Control of Precipitation from Cumulus Clouds by Various Seeding Techniques[1]

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CUMULUS CLOUDS are formed when moist air is heated by the sun's rays shining on underlying land. As the warmed air rises it cools, until finally at a certain altitude the moisture condenses at the cloud base, forming small cloud droplets. By this condensation of moisture, a great deal of heat is generated, which may overcome locally the natural stability of the atmosphere. The formation of the cloud, therefore, increases still more the tendency of the air to rise, so that once started, the cloud continues to rise and even accelerate until stopped by an overlying layer of very stable air.

When the cloud reaches the freezing level, the water drops in the cloud ordinarily do not freeze. The cloud is then said to be supercooled. The particles in the supercooled cloud turn to ice only if there are minute particles of ice or certain other foreign particles called *sublimation nuclei.* Sometimes these particles are already present but they may be introduced artificially by the seeding techniques described by V. J. Schaefer (*2*) and B. Vonnegut (*3*).

If no nuclei are present, or if there are too few, the cloud may rise to very great heights, where the temperatures are far below freezing, without many snow crystals forming. Such clouds ordinarily give no rain. The cloud may rise with increasing velocity to a height of 25,000 feet or 35,000 feet, and its inertia may carry it up to and even through a layer of stable air (temperature inversion) so that it becomes colder than the surrounding air. It then slumps back to a lower level, and some of the moisture that has previously condensed evaporates again. Under such conditions, no rain is produced.

If, however, the cloud rises so high that the temperature gets down to $-39°$ C, as it usually does at about 33,000 feet altitude, ice crystals of very minute size are formed in great numbers and almost instantaneously. The number of such particles may amount to 10^{12} per cubic inch. These come into contact with the supercooled water droplets and immediately cause them to freeze. This liberates a large amount of heat simultaneously over the whole top of the cloud, which rises still further. The top of the cloud thus forms a huge vortex ring which may be called a "ring crown." This is an irreversible process. If for any reason the cloud descends again, it will never go as low as if the ice crystals had not been formed. The heat generated usually makes the top of the cloud float away from the lower part, as a circular cirrus cloud of ice crystals. In its early stages it has the shape of a mushroom, or it may look more like a pancake.

The ice crystals then have the same size as the original water drops. They do not fall out of the cloud any more easily than do the water droplets of an ordinary supercooled cloud at high altitude. The pancake grows and gets thinner, usually increasing in diameter at the rate of about 25 miles an hour. At these very high altitudes, the wind is sometimes in a different direction from that near the lower part of the cloud, and so the pancake gradually drifts off to one side.

The ordinary anvil top of a thunderstorm in the North Temperate Zone of the United States is usually very unsymmetrical. We do not often see these circular pancake anvils that are characteristic of the tropics. I refer to them as "cirrus-pumping" pancake or mushroom clouds. One large cloud of this type may sometimes pump out cirrus clouds that spread over 10,000 square miles. Outside of the tropics, they may often occur during the summer in semiarid regions such as New Mexico or Arizona. Dr. Schaefer has observed them in Idaho during the summer. I have never seen a cloud of this type in the eastern part of the United States.

The characteristic thing about these convective clouds is that they form when the number of nuclei present in the atmosphere is so small that too few ice crystals develop in the cloud to use up any large fraction of the water in the supercooled droplets. Therefore, these few ice crystals that do form grow to relatively large size and fall out without setting up a chain reaction.

The large area of cirrus clouds usually formed by the cirrus-pumping mushroom provides shade for the underlying land and prevents it from heating so that no other cumulus clouds grow in the immediate neighborhood. Therefore, the conditions that lead to cirrus-pumping mushroom clouds make the production

[1] Based on a paper presented January 25, 1950 before the American Meteorological Society in New York City.

of rain from such clouds a very inefficient process. This is one of the main reasons that there is so little rain in Honduras and Costa Rica and other parts of Central America during the dry season. There is usually no lack of clouds over the higher mountains of these countries, but the clouds that do form often rise to 35,000 feet and even 40,000 feet and yet give no rain.

Then how *does* rain form from cumulus clouds? Nuclei must be present in order to get rain. The sublimation nuclei that occur in the atmosphere vary in concentration from about 1 particle per cubic meter of air to about 10^7 particles per cubic meter. They vary tremendously at different times and places. Furthermore, the naturally occurring nuclei differ in regard to the temperature at which they become effective. Most naturally occurring sublimation nuclei are not effective unless the temperature is below about $-20°$ C (0° F). That is, clouds that contain such nuclei will form ice crystals only when they reach high altitudes, such as 25,000 feet or 30,000 feet. In other cases, the nuclei may become effective at lower altitudes.

If the concentrations are low—about 100 or 1,000 per cubic meter—only one snow crystal forms in the supercooled cloud for each nucleus present. These grow rapidly in size and soon begin to fall so that in a cloud without high vertical velocities, the snowflakes fall out of the cloud as fast as the nuclei enter it, and the result is that nothing happens—just a trace of rain falls.

To get heavy rain, a chain reaction must occur, by which one snow crystal produces two, and two produce four, and four eight, etc., giving a runaway effect. This is like the spread of a contagious disease or like a fire spreading through a haystack. The chain reaction that leads to a thunderstorm or any very heavy storm usually starts by a fragmentation of the snowflakes. The snow crystals begin to collect into aggregates and then knock against one another and break into fragments which are carried back up into the cloud so that each in turn grows into a large snowflake.

The conditions that are necessary for the beginning of such a chain reaction are very critical. There has to be a certain minimum number of nuclei of a given type, and the process is greatly helped by turbulence within the cloud. The critical conditions occur at some one point in the cloud at a certain altitude and time rather than throughout the cloud as a whole. Thus, the cloud that develops is unsymmetrical and is entirely different in shape from the mushroom cloud of the tropics, where the whole top of the cloud suddenly goes over into ice crystals when it reaches the level corresponding to $-39°$ C.

Where the chain reaction starts, there is a local evolution of heat. If this occurs first at a rather low altitude, then the warmer air produced by the freezing of the moisture rises and stirs up the whole cloud. If heat is generated near the ceiling of a closed room, the hot air stays there, but if it is introduced near the floor, it stirs up all the air in the room.

We can conclude that heavy natural rain from large supercooled cumulus clouds occurs only when both of two separate conditions are fulfilled. First, the weather conditions must be favorable; that is, the *synoptic situation* must be favorable. There must, for example, be sufficient moisture and wind to carry it to the place where the cloud is growing. Second, there must be a concentration of sublimation nuclei to generate sufficient heat within the cloud to overcome the stability of the atmosphere and cause the clouds to grow rapidly and produce turbulence. This turbulence is needed to set up the chain reaction essential for the occurrence of heavy, self-propagating rain showers.

Artificial Seeding

In the early experiments in seeding cumulus clouds with dry ice, relatively large amounts of the dry ice were dropped at the top of the clouds. It was crushed to such sizes that there were many fragments about ½ inch or ¾ inch in diameter, which would fall through the entire cloud and reach the freezing level before evaporating. When this is done, enormous numbers of minute ice crystals or sublimation nuclei consisting of ice are produced at all levels within the cloud. Overseeding frequently occurs, so many nuclei being produced that the snowflakes that form may even outnumber the original water drops, and they tend not to fall out of the cloud. The heat generated makes the top of the cloud float off, separating itself from the lower part. Thus the cloud is often dissipated without producing rain.

The use of a single pellet of dry ice, about a ¾-inch or 1-inch cube, may have distinct advantages for seeding. Although the falling pellet produces a high concentration of nuclei along its path, the cloud as a whole will have parts that are underseeded. Under these conditions, large snowflakes will form at all altitudes above the freezing level, and this is more apt to produce self-propagating storms and may lead to heavy rain. The best results are obtained by putting the pellet into the cloud at the right place and at a time when the cloud is ripe or has grown to a condition capable of sustaining a continuing chain reaction.

Often, heavy rain may best be obtained from a large cumulus cloud by using a single pellet of dry ice shot into the side of a cloud from a Very pistol.

For this purpose, the plane does not need to enter the cloud but can fly near its outer surface and the pellet can be shot to a horizontal distance of 700 feet or more into the cloud. If this is done at a height of 1,000 or 2,000 feet above the freezing level, the heat generated by the freezing of the supercooled water droplets is generated only in the lower part of the cloud, greatly increasing the turbulence and favoring the start of a chain reaction.

The best way to dissipate large cumulus clouds or to stop their growth is to introduce high concentrations of ice nuclei near the top of the growing cloud. This localized overseeding of the top can be accomplished conveniently by the use of a device called a "Trickler," which lets liquid carbon dioxide escape, only a few grams per second, through a hole 0.003 inch in diameter.

Enormous numbers of ice nuclei are produced along the line of seeding, but the minute snow crystals that form do not fall into the lower part of the cloud. The upper part of the cloud thus lifts off from the lower part, and the ice crystals do not get into the part of the cloud where they could cause turbulence and set up a chain reaction. It is also possible to use very finely pulverized dry ice that falls only a few hundred feet before evaporating. Or a single large piece of dry ice can be towed in a net behind the plane.

Artificial seeding has many advantages. By properly choosing the point of seeding, effects can be produced that do not occur naturally. Under natural conditions, the probability of rain varies, depending upon the number and type of natural sublimation nuclei. In the tropics the number of nuclei is low during the dry season. Spontaneous seeding of the clouds then occurs only at very high altitudes and ice forms spontaneously only at the $-39°$ C isotherm. Further north, it is more common to have nuclei that are effective at higher temperatures, and these may be present in larger numbers so that clouds frequently tend to seed themselves at low altitudes.

The cirrus-pumping mushroom clouds of semiarid regions ordinarily give no rain or are very slow in starting to produce rain. When nuclei, such as those from dry ice or silver iodide, are introduced into these clouds at elevations only a little above the freezing level, the cloud is completely modified within 10 or 15 minutes. Ice crystals are formed at low altitudes and grow rapidly to such size and number that they start the chain reaction long before the cloud reaches the $-39°$ C level, and thus the cloud becomes an efficient rain producer.

The pancake top can be prevented from forming if the cloud is seeded when it reaches altitudes where the temperatures are only $-10°$ C or $-20°$ C. One or two pellets of dry ice introduced just above the freezing level are enough to transform a cloud into an efficient rain producer. Many of the ice crystals that are formed by seeding at low altitudes remain in the cloud and are carried up into any anvil top that may develop. Later they fall out and snow is thus entrained into the lower parts of neighboring cumulus clouds, preventing widespread overcast, so that nearly all the moisture in the cloud comes to the ground in the form of rain. With the circulation set up by a chain reaction, such clouds may continue to give rain for many hours.

Silver iodide smoke introduced below the cloud base, either on the ground or by a plane flying below the cloud, is an exceptionally easy and advantageous way to increase the rainfall in those areas where cirrus-pumping clouds would normally prevent rainfall. Seeding of this kind may modify the synoptic situation over wide areas.

The control of a system of cumulus clouds requires knowledge, skill, and experience. Failure to consider the importance of the type of seeding, the place, and the time, and also the failure to select the best available clouds, explain why the Cloud Physics Project of the U. S. Weather Bureau was not able to obtain "rainfall of economic importance."

Seeding Experiments in New Mexico

For many years, I have been developing philosophical ideas in regard to cause and effect relationships in science (*1*). The causality that used to be characteristic of classical physics applies strictly only to *convergent phenomena,* which depend upon a large number of separate events whose effects converge to give a well-defined average. There are, however, in atomic physics, as well as in human affairs and meteorological phenomena, what we may call *divergent phenomena,* where large important events grow from small beginnings that produce diverging results. Shower formations such as those in arid regions like New Mexico are good examples of divergent phenomena.

On this basis, the synoptic situation and the concentration of sublimation nuclei are important only insofar as they determine the *probability* that a shower will occur. Neither factor alone is the direct cause of the shower that occurs at a definite place or time.

To get a heavy shower or thunderstorm requires, as we have seen, the presence of natural or artificial nuclei, in sufficient numbers to convert a portion of the supercooled cloud into ice crystals, thereby generating heat sufficient to overcome the stability of the atmosphere and set up a chain reaction in the production of new snow crystals.

According to the Boltzmann equation, the number of molecules per second that evaporate from a given heated surface of any known substance is given by

$$n/n_0 = e^{(-Q/KT)} \quad (1)$$

where n_0 is a constant, Q is the heat of evaporation per molecule or the energy per molecule that must be overcome in the escape of the molecule from the surface forces, and KT measures the average kinetic energy of the molecules.

By analogy, we may assume that the probability of the start of a shower in a given area and time interval varies in a similar way with the ratio of two energies: that needed to overcome the atmospheric stability and that available by the conversion of supercooled water droplets into ice crystals. In a semiarid country like New Mexico we may take the average rainfall, R, in a 24-hour period over a given area, as a measure of the probability of shower formation. We are thus led to the equation:

$$R/R_0 = e^{(-C_1/C)} \quad (2)$$

where R_0 is the maximum average rain over the area that could be produced by the optimum concentration of nuclei, C is the actual concentration of nuclei, and C_1 is the concentration that would be needed to make $R/R_0 = 1/e = 0.37$. The quantity C_1 is determined by the synoptic situation, which is presumably determinable from data given on weather maps with additional data involving local conditions such as orographic effects. Thus, the probable rain depends on the ratio between two factors C_1/C, where the first factor is a measure of the synoptic situation and the second factor is the concentration of sublimation nuclei, natural and artificial.

Equation (2) can also be written

$$C/C_1 = 1/ln(R_0/R). \quad (3)$$

Thus from observed rainfall data, we can calculate C/C_1.

If sublimation nuclei are generated at a point on the ground or in the air, then in presence of vertical convection that distributes the nuclei, the concentration of the artificial nuclei will vary inversely as the distance D from the source at distances beyond that required for uniform vertical mixing. Thus the quantity C/C_1 found from the observation will vary linearly with the reciprocal of the distance D, so that in general if C_1 is reasonably constant

$$C/C_1 = C_0 + E/D \quad (4)$$

where C_0 is a measure of the natural nuclei already present in the atmosphere and E is a constant under given conditions.

We have used this probability theory to analyze the data obtained in seeding experiments conducted by Project Cirrus, for the U. S. Army Signal Corps and the U. S. Navy near Albuquerque, New Mexico. In the first test chosen for analysis, conducted on October 14, 1948, it was found that about 0.35 inch of rain was produced over an area of at least 4,000 square miles. This corresponds to 100,000,000 tons of rain. Later calculations showed that the total rain area corresponded to a rainfall of about 800,000,000 tons, or roughly 200 billion gallons of water.

Four seedings were carried out that day. The first one, in the morning, was done by Dr. Vonnegut's method with about two ounces of silver iodide dispersed by dropping impregnated burning charcoal pellets from an airplane at 12,000 feet. The other three seedings involved amounts of dry ice from 15 to 25 pounds. Very striking results were produced by the dry ice; there were two thunderstorms, which were photographed for about an hour and a half.

More widespread effects were produced by the operation of a silver iodide generator on the ground in the later tests, held during July 1949. The first seeding with silver iodide in this experiment was on July 15, 1949, but the generator was not run for more than a couple of hours on any 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 a total of 300 grams of silver iodide was used. Tests made by Dr. Vonnegut have shown that each gram of silver iodide dispersed under these conditions produces 10^{16} sublimation nuclei that are slowly effective at $-5°$ C but very rapidly effective at $-10°$ C.

We chose for analysis the data obtained on two days, October 14, 1948, and July 21, 1949. 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 amounts of rain. Both mornings were nearly cloudless, and on both days southwest winds prevailed from the cloud bases at 12,000 feet up to 20,000 feet. At lower and higher altitudes and later in the day, there were also winds from the east, west, and northwest. On both days, visual effects indicating 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 much improved over those of the preceding October. On October 14, 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 any relation to 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, and they included lapsed time motion pictures with frames every few seconds.

Shortly before 8:30 a.m. on July 21, 1949, a single large cumulus cloud began to form about 25 miles south 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 north about 10 miles an hour, 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. At 9:57, when the top of the cloud was at 26,000 feet (temperature $-23°$ C) the upward velocity of the top of the cloud increased quite suddenly, so that the cloud rose 1,200 feet per minute until at 10:12 it had reached 44,000 feet (temperature $-65°$ C). At 10:06, when the top of the cloud was 36,000 feet (temperature $-49°$ C) the first radar echo return was obtained from the cloud at an altitude of 20,500 feet (temperature $-9°$ C). The distance given by radar was 25 miles 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 1 square mile at that time and deep within the mass of the cloud. Within 4 minutes, the precipitation area had increased to 7 square miles and within 6 minutes after the first echo appeared, the precipitation had extended upward to 34,000 feet, where the temperature was $-43°$ C.

The chain reaction in this cloud started at low altitude, at a time and place that agreed well with the trajectory of the silver iodide smoke. The first flash of lightning was seen at 10:10, 4 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 westward, but the lower part of the cloud from which the rain was falling moved gradually to the northeast.

At 10:47 a second cloud, about 8 miles still further to the northeast, developed a radar echo, and from that time on during the day the number of rainstorms increased, producing very heavy showers in the neighborhood. During the late afternoon, 1.2 inches of rain fell at the station where the generator was located. There was exceptionally heavy rain at Santa Fe.

River flow data. On the morning of July 22, I had occasion to fly from Albuquerque to Los Alamos and on the way passed over Domingo on the Galisteo Creek near the place where it enters the Rio Grande River. This creek looked like a large river carrying perhaps a third as much water as the Rio Grande. I asked the pilot about this stream and he said that it was merely a dry wash and that never before had he seen any appreciable amount of water in it. Recently, I have obtained from the U. S. Geological Survey, through the kindness of Mr. S. E. Reynolds of the New Mexico School of Mines at Socorro, data on the flow in the Galisteo Creek for every day since June 1946 and similar data for the Pecos River at Santa Rosa. Within the 30-hour period after the river flow began on July 21 the flow in the Galisteo Creek amounted to 3,000,000 tons, or 0.65 billion gallons. The area of the watershed of the Galisteo River is about 500 square miles. The flow in the Pecos River amounted to 12,000,000 tons, or 3 billion gallons, and the area of the basin is 2,700 square miles.

It is of interest to note that the average flow rate of 3,900 cubic feet per second for the day of July 21, 1949, in the Pecos River was considerably higher than any day since June 1946. In the case of the Galisteo River there was only one day in that three-year period that gave slightly more rain than on July 21.

Rain gauge data. The Weather Bureau publishes climatological data for New Mexico monthly, about two months after the end of the month in which the data were recorded. About 300 stations well distributed over New Mexico give the total rainfall for each day and, of these, about 70 stations give hourly reports of rain. For the tests that Project Cirrus made in July 1949, the Weather Bureau also installed 24 additional recording rain gauges within the range of about 40 miles of Albuquerque. Several months have been spent in making a careful analysis of these rainfall data and even extending them into the states of Arizona, Colorado, Kansas, Oklahoma, and Texas.

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 5 percent, but certainly not more than 10 percent. If this were true, it would be possible to conclude that seeding operations had economic value only if experiments are carried on many hundreds of days, and a statistical analysis were made of the rainfall data for all of these operations. The data actually show, however, that the rainfall on both October 14, 1948, and July 21, 1949, was exceptionally high and could not possibly have been accounted for as the result of naturally occurring rain.

The map of the state of New Mexico, which represents about 120,000 square miles, was divided into eight octants or 45° sectors radiating out from Albuquerque. Then concentric circles having radii of 30, 75, 125, and 175 miles 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 October 14, 1948, and July 21, 1949, 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, which was found in this case to be + 0.78. The chance that such a high value would occur among these figures if one set of them were shuffled giving a random distribution is only 1 in 10^7 or 1 in 10 million. Such close agreement in the distribution on two days could thus hardly be the result of chance. 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 on the fact that on both days the probability of rainfall depended on the nuclei that spread radially out from Albuquerque, the concentration decreasing as the distance from Albuquerque increased.

The next step was to analyze the characteristics of this distribution that are so similar on these two days. On each day nearly all of the rain occurred within four of the eight octants. Each sector was divided into 4 to 6 parts, arranged radially so that each would contain equal numbers of observing stations (about 8 per region). The average rainfall rose rapidly to a maximum in intensity about 30 miles from the point of seeding and in each of the 4 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), indicating 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 made it possible to separate the effects of the artificial silver iodide nuclei from that of the background of sublimation nuclei already present in the atmosphere. The results showed that $C_0 = 0$, so that there was no appreciable background on either of these two days. 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 agreement between the intensity of the average rainfall in separate regions and the theoretical equations was 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, showing that the observed agreement was not accidental. Taking all the octants together, the probability factor rose to about 10^8 to 1.

Time of starting of the rain and its variation with the distance from the generator. For each of the eight octants that showed appreciable rainfall, 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 15 miles an hour and on October 25 at a speed of about 25 miles an hour. These velocities agree well with the wind velocities observed at various altitudes.

The method of the 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 of the order of 10^8 to 1.

Taking these results all together, it seems to me that they prove conclusively that silver iodide seeding produced practically all of the rain in the state of New Mexico on these two days. The results for the other days of the experiments, although somewhat more complicated, due to the overlapping of the effect of seeding on successive days, are almost as striking, and the probability factors are very high.

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. On July 21, 1949, the 300 grams of silver iodide generated yielded 3×10^{18} nuclei. The analysis of the rainfall data shows that a concentration of 1 milligram of silver iodide per cubic mile of air is enough, under the synoptic conditions that prevailed in New Mexico, to give a 1-in-3 chance that heavy rain will occur during any one day at any place. Assuming the atmosphere to be 5 miles thick, 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 $1.00 for 4,000 square miles.

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, 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."

It is interesting to note that 30 milligrams (1/1,000 ounce) of silver iodide (cost 0.2 cents), when distributed in 30 cubic miles of air, liberate as much heat when it enters into the bases of large supercooled cumulus clouds 6 miles in diameter as the explosion of an atomic bomb. This is the heat freed when the supercooled cloud changes to ice crystals.

I have been developing a new theory of the rate of growth of snow crystals in supercooled clouds containing known numbers of sublimation nuclei. It turns out that the initial growth occurs in accord with a diffusion theory proposed many years ago. But when the snow crystals grow to a size of a few tenths of a millimeter, and especially when the air is turbulent, the crystals grow 10 to 50 times faster than the rate given by the older theory. This is in accord with observations of the extraordinary speed with which some cumulus clouds turn into active thunderstorms, such as the cloud of July 21, 1949, and another cloud on October 14, 1948. And the concentration of 1 milligram per cubic mile, which was found to be so effective in producing showers, is just the concentration that is needed to convert all supercooled water droplets into ice crystals within about 4 minutes.

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 3 times as much iodide one would get 9 times the rainfall. The intensities of the showers would be no greater, but they would extend over a greater area.

An analysis of the July 1949 rainfall in New Mexico, Arizona, Colorado, Oklahoma, Kansas, and Texas gives evidence that a band of heavy rain progressed in an easterly direction during the period of July 20 to July 23 from southern Colorado across the southern half of Kansas, where it gave 3 to 5 inches of rainfall in many places. It may have been dependent on the silver iodide nuclei generated near Albuquerque between July 18 and 21 and in central Arizona between July 19 and 21. Furthermore, the heavy rains that spread throughout New Mexico from July 9 to 13, before the start of Project Cirrus seeding experiments, appear to have depended on silver iodide seeding in Arizona on July 5 and 6.

It is very important that regular tests be carried out on certain selected days of each week 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.

I believe the time is now ripe for beginning an intensive study of tropical hurricanes. It is highly probable that by using silver iodide generators at sea level in the regions where large clouds first begin to grow into incipient hurricanes, the hurricanes can be modified and even prevented from reaching land.

References

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