	5 790.5	2 871.5	-0.197
1974+1975	24 632.5	22 338.5	9 458.5	-2.38*	23 383.5	23 587.5	10 473.5	-1.55
1974+1976	24 230.0	22 741.0	10 180.0	-1.96*	23 632.0	23 339.0	10 545.0	-1.47
1975+1976	24 044.5	22 926.5	11 293.5	-0.52	23 666.5	23 304.5	11 676.5	-0.36
All Years	54 643.5	50 926.5	23 196.5	-2.20*	52 981.0	52 589.0	24 511.0	-1.27

THE PRECIPITATION ENHANCEMENT PROJECT OF THE WORLD METEOROLOGICAL ORGANIZATION,
PROGRAM AND PROGRESS

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ABSTRACT. In the first half of 1981 the Precipitation Enhancement Project, PEP of WMO will be in the third year of its Site Selection Phase in the Duero River basin centered about Valladolid, Spain. The purpose of this field investigation is to establish if the clouds and cloud systems are suitable for seeding to enhance precipitation, and if they occur frequently enough. The basic goals of PEP are discussed and an up-to-date view is presented on the status of the operation.

1. INTRODUCTION

The Seventh World Meteorological Congress in 1975 agreed that the time had come to embark upon an internationally planned, executed and evaluated experiment in artificial precipitation augmentation, and approved the WMO Precipitation Enhancement Project (PEP). The Eighth Congress in 1979 endorsed the more detailed plans for PEP dealing with the continuation of the field measurement program of the Site Selection Phase 3 (SSP-3) and the preparation for the seeding experiment, should the site in Spain be found suitable. It allocated substantial funds for management, scientific planning and international coordination. Thereby, it has to be remembered, that WMO carries out large projects with the help of resources committed and scientists seconded by its Members, i.e. the different national weather services.

The objectives of PEP are listed in Appendix A. They were discussed by List (1976), who also gave background and progress in planning in the early stages of this international venture.

PEP consists of three phases. They are:

Site selection;
The seeding experiment;
Evaluation.

The selection of the site for conducting the main (seeding) experiment, the second part of PEP, has always been regarded as crucial to the whole project. It must take account of the major aim of PEP, which is to demonstrate at a statistically significant level whether precipitation at the ground can be increased or not over an area where it would also provide economic benefits.

After an initial selection of the more promising six sites (in Algeria, Australia, India, Spain, Tunisia and Turkey) from among 16 originally proposed, numerical simulation experiments were carried out on the basis of rainfall data. Their purpose was to establish if a hypothetical increase in rainfall of 10 to 20% would be detectable above the natural local precipitation variability, as evident from the records over the previous ten or more years. The Commonwealth Scientific and Industrial Research Organization of Australia performed these experiments.

In the light of the results, together with visits to proposed sites and climatological studies, WMO Executive Committee Panel of Experts on Weather Modification reached the conclusion that the sites in Australia and Spain best met the conditions required for the PEP experiment. Because no substantial resources could be made available for a study of the Australian site, SSP-3 was limited to Spain by the PEP Board. This led to the third stage in Spain of the site-selection phase which is aimed at establishing if the clouds over the proposed site are suitable for seeding and whether they occur frequently enough to warrant expectations of a detectable and significant precipitation increase. To do this requires an intensive on-site cloud and cloud microphysics investigation extending over two or three years. Such a study is now under way.

The Plan for PEP appeared as WMO PEP Report No. 3 in 1976, whereas the Operations Plan for SSP 3 appeared as No. 11 in 1978. The PEP Design Document is Report No. 9 (1978). These are the key planning documents which were laid out by the Panel, the Scientific Planning Group at the WMO Secretariat, together with seconded scientists from all over the world. Important detailed aspects of PEP were studied (and are continued to be studied) by groups of experts and led to other documents (see Appendix B) related to precipitation enhancement. (WMO's documentation of its programs and their progress is also important to its Members, because of the value of expert and technical advice).

2. THE SITE-SELECTION PHASE, STAGE 3.

The Spanish site is located in the north-western part of the country in the Duero River basin. The city of Valladolid (population about 240,000) is near the center of the area; the field headquarters is installed at the local airport (Figure 1). The precipitation climatology can be summarized as follows for the period January to May (when precipitation enhancement is considered): Monthly average of precipitation 44mm, number of days with precipitation in Valladolid 10, in Salamanca 9; days per month with low or middle clouds 25, days with clouds of vertical development 6. For further details see PEP Report 10.

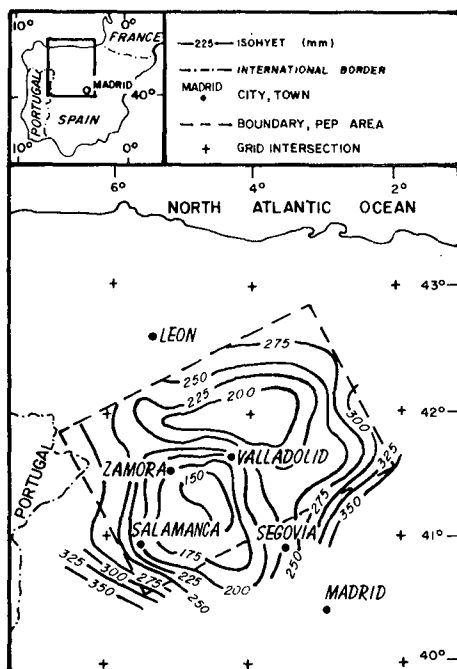


Fig. 1. Location of the SSP-3 site in Spain. Isohyets of rainfall (mm) for the period Feb. to June (from PEP Report No. 9)

The EC Panel on Weather Modification stated about the Spanish site:

- a) The statistical simulation experiment on the detectability of a seeding effect within the variability of the natural rainfall met the requirements.
- b) The terrain in the experimental area is uniform and suitable.
- c) The available data base at the basic meteorological facilities, as well as the possible logistic arrangements are satisfactory.

SSP-3 is the preparatory, on-site study of microphysics and mesoscale structure of clouds and cloud systems by aircraft, radar, radiosondes, satellite and other measuring systems. It should tell, whether the Spanish site exhibits a good weather modification potential or not, considering that the best-known seeding technique by silver iodide dispersion is going to be used. The paper by Cunningham (1980) is giving an overview of this phase, which started in early 1979 and will continue until the end of the 1981 season.

The question of suitability is very difficult to answer if the advantages do not clearly show. Such a situation seems to develop at the Spanish site. The meteorological systems which have been investigated in 1979 and 1980 show cloud regions with low ice crystal concentration, but the latter are embedded in clouds with ample ice particles. More observations need to be made to prepare a basis for a decision.

3. THE PRECIPITATION ENHANCEMENT EXPERIMENT

The detailed operational plan for the statistical seeding experiment will be based on the

outcome of SSP-3 with its information on cloud systems and cloud microphysics. Nevertheless, a few statements about the type can already be made:

- 1) The clouds considered for modification are those associated with cyclonic activity. The associated airmasses are modified maritime with cloud droplet concentrations generally less than 500cm^{-3} .
- 2) The direct target area is about $10,000\text{ km}^2$, with a total area available for controls and the study of extended area effects of approximately $50,000\text{ km}^2$.
- 3) Precipitation enhancement is to be achieved by increasing the ice crystal concentration in supercooled clouds by the release of AgI from aircraft, either from burners or droppable flares. The seeding is supposed to affect the colloidal stability of the clouds and may also have effects on their dynamics.
- 4) The basic evaluation of the seeding effect will be statistical in nature and based on the rainfall at the ground.
- 5) An experiment duration of five years is contemplated, assuming that a 10-20% change in seasonal precipitation will be detectable at an acceptable level of statistical significance.
- 6) The seeding success is to be judged on the basis of rainfall at the ground. A dense network of rain gauges many of the recording type, will be required to obtain sufficient information on precipitation.
- 7) The experimental unit for randomization and the primary evaluation interval is, at the moment, considered to be a 24-h period.

It has been stated repeatedly, that any conclusions from the statistical experiment need to be backed-up by physical insight into the seeding effects through thorough cloud and cloud-microphysical studies during the seeding experiment. PEP should provide not only statistical results. The successful outcome of the project requires a strong program of meso- to microscale physical measurements, complemented by a substantial modelling effort.

The measurement parameters illustrate the extent of PEP. They are:

- precipitation amount, intensity, duration and spatial distribution at the ground;
- synoptic meteorological variables at several points over the experimental area;
- local radiosonde information;
- cloud systems characteristics, including mesoscale organization (with satellite input);
- cloud base and top heights and temperatures, cloud liquid and total water content, droplet and drop size distributions;
- ice particle type, concentration, size and distribution spectrum;
- ice nucleus and CCN concentration below cloud base and at ground;

- (radar) echo top heights;
- radar reflectivity (volume scan);
- raindrop size distribution at the ground at one or two sites;
- characteristics of the seeding plume.

The reasons for taking these measurements are many fold:

- a) The power of the statistics is to be increased by the use of precipitation covariates which will be sought in SSP-3. Possible examples are: synoptic situations, cloud top height, ice crystal concentration, 500 mb temperature, and droplet concentration.
- b) The microphysical measurements will be necessary to document a direct causal relation between seeding and rainfall.
- c) Extended area effects, as supported by large area rainfall measurements, may also be established through observed changes in the dynamics and microphysics of cloud systems. Tracer studies of seeding plumes are necessary for the same reason.
- d) The transferability of PEP results to other parts of the globe is of great interest, because it could significantly influence the design of operations elsewhere. However, procedures and conclusions can only be transferred through conceptual models constructed from extensive measurements in the areas of concern, as well as in the PEP experimental site.
- e) The measurement parameters listed above may also serve for the development of adequate numerical cloud models, which might be used in the prediction of weather modification effects.
- f) The precipitation efficiency of cloud systems, combined with their total precipitation, needs to be assessed in order to provide insight into extra area effects and the question of optimizing seeding strategy.

No weather modification project would be complete without studies relating to the impact on the environment (ecological and societal). First environmental and hydrological studies have already been undertaken (PEP Reports 4 and 12) and an economic analysis of the value of the additional rainfall is presently under study.

4. ORGANIZATIONAL STRUCTURE

The overall management of PEP within WMO is under the control of the PEP Board. This body was formed in 1976 and is also responsible for resources for PEP. The scientific responsibility is with the EC Panel of Experts on Weather Modification, which acts in an advisory capacity. The Scientific Planning Group (SPG) at the WMO Secretariat in Geneva is the acting arm of the Board and is in charge of plan preparation for the different phases of PEP and the conduction and coordination of operations in the field. The SPG is also in charge of plan preparation for the different phases of PEP and the conduction and coordination of operations in the field. The SPG is also in charge of the overall evaluation. A member of the SPG acts as the Field Project Coordinator in Valladolid and is in charge of the daily operations. A Spanish liaison officer is assisting him. Last but

not least there is an advisory group to the SPG, which consists of scientists actively participating in the field study. The countries participating SSP-3 are providing whole packages of contributions, consisting mostly of scientific and technical personnel and hardware for a specific aspect. They are also responsible for the basic evaluation of the data they collect. A major contribution is provided by the host country, because it is responsible also for basic facilities like hangar, field headquarters, communications, synoptic network, raingauge network, etc.

5. TIME SCHEDULE

Most weather modification experiments in the past have been conducted in two stages: exploratory and confirmatory. The results of a randomized exploratory experiment are often ambiguous until post hoc stratifications of meteorological conditions are carried out. These may reveal that a modified seeding strategy or a restriction of seedable events would produce significant statistical results. To test whether the results of this post hoc stratification were due to chance or not, a confirmation experiment needs to be designed.

Until sufficient knowledge has been accumulated about the PEP site and its meteorological characteristics, it is difficult to formulate a seeding strategy for PEP to become directly a confirmatory experiment. However, the Panel believes that building upon worldwide experience, by appropriate observations during SSP-3 and the design and setup phase, a sufficiently refined seeding strategy can be devised to avoid most or even all of the exploratory phase. SSP-3 really represents already a part of it. Studies of seeding plumes, which may be started also in a pre-seeding phase, may further help to lead more directly into the seeding experiment.

The question of "normality" of the three seasons of SSP-3 is another important problem. It is hoped that satellite data and synoptic studies will establish if the field measurements of this phase are representative in the average of what can be expected for a 5 year seeding experiment.

There is another point which needs to be taken into account in a time schedule of a WMO experiment: the budget cycle of the organization. The funding is provided by WMO Congress, which takes place every four years, with the next one coming up in spring of 1983. Further, the budget proposals need to be considered first by the WMO Executive Committee, which meets every year in spring.

Considering the different boundary conditions and also assuming efficient field studies (and their evaluation), the following time plan of (past and future) activities can be set:

First proposal of PEP by EC Panel:	Nov. 1974;
PEP approval by WMO 7th Congress:	Spring 1975;
Site Selection Phases 1 and 2:	1975-1978;
PEP design:	April 1978;
Operations plan for SSP-3:	September, 1978;
Start of field program SSP-3:	March, 1979;
Completion of SSP-3 field program:	May, 1981;
First evaluation and decision on the suitability of the Spanish PEP site:	Dec., 1981;
Operations plan for the PEP seeding experiment and supplementary measuring program at PEP site, if found necessary:	1981-1982;

Review of PEP concept and approval of operations plan: Early 1982;
Start of randomized experiment: 1983;
Completion of randomized experiment: 1987;
Completion of major program and evaluation: 1988/1989.

6. SUMMARY AND COMMENTS

Initiated in 1974, the WMO Precipitation Enhancement Project is now reaching the half-time point of the field measurements of the Site-Selection Phase 3. This stage is now carried out on the only considered site (area of Valladolid in Spain) with substantial resources from a series of countries. No conclusions can be made at this point about the suitability of this site for a precipitation enhancement experiment - except that it is not a clear cut positive situation. The problem is twofold: It is not known yet if the deep cloud systems, which consist mostly of glaciated nimbostratus and produce about 70% of the total precipitation, do contain zones with supercooled water (susceptible to seeding) often enough and over sufficient time spans to make their seeding worthwhile. The other systems seem to be suitable for seeding, with the exception of the cumulo nimbi. However, preliminary statistical experiments show that the precipitation from the remaining shallow systems alone need to be nearly doubled to be detectable. Thus it will be up to some simplistic models to show if this is a reasonable expectation or not. The field season of 1981 should help to provide answers to these questions.

The detailed planning of the PEP seeding experiment needs to be carried out parallel to the evaluation of SSP-3 in order to be able to propose a sound project to WMO Congress 1983. Other avenues of attack of weather modification problems by WMO need also be developed in case the Site-Selection Phase applied to the Spanish site gives a negative result. There is also a possibility that another type of evaluation may be proposed in case the areal increase of precipitation at the ground is an unsatisfactory measure of seeding success. This could be the case if the rain increase is linked to convective situations which are normally associated with high precipitation variability.

If the Spanish site is found to be promising for a seeding experiment, it should be possible to start with the main PEP operation, the seeding experiment, in the 1983 season. This however, may require some initial plume dispersion and other preliminary studies.

The duration of a precipitation enhancement experiment is normally of the order of 10 years or longer. PEP is no exception. Like all the other ventures in weather modification, it will be judged not according to the standards acceptable when it was conceived, but at the standards acceptable to the scientific community when it is finished. This means that the planners have to be able to look into the future and make innovations in their planning that make PEP survive the test of time. This is not impossible. It requires, above all, a solid physical basis.

For example, it is suggested that radar volume scan is used to find relationships describing the evolution of radar echoes (as it has been done by

Prof. Austin at McGill) in "regular" precipitation, and then look for the same in seeded situations. The difference would then represent a measure of the seeding effect, a seeding signature, i.e. a physical measure of the modification attempt. Not only that, it would also show where the seeding effect had taken place.

Beside the regular investigations the 1981 season will also be concerned about radar patterns and signatures which may or may not be associated with seedable cloud regions. For convection the recent meeting of the principal investigators of SSP-3/1981 in Montreal, December 15-18, 1980, suggested wind inhomogeneities (indicating updrafts or downdrafts) as measured with the MRL-5 radar, VAD (Velocity Azimuth Display) divergence measurements with Doppler radars, and radar signal ratios between the normal bright band level and a level below it.

At the suggestion of a WMO meeting held in Toronto, December 8-12, 1980, on the application of cloud models to seeding experiments, a closed box model will be used to indicate the degree and time evolution of a co-existence of high liquid water contents (higher than 0.2g/m^3) and high ice particle concentrations (bigger than 1 per liter) --as was observed during SSP-3/1979-1980. A 1-dimensional cloud model should also be applied to test its use for the prediction of the height of convective clouds.

The interesting aspect of PEP is the search for a promising site and the establishment of suitability (for seeding) criteria. This is quite new ground and new concepts need to be developed without resorting to a full fledged statistical seeding experiment - which is the only way to obtain a "firm" final answer. Perhaps the "Austin" method could be extrapolated to a suitability criterion.

Another possibility could be to use the other six upper air sounding stations around Valladolid to link the cloud systems evolution to the large scale flow and see in which way it was affected by a seeding operation (Cho and List, 1980). This would require roughly 90 min. sequences of sonde releases, but it could be limited to a restricted number of interesting days. Maybe there are other ideas forthcoming which are also worth consideration.

Finally, it must be stressed that PEP was never intended to answer once and for all, whether precipitation enhancement as an operational concept is feasible or not. The results will at best be conclusive only for the area in which the main experiment is conducted. However, if the PEP results are positive and the physics is well understood, there is a good chance that rainmaking will be possible under similar conditions elsewhere.

ACKNOWLEDGEMENTS

The source material for this personal view of PEP is found in decisions and reports of the WMO Congress, its Executive Committee, the PEP Board, the EC Panel/CAS Working Group on Cloud Physics and Weather Modification, the Scientific Planning Group at the WMO Secretariat, the series of the Weather Modification Program reports and in Technical Note No. 154, "The scientific planning and organization

of precipitation enhancement experiments, with particular attention to agricultural needs" by Dr. J. Maybank.

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APPENDIX A: OBJECTIVES OF PEP

The WMO Executive Committee, at its twenty-eighth session in 1976, defined the scientific objectives of the Precipitation Enhancement Project as follows:

(a) To provide Members with reliable information about the probabilities of successful artificial intervention in meteorological processes with the object of increasing the amount of precipitation over an area of the order of 10,000 km². The size of the area for the proposed project (i.e. the target and nearby control areas) should be somewhere around 50,000 km², a scale large enough to provide adequate evaluation of scientific feasibility and economic benefit, but small enough to permit the use of adequate methods for seeding and observations;

(b) To demonstrate at a satisfactory statistical significance level over a relatively short experimental period (five years), that any increase observed is not a chance event but is associated with the seeding. The principal evaluation of this experiment will be in terms of precipitation at the ground;

(c) To obtain sufficient understanding of the meteorology and cloud physics in the area of the experiment to ensure that the statistical association of seeding, and any increase in precipitation, will be generally acceptable as a cause-and-effect relationship;

(d) To make an examination outside the target area in order to determine whether any benefits of seeding extend over areas greater than the target area, or whether there has merely been a comparatively local redistribution of precipitation;

(e) To make systematic measurements, varying from

mesoscale to cloud micro-structure, in order to develop additional co-variates to strengthen the power of the statistical analysis;

(f) To obtain well-documented scientific evidence that may lead to the optimization of the effects of seeding. For this purpose, a series of systematic cloud physics measurements should be taken on a routine basis. This would allow the application of statistical techniques to relevant physical parameters and could shed more light on the quantitative aspects of seeding techniques;

(g) To be able to make some recommendations about the applicability of the PEP procedures to other areas of the world;

(h) To assess the environmental impact of precipitation-enhancement activities, both within and outside the experiment target area.

APPENDIX B: REPORTS WMO PRECIPITATION ENHANCEMENT PROGRAMME

Report No. 1: Report of the First Session of the Interim Precipitation Enhancement Project Board, Geneva, November 1976;

Report No. 2: Position Papers used in the Preparation of the Plan for PEP;

Report No. 3: Plan for Precipitation Enhancement Project;

Report No. 4: A Review of the Hydrological Aspect of Evaluation of Precipitation Enhancement;

Report No. 5: Cloud Seeding Reagents;

Report No. 6: Areal Extent of Seeding Effects in Relation to the Precipitation Enhancement Project;

Report No. 7: Aircraft Instrumentation for Cloud Physics Research Weather Modification Programs;

Report No. 8: Report of the Second Session of the Interim Precipitation Enhancement Project Board, Geneva, April 1978;

Report No. 9: PEP Design Document;

Report No. 10: Survey of the Climatology and Synoptic Weather Patterns at the Proposed PEP Site in Spain;

Report No. 11: Operations Plan for Site-Selection Phase 3;

Report No. 12: Preliminary Environmental Impact Study of the Site Proposed for PEP;

Report No. 13: WMO Training Workshop on Weather Modification for Meteorologist - Lecutre Notes;

Report No. 14: The Dispersion of Cloud Seeding Reagents;

Report No. 15: PEP Site Selection Phase-3, 1979 Field Programme - Overview and Data Catalogue;

Report No. 16: Report on the Third Session of the Precipitation Enhancement Board, Geneva, September, 1979;

Report No. 17: Statistical Design Considerations for Precipitation Enhancement Projects;

Report No. 18: PEP Site Selection Phase-3, 1979 Field Programme - General Weather Conditions and Rainfall Characteristics;

Report No. 19: PEP Site Selection Phase-3, 1979 Field Programme - Two Studies of Precipitation Patterns;

Report No. 20: Report of the Fourth Session of the Precipitation Enhancement Project Board, Villanubla, Spain, May 1980;

Report No. 21: PEP Site Selection Phase-3, 1980 Field Season - Overview and Data Catalogue.

HAIL SUPPRESSION ACTIVITIES IN THE SOVIET UNION

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Hailstorm modification activities to prevent hail damage have been carried out in the Soviet Union for more than 15 years. Great interest to the national economy and high benefit-to-cost ratio of the hail protection program have motivated a considerable increase in the volume of hail suppression operations in the USSR.

Ten hail suppression divisions are currently operating in the Soviet Union. They comprise 53 groups (detachments). In 1979, these detachments protected crops from hail damage over an area of 6.5 mln ha. Results of hail suppression projects during the period 1975 to 1979 are presented in Table 1. Analysis of the hail protection results show that on the average, crop losses due to hail in the protected area have been reduced by more than 70 percent as compared with the many years' average damage and the losses in the control areas. The cost of the crop being preserved amounts to the sum of tens of millions of roubles.

However, we are still far from completely solving the hail problem, in spite of the fact that considerable progress has been made towards the solution of it in the last few years, since in some cases damaging hail is observed over the protected area. Reliable hail protection is the most complex problem in case of the development of very severe hail clouds.

A special research and experimental site (polygon) instrumented with a modern radar and meteorological equipment has been set up in the North Caucasus to study meteorological and aerodynamic conditions of the formation and development of very severe hail clouds, as well as investigate the process of hail formation and growth in clouds, and improve the existing techniques of artificial modification of hailstorms of various intensities.

Recent studies by the Soviet scientists (Abshaev M. T., Bibilashvili N. Sh., and others) made it possible to more accurately define the spacial structure of hail cores in a cloud, the location of hail initiation, and the area and structure of updrafts, as well as to measure the period of hail core formation and the velocity and direction of their motion. Experiments on hail cloud modification aimed at their suppression showed that seeding should be done in the early stage of hail formation (when conditions are formed for hail initiation) rather than in the hail growth stage as it was suggested earlier. At this stage, it is much easier to achieve positive results from seeding with crystallizing reagents, making the most use of the effect of unstable equilibrium of a supercooled waterdrop cloud and stimulating premature (prior to hail formation) rainfall. Injection

TABLE 1
RESULTS OF ANTI-HAIL PROJECTS IN THE USSR (1972-1979)

6

Region of project	1972		1973		1974		1975		1976		1977		1978		1979	
	TA	EC	TA	EC	TA	EC	TA	EC	TA	EC	TA	EC	TA	EC	TA	EC
Caucasus	446	44	435	99	441	66	490	60	484	46	631	60	600	84	600	92
Krasnodarsky region	520	82	540	61	540	83	542	67	458	87	575	50	625	59	635	73
Ukraine SSR	110	100	210	91	210	82	210	82	275	88	390	99	390	99	395	99
Uzbekistan	243	92	282	81	282	94	300	100	300	89	400	98	410	80	500	97
Georgia	250	95	250	97	250	87	350	99	350	95	350	98	380	97	400	94
Azerbaijan	320	100	447	86	447	92	570	99	737	89	737	97	752	99	822	97
Moldavia	360	96	490	88	500	86	600	95	730	89	810	91	910	73	1000	96
Tadjikestan	320	94	370	82	380	95	420	93	450	79	520	91	550	89	550	71
Armenian	721	70	720	73	750	80	720	70	911	95	911	99	920	99	920	99
Total	3290	86	3684	85	3800	81	4202	86	3695	84	5006	85	5537	86	5822	91

TA - total area protected (thousands of ha)
 EC - efficiency coefficient (%)

tion of crystallizing reagents in the later stages of hail formation is practically useless.

It was found that a wide range of hailstorms may occur depending on the thermodynamic state of the atmosphere and wind regime, these hailstorms having substantially different structure and dynamics. Much like Marwitz (1972) and Browning and Foote (1976), we recognize three main types of hailstorms: single cell, multicell and supercell ones.

Experimental studies showed that one should differentiate modification techniques depending on the type of a hailstorm, dividing them into those aimed at suppression the fall of hail from the hail-forming cells and those preventing the formation of hail in the newly developing convective cells.

In case of single cell hailstorms, modification aimed at suppression the fall of hail is practically useless, since individual cells are typically axi-symmetric and not mobile, and they have a single-stage process of hail formation. Precipitation from these clouds suppresses updrafts, thus causing a convective cell to decay. In this case, it is necessary to carry out modification so as to prevent primarily the formation of hail in the newly developing cells. Those cells are seeded which occur at a level of the $-6^{\circ}\text{C} + -8^{\circ}\text{C}$ isotherms and over, seeding being conducted just after the appearance of their first radar echo. The period of hail formation from this moment on is short and in some cases does not exceed 5 minutes. Seeding in proper time is therefore required for the most effective modification with a minimum consumption of seeding agent. Schematic diagram showing single cell cloud seeding is given in Fig. 1.

Cell elements of a multicell hailstorm have the structure and behavior similar to those of a single cell, but they exhibit a considerable asymmetry and tilt. Due to this, descending precipitation suppresses updrafts only partially, resulting in longer lifetimes of individual convective cells and providing a hailstreak which is nearly continuous. A characteristic feature of multicell hailstorm modification aimed at preventing the propagation of hail formation process is the necessity to suppress the newly formed convective cells and the formation of hail in the mature convective cells.

The greatest effect for this type of modification can be achieved by preliminary seeding of the near-cloud space ahead and in the direction of hail formation process propagation in the weak-echo region beneath the overhang of radar echo. Schematic diagram showing multicell hailstorm seeding in case of prevention of hail formation process propagation is given in Figure 2.

Modification of multicell hailstorm (which has not reached the mature stage of evolution) aimed at preventing hail formation is conducted much in the same manner as in the case of a single cell storm. Schematic diagram showing multicell hailstorm seeding to prevent hail formation is given in Figure 3.

Supercell clouds have a unicellular structure which is circular or elliptical with a characteristic horizontal dimension of 20 to 30 km and a vertical extent of 12 to 15 km. These clouds have an extensive zone (5 to 12 km) of strong organized updraft (25 to 40 m s^{-1}) on the right forward flank

in the frontal part. The updraft zone is revealed as a weak-echo region bounded by a strong echo vault from above, the lower portion of overhanging echo in the frontal and right-flank part, and high-refractivity gradients on the opposite side. A supercell cloud has a lifetime of one to several hours and is accompanied by severe damaging hail in a streak 10 to 15 km wide and several tens of kilometers long. Supercell hailstorms form in a highly unstable atmosphere with a moderate to strong wind shear.

Supercell hailstorm evolution begins with the initiation of organized updraft zone which can be recognized by the appearance of radar echo hook, overhang and its lower portion on the right flank. Because of this, it is necessary to begin supercell hailstorm modification aimed at preventing hail formation as soon as these indications are observed. This preventative modification is conducted in much the same manner as modification of an isolated developing cell in a multicell hailstorm, i.e. the entire area in the upper part of the high refractivity region is seeded at a level of $-8^{\circ}\text{C} + -12^{\circ}\text{C}$ isotherms and 1 km higher if it extends to higher altitudes, as well as the entire regions of weak echo, overhang and its lower right-flank portion at the $-2^{\circ}\text{C} + -6^{\circ}\text{C}$ level. Due to this, the hail growth zone located above the updraft in the lower right-flank portion of overhanging echo, which in turn will result in the disturbance of continuous self-maintained and self-generated supercell process and consequently, in its decay. So far, these works have been experimental by their nature. However, the results of the modification operations carried out in the North Caucasus (Pomtel'nikov V.A., Shtul'man N.G.) showed that in principle, supercell hailstorm suppression is possible.

Soviet scientists continue to test the method of hail suppression suggested at the Transcaucasian Hydrometeorological Research Institute (Lomnadze P. N. et al.) in Georgia. Hygroscopic reagents (NaCl) are injected into the warm part of a cloud and simultaneously or just after that, crystallizing reagents (AgI) are introduced into its supercooled part. Large droplets begin to form rapidly on salt particles due to condensation in the warm part of the cloud, this process being followed by their conversion to precipitation-size particles by coagulation with smaller droplets. Falling from the cloud, precipitation particles reduce its liquid water content. At the same time, some large droplets may be carried to the upper part of the cloud where they may freeze and increase the number of hailstone embryos acting as competing embryos. Crystallizing particles introduced simultaneously into the supercooled part of the cloud act as main competitors for natural hailstone embryos.

This method used since 1967 gives good results for the treated regions. It should be noted that the experiments carried out during the period 1978 to 1979 showed sufficiently high effectiveness of hailstorm modification even in those cases where only hygroscopic reagent was used for seeding. This method appears to deserve further study.

In the hail suppression systems in the Soviet Union and some other countries hailstorm modification is conducted by means of ground-based artillery and rockets.

On the average, each anti-hail detachment has 25 to 60 operational days during a season and treats 50 hailstorms or more, consuming 18 to 30 artillery shells and 3 to 6 rockets per storm, this number sometimes amounting to hundreds of shells and dozens of rockets depending on the type of hailstorms.

The Soviet reagent delivery system adequately complies with the main requirement of modification method - to provide for the precise and expeditious delivery of aerosol into the supercooled part of a cloud at any time and practically in any weather situation.

It is our opinion that the aircraft used for cloud seeding with crystallizing reagent aerosols do not adequately comply with the requirements imposed. This is primarily due to the fact that seeding aircraft might not provide for the expeditious delivery of appropriate amounts of reagent directly into the area of hail initiation and growth in a cloud because of stringent flight and maneuver limitations when flying at the cloud base level in stormy weather (especially, in mountainous regions). It appears that the use of high-altitude aircraft for this purpose will be severely complicated by high flight speeds and limited precision of reagent injection from high altitudes to the -5°C + -10°C levels.

Analysis of the results of hail suppression activities suggests that a better insight into hail physics is essential to increase the effectiveness of hail protection. Therefore, there is an urgent need to develop a theoretical model of hail cloud in real space and time.

The most complete numerical model of hail cloud in the USSR with the best operation performance is that developed by Prof. Kachurin L. G. and his associates. It is a two-dimensional non-steady state model taking into account both thermodynamical and microphysical processes which lead to hail

formation, growth and fall from a cloud. Using this model, the first experiments were carried out to compare the results of calculations and observations of radar reflectivity and kinetic energy of a hailstone flux (Kartsivadze A. I.). This model enables one to analyze actual hailstorms, both naturally developing and modified with crystallizing reagents. The results of numerical analysis showed that the competing embryo concept (i.e., competition between natural and artificial crystals) which forms the basis of the method of hail cloud modification is well-founded from the physical point of view; in principle, hail formation suppression by introducing crystallizing reagents into the supercooled part of a cloud is possible; and the effectiveness of modification is an extreme function of both the concentration of artificial ice nuclei and the level of their injection.

At the present time, the results of studies and experiments on the physics of convective clouds and experience gained in the hail suppression activities in the USSR have been summarized and will be published in the form of Hail Suppression Management and Procedure Manual. It will present physical fundamentals of modification of clouds with various structures, radar methods of hail detection, procedure of making specialized weather forecasts, and estimates of the economic effectiveness of hail suppression activities.

Analysis of the state of the art of hail suppression works in the Soviet Union and other countries shows that further increase in the effectiveness of hail suppression operations involves thorough and comprehensive studies of hail physics and the methods of hailstorm suppression.

As many countries have shown great interest in the development and improvement of hail suppression methods, it seems timely to consider the possibility of setting up an international research project on hail suppression engaging all interested states.

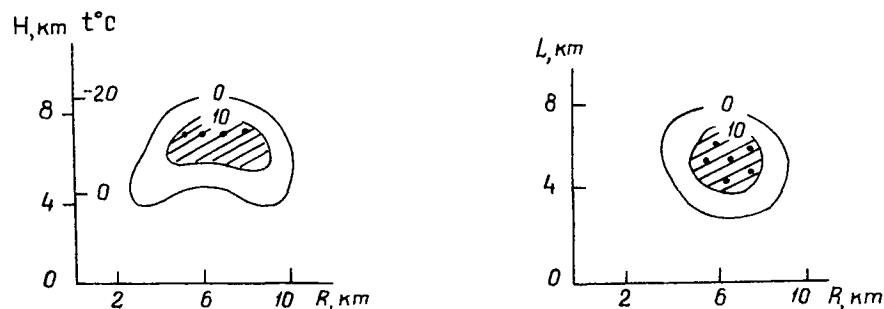


Figure 1. Schematic diagram of single cell cloud seeding in the experiments on hail formation suppression. Reagent was injected at position of dots.

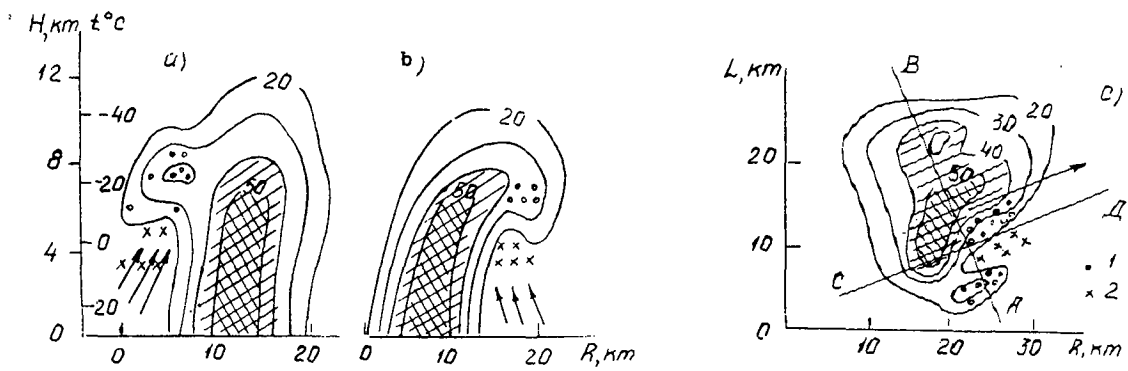


Figure 2. Schematic diagram of multicell hailstorm seeding in the experiments on prevention of hail formation process propagation:

- a) - vertical section along the line AB (in Fig. 2c) through the weak-echo region in the plane normal to the direction of cell motion;
- b) - vertical section along the line CD (in Fig. 2c) through the maximum radar echo and the weak-echo region in the plane parallel to the direction of cell motion;
- c) - horizontal section at an altitude of about 6 km;
- 1,2 - location of reagent injection into the region of hail formation and initiation, and into the updraft zone, respectively.

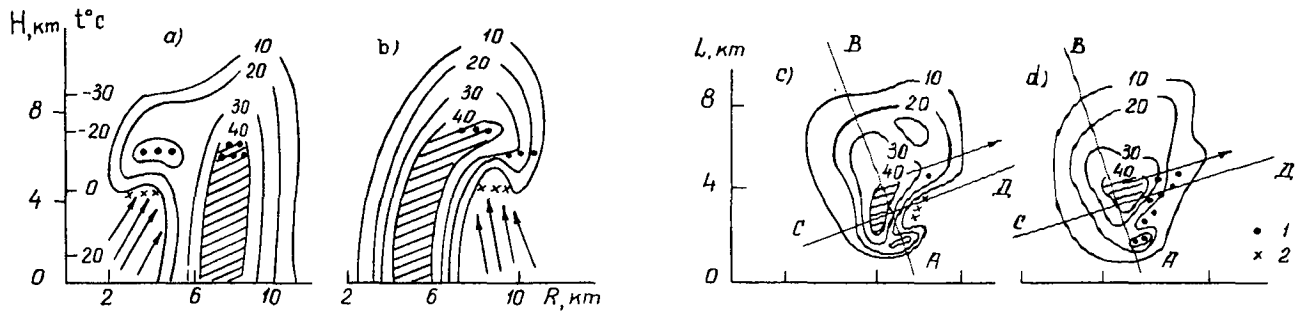


Figure 3. Schematic diagram of multicell hailstorm seeding in the experiments on hail formation prevention:

- a) - vertical section along the line AB (in Fig. 3c) through the weak-echo region in the plane normal to the direction of cell motion;
- b) - vertical section along the line CD (in Fig. 3c) through the weak-echo region in the plane of main cell motion;
- c) - horizontal section at a level of the $-2^{\circ}\text{C} - -12^{\circ}\text{C}$ isotherms;
- d) - horizontal section at a level of the $-10^{\circ}\text{C} - -12^{\circ}\text{C}$ isotherms.

PLANNING OF THE EXPERIMENT ON PRECIPITATION ENHANCEMENT
IN LAKE SEVAN BASIN

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I. INTRODUCTION

High mountain Lake Sevan is the principal regulator of the Armenian water resources used for irrigation, energy, and general water supply purposes. The lake resources have diminished substantially. In less than 50 years some 23 billion cubic meters of water have been drained from Lake Sevan, which constitutes about 40% of its secular resources. As a result, the lake water level has lowered by more than 18 meters.

Lake Sevan waters irrigate vast territories where valuable agricultural crops are cultivated. The estimated need from Lake Sevan waters is approximately 500 million cubic meters per year. However, only about 170 million cubic meters can be taken from the lake without lowering its water level. Hence, the Lake Sevan problem is to find additional sources which could provide for 330 million cubic meters of water per year. At the same time the problem of lake conservation is a strong aspect.

River water from neighboring basins is used to solve a portion of the problem. Another method of obtaining supplemental water is cloud modification.

2. THE EXPERIMENT

The principal task of the experiment is to study the possibility of artificial precipitation enhancement in the Lake Sevan Basin. However, besides the practical importance of this work, the Sevan experiment has a number of scientific, technical, and organizational aspects. They are:

- A. Estimation of precipitation amounts that can be obtained in Lake Sevan Basin by cloud system modification.
- B. Estimation of the possible effect of cloud modification in the Lake Sevan Basin on precipitation amounts in the adjacent areas.
- C. Development of a notion on precipitation producing mechanisms in the Lake Sevan Basin.
- D. Obtaining detailed data on precipitation distribution in the basin.
- E. Testing new cloud modification methods.
- F. Optimizing the conditions and techniques of modification.
- G. Generalizing the experience and results

obtained for use in other regions.

3. METEOROLOGY

Physico-meteorological conditions in the Lake Sevan Basin are favorable for conducting precipitation enhancement experiments. The mean annual precipitation in the Lake Sevan Basin is approximately 550mm, ranging from 370mm at the lake surface to 800-1,000mm near the mountain peaks of the Gegamsky Range (Fig. 1).

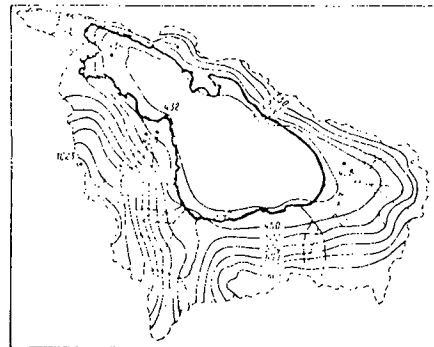


Fig. 1 Annual precipitation amount distribution in Lake Sevan Basin.

The numbers of precipitation days during the year range from 110 days in the lake region to 140 days near the peaks of the Gegamsky Range. The majority of these days are associated with 110 to 120 passing fronts. In winter the precipitation falls mainly from stratiform clouds, and in the summer from convective clouds.

4. PRELIMINARY CONSIDERATIONS

To solve the above mentioned tasks, a meteorological site is being created in the Lake Sevan Basin. This is now equipped with modification and control means necessary for conducting preliminary precipitation enhancement experiments and estimating the results.

Cloud modification experiments aimed at obtaining additional precipitation are based on cloud phase instability. Silver iodide is used as the nucleating reagent. Remote control pyrotechnic ground generators and aircraft serve as the seeding methods.

Rational arrangement of the generators called

for the information on basic circulation parameters in the Lake Sevan Basin, as well as on the character of the reagent diffusion. The circulation in the Lake Sevan Basin was studied by simulation methods. This involved blowing the basin model in the wind tunnel (Gorlin, 1973; Vulfson, 1975) and by numerical modeling (Sherskov, 1978). In the numerical modeling studies, the temperature difference between the lake surface and the land was taken into consideration.

Model blowing in the wind tunnel revealed the complicated nature of the air circulation in the Lake Sevan Basin. It becomes especially clear in the vertical motion field (Fig. 2). There are areas of rather intensive ascending and descending currents over the lake.

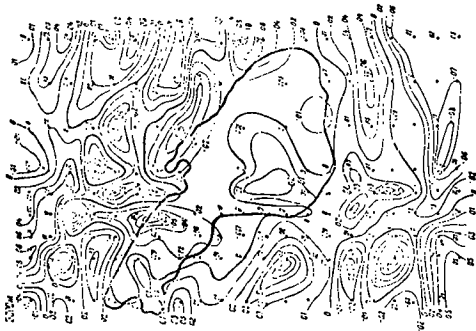


Fig. 2. Areas of ascending and descending motions at northward direction of the leading current; isolines - ratio of the wind speed vertical component to the undisturbed current speed.

In particular, the numerical simulation indicated that in winter the ascending motions over the non-freezing lake are comparable with and often exceed the upslope motions. The existence of the lake seems equivalent to the existence of the mountain range with rather steep slopes.

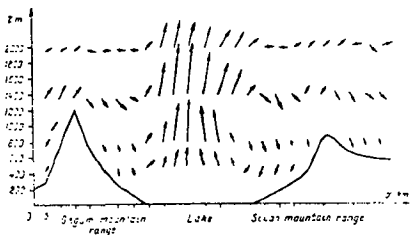


Fig. 3. Velocity field at westward direction of the undisturbed current.

Preliminary calculations of the reagent diffusion showed that with the generators installed near the range peaks at a distance of 6 to 8 km from each other, the area seeding efficiency will be 20% to 40% depending on the meteorological conditions.

"Yak-40" aircraft equipped with pyrotechnic cartridge cassettes and acetone generators are used for airborne seeding.

A Meteotron type installation based on six turbo-jets with a common after burner is being constructed in the Lake Sevan Basin as a non-traditional modification means. The ascending air jet formed by the Meteotron is supposed to be used for local rearrangement of frontal strati or nimbostrati into cumulonimbus for the purpose of transforming widespread precipitation into a shower type near the installation. Theoretical calculations indirectly confirm the possibility of such transformation.

5. EVALUATION

The experiment effectiveness will be evaluated by the results from direct measurements of precipitation amounts. A provisional precipitation gage network based on standard equipment has been established for this purpose which, together with the already existing network, comprises 81 separate points. The gage locations are in places of habitation situated mainly near the lake. An automated precipitation gage network is established to provide for equal density of precipitation observations over the whole basin area, including the mountain region and the lake surface. The network will consist of two subsystems. The first is an "operative" one consisting of a few tens of temperature, wind, and precipitation detectors which radio their indication several times each day. The second is a "memorizing" one which will store precipitation information for about six months at about 200 points. The first subsystem will be used mainly for making decisions on cloud modification and controlling meteorological conditions during the experiments. The second subsystem will be used for providing an estimate of the effect for use in numerical studies.

The amount of snow precipitation will be estimated at each point by the increase of the snow water content, which in turn will be determined by the decrease of the cosmic ray intensity within the snow (Kolomeets, 1979). At present there are nine automatic meteorological stations established in the basin mountain region. A fully automated precipitation gage network will be finalized in 1983. Radio locators will also be used as an indirect method for measurement of precipitation amounts.

At present the site has at its disposal the following:

- A) Eight groups of remote control ground generators (46 units) equipped with 966 cassettes (21 cassettes at each generator) with silver iodide based pyrotechnic compound. The cassettes can be fired at all or individual generators, all at once, or in sequence and in any quantity. The burning time of each cassette is about one hour. There are about 10^{14} ice forming particles released in the atmosphere during each hour.
- B) "Yak-40" aircraft equipped for cloud seeding.
- C) Two radio locators for cloud and precipitation observations.

- D) 90 precipitation gage network points including 9 automatic meteorological stations.

In addition to the above, a "Supermeteo-tron" installation is being constructed at the Lake Sevan site. The distribution of instrumentation is shown in Fig. 4.

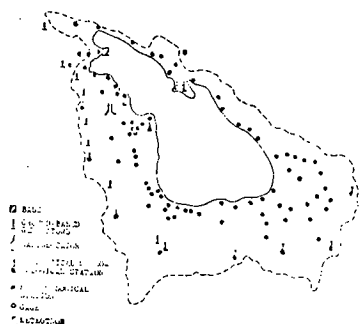


Fig. 4. Meteorological site scheme

6. EXPERIMENTAL PHASE

The planning of the experiment was based on complex considerations of the following questions:

- A) The results of climate-synoptic analysis of precipitation formation processes in the Lake Sevan Basin, some precipitation climatological data, and in particular the precipitation forming ability of different clouds or cloud systems.
- B) Experimental unit duration for different cloud systems suitable for modification, the adequacy of the available precipitation gage network, and the requirements for the precipitation gage network now under design.
- C) Modification schemes commonly used in experiments on precipitation enhancement and the expedience of its application on Lake Sevan Basin conditions.
- D) Necessary and desirable physico-meteorological information on decision-making processes, considerations on operating the experiment, and estimation of results.
- E) The development of numerical models which may be useful in both the development of modification methods and for providing an estimate for experimental results.
- F) Possible predictors based on statistical models, numerical models, or historic synoptico-meteorological data.
- G) Various methods for use in the estimation of experimental results.

The above mentioned points are illustrated in Figure 5. The solid lines show current investigated questions or actions which have been carried out. The dotted lines illustrate the activities now in progress.

It seems impossible to find modification and control sites far enough from each other in the Lake Sevan Basin, thus cross-over seeding schemes have been rejected. A randomized modification

scheme within a single site turned out to be the only possible scheme and this was subsequently adopted.

As a modification objective the winter frontal clouds with low and medium levels and independent of precipitation were taken. In summer, the non-precipitating cumulus clouds were taken.

The seedability conditions for winter frontal clouds are considered to be:

- A) The existence of layers of supercooled liquid cloud droplets
- B) Wind directions in the range of 160° to 330° in azimuth at levels of 700mb and 500mb
- C) The 700mb temperature not to exceed -3°C
- D) The possibility for nuclei from either the generators or the aircraft to reach the supercooled cloud layers.

In the case of seedability conditions for summer cumulus clouds, the following criteria are pertinent:

- A) Existence of a convective cloud system with thickness not less than 2-3 km.
- B) Single convective clouds with thickness of more than 4 km within the basin.
- C) Synoptic situation favorable for convection.
- D) Existence of supercooled cloud droplets with temperatures not warmer than -7°C .
- E) The absence of significant natural crystallization.

The 12-hour period from 0700 to 1900 hours (an interval between two referenced times of precipitation measurements on the meteorostations) was taken as the experimental unit length in convective cloud modification. The 24-hour period from the referenced time of precipitation observations preceding the beginning of seeding is the experimental unit length in winter frontal cloud modification. The 24-hour period following the modification events are declared "buffer" periods to avoid the possible effects from contamination of the basin by ice nuclei. These 24-hour periods cannot be used as experimental units independent of the weather.

A block diagram which illustrates how the head of this experiment makes decisions on the modification activities is shown in Figure 6.

The head of the experiment at a certain time (T) makes a modification decision on the basis of synoptico-meteorological data, the existence of specific cloud types, and the general conditions under which modification can be attempted. The head gives orders to start the observations in accordance with available programs, calculates the quantity of required nucleating reagent, estimates the locations of the introduction of the reagent, and carries out the randomization procedure (opens envelopes which contain "yes" or "no" instructions). In the case of "yes", the generators are started or the airborne seeding

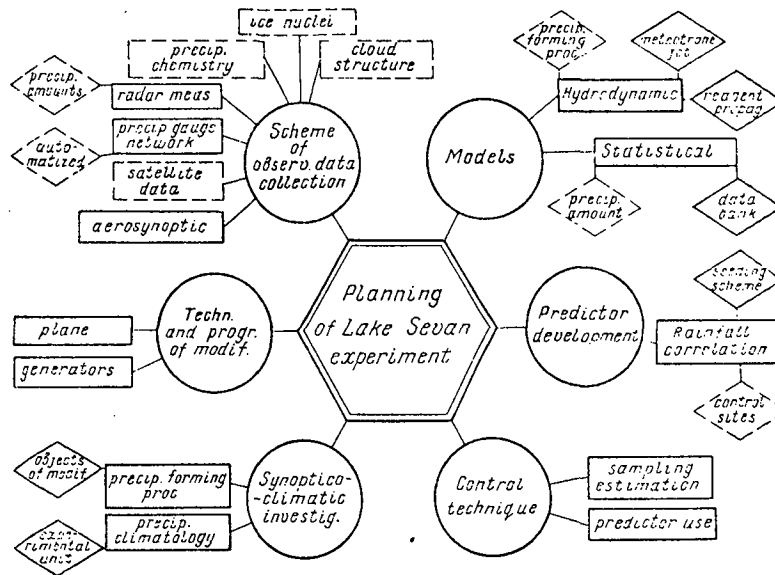


Fig. 5. The experiment planning scheme

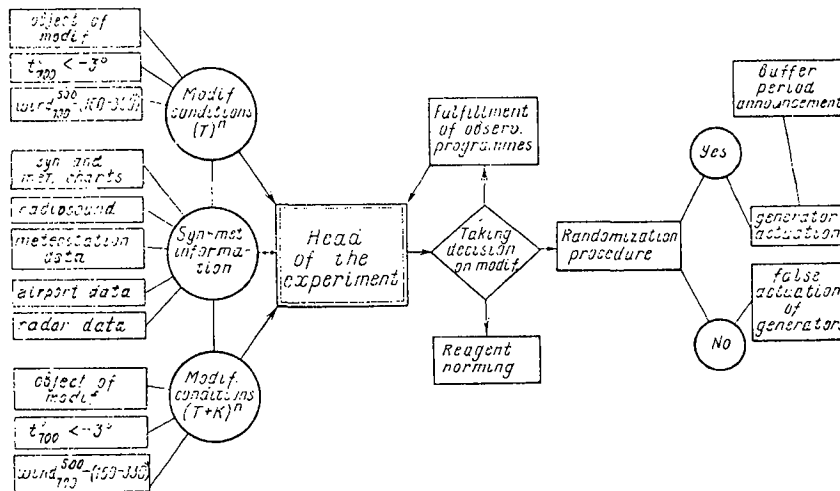


Fig. 6. Block diagram showing decision procedures.

is initiated. In the case of "no", the false starting of ground generators is made and the aircraft carries out only cloud and atmospheric parameter observations. The experimental unit and the operation of equipment is known only to the person who opens the envelope.

7. FURTHER EVALUATION CONSIDERATIONS

The estimation of results from precipitation enhancement experiments is one of the most complicated and least investigated questions in this field. An estimation of precipitation enhancement

with the help of sampling sums (Kolmogorov, 1979) was adopted as the principal method for the statistical analysis of the results of precipitation enhancement experiments in the Lake Sevan Basin. The above mentioned estimation is made by comparing precipitation sums on modification days and on control days. A "reconstructed" precipitation amount is used for the estimation. This method allows for an estimate of precipitation sums for the days when precipitation was not actually measured.

Generally speaking, estimations by way of comparing precipitation for modification days and

control days have been made during previous years. However, the results obtained were not evaluated by confidence intervals, or were evaluated in supposition of certain mathematical models of the effect (Gabriel, 1967), or stochastic model types (Neyman, 1967), describing data on natural precipitation amounts. The advantage of the method suggested by Kolmogorov over previous methods is that it allows an estimate of the modification effects by confidence intervals without the above mentioned suppositions. Variance of the estimate of modification effects can be substantially reduced if there are good predictors of precipitation amounts at the site. Much attention has been devoted to the discovery of such predictors.

At present a statistical model of precipitation amounts per experimental units, depending upon synoptico-meteorological conditions, is being developed. The construction of such a model is based on many years' data on precipitation amounts in the Lake Sevan Basin as well as on data from atmospheric phenomena which cause or attend precipitation. These phenomena comprise the existence and types of atmospheric fronts, their direction and speed, the cloud forms and heights, the stratification of air masses in which precipitation is formed, values of temperature, moisture and pressure near the earth's surface and at standard levels, barometric and thermal tendencies, wind direction and speed, etc. The construction of such models should provide an opportunity to forecast the average natural precipitation amount in the basin by the combination of the above mentioned cloud and atmospheric phenomena. A special data archive is being established for the model development.

Under certain synoptic conditions, the precipitation amounts in the control sites outside the Lake Sevan Basin correlate quite well with precipitation amounts within the basin. The models can use these data for particular cases of predictors. Depending on all conditions, the precipitation amounts in the Lake Sevan Basin will be "forecast" from the precipitation amounts at one or combinations of other sites.

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AN INDICATOR OF PRECIPITATION ENHANCEMENT DUE TO CLOUD SEEDING
 AIMED AT REDUCING HAIL

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1. INTRODUCTION

Precipitation, as one very complex meteorological element, has a significant influence on the character of human activity. Therefore, any enhancement of precipitation is important. The techniques of seeding, types of seeding material, and choices of whether or not seedable conditions exist on any given day are different from country to country and from project to project within countries.

In Serbia (Yugoslavia), hail suppression programs have been conducted from 1967 to the present time. In the early years, seeding was conducted only in three target areas. Now these target areas ($5.5 \times 10^4 \text{ km}^2$) cover all of the Republic of Serbia. Seeding has been conducted by rockets (SAKO 6) which are fired from ground locations. Hail suppression operations are conducted during both day and night hours.

Reduction in all types of damage is the main purpose of this cumulonimbus seeding. However, if we keep in mind some particular seeding methods (Radinovic, 1972; Federer, 1977), it is logical to assume that some precipitation enhancement may result from the cloud seeding activities aimed at reducing hail.

At the present time we have no satisfactory theory for predicting the amount of precipitation which will fall from cumulonimbus clouds. Neither can we totally explain the amounts which may be caused by seeding. Statistical procedures must be used in order to evaluate that portion of precipitation which might fall as a result of seeding (Battan, 1966; Gagin and Neumann, 1976; Woodley, 1977).

The primary purpose of this paper is to indicate a way by which the mean enhancement of precipitation at a point is a possible consequence of precipitation augmentation from individual cumulonimbus clouds and groups of clouds during the period of seeding for hail suppression.

2. CRITERIA FOR OPERATIONAL DAYS

The target area ($2.5 \times 10^3 \text{ km}^2$) is located around the town of Loznica in the northwest part of Serbia. Hail suppression was conducted during the 10-year period 1970-1979. Within the total target area are located more than 50 rocket stations (Fig. 1). Because there are no complete meteorological data within the total operational areas, this evaluation is limited to the area of Loznica.

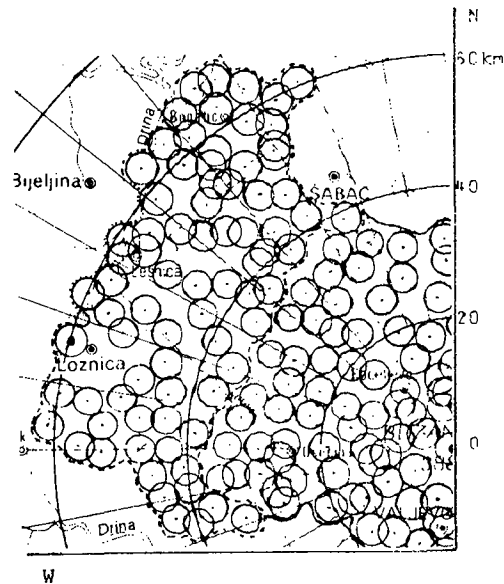


Fig. 1 The network of the ground based rocket stations. Hail suppression polygon of Loznica is encircled with a broken line.

On the basis of complete meteorological data in Loznica for the summer month of May through September during the 10-year period, convective weather types (DCTW) were selected. By definition, the days with convective types of weather are those on which cumulonimbus clouds with precipitation appeared at the meteorological station at least once per day (Cadez, 1964). Verification is on the basis of observed showers of rain or hail from the cumulonimbus clouds.

The selection of days with simultaneous cumulonimbus and precipitation is important because over the long time period of 10 years we can determine the type of most frequent precipitation occurrence. As will be noted later, almost all summer precipitation comes from convective clouds whose initiation and growth depend largely on local topographic characteristics in this region.

The days on which cloud seeding was conducted under the objective conditions of the DCTW are separated on the basis of reflectivity from the cumulonimbus ($\log Z > 3$), the temperature at the top of the accumulation zone ($T \leq -14^\circ\text{C}$), and the temperature at the radar echo top ($T \leq -28^\circ\text{C}$). Precipitation echoes are measured with 10 cm radar systems. All cumulonimbus clouds observed at a distance within 30 km from Loznica are seeded with ground based rockets. Days on which cumulonimbus clouds develop are noted as SDCTW.

The heights of the 0°C, -14°C and -28°C isotherms are determined on SDCTW days from the rawinsonde data at 1200 GMT. Mixing ratios are determined at each of these heights. The mean height of the noted isotherms are calculated for each month from May to September.

$$\bar{h}_i = \frac{1}{n} \sum_{j=1}^n h_{ij} \quad (1)$$

and the mean values of the mixing ratio

$$\bar{r}_i = \frac{1}{n} \sum_{j=1}^n r_{ij} \quad (2)$$

where n is the number of the SDCTW and i the levels.

Also the standard deviations are calculated

$$\sigma_{h_i} = \left\{ \frac{1}{n} \sum (h_{ij} - \bar{h}_{ij})^2 \right\}^{1/2} \quad (3)$$

and

$$\sigma_{r_i} = \left\{ \frac{1}{n} \sum (r_{ij} - \bar{r}_{ij})^2 \right\}^{1/2} \quad (4)$$

An equal number of SDCTW days per summer month as it occurred in the 10-year seeded period were selected from an immediately previous unseeded period. These days selected from DCTW which occurred in the preceding unseeded period were noted to have heights of the significant temperatures and mixing ratios similar to those noted during the seeding period with standard deviations calculated from (3) and (4).

In this way, two sets of equal number of days were selected: one from the seeded period and the other from the preceding unseeded period. It has been assumed that on days of apparent similar weather types, characteristic parameters are reasonably equal. Therefore, it is further assumed that for a long time period it can be expected that differences in some precipitation parameters due to the seeding may be detected.

3. DESCRIPTION OF PRECIPITATION AND RESULTS FROM COMPARISONS OF SEEDED AND UNSEEDED PERIODS

The 24-hour precipitation amounts are considered for the selected days from the 1970-1979 period. Unfortunately, it is impossible to determine which portion of the total precipitation is from cumulonimbus or stratiform clouds, or from combinations of the two cloud forms. However, measurements indicate that the contribution of precipitation from stratiform clouds during summer months is small (Fig. 2).

As noted from Figure 2, the ratio between the mean monthly precipitation amounts from the DCTW events (P_{ci}) during the considered period and the mean total monthly precipitation amounts (P_i) are not far from unity.

$$k = \frac{P_{ci}}{P_i} \quad (5)$$

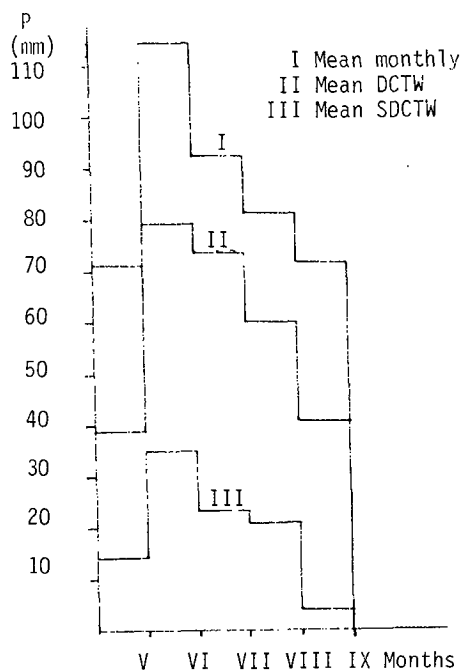


Fig. 2. The different type of the mean monthly amount of precipitation for seeded period in Loznica.

For the months of May through September, the coefficient k has values of 0.54; 0.69; 0.80; 0.74; and 0.57 respectively. This indicates that 80% of the total precipitation which occurred in July fell on days with convective type weather. In May and September the DCTW precipitation amounts are somewhat greater than 50%. Very often in May there are invasions of cold fronts. After these invasions, stratiform clouds occur from which there are no showers or thunderstorms (Curic, 1979). Stable weather situations dominate the month of September. Inversions are sometimes formed in these subadiabatic atmospheric conditions. On occasions a few cumulonimbus with precipitation have been noted to develop when the convection moves upward through the inversion layer.

Inasmuch as the purpose of this paper is to evaluate precipitation from seeded clouds, it is most interesting to consider the events which occur during the SDCTW days. As noted in Figure 2, the mean monthly amount of such precipitation is three times less than the total monthly amounts. Nevertheless, the precipitation from SDCTW days (P_{sci}) are significant so an enhancement of 10% or greater is important for agriculture. A coefficient which expresses the ratio between the mean monthly precipitation amounts of DCTW and the SDCTW is expressed as follows:

$$K_s = \frac{P_{ci}}{P_{sci}} \quad (6)$$

For each of the months from May through September these ratio values are 0.38; 0.44; 0.32; 0.36; and 0.10 respectively. The smallest value of K_s noted in September is likely caused by the stable weather which does not allow inten-

sive cumulonimbus developments.

By the same procedure, an equal number of SDCTW days per month were tabulated from data obtained during the immediately preceding 10-year unseeded period. The mean total monthly precipitation amounts and mean monthly precipitation for DCTW were reduced from the same length of period. These comparisons are presented in Figure 3.

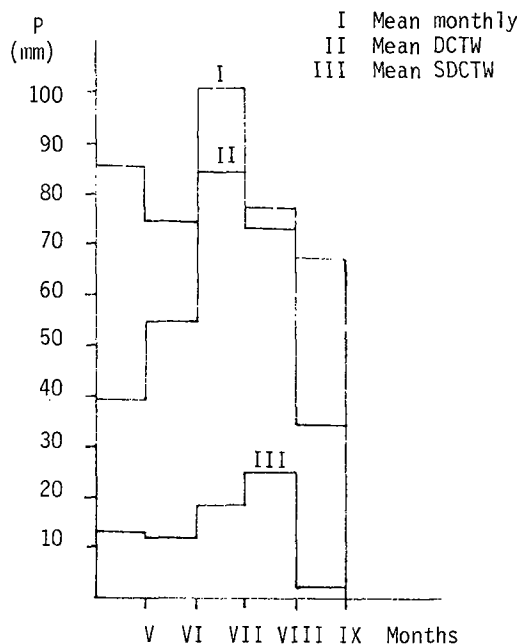


Fig. 3. Same as Fig. 2, but for unseeded period.

The values of the coefficients from (5) for the unseeded period are 0.46; 0.74; 0.79; 0.94; and 0.49 respectively from May through September. As it was for the seeded period, nearly all summer precipitation came from convective days during this period. This is particularly noted in August with a coefficient of 0.94. Coefficients were also developed from (6) with values of 0.33; 0.21; 0.23; 0.34; and 0.08.

A comparison of the coefficients from (5) and (6) for both the seeded period and for the immediately preceding period suggests an increase in precipitation during the seeded period. For long periods of ten years or more we would expect that cumulonimbus, in the mean, have characteristics similar to those noted in other similar periods. Hence, the greater values of coefficient K_c may result from seeding activities. This apparent enhancement expressed as a percent is 4%, 23%, 10% 2% and 4% respectively from May through September. These values agree reasonably well with the results of Medvedev (1976). It is interesting that the largest value of apparent enhancement occurs in June, and may be the result of the larger amounts of seeding material which have been carried into the cumulonimbus clouds.

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PHYSICAL-STATISTICAL METHODS FOR ESTIMATION OF HAIL SUPPRESSION
EFFICIENCY AND SOME ESTIMATES OF SUPPRESSION RESULTS CONCERNING
TARGET AREAS IN BULGARIA

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1. INTRODUCTION

The problem of devising a reliable method for estimation of hail suppression economical efficiency is still standing before the studies in that field. Various modifications of the two basic methods, the so called Control Area (CA) and Time Series (TS) that have been used in the practical hail suppression activities till now, do not give promising results in Bulgaria. The major reasons for that are: large variability in the hail damage yearly distribution with comparatively short data series, impossibility in selection of suitable CA, the hail phenomena frequency and intensity variability during the separate years, variability of hail damage percentages on the various crops etc. Thus, for example, for a period of 15 years the yearly distribution variability of the hail losses are from 7 to 182% in relation to the mean annual losses for the territory of Bulgaria -/7/ and /8/. The modelling of the estimates that have been carried out recently (Buikow, 1977) by the use of some of those methods show relatively great errors in the hail suppression efficiency calculations.

Those facts indicate that a new approach should be found for the solution of that problem, especially as regards regions, where no preliminary experiments have been carried out before the actual organization of the hail suppression activity.

2. BASIC PRINCIPLES OF THE PHYSICAL-STATISTICAL METHOD (PSM) FOR ESTIMATION OF HAIL SUPPRESSION EFFICIENCY

The extent of hail crop damage from each separate hailfall depends on a number of factors:

a) General - climatic, synoptic, thermodynamical and microphysical factors which determine the atmospheric conditions for the development of Cb hail clouds.

b) Local Specific - number, vertical development and structure of Cb clouds over a given region, duration and swath length of their hailfall, hailstone's size distribution and concentration, direction and speed of hail-storm squalls, rainfall intensity, crop structure, phenophases, resistance and cost.

Due to the lack of statistical information history, as mentioned above, about the hail processes and the suppression site, we have opted for a so called physical-statistical method (PSM) for hail suppression prevailing in the country the most suitable factor, on which the method in question is based, is the atmospheric instability energy index as analytically expressed above:

$$\Delta T_{\Sigma} = (T' - T)_{700} + (T' - T)_{500} \quad (1)$$

where T' and T are temperatures of the state and stratification curves respectively, for 700 and 500 mb levels. A high correlation between ΔT_{Σ} and rainfall intensity has been found by Prof. K. Stanchev et al./6/. In the determination of ΔT_{Σ} values the method of Prof. Stanchev, based on a simplified Cb cloud model is used (1960, 1965, 1970). The temperature stratification as obtained from the nearest in time and location radiosounding ascent is corrected for advection factor. Surface pressure, humidity and temperature measured on the site are used. The advection of temperature and humidity for isobaric levels 850, 700, 500 and 300 mb are accounted for through the use of synoptic maps.

Next stage is detection of statistical relations from the type:

$$L^* = f(\Delta T_{\Sigma}) \quad (2)$$

where hail damaged crop areas P^* , damaged areas P_0^* reduced to 100% and hail crop losses S^* from every hail day may be used for a predictand L^* . Those data are secured by the State Insurance Institute and are representative enough in Bulgaria, for the insurance system includes 90% from the whole cultivated area. The first concrete relations from the type $P^*(\Delta T_{\Sigma})$ and $S^*(\Delta T_{\Sigma})$ are defined from the historical data for a region with 1507 km² area in North Bulgaria (Prof. Stanchev and P. Simeonov/8/). Hail suppression in this region has been carried out since 1974 (Bardarski Geran Hail Suppression Site - HSS). Prior to the actual organization of the hail suppression activity, insurance and aerological-synoptical data for a period of 68 hail days have been used. The regression curves are obtained separately for May, June, July and August (Fig. 1). In this way the crop phenophases effect on the extent of hail damages are accounted for indirectly. On the other hand, the influence of the monthly climatic peculiarities in the stratification upon the values of ΔT_{Σ} are accounted for, as well. It has been found out /8/ that the most probable expected losses P_0^* and S_0^* may be determined by the

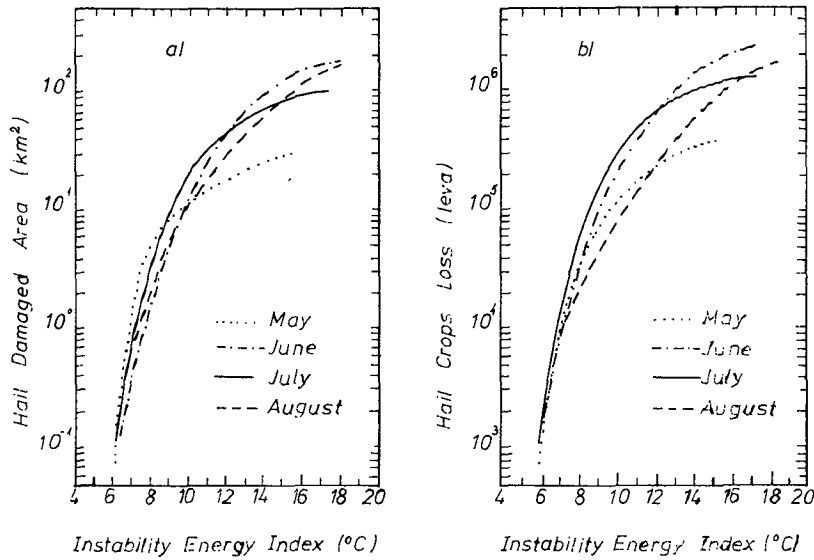


Fig. 1 Regression curves obtained from historical hail days data (1968-1972) concerning Bardarski Geran HSS (1507km² target area)

curves in Fig. 1 through ΔT_{Σ} values with relative mean-annual errors of 14% and 6% respectively.

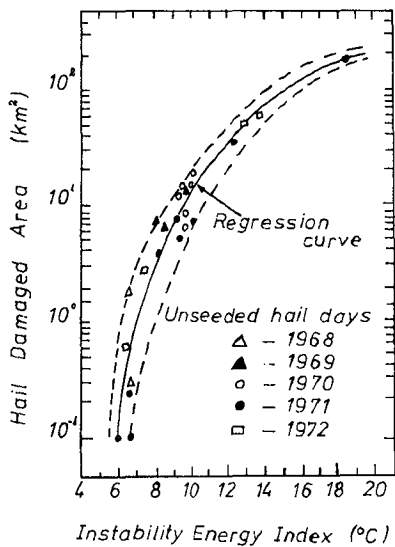


Fig. 2. June regression curve (from Fig. 1a) The area of natural variations is enclosed by broken lines

This figure presents the position of the historical points around the June regression curve.

By means of a regression analysis 8 prediction equations are obtained for the graphical relations shown in Fig. 1. The equations are of the following type:

$$\hat{L}^* = a_0 + a_1 \Delta T_{\Sigma} + a_2 (\Delta T_{\Sigma})^2 + a_3 (\Delta T_{\Sigma})^3 \quad (3)$$

The correlation coefficients are of the order

of 0,82-0,95 for the eight different equations.

The effect from the hail suppression activity during a given summer season on the damaged areas and hail crop losses may be calculated by the following formulae:

$$\delta P^* = \sum_{i=1}^n \frac{bP_{oi}^* - P_{ri}^*}{bP_{oi}^*}; \quad \delta S^* = \sum_{i=1}^n \frac{cS_{oi}^* - S_{ri}^*}{cS_{oi}^*}; \quad i=1, n \quad (4)$$

where P_{ri}^* and S_{ri}^* are the actual damaged areas and insurance hail crop losses respectively, and b and c - corrective coefficients accounting for changes in crop areas and value of crop production from one year to another.

$$b = P / \bar{P} \quad \text{and} \quad c = V / \bar{V} \quad (5)$$

where P and V are the size of crop area and value of total crop production, respectively during the hail suppression season, and \bar{P} and \bar{V} are the mean-annual costs of these entities from a historical period of several years.

The following indexes for estimation of hail suppression economic efficiency during a given season are introduced.

$$\begin{aligned} \mathcal{E} &= \frac{\frac{1}{k} \sum_{i=1}^n (cS_{oi}^* - S_{ri}^*) - (R_1 + R_2)}{\frac{1}{k} \sum_{i=1}^n cS_{oi}^*} \\ \mathcal{E}_b &= \frac{\frac{1}{k} \sum_{i=1}^n (cS_{oi}^* - S_{ri}^*)}{R_1 + R_2} \quad i=1, n \quad (6) \end{aligned}$$

where \mathcal{E} is the relative economic efficiency in

relation to the expected losses, E_b - pay-back of current expenses invested in the hail suppression, R_1 - rocket costs and R_2 - payment for salaries, transport, materials, etc., K - percent insurance coverage of the total value of production.

In some individual cases a climatic similarity between the basic region and another nearby region with HSS may be found in the space-time distribution of the hail processes and hailfall. In such cases the statistical relations of Fig. 2 are adjusted to the second region, as well. In a first approximation this is done by multiplying the whole range of expected P_2^* and S_2^* loss values from the regression curves of Fig. 2 by the following coefficients respectively:

$$k_{p_2} = \bar{P}_2 / \bar{P}_1 \quad ; \quad k_{s_2} = \bar{V}_2 / \bar{V}_1 \quad (7)$$

where \bar{P} is the average crop area in the region, \bar{V} is the mean total cost of production during the historical period, index "1" refers to the basic region, while index "2" refers to the region to which the regression is adjusted. The representativity of this adjustment is checked by working out historical data from the second region and examining the deviations from the basic statistical relations.

If a high correlation with hail losses is determined, the PSM could be extended by including some other predictors, as well. Such kind of studies are under development now.

3. PRELIMINARY ESTIMATES CARRIED OUT BY THE PSM AND ANALYSES

Using PSM the hail suppression efficiency of the activities carried out during the period 1974-1977 at Bardarski Geran HSS is estimated and the results are given in publications /9/ and /11/. In this report we shall dwell on the estimates carried out for Gelemenovo (South Bulgaria) experimental HSS having a target area of 1480km². In this way the possibilities for the Method's adaptation, as we mentioned above, will be shown. The regression relations from the type $P^*(\Delta T_\Sigma)$ are adjusted with a coefficient $k_{p_2} = 0,66$, and those from the type $S^*(\Delta T_\Sigma)$ with a coefficient $k_{s_2} = 1,36$. The adjusted curves for July are given on Fig. 3. The narrow scatter of the historical cases from 1968 is obvious.

The hail suppression efficiency analysis for the days of July shows that there is no effect for the three operational days of 1976, which has fallen in the range of natural variations; a reduction of hail damages is achieved for 5 days of 1975 and 1976; there is a full effect for the rest of the days - no hail losses are registered.

The PSM enables the classification of the hail days according to the value of ΔT_Σ energy index into 3 generalizing groups:

- slight $5.5^\circ \leq \Delta T_\Sigma < 9.0$
- moderate $9.0^\circ \leq \Delta T_\Sigma < 12.0$ (8)
- heavy $12.0^\circ \leq \Delta T_\Sigma$

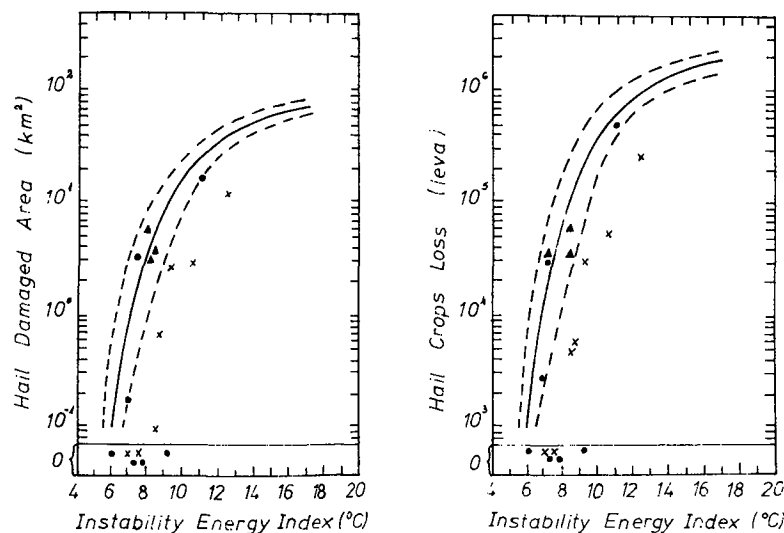


Fig. 3 July regression curves adjusted to Gelemenovo experimental HSS: unseeded (historical hail days from 1968 (▲); hail suppression efficiency during hail days of 1975 (X) and 1976 (◆)

Year	Number of seeded days	Number of hail-loss days	Expected damaged areas(thous.ha)	Actual damaged areas(thous.ha)	Percentage of decrease of damaged to expected areas	Expected crop-hail losses (thous.leva)	Actual crop-hail losses(thous.leva)	Percentage of decrease of crop-hail losses to expected ones	Expenses for rockets (thous.leva)	Other expenses	Relative economic effectivity (%)	Pay-back (leva/one lev)
1974	14	6	6,2	0,6	90	1241	83	93	264	354	68	3,75
1975	45	17	19,4	5,0	74	4042	940	77	1440	290	55	3,59
1976	24	9	8,2	3,8	54	1798	770	57	426	323	22	2,74
1977	23	14	34,2	17,5	49	5480	3969	28	844	373	16	2,48

Table 1. Hail suppression estimate results obtained from Gelemenovo experimental HSS

Year	Number of seeded days	Number of hail-loss days	Maximum of instability energy index ΔT_{Σ} ($^{\circ}\text{C}$) in the year	Percentage distribution of the number of seeded days			Estimates using time series method			Estimates using phys.-stat.method	
				$5,5^{\circ} \leq \Delta T_{\Sigma} < 9^{\circ}$ (%)	$9^{\circ} \leq \Delta T_{\Sigma} < 12^{\circ}$ (%)	$\Delta T_{\Sigma} \geq 12^{\circ}$ (%)	The extent of hail-activity in the year	Decrease of damaged to expected areas (%)	Decrease of crop-hail losses to expected ones (%)	Decrease of damaged to expected areas (%)	Decrease of crop-hail losses to expected ones (%)
1	2	3	4	5	6	7	8	9	10	11	12
1974	14	6	10,6	72	28	-	slight	95	75	90	93
1975	45	17	12,5	78	20	2	moderate	98	16	74	77
1976	24	9	11,5	80	16	4	moderate	92	31	54	57
1977	23	14	16,2	40	48	12	heavy	86	74	49	28

Table 2. Comparison between efficiency estimates obtained by the two methods - TS and PSM

It is very important to know whether a hail storm from the heaviest type (ΔT_{Σ} from 15° to 18°) has occurred during a given year, which causes 60-80% from the total annual losses.

The separate estimated years in Table 1 are characterized by hail phenomena frequency and intensity variability. The high efficiency obtained in 1975, in spite of the high frequency of hail days, is due mainly to the high number of slight and moderate hail processes. There is a rapid efficiency decrease in 1977. In spite of relatively moderate frequency of hail storms during that year, the percentage of moderate and heavy storms is higher and there is a case of 1 heavy hail storm with $\Delta T_{\Sigma} 16,2^{\circ}$.

Now in Bulgaria a variant of the TS method is

applied for estimation of hail suppression efficiency. The hail suppression years are classified according to general aerological-synoptical criteria as slight, moderate and heavy hail years. According to this classification the minimum, medium and maximum values of damaged areas are chosen respectively from the historical series. Then this concrete value is compared with the actual damage area's value for the hail suppression year. Table 2 presents a comparison between efficiency estimates having equal indexes but obtained through the two methods TS and PSM. The years are classified by criteria (8) and the absolute maximum value of ΔT_{Σ} in a given year. Greater variability may be observed in the estimate values carried out by the TS method - columns 9 and 10. This is a result of considerable variations in the extreme values in relation to the mean-annual value obtained from the historical series. The

application of the TS method in 1977 was quite complicated. The value of total damaged area in 1977 occurred to be higher than the value of the maximum damaged area as obtained from the historical (1957 - 1971) time series. In other words, there is no guarantee that the new hail damage maximum value will be obtained during hail suppression seasons within the expected limits.

4. CONCLUSION

The PSM for estimation of hail suppression efficiency which is developed at the Institute for Hydrology and Meteorology (ISM) is better grounded scientifically in comparison with the TS methods that have been used till now. It enables the classification of hail days according to the energy indexes of the atmosphere, examination of hail suppression efficiency for separate summer seasons and determination of the effect for separate operational days. The results obtained by the PSM single out the cases where no marked effect is achieved, so that all developing and experimental activities could be directed towards the study of such kinds of hail processes.

Our aim is, of course, a further perfection of the PSM using a wide range of historical information. It would give possibilities for testing of other representative predictors. Some of them are already under investigation and the preliminary results are quite encouraging.

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STUDIES OF THE INFLUENCE OF EXPLOSION UPON THE
DEVELOPMENT PROCESSES OF CONVECTIVE CLOUDS

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1. INTRODUCTION

Hail suppression by the explosion method has been used for many years in China. Generally the small gun, small rocket, and anti-aircraft gun are used as delivery systems. According to the analysis of data in some counties of China (1, 2) hail suppression by the explosion method has obtained some successes in the reduction of hail damage. However, the question of the actual influence of explosions on hail clouds still remains unknown. Vittori (3) noticed the mechanical effect of a shock wave on hailstones (mechanism of cavitation). Goyer (4) had demonstrated that the mechanical effect of weak shock waves can induce freezing in supercooled water. However, the experience of hail suppression in China indicated that the explosion can rapidly induce the formation of such phenomena as precipitation, hole in the cloud, weakness of cloud intensity, etc. (5, 6, and 7). These phenomena cannot be explained by the above mentioned mechanism. Since 1972 a series of simulated and field experiments have been conducted for purposes of clarifying the physical influence factors of explosions on the development of convective clouds.

2. SIMULATED EXPERIMENT OF EXPLOSION EFFECTS ON UPDRAFT FLOW

We consider that convective clouds form and develop by a continuous updraft flow which could be influenced by an explosion. In this experiment, a convective updraft is simulated by a smoke column. As a point source of explosion, we use the specific small gun or packet of gun powder. The motion of the smoke column has been given detailed observation, along with the use of cine cameras.

In these experiments the main similarities are considered as the geometrical and dynamical similarities. For convective clouds, the vertical dimension of the updraft flow column is an order larger than the horizontal dimension. The width of the smoke column of two kinds are taken as 0.5 cm and 1.0 cm, corresponding to 15 cm and 30 cm in length within our experiment. The ratio of length to width is about 30, which is geometrically similar to the cloud updraft flow.

The equation of the vertical motion in and below the convective cloud is

$$\frac{\partial W}{\partial t} + W \frac{\partial W}{\partial Z} = g \frac{T'}{T} + k \frac{\partial^2 W}{\partial Z^2} + F \quad (1)$$

where W = vertical velocity, t = time, g = gravity acceleration, T and T' = the temperature of environmental air and the temperature difference between the cloud and the environment, k = the turbulent mixing coefficient, and F = the external force.

For the stationary motion of simulated smoke columns there are two main non-dimensional parameters, namely the Reynolds number and the Froude. The values of these two numbers in atmospheric convection and in our simulated experiment are listed in Table 1. Here it is shown that the verge number in the atmosphere and the experiment is similar, but the magnitudes of the Reynolds number in the experiment are much larger than unity. For this reason, the second term on the right side of the equation (1) can be neglected.

There are still two non-dimensional parameters. One is the ratio between non-stationary force and inertial force, namely the Strouhal number. The other is the ratio between inertial force and external force. We consider that the effect of an explosion on a smoke column is an external force and can be expressed by the gradient force of super pressure of shock waves produced by the explosion, namely:

$$\frac{1}{\rho} \frac{\Delta P}{\Delta H}$$

Where P is superpressure, ρ is the density of the air. In such a way this ratio can be written as the Euler's number, namely

$$\frac{W^2/P}{H/\rho H} = \frac{W^2 \rho}{P}$$

A special small gun which accommodates one to two grams of common gun powder is used as an explosion source in the indoor laboratory. The intensity of the shock wave (super pressure) was measured at different distances. The change of the smoke column after the explosion has been photographed by cine camera. According to the movement of the characteristic point in the smoke

TABLE 1. Values of parameters of convective updraft and smoke column

	H(m)	W(m/s)	k(m/s)	T'(c)	Re	Fr
Atmospheric convective updraft	1000	5	50	0.5	100	1.2
Smoke column						
Kind 1	0.15	0.4	0.2×10^4	33	3000	1.1
Kind 2	0.30	0.7	0.2×10^4	49	10000	1.0

column, we can measure the speed of the smoke. The main results of the experiment are:

A. Reduction of the smokes upward speed and the oscillation of the smoke column can be observed about 0.2 to 0.3 sec. after the explosion. The smoke column has restored to its original speed and overall state one second following the explosion. Thus, we obtained a Strouhal number (st) of 0.5 to 0.3.

B. Critical super pressure of the shock wave which starts to induce an oscillation of the smoke column of type 1 is 2 grams per cm, and for smoke column type 2 the critical super pressure is 7 gm per cm. Therefore, the non-dimensional parameters for the Euler's number (E) are 0.8 and 0.7 respectively.

According to the principle of similarity we can conclude that the explosion with ordinary intensity (its super pressure of shock wave is not less than 54 gm. per cm) can influence the updraft, if the convective updraft speed in the atmosphere is not larger than 3 meters per sec. It is necessary to trigger an explosion with a large intensity (super pressure larger than 600 gm. per cm) for providing some influence on the updraft, if the convective updraft speed is greater than 10 meters per sec.

C. When the super pressure is greater than 3 grams per cm, a 20% to 30% reduction of upward smoke speed has been observed.

The time of unsteady change within the convective updraft following the explosion is about 100-260 seconds. Therefore, the effect of the explosion in and below the convective cloud can be maintained for several minutes. Continuous gun shots of anti-aircraft guns would give a continuous influence on the convective updraft and, eventually, influence the process of cloud development.

3. INFLUENCE OF EXPLOSION (GUNSHOTS) ON PRECIPITATION (7)

During the two year period 1973-1974, a total of 44 field experiments were conducted to examine the influence of explosions (gunshots of anti-aircraft guns) in convective clouds and in altostratus clouds. The raindrop spectra were observed at ground level before and after gunshots. The following conclusions can be made from these experiments:

A. Gunshots can produce precipitation from cumulus congestus clouds in which precipitation had not appeared before the gunshots. Within 13 experiments, precipitation was generated following the gunshots in 10 cases. One example of an experiment is shown in Figure 1. It is noted that raindrops with diameters of 1-2 mm were observed three minutes after the gunshots. Additionally, the intensity of precipitation quickly increased within six minutes after the gunshots.

B. Gunshots on precipitating cumulus clouds can enhance precipitation (21 cases from 26 experiments). The enhancement of precipitation from altostratus precipitus following gunshots was observed in six cases from eight experiments. The main rain parameters (intensity of precipitation, concentration and size of raindrops) quickly increased; in

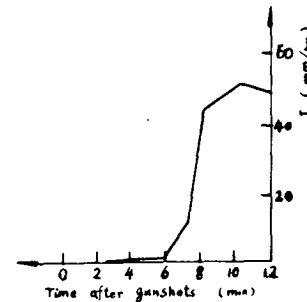


Fig. 1 Time variation of precipitation intensity after gunshots (28 July 1973, cu cong)

general, some three to seven minutes after the gunshots. The period of increase of all rain parameters after gunshots is very short. The parameters are usually restored to their initial states in seven minutes. An example of the time variation of the rainfall, and the rain spectrum, before and after the gunshots are shown in Figs. 2-A and 2-B.

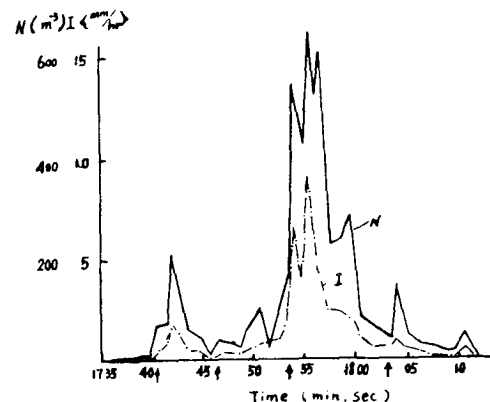


Fig. 2-A. Time variation of rainfall before and after gunshots (21 Aug. 1974 cu cong)

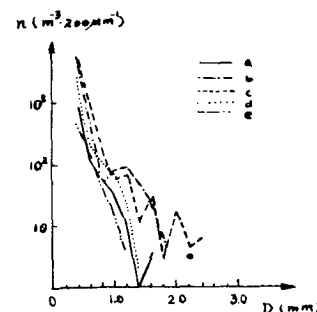


Fig. 2-B. Time variation of rain spectrum before and after gunshots (21 Aug 1974, cu cong)

- a, 1 min. 5 sec. before gunshots, $I=1.04$ mm/hr
- b, 0.5 min. after gunshots, $I=6.54$ mm/hr
- c, 2 min after gunshots, $I=9.22$ mm/hr
- d, 6 min. after gunshots, $I=2.05$ mm/hr
- e, 8 min. after gunshots, $I=0.59$ mm/hr

C. The double maxima in rain spectrum following the gunshots on cumulus and altostratus clouds was observed. An increase in the concentration of raindrops with diameters of 1-2 mm is obvious.

The above mentioned phenomena show that the effective gunshots may be dynamical. The gunshots could influence precipitation through alterations of the updraft in and below cloud. Preliminary calculations indicate that once an explosion alters the convective updraft, the existing raindrops in the cloud can fall ahead of schedule, or the intensity of precipitation may suddenly increase, and the rain spectrum on the ground will be altered in two-three minutes following the gunshots. The appearance of a double maxima in the rain spectrum indicates that the gunshots could promote the coalescence of small droplets as well as shatter the larger drops.

4. INFLUENCE OF EXPLOSIONS ON THE EVOLUTION OF CUMULUS HUMULIS

During the 1973-95 period, the experiments of gunshots on developing cumulus humulis were activated in the field. The location of gunshots was generally selected at the top of the cloud tower. The change of the cloud top and the appearance of the overall cloud was observed by cine camera, theodolite, and range finders. In most cases within the 13 experiments, the dispersion of cloud bubble was observed. The time variation of the height of the two cloud bubbles is presented in Figure 3.

The bubble C. is with gunshots, and the bubble B. is the control without gunshots. It is noted that the top of the cloud bubble C. moved downward following gunshots while the top of cloud bubble B. maintains its original tendency upward.

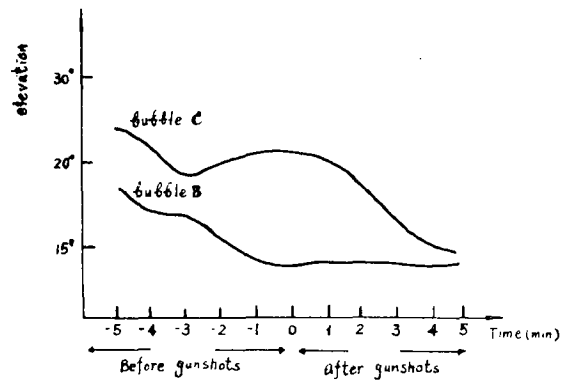


Fig. 3. Time variation of elevation (height) of convective bubbles (16 July 1974 Cu hum)

Another example of an experiment is presented in Figure 4. At the cloud top where a gunshot was administered there appeared a gap with a width of 100 meters in about two minutes after the gunshot. In three minutes after the gunshot this gap becomes an obvious hole and then the cloud disperses. This appears to be another form of the influence of gunshots on particular parts of the clouds. The dispersion of small clouds after gunshots has been observed many times and we consider this an impossible chance variation.

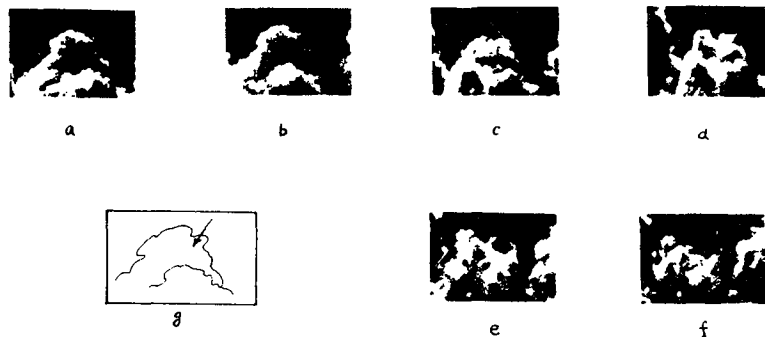


Fig. 4. Influence of gunshots on the local structure of cumulus humilis (19 July 1974)

- | | |
|---|-----------------------------|
| a. 0.7 min. before gunshots | b. On the time of gunshots. |
| c. 1.5 min. after gunshots. | d. 2 min. after gunshots |
| e. 3 min. after gunshots. | f. 3.5 min. after gunshots |
| g. The pointed site which shells came into. | |

It is interesting to note that the shells had been placed on the median part of the cloud during experiment of 26 July 1974. Following the gunshot, the cloud quickly increased in the form of a thin column with loose structure. This is a rare phenomenon in natural processes of cloud development.

5. RADAR OBSERVATION OF THE EXPLOSION EFFECT ON HAIL CLOUDS.

During the 1975-1977 period of hail suppression experiments, 11 hailstorms and thunderstorms which were treated by anti-aircraft guns were observed in detail by radar within the county of Xiyang of province Shanxi (8). Some notes on the radar observations in regards the explosion effect on hail clouds are presented in Table 2. In nine of the eleven cases some obvious changes occurred in the main characteristic of radar echo and its evolution.

At the site of the gunshots in the hail clouds there appeared an echo or weak echo region, then the echo hole develops and moves downward. Sometimes this hole extends to the base of the cloud with a diameter usually in the range of 3 to 5 km. The maximum time of maintaining this effect is greater than 15 minutes. In seven of the hail cloud experiments there appeared a descent

of echo top, a weakness of cloud and split of the intense echo region following the gunshots. Five of the hail cloud echo tops from seven experiments descended in the range from 1 to 6 km.

It was found that the effects are obvious when the gunshots are concentrated on the updraft region or echo wall where there is an intense gradient of reflectivity. These phenomena suggest that the explosion promotes the descent of echo and raindrops so that an echo hole or weakness in the echo region quickly appears at the level of the gunshot. The effect of the explosion appears to be a trigger mechanism where the duration of the echo hole is only several minutes. The further extension of the echo hole which causes the reduction in cloud top appears to depend on the down-draft and descent of precipitation particles.

6. SUMMARY

Based on the above mentioned experiments and observations a physical hypothesis of influence on convective clouds by explosions has been proposed. This is noted in Figure 5. The shock wave produced by the explosion obviously disturbs and alters the primitive updraft in the cloud.

Above the level in the explosion the more important effect is the promotion of an updraft enhancing the development of cloud top.

Table 2. The situation of radar observation about explosion effect on hail clouds.

No	dates	time of gunshots	number of the shot shells	main characteristic of radar echo and its evolution
1	14 July 1975	18:15-18:40 18:15-18:40	234 85	on the shot site of cloud appeared obvious echo hole with maximum diameter 4-5 Km. top of echo fell down 1.6 Km, cloud weakened.
2	11 Aug. 1975	22:00-22:15	28	on the shot site of cloud appeared small hole.
3	6 July 1976	15:50-16:20	75	on the shot site of cloud appeared obvious echo hole with diameter of 3 Km, top of echo fell down about 5 Km, cloud weakened.
4	10 July 1976	19:03-19:10	66	on the shot site of cloud appeared echo hole, intense echo region split.
5	11 July 1976	12:25-12:45	67	on the shot site of cloud appeared a gap of echo.
6	12 July 1976	14:20-15:00	56	on the shot site of cloud appeared a small hole, but it was not obvious.
7	22 July 1976	15:37-15:52	200	on the shot site of cloud appeared an echo hole with diameter of 5-6 Km, top of echo fell down 6 Km after gunshots, cloud gradually split and dispersed.
8	25 June 1977	18:30-18:40	60	on the shot site of cloud echo weakened, its top fell down 3-4 Km.
9	29 June 1977	12:37-12:49	31	on the shot site of cloud appeared an echo hole with diameter of 2-3 Km.
10	29 June 1977	17:05-17:30	174	on the shot site of cloud appeared obvious echo gap with size of 3-4 Km intense echo region weakened.
11	1 July 1977	16:35-16:42	40	no obvious change

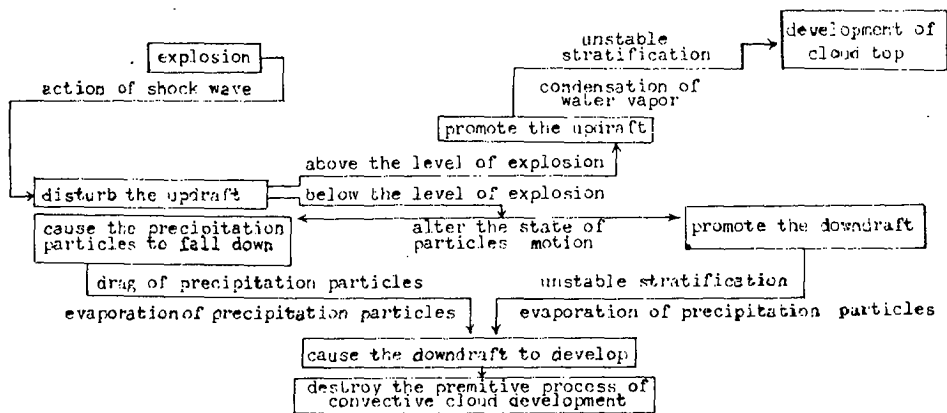


Fig. 5. A diagram of physical hypothesis of influence of explosion on convective cloud.

7. REFERENCES

Below the level of explosion the downdraft flow is induced. Alteration of the updraft can destroy the primitive state between the motion of rain particles and airflow, then the descent of precipitation particles is produced. Because the drag of falling particles and evaporation of raindrops through the path of descent the downdraft is accelerated. Eventually the development of this downdraft can destroy the primitive process of cloud evolution. Possibly, this can produce a rainfall or hailfall earlier in the life cycle of the cloud and prevent further formation in growth.

According to the hypothesis noted in Fig. 5, the effect of an explosion in convective clouds will be larger than in stratiform clouds. The effect will be much larger in severe storms, provided the intensity of the explosion is large enough within the areas of instability and intense vertical motion. Within convective clouds which contain existing precipitation particles, the effect of explosions will be larger than in those without precipitation. Therefore, the more obvious effect will be observed in the situation of gunshots placed within the accumulation zones of convective clouds. These hypotheses are waiting for a quantitative investigation.

The authors wish to express thanks and deep appreciation to the late Professor Gu Zhen-chao for his unforgettable lead and support.

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PRELIMINARY ANALYSIS OF REPORTED WEATHER MODIFICATION ACTIVITIES IN
THE UNITED STATES DURING 1980 AND COMPARISON WITH DATA FOR 1973-1979

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1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) has been delegated responsibility for administering a weather modification reporting program under Public Law 92-205. The law requires that all non-Federally sponsored attempts to modify the weather be reported. Federal agencies also report their weather modification activities to NOAA under interagency agreements. Since 1972, the reporting program has become the single, authoritative source of data on weather modification projects carried out in the United States and its territories.

The reporting procedures include the submittal of Initial, Interim, and Final Reports covering weather modification activities for individual target areas. Initial reports are to be submitted 10 days or more prior to actual modification activities. Interim Reports are required for those projects active on January 1 of each year and must be filed within 45 days. A project may be carried out intermittently at one location for one or more years, or a project may begin and end within a year. Often, projects are completed early in a year and restarted near the end of that year at the same location with the same techniques. In this case, only one project at the one location would be used in summarizing the number of projects for the calendar year.

As of the deadline for manuscript submission, all the required reports for CY 1980 had not been filed. A complete summary report will be published later by NOAA and will be available from the author. This paper includes a preliminary analysis of reported weather modification activities for most of CY 1980 and a limited comparison of the results with some previously published data for prior years (National Oceanic and Atmospheric Administration, 1980).

2. ANALYSIS

Table 1 provides information on activities reported from January-December 10, 1980. Although 61 reports were received, there were only 48 separate locations where attempts to modify the weather were carried out during the year. The data show that 19 percent of the nonduplicative activities were supported totally or in part by Federal funds.

Table 2 shows the various types of operators and sponsors of weather modification activities in CY 1980. The "Private" category covers individuals such as a ranch owner or farmer. A group of farmers and others in a county (or counties) would qualify as a community association. Federal sponsors were the Air Force, Bureau of Reclamation,

National Oceanic and Atmospheric Administration, and the National Science Foundation. The total number of sponsored activities (52) is greater than 48 (the number of separate locations with activities) because several projects had more than one sponsor.

Table 3 summarizes the number of weather modification activities and the target areas for each State during the year. The total target area within the 20 states represents 3.2 percent of the area of the United States. Ninety-six percent of the activities were located west of the Mississippi River.

Table 4 shows that most weather modification activities were to increase precipitation. Seven activities had two purposes -- rain increase and hail alleviation.

Table 5 shows that ground-based AgI burners were used in 42 percent of the activities in CY 1980. Aircraft were used in 68 percent of the projects during the year.

3. COMPARISON OF DATA REPORTED SINCE 1973

Table 6 presents weather modification activity data for CY 1980 and for CY 1973-1979. The data for CY 1973-1979 were extracted from a previous report (National Oceanic and Atmospheric Administration, 1980). A comparison of the data shows that weather modification activities in 1980 were lowest since the reporting program began in 1973.

Compared with CY 1977, the year with the most activity, the results for CY 1980 indicate that there were 47 percent fewer activities, 80 percent fewer community association sponsors, 13 percent fewer States with activities, and a 56 percent reduction in total target area. However, there were increases in the categories of municipal water districts, university operators, and state sponsors. The number of commercial modifiers and utility sponsors remained constant.

4. REFERENCE

National Oceanic and Atmospheric Administration, Summary of Weather Modification Activities Reported in 1979, National Oceanic and Atmospheric Administration, Rockville, Maryland, July 1980, 42 pp.

Table 1 -- Weather Modification Activities in the United States During CY 1980

Total reported activities	61
Nonduplicative activities	48
Nonfederal	39
Federal (all or in part)	9

Table 2. -- Operators and Sponsors of Weather Modification Activities for CY 1980

	Operators/Activities		Sponsors/Activities	
	2	3	4	9
Federal				
Nonfederal	26	44	44	43
Commercial	17	30	0	0
Water Districts	5	6	13	13
Universities	3	6	2	2
Utilities	1	2	3	4
States	0	0	7	11
Cities	0	0	3	3
Airlines	0	0	10	4
Private	0	0	1	1
Resorts	0	0	2	2
Community Associations	0	0	3	3

Table 3. -- Activities and Cumulative Target Area, By State

	CY 1980	
	Activities	Area (mi ²)
Alaska	3	103
California	12	9,276
Colorado	3	4,900
Delaware	1	2,057
Florida	1	4,800
Idaho	2	160
Illinois	1	1,000
Kansas	1	10,641
Mass.	1	6
Montana	1	28,260
Nebraska	1	1,200
Nevada	4	5,605
North Dakota	3	15,578
Oklahoma	1	250
Oregon	1	10
South Dakota	1	2,682
Texas	4	18,584
Utah	3	11,210
Washington	5	1,995
Wyoming	2	655
	51*	118,973

*Some projects were conducted in adjoining States and crossed State boundaries.

Table 4. Purpose of Weather Modification Activities

Purpose	CY 1980
Increase precipitation	33
Alleviate hail	7
Clear fog	9
Research/testing	6

Table 5. -- Weather Modification Apparatus, Seeding Agents and Activities in CY 1980

<u>Apparatus and Agent</u>	<u>Activities</u>
Only ground-based AgI generators (burners)	13
Ground-based AgI generators and aircraft AgI pyrotechnics	7
Ground-based propane dispensers	2
AgI burners and pyrotechnics on aircraft	4
AgI pyrotechnics only on aircraft	8
Aircraft with CO ₂ dispensers	9
Aircraft with pyrotechnics and CO ₂ dispensers	1
Aircraft with AgI generators and CO ₂ dispensers	4

Table 6.--Comparison of weather modification activity data
for calendar years 1973 - 80

	<u>CY 1973</u>	<u>CY 1974</u>	<u>CY 1975</u>	<u>CY 1976</u>	<u>CY 1977</u>	<u>CY 1978</u>	<u>CY 1979</u>	<u>CY 1980</u>
Reports received	65	85	85	74	102	73	64	61
Nonduplicative activities	57	71	72	62	90	61	49	48
Nonfederal activities	55	62	58	53	79	48	39	39
Federally sponsored projects	-	9	14	9	11	13	10	9
Commercial modifiers	19	19	15	17	17	14	15	17
University operators	1	5	5	2	2	2	2	3
Federal operators	-	2	5	4	2	2	2	2
Community sponsors	14	23	22	18	25	11	4	5
Municipal sponsors(water dist	9	9	8	7	7	6	11	13
Utility sponsors	3	2	3	4	3	4	3	3
State sponsors	1	2	2	5	6	8	7	7
States with activities	18	20	25	24	23	19	19	20
Total target area (mi ²)	132,685	153,039	163,194	198,391	270,690	235,519	123,880	118,973
Ave. target area for nonfog activities (mi ²)	3,084	2,637	2,859	4,406	3,469	4,360	3,095	3,042
Modification days (total)	1,810	2,503	1,783	1,963	2,603	1,688	1,238	- -
Modification days (for precipitation)	1,748*	2,250*	1,330*	1,610	2,341	1,357	1,087	- -
Modification days (fog)	39	43	88	161	92	75	90	- -
Dry ice used (kg)	8,982	21,055	20,662	48,172	48,077	19,389	17,463	- -
Silver iodide used (kg)	906	1,019	1,587	1,031	1,412	1,493	902	- -
Liquid propane used (gal)	-	13,356	5,614	17,988	12,295	17,728	11,077	- -
Polyelectrolyte used (kg)	399	45	1,265	5,183	2,353	1,575	641	- -
Hours of operation (air)	1,690	4,559	1,662	1,791	3,309	2,649	2,398	- -
Hours of operation (ground)	34,065	45,986	47,026	52,927	77,320	78,140	15,605	- -

CY 1980 data January through December 10.

*Estimated

-Data incomplete

ANOTHER FIRST FOR WEATHER MODIFICATION

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Weather modification studies thirty years ago led to the first use in meteorology of a new and powerful statistical technique, now widely applied. This is how it happened.

In 1950 Dr. Irving Langmuir and his colleagues in Project Cirrus were conducting exploratory experiments in Weather Modification in New Mexico. After observing what appeared to him as extended area effects, Dr. Langmuir decided to design a definitive experiment by introducing a periodic signal through local area silver iodide seeding. Briefly, by seeding on only a few consecutive days during a week, he hoped to demonstrate that precipitation (and perhaps other weather elements) over a large area would be affected. After several months of operation on this periodic schedule, his preliminary analysis suggested that not only precipitation but general circulation indices over the mid-west and eastern U.S.A. showed a 7-day cycle in phase with the silver iodide seeding in New Mexico.

Recognizing the statistical aspects in the problem of analysis and evaluation, Langmuir approached Professor Sam Wilkes of Princeton University, president of the American Statistical Association at that time. In the meantime, the announcement of the Langmuir analysis produced a small shock wave (or at least skepticism) in the meteorological community. In any case, it presented a scientific challenge, and as a Weather Bureau statistician I was requested to look at his data and make an independent evaluation of his claims.

At this time, the latest thing in time series analysis was Professor M.G. Kendall's "Contributions to the Study of Oscillatory Time Series." The monograph was dedicated to George Udny Yule, with a quotation from J.A. Venn's "The Logic of Chance":

To borrow a striking illustration from Abraham Tucker, the substructure of our convictions is not so much to be compared to the solid foundations of an ordinary building, as to the piles of the houses of Rotterdam which rest somehow in a deep bed of soft mud.

Desiring to be up to date, I decided to use the techniques described, and proceeded with the analysis of the data. My preliminary results tended to confirm the claims of Langmuir and, after a visit from Max Woodbury of the Statistics Department of Princeton University, we soon decided that a group of us at the Weather Bureau should visit Princeton to discuss my analysis and the implications of the results. I remember the train ride to Princeton, with Harry Wexler, Jerry Namias, Ben Holzman and Joe Fulks.

In attendance at the conference in Princeton were Julian Bigelow, Jules Charney, John Von Neumann, Max Woodbury, Carl Rossby and John Tukey. After I presented my analysis and described the techniques used, the young mathematical statistician suggested that this was not the way to analyze such data. He then described an alternative method, couched in the jargon of communication theory with abstract illustrations about trying to measure the movements of electrons jumping around in an electric light bulb.

Nobody understood what he was talking about, with the possible exception of Johnny Von Neumann. Fortunately, however, the message eventually got across. It was, of course, the method of spectrum analysis which since has had such a tremendous impact on meteorology and other sciences. I went ahead to use the method in what was probably the first application of spectrum analysis to weather data.

In August 1951 I was invited by Dr. Tukey to present the results at the Time Series Seminar at the University of Connecticut at Storrs. Among the statisticians in attendance were Chester Bliss, Churchill Eisenhart, Max Woodbury, and numerous graduate students. Principal speakers were R. B. Blackman ("Introduction to spectra of time series"), M.G. Kendall ("Testing significance of serial correlations in the general case"), Leo Tick ("Time Series problems in experimental hydrodynamics"), and John Tukey ("Simultaneous Analysis of Two or More Series"). My presentation followed one by Kendall, who was very skeptical about the advantages of spectrum analysis. In my introduction I remarked that I was using the Tukey method of spectrum analysis "which according to Tukey is the best available method." After the chuckles subsided, John took his feet from the chair in front of him, removed a prune seed from his mouth, and interrupted with, "I'm glad you said it is the best available method!"

Today we all know what happened with spectrum analysis after that first use in a weather modification analysis.

*Revised from introductory remarks at Sixth Conference on Probability and Statistics in Atmospheric Science, Banff, 10 Oct. 1979.

SUMMARY OF REPORT ON
CRITERIA FOR WEATHER MODIFICATION
OPERATIONS AND EFFECTIVE EVALUATION

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We have completed a report relating to the evaluation of future operational modification projects. This is a short summary of that report offered to inform potential interested parties. Copies of the report can be obtained upon request. Our report treats the key issues and presents recommendations for weather modification operations. The primary objective is to provide guidance for achieving effective, reliable evaluation of seeding results, and, consequently, to establish credibility in these evaluations and provide scientific information leading to better understanding and greater skills in the future in this applied field of the atmospheric sciences.

Four basic tasks common to all weather modification operations and that ultimately affect the quality of the evaluation are discussed. These include 1) design of operations, 2) selection of seeding criteria, 3) conduct of seeding missions, and 4) collection and recording of data.

Operations are divided into two general classes for specifying operational criteria. These are common commercial type in which all weather situations satisfying the seeding criteria are treated, and the more scientific piggyback operations in which some randomization is applied, and in which measurements are more sophisticated and comprehensive. The latter type are envisioned as having governmental support of the piggybacking scientific effort.

Design recommendations are presented; basic steps which should be followed in all weather modification operations are listed; potential inputs for determining seedability discussed; components of operational systems outlined; and, requirements for data collection and recording designated.

A number of key issues and recommendations are presented at the end of the report. For example, atmospheric scientists skilled in synoptic meteorology and climatology and in cloud physics and dynamics are considered essential members or consultants to the design team for all types of seeding operations. Also seeding criteria should not only be based on acceptable meteorological concepts, but should take advantage of the latest advances in seeding technology, and apply useful information revealed by a review of the synoptic climatology of clouds, precipitation, storms systems, and other pertinent weather factors in the project area. Seeding criteria should be defined in detail by the operator and the methods used to recognize cloud seeding opportunities clearly stated in the design document. Furthermore, it is essential to have routine measurements of those meteorological factors

from which seedability is determined made at a frequency that permits effective analysis and assessment of all weather situations during the operational period. These are basic requirements for all types of weather modification operations.

The report points out that basic requirements for carrying out seeding missions will differ substantially depending upon such factors as the type of operation (commercial or piggyback), the seeding variable (rain, hail, snow), the climate region in which the target lies, the time of the year, and whether aircraft or ground generators are used to transport the seeding material. However, it is stressed that the primary objective in all types of seeding missions must be to carry out the cloud treatment by applying those techniques dictated by the seeding criteria in use and satisfying any other requirements of the project design.

Radar is viewed as a basic requirement for all precipitation modification operations, since it is an excellent tool for real-time monitoring to recognize seeding opportunities, to re-assess seedability predictions, and to recognize severe weather events in sufficient time to abort seeding missions. Furthermore, radar is considered essential to verification of seeding activities over the target area.

In piggyback operations in which minimum needs for commercial-type operations are exceeded, it is recommended that installation and operation of precipitation networks for improving the measurement accuracy of the treatment variable (rain, hail, snowpack) should have top priority. Second priority should be aircraft for measuring key atmospheric variables essential to evaluation of seeding effects and helpful in addressing the causation problem.

Detailed documentation of data is considered absolutely essential to reliable evaluation of seeding operations, and it is stressed that all data used in any way in the planning and execution of operations should be archived in the most expeditious manner for future use. This archiving is viewed as accomplished best by a state or federal depository for essential records.

The report is available at Illinois State Water Survey, Box 232, Urbana, IL 61801.

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SOME SELECTED PUBLICATIONS IN WEATHER MODIFICATION (1970-1980)

- CONTROLLING THE WEATHER. Howard J. Taubenfeld, 1970. Dunellen Publishing Co., New York, New York, 10022
- WEATHER AND CLIMATE MODIFICATION. Committee on Atmospheric Sciences, National Science Foundation. Grand River Books, Detroit, Michigan. 1980
- WEATHER MODIFICATION IN THE PUBLIC INTEREST. Roberg G. Fleagle, James A. Crutchfield, Ralph W. Johnson, Mohamed F. Abdo. American Meteorological Society and the University of Washington Press. 1974.
- MAKING RAIN IN AMERICA: A HISTORY. Jeff Townsend. Dept. of History, Texas Tech University, Lubbock, Texas. ICASALS Publication #75-3. 1975
- HAIL SUPPRESSION: SOCIETY AND ENVIRONMENT, SELECTED CONTRIBUTIONS TO THE TECHNOLOGY ASSESSMENT OF HAIL SUPPRESSION. Barbara C. Farhar, Institute of Behavioral Science, University of Colorado. 1977
- LEGAL AND SCIENTIFIC UNCERTAINTIES OF WEATHER MODIFICATION. Edited by William A. Thomas, American Bar Foundation for the National Conference of Lawyers and Scientists. Proceedings of a symposium convened at Duke University, March 11-12, 1976. Duke University Press, 1977.
- HAIL SUPPRESSION - IMPACTS AND ISSUES. Stanley A. Changnon, Jr., Ray Jay Davis, Barbara C. Farhar, J. Eugene Haas, J. Loreena Ivens, Martin V. Jones, Donald A. Klein, Dean Mann, Griffith M. Morgan, Jr., Steven T. Sonka, Earl R. Swanson, C. Robert Taylor and Jon Van Blokland. Final report, Technology Assessment of the Suppression of Hail. Illinois State Water Survey, April 1977.
- ENVIRONMENTAL IMPACTS OF ARTIFICIAL ICE NUCLEATING AGENTS. Donald A. Klein, Colorado State University. Dowden, Hutchinson and Ross, Inc. 1978.
- THE MANAGEMENT OF WEATHER RESOURCES, VOLUME I - Proposals for a National Policy and Program. Report to the Secretary of Commerce from the Weather Modification Advisory Board. 1978.
- THE MANAGEMENT OF WEATHER RESOURCES, VOLUME II - The Role of Statistics in Weather Resources Management. Report of the Statistical Task Force to the Weather Modification Advisory Board. 1978.
- COMMUNICATIONS IN STATISTICS, THEORY AND METHODS. Vol. A-8, No. 10 and 11, 1979. Special Issue on the Statistical Analysis of Weather Modification Experiments, Marcel Dekker, Inc., New York.
- NATIONAL WEATHER MODIFICATION POLICIES AND PROGRAMS. A report to the President and Congress. U. S. Department of Commerce, November 1979.
- PAPERS IN METEOROLOGY, U.S. NATIONAL REPORT, 1979-1978. 17th General Assembly International Union of Geodesy and Geophysics, Canberra, Australia, Dec. 2-15, 1979. American Geophysical Union, Washington, DC 20009.
- STATISTICAL ANALYSIS OF WEATHER MODIFICATION EXPERIMENTS. Edited by Edward J. Wegman and Douglas J. DePriest. Lecture notes in Statistics, Vol. 3, Marcel Dekker, Inc., New York, 1980.
- THE SIERRA ECOLOGY PROJECT, Vol. 1 through 5. James L. Smith and Neal H. Berg, Pacific Southwest Forest and Range Experiment Station, 1980. Work performed under contract with the Water and Power Resources Service, Office of Atmospheric Resources Management, Denver, CO.
- WEATHER MODIFICATION AND CLOUD SEEDING. Arnett S. Dennis, International Geophysics Series, Vol. 24, Academic Press, NY, 1980.
- THE RAINMAKERS. American "Pluviculture" to World War II. Clark C. Spence, University of Nebraska Press. 1980.

AN ABBREVIATED HISTORY OF THE WEATHER MODIFICATION ASSOCIATION

<u>Meeting date</u>	<u>Location and Attendance</u>	<u>Host*</u>	<u>Highlights and/or Historic Items</u>
1950	Bishop Riverside	-	Original discussion between personnel at the California Electric Power Company offices. Completion of three years of snowpack increase on Bishop Creek Watershed.
4 Apr'51	Riverside (6)	-	Organizational meeting: Cundiff (CEPC), Hartman (SCEC), Lang (SCEC) Battle (WMC), Elliott (NAWC), Bollay (NAWC).
17 Apr'51	Pasadena (8)	NAWC	Organizational meeting: Name changed from Artificial Precipitation Operators Association to Weather Control Research Association. Articles of Incorporation organized.
17 May'51	Pasadena (24)	NAWC	Discussions of legislation, licensing and dues structure (\$50/three years and \$10/year for affiliate). Observations of excessive glaciation at -6°C (Sierra Range).
2 Aug'51	Los Angeles (10)	SCEC	Schaefer nuclei counter discussions. California Licensing Act passed July 1951.
5 Nov'51	Los Angeles (16)	SCEC	California Division of Water Resources \$50,000 program on evaluations. California licensees total 7.
12 Mar'52	Los Angeles (20)	SCEC	Pending CDWR \$50,000 program. WCRA financial statement: Receipts include three three-year at \$50 and four affiliate at \$10 -- total \$190; expenses, \$37.87.
10 Dec'52	Los Angeles (16)	SCEC	\$500,000 appropriation for Department of Commerce ACN project (Seattle) Proposed California Random Cloud Seeding Project.
18 May'53	Los Angeles (18)	SCEC	Evaluation of the six-year California Electric Power Company Snowpack Increase Program (Bishop Cups).
9 Dec'53	Los Angeles (22)	SCEC	Federal Advisory Committee on Weather Control created by Congress on 13 Aug. 1953. Committee appointed 9 Dec. 1953. Approved by Congress 25 January 1954. Howard T. Orville, Chairman.
10 Jun'54	Los Angeles (18)	SCEC	Activities of Advisory Committee on Weather Control (ACWC) -- Discussion of "controls" -- evaluations proposed by California Division of Water Resources.
18 Feb'55	Los Angeles (23)	SCEC	Activities of ACWC -- WCRA Committee to Formulate By-Laws (Henderson, Lewis and Elliott).
23 Mar'55	Los Angeles (32)	SCEC	Informal meeting with the Task Force of ACWC (Howard Orville, Joe George, Fred Berry, Ken Spengler). First transcript of a WCRA meeting.
14 Feb'56	Los Angeles (41)	SCEC	Recommend extension of ACWC -- approved the bylaws of WCRA -- transcript of meeting -- first resolution of WCRA commending ACWC -- meeting attended by members of ACWC.
16 Nov'56	Los Angeles (16)	SCEC	Proposed Santa Barbara randomized program -- activities of ACWC -- New York hail suppression program.
18 Feb'57	Los Angeles (25)	SCEC	ACWC extended (S.2913) -- report by ACWC members -- S.86 introduced (Case -- 3 January 1957) -- "Cloud Modification Research Act of 1957" (HR 5232, a companion bill). Senate hearings on S.86 -- Washington.
Nov. '57	Meeting postponed until early 1958 in order to have available the final report of the National Advisory Committee on Weather Control.		
19 Feb.'58	Los Angeles (21)	SCEC	Report of the NACWC dated 31 December 1957 (Berry) -- supports positive effects from orographic seeding and recommends "no controls" -- WCRA resolution commended ACWC. (8 corporate and 11 individual members).
25 Feb'59	Los Angeles (21)	SCEC	First suggestion to hold WCRA meeting elsewhere -- weather modification by Department of Interior (S.943) -- Forest Service Lightning Suppression Equipment -- NSF Reporting Functions.

19 Dec '59	Los Angeles (16)	SCEC	AMS-ASCE meeting, Denver, Colo. -- controversy appears to be diminishing -- new dues: Corporate \$15.; Individual \$2.00. -- Skyline Conference 1-3 May 1969, Virginia.
10 Mar '60	San Francisco (40)	CDWR	California long range programs continue (SCEC on San Joaquin and KRCD on Kings) -- Santa Barbara Proj. -- requirement for new evaluation technique -- Forecasting difficulties.
1 Dec '60	Altadena (26)	MRI	California has five licensed groups and 13 projects -- Interim Report on Santa Barbara Project -- Radar observations and precipitation measurements-- CSU thunderstorm studies.
15 Mar '61	Sacramento (19)	CDWR	Use of Weather Bureau WSR-57 Radar System -- Dept. of Interior programs (USBR) -- Development of pyrotechnic cloud seeding devices.
13 Dec '61	Altadena (20)	MRI	Tor Bergeron speaks on "The Possibility of Artificial Control of Rainfall on the Globe" -- Santa Barbara Project now supported by NSF.
26-27 Apr '62	Fresno (19)	CDWR	First two-day meeting of WCRA -- discussion of Yellowstone Field Research Expedition -- strong comments on desirable relationships in weather modification projects: Experiment vs. production, scientists versus operators, statistician vs. layman, statistician vs. physical scientist.
15 Mar '63	Santa Barbara (29)	NAWC	Joanne (Malkus) Simpson of UCLA reports on "Rainmaking Experiments With Natural and Artificial Heat Sources" -- Edward Morris discusses "Legal Aspects of Weather Modification" -- St. Amand reports on "Naval Research in Weather Modification".
3-4 Apr. '64	Reno (40)	DRI	Doyne Sartor (NCAR) presents "A Coordinated Approach to Weather Control" -- Continued pyrotechnic development -- Wyoming research (Elk Mt. -- Williams)
10-11 Dec '64	China Lake (26)	NOTS	History of pyrotechnic development -- demonstrations by Pierre St.-Amand -- At this point in WCRA history, no routine procedure had ever been set for dues collection -- present membership includes four corporate members (AI, DRI, SCEC, L.A. Flood Control District) and 29 individual members -- bank balance of \$355.31.
21 Jun '65	Los Angeles (23)	SCEC	National Academy of Science Publication 1236 (critical) -- Panel on Weather and Climate Control met in Boston the previous week -- WCRA passed resolution to request NAS to withdraw its preliminary report -- Ralph Huschke of the Panel attended meeting and noted their final report will be entirely new -- Symposium on Economic and Social Aspects of Weather Modification, Boulder, 1-3 July 1965.
14 Feb '66	Executive and Policy Committees Meeting to formulate a position statement on weather modification legislation. Produced a strong paper urging separate regulatory group, utilization of private manpower, encourage private industry, federal protection on liability.		
18 Mar '66	San Francisco (23)	CDWR	Review of NAS report -- Congressional bills: Interior S.2875 (Anderson) Commerce S.23 (Anderson) Commerce S.2916 (Magnuson) -- First consideration of using WCRA as a vehicle for liability insurance -- 5th Berkeley Symposium on Mathematical Statistics and Probability, January 1966.
Oct. '66	Reorganization Committee (Mordy, Eberly, Elliott, McCready, and Powers) met to discuss possibilities for upgrading the entire WCRA organization.		
7 Nov '66	Los Angeles (19)	LADWP	First suggestion of a Journal -- most federal legislation died with adjournment of Congress.
16-17 Mar '67	Sacramento (34)	AJG	Legislation at federal level which would license and regulate (both Commerce and Interior) -- state legislation on licensing -- WCRA certification proposed -- ICAS report 10a, "A Recommended National Program in Weather Modification", November 1966.
21-22 Sept. '67	Altadena (53)	MRI	Continued discussions on a possible Journal -- Committee revised the Constitution and Bylaws -- organization name changed to Weather Modification Association -- Certification and Publication Committees appointed -- Dues change -- Individual \$12.; Association Corporate \$24.; Corporate, \$100. Texas Weather Modification Law passed and pronounced that Weather Modification was not an ultra-hazardous activity.
26-27 Feb. '68	Logan (30)	USU	Theme concept: "Targeting and Plume Tracing" -- Legislative Committee working on a model law (first draft) -- 18 requests for certification have been received -- the last of the NSF reporting function (1959-68). WMA balance of \$1,799.77.

16-17 Sept. '68	Rapid City (60)	SDSM	Theme: "Generation of Seeding Material" -- Initiated approval of the first Journal of Weather Modification -- Review of regulatory legislation: Commerce S.373 (Magnuson), Commerce HR 9212 (Staggers), Interior HR 5734 (Staggers) -- NOAA gets reporting function -- evolution of pyrotechnics -- chemistry of AgI production -- Naval Weapons Center, China Lake, Calif.
17-18 Feb '69	Santa Barbara (56)	NAWC	Presentation of elements of a model law for regulation of weather modification activities -- first inputs from sociologists.
15-16 Sep '69	Ft. Collins (42)	CSU	Established a "permanent" mailing address: Box 125, Altadena, CA. -- presentation of nucleation theory (St.-Amand, et al) -- Israel program -- USBR programs -- WMA balance: \$2,965.56.
10 Apr. '70	Santa Barbara (30)	NAWC	Synopsis of insurance situation -- proposed assemblage of "expert witnesses" -- discussion on possible executive secretary -- distribution of WMA sponsored model law -- discussion on first issue of JWM -- Dr. Vincent J. Schaefer elected an Honorary Member of WMA.
8-9 Oct. '70	Las Cruces (36)	NMSU	Theme: "Programs for the 70's" -- USBR programs -- NSF programs -- Private sector programs -- HR 18180 and S.4091 -- presentation of first volume of JWM.
18-19 Feb. '71	Riverside (40)	USFS	Discussions on warm cloud seeding -- ammonium nitrate and urea -- discussions on cold cloud seeding processes -- consideration of extra area effects -- further discussion on seeding devices -- explanations of AgI-NH ₄ I solutions (advantage over AgI-NaI) -- WMA bank balance of \$4,847.57.
21-22 Oct '71	Norman (69)	WSI	Most recent Santa Barbara experiment -- Climax experiment -- the status and desirability of federal weather modification legislation -- legal aspects of weather modification -- role of the federal government in emergency drought relief programs -- summary of first International Conference on Weather Modification, Australia, September 1971 -- Federal role vs. private role in applied weather modification for the benefit of man.
24-25 Feb. '72	Fresno (60)	AWRR/AI	Position statement on drought relief programs -- resolution on NOAA preparation of regulations. Project Skywater Conferences -- discussions of Project Storm Fury -- environmental impact statements.
28-29 Sep '72	Ft. Collins (54)	WSS	Suggested changes in constitution and bylaws -- preparation of new format -- review of resolutions regarding allocation of responsibilities for emergency drought relief measures and the NOAA Weather Modification Project Reporting requirements under Public Law 92-205.
29-30 Mar. '73	Austin (58)	TWDB	Texas weather modification programs -- rules and regulations related to the Act -- WMA balance of \$3,904.52
13-14 Sep '73	Champaign (61)	ISWS	WMA draft of a Military Use Statement -- discussion of Vol. 5 of JWM
21-22 Mar '74	Huntington Beach (63)	DC	Acceptance of new Constitution and Bylaws -- Abolish Association Corporate Member -- opposition to Haskell Bill (S.3028).
2-3 Oct. '74	Seattle (54)	WSDC	The North American Interstate Weather Modification Council organized earlier this year. WMA resolution supporting NAIWMC.
20-21 Mar. '75	Santa Barbara (57)	NAWC	Bellmon Bills S.3313, S.3314, S.3315 -- Sisk Bill HR 2742 -- proposal of weather modification book.
4-5 Sept. '75	Calgary (71)	CDA	Sisk Bill HR 2742 (Wilderness/Weather Modification) -- Bellmon Bills, drought relief research and operations (S.2706, S.2707) and Weather Modification Council (S.2705) -- discussion of North Dakota and Utah State Weather Modification Programs -- total WMA members 152; corporate 10; student 3. Bank balance \$10,485.25.
1-2 Apr. '76	Los Angeles (102)	WMA	The Silver Anniversary Program
7-8 Oct. '76	Rapid City (75)	SDSM	JWM information brochure - Bellmon Bills S2705, S2706, S2707, and S3383. Sec. of Commerce development of a National Policy and a research and development program on weather modification - Technology Assessment of Hail Suppression in the U.S. (TASH).
14-15 Apr. '77	Salt Lake City	SU	National Weather Modification Policy Act (PL 94490) still lacks appropriate funding - introduction of National Climate Program Act in 95th Congress (S421)

10-13 Oct. '77	Champaign/ Urbana	ISWS	First draft of the new Standards and Ethics Statement - passage of the National Climate Program Act - National Weather Modification Advisory Board - first suggestion of refereed and non-refereed Journal.
6-7 Apr. '78	Tucson	CLASU	Adoption of the new Standards and Ethics Statement - WMA constitutional changes - activities by the National Weather Modification Advisory Board - development of new type pyrotechnics for Project Storm Fury - the WMO Precipitation Enhancement Program.
5-6 Oct. '78	Newport Beach	DC	First consideration of Certification Program revision - draft of the bill evolving from Weather Modification Advisory Board activities - new California Weather Resources Management Act of 1978 - Weather Modification Advisory Board report - Strong WMA workshop for discussion of the WMAB Report - official WMA statement on the WMAB Report.
12-13 Apr. '79	Reno	MWS	Panel discussion on the final report of the National Weather Modification Advisory Board - Mike Glaser (NOAA) summary on Status of Secretary of Commerce's Report in response to National Weather Modification Act of 1976 (PL 94-490). - Stevenson and Bellmon Bills in response to WMAB Report and Commerce Report - WMA final resolution on the WMAB Report - Recommendations for revisions in the WMA Certification Program.
8-9 Oct. '79	Banff, Alberta	WMA	Final modifications to the new WMA Certification Qualifications and Procedures - progress of Stevenson and Bellmon Bills in regards National Weather Modification Research and Development Program - Ferris Webster presentation of NOAA position - Bank balance \$10,026.43.
24-15 Apr '80	Santa Barbara	NAWC	New certification program has continued discussion and ready for final draft under Keith Brown's chairmanship. WMA Articles of Incorporation finalized. At the federal level a new 13-member Advisory Board to the Subcommittee on Atmospheres and Oceans, Science, Technology and Space Committee is currently under organization. New format proposals for the JWM were approved to be effective with Volume 13, No. 1.
2-3 Oct. '80	Albany, NY	SUNY	The theme of "The Langmuir Connection" produced historic overviews from Vincent Schaefer, Ray Falconer, Bernard Vonnegut and Duncan Blanchard. Important comments from these persons who were an active part of the actual historic development of weather modification did much to correct the record of the science and technology. Whiteface Mountain field trip provided further insight to the importance of early experiments in cloud modification and basic cloud physics.

* AI Atmospheric Incorporated
NAWC North American Weather Consultants
SCEC Southern California Edison Company
CDWR California Dept. of Water Resources
MRI Meteorology Research Incorporated
CSU Colorado State University
USFS U.S. Forest Service
AWRR Atmospheric Water Resources Research
TWDB Texas Water Development Board
DC Deepwater Chemical Company, Ltd.
CDA Canadian Dept. of Agriculture
SU State of Utah
MWS Mountain Weather Service

DRI Desert Research Institute
NOTS Naval Ordnance Test Station
LADWP L.A. Department of Water and Power
AJG Aerojet General
USU Utah State University
SDSM South Dakota School of Mines and Technology
WSI Weather Science Incorporated
WSS Weather Scientific Services
ISWS Illinois State Water Survey
WSDC Washington State Dept. of Conservation
CEPC Calif. Electric Power Company
CLASU College of Law - Arizona State University