19 October 1962, Volume 138, Number 3538 SCIENCE

The Problem of Weather Modification

What went wrong with the rain-making program? Is there any hope?

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Demonstrations made in laboratory cold boxes and on supercooled clouds of the atmosphere by Langmuir, Schaefer, Vonnegut, and others during the late 1940's stimulated a vast interest in weather modification programs throughout the world. This interest appears to have reached its height about 1952, but after a sustained peak of two or three years, interest diminished rapidly; now it is very difficult to obtain private financial support for attempts at weather engineering. It appears that statistical tests applied to the results of many of the efforts did not support the claims of the operators, nor did they satisfy the hopes of those who paid for the services.

In view of the tremendous amount of effort that has been devoted to weather modification during the past 15 years, and of the competence of many of the men dedicated to these efforts, it seems desirable to examine the status of the art during this lull in activity. We should, I believe, find out what went wrong; we should write down what has been learned.

The greatest advance in our learning probably has been the realization that it is desirable to develop a better physical description of processes in the atmosphere. Improved descriptions appear necessary for a better understanding of the factors used by synoptic meteorologists in forecasting the weather.

History very probably will credit the late Irving Langmuir with having provided the impetus for the establishment of modern atmospheric physics. As a result of his ability to stimulate and at times provoke interest, we are now seeing very exciting developments in the atmospheric sciences.

Where do we now stand on physical facts related to weather modification? First, we can say in retrospect that the laboratory cold box experiments were good *laboratory* experiments. Just as certainly we can say that it is possible to seed supercooled clouds in such a way as to increase enormously the production of ice crystals and thereby modify the condition and the course of development of such clouds. Also, as we might have expected, handbook data on the vapor pressure over ice relative to the vapor pressure over water at the same temperature are well illustrated in the preferential growth of ice crystals in some natural clouds, as well as in laboratory cold boxes.

The basic assumption in the rain-making hypothesis was that the natural atmosphere frequently lacked ice-crystal nuclei effective in the temperature range from 0° to −15°C. We still find a sparsity of such nuclei, but they are no longer considered necessary in the processes of initiating shower precipitation. Ice in the form of hail may develop from the freezing of a drop of liquid water. There is growing awareness that water drops freeze with moderate supercooling if they are large enough. I should like to add that relatively extended *time* appears to favor glaciation in a supercooled cloud. This, I suspect, may be due to the fact that time is required for the chance coalescence of relatively large drops, an event which, under conditions of supercooling, might be expected to cause immediate freezing. Also the probability that an undisturbed drop will freeze increases with time. There appears to be no need for sublimation nuclei of the foreign-particle type, once drops start to freeze.

Another assumption implicit in the rain-making hypothesis was that, through seeding, the number of clouds of a certain height, shape, and water content capable of producing precipitation on the ground would be significantly increased. As I explain later, this assumption must be discarded on the basis of energy considerations.

These revisions in what appears to be acceptable as physical fact at this time remove the props from under the original rain-making hypothesis. In short, the atmosphere has the necessary ingredients for making rain, although it may at times be deficient in water vapor and available energy. *Indeed, a lack of large numbers of sublimation nuclei effective in the temperature range from 0° to −15°C is a necessary condition for shower precipitation in arid regions.*

If we accept these conclusions as they apply to cloud seeding and to the precipitation behavior of clouds, we then ask, "What can you do by seeding clouds?"

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Heat Flow and Condensation

A better and more useful appraisal of the rain-making problem is possible if we think of rainfall not as a primary process in the atmosphere but as a by-product of heat flow—as being governed by heat flow from warm places to cold places, from low latitudes to high latitudes, and specifically, for present purposes, by the transfer of energy from surface and near-surface layers to colder layers aloft by the condensation of water vapor to form precipitation in convective storms.

The average annual rainfall over the surface of the earth is estimated to be about 100 centimeters. The water vapor in the atmosphere is supplied by evaporation from the earth's surface. The power required for this evaporation is derived from radiant energy from the sun, more than half of which is incident upon the earth between latitudes 25 degrees north and 25 degrees south. Evaporation takes place where the surface is warm and moist, and here the energy of vaporization is absorbed. This latent energy, carried by the water vapor, is injected into the higher atmosphere and transported laterally. When liquid water or ice is formed in the atmosphere, latent heat is added to the local air, causing the temperature to be higher than it would have been without the change of phase. The evaporation of liquid water or the melting of ice would, of course, produce the reverse temperature effect.

Relatively simple calculations show that the amount of power required to maintain the water cycle is approximately one-third that of the total heat budget of the earth. A careful tracing of the annual heat cycle of the earth, starting with high-temperature radiation received from the sun and ending with low-temperature radiation back to space, shows the importance of the water cycle in energy transfer. The amount of power required to maintain the water cycle is from 80 to 85 percent of the total power required to maintain the circulation of the atmosphere and to provide for the water cycle (*1*).

Although we are concerned here with the vertical transport of the available energy of latent heat, it must be recognized that the water cycle is very effective in transporting energy from low to higher latitudes. Most of the water precipitated on the earth derives from water vapor added to the atmosphere in equatorial regions. Each gram of water returned to the oceans by rivers, streams, and underground movements represents approximately 600 calories of heat added to the atmosphere over the collecting areas of the continents. In a very real sense the atmosphere, and much of the earth, is steam-heated and steam-operated.

Major changes in climate would result from any widespread application of an atmospheric chemical or physical process which would hinder the mechanism of precipitation. I have suggested that the glacial periods may have resulted from such processes. There may be better ways of making a glacial period, but inhibiting rainfall in the higher latitudes would increase cloudiness, and the resulting higher albedo would diminish the total heat budget. This action, together with diminished heat transfer from the tropics, might lower the temperature to such an extent that even the lower-than-normal precipitation would produce an accumulation of ice.

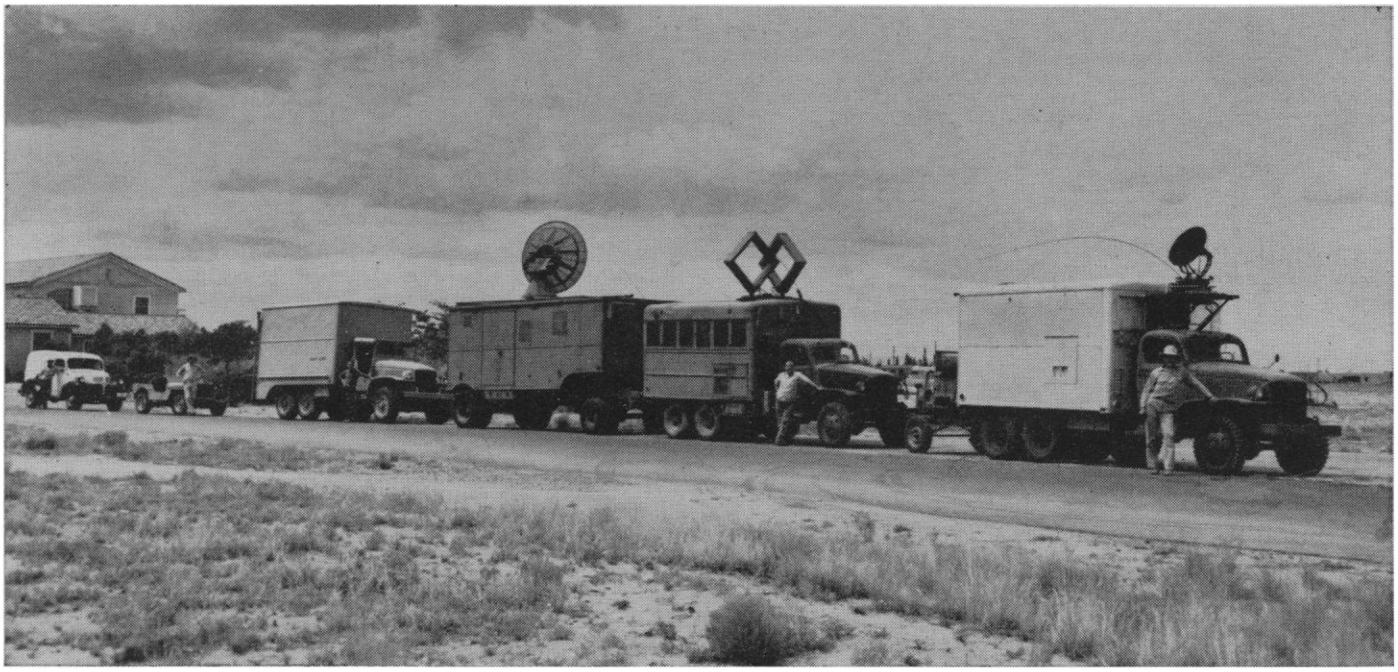
In considering the role of condensation in the vertical transport of energy it is necessary to take account not only of the amount of precipitation that falls on the ground but also of the vast amount of precipitation that is condensed at high levels and falls into the lower atmosphere, where it evaporates before reaching the ground. On an average July day in New Mexico, for example, approximately 4 grams of water would be required to saturate the air from cloud base to land surface over each square centimeter of surface. Even when saturation is not achieved, the increased ventilation by wind shear below the cloud will increase the amount of evaporation. Thus, light precipitation from the cloud base evaporates completely, and heavy rainfall may be 1, 2, or 3 centimeters less than it would be without this evaporation.

The downward movement of precipitation with respect to the ambient air, regardless of whether the precipitation reaches the surface or evaporates into the air, reduces the thermodynamically available energy of the local system. That is, the possibility of thermal-energy transfer is reduced because the source has been cooled and the sink has been heated. This action serves to control the quantity of precipitation because the action necessarily is catastrophic and the entropy of the local atmosphere soon rises to such an extent that further increases take place slowly.

The occurrence of a simple convective storm depends upon the amount of available energy that is stored and upon the manner in which that energy is dissipated. It is interesting in this connection to note that the topographic features and the surface covering of the earth may have a considerable effect upon the precipitation pattern of the region. In the southwestern United States, for example, the mountains that are warm—warmer than the air at the same altitude over the valleys—serve as convection chimneys and provide a leakage of energy upward, tending to prevent the storage of large amounts of energy that might otherwise be dissipated in catastrophic storms. Tornadoes, we suspect, are of interest in this connection; they develop over thermally uniform surfaces in a manner which makes it possible for large amounts of energy to be held in a state of conditional stability for release as the divergent conditions favorable to storm development occur. Severe tropical storms which occur over the oceans must result from the same condition of uniformity of energy distribution. It appears that these severe storms start quite normally but, under conditions of high-energy storage, lack the essential control mechanisms of well-behaved storms. Tornadoes cannot fill the upper heat sink because the sink is continually refreshed by high shear winds aloft. Intuitively, one might expect the same mechanism in giant storms of the tropical oceans. Here the act of removing the heat from aloft may be accomplished by a toroidal circulation over a vast area of the ocean—a condition which would not be sustained over land areas because of surface friction and the lack of a ready supply of saturated air.

Growth of a Thunderstorm

At this point we should note that most clouds do not develop into rain-producing mechanisms. For each thunderstorm that develops in the southwestern United States, perhaps a hundred promising small clouds may appear and not develop into thunderstorms or rain-producers. In the early stages, any of these small clouds is, to all outward appearances, a budding thunderstorm. The most experienced ob-



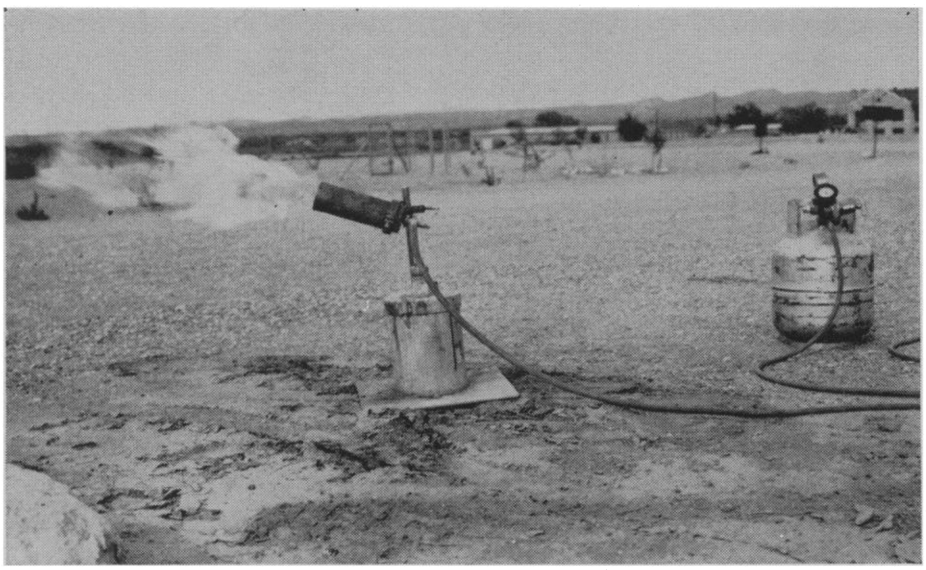
A thunderstorm laboratory on the move, in 1949. S. E. Reynolds, beside the first truck, was in charge.

server will be unable to designate the one that will diverge favorably in its pattern of growth and become a thunderstorm. In the fully developed storm and its associated circulation, use is made of the available energy (water vapor included) over a large area. The small clouds—the clouds that do not meet the requirements for full development—frequently disappear rapidly on being reheated through induced subsidence. In other instances the growth of these clouds is arrested and, finally, the water droplets evaporate into the surrounding air. These clouds usually are composed of such small drops that they reevaporate at approximately the level at which they were formed, and, except for their effect on radiation, their cycle has not dissipated greatly the potential of the local system. This conservation of potential is one of the things which makes the atmosphere work; it makes big events possible. When continued condensation takes place, sensible heat is added to the local atmosphere. If this occurs at intermediate levels, a feedback system is developed, favoring further movement of the air by convection. The fact that precipitation requires a set of circumstances favorable to feedback leads to sporadic instability and thus serves to prevent the atmosphere from achieving a relatively steady state.

A thunderstorm in arid regions requires a vast amount of space from which to derive its water and its energy. Unfortunately, we do not know enough about this question to cite numbers, but a good estimate is that a convective thunderstorm typical of the southwestern United States requires a region of atmosphere covering 1000 or more square miles of land to develop and sustain its action.

For a better appreciation of the characteristics of arid-land thunderstorms, let us follow developments on a typical day of thunderstorms in New Mexico. We start with a clear sky on a July morning. No cloud is in sight. The sun is bright, and the surface temperature-inversion is diminished by small convection cells which start to form within an hour after sunrise. At 9:30 or 10:00 o'clock (time 0), the thermals are well-developed and the condensation level (approximately 4200 meters above mean sea level; temperature, +5°C) is penetrated in one place, as evidenced by the appearance of a small cumulus cloud no taller than it is wide and less than 100 meters in diameter. When we look again, our little cloud has evaporated into the relatively stable but too-dry air at its top and sides. Soon the cloud reappears in the same location—that is, in the same air. This time it is a little taller, but it fades out as before. After three or four tries, the cloud surges upward with what appears to be increased determination. The air is still too dry, however, and perhaps this time the top will pinch off, becoming indistinct at its boundaries and finally falling downward, as if to merge with the part from which it was detached.

Other small clouds appear, and they also try and try again. The number of clouds increases, and although they are in widely differing stages of development, five or ten of them may have conditioned the space around them to such an extent that they are able to extend upward to a height of from 500 to, possibly, 1500 meters. The time now is plus 90 minutes, more or less. Three or four of the clouds look promising. They are growing rapidly in height and in thickness. They are bulbous at the top and appear "hard" as they pulse upward. While we have been watching these clouds and guessing which would be the winner, another cloud, possibly 30 kilometers away and heretofore inconspicuous, has pushed up very rapidly. Let us call it Q. Although Q's upward growth is pulselike, it rises to a height where the temperature of the top may be −15° or possibly −20°C. (The time now is plus 150 or 200 minutes.) Very soon cloud Q shoots upward and outward explosively, reaching a height of 10 or 12 kilometers above mean sea level. Rain falls from the cloud base. The cloud grows in width, and new upward pulses occur along the upper sides. New patches of rain fall, and soon there is an extended area of heavy rain at the ground. It is very interesting and very significant that the other clouds of the neighbor-



A butane burner dispensing silver iodide crystals in the Langmuir periodic seeding experiment.

hood (perhaps an area 60 kilometers in diameter) failed to develop. Indeed, they very probably evaporated completely under the subsidence action of *Q*, which stands alone as a going concern. Actually, our thunderstorm cloud does not stand still; it moves along as if guided by the terrain, to which it is sensitive because of its downdraft.

What has happened? At time 0 minus a few minutes the atmosphere was clear, no part of it was saturated. The storm developed in that clear air. Rainfall over a considerable land area was 2 centimeters, and probably almost an equal amount of water was lost to the dry air under the cloud as it moved along. We know that such losses into the lower air occurred, because "scud" clouds very near the surface appeared soon after the storm. After the rain was over, there was still a very tall cloud, all parts of which were saturated and which contained considerable liquid water and ice.

Obviously, the storm just described got its water and its energy from a large volume of the atmosphere. Herein lies one of the forecaster's problems. He can, with good reliability, say that a thunderstorm will not occur when he sees that conditions are unfavorable. It is quite another thing to say, with reliability, that a local storm will occur, even though the conditions appear to be most favorable. He cannot know the atmosphere in sufficient detail to pick out in advance the place of occurrence within the large area necessarily involved.

Making rain as you go! A silver iodide dispensing burner mounted on an automobile.

Essential Conditions

The man who seeks to modify the weather on a day such as that of our thunderstorm has a problem which, to the best of my knowledge, he has not recognized: he must make certain that *whatever is done by way of attempting to induce precipitation be done in such a manner as to preserve all those conditions within the system which make it possible for precipitation to take place*. His procedures up to now have been precisely those that would be expected to fail to meet this requirement—that would be expected to render the system incapable of producing effective rainfall under the circumstances here considered.

An essential feature of thunderstorms is a tall cloud column of water droplets. At the present time it is reasonably safe to say that the initiation of precipitation through making water droplets large enough to fall or to freeze at moderately reduced temperatures does not depend upon the prior existence of sublimation nuclei, nor upon ice grown directly from the vapor phase. Moreover, analysis shows that if the water-vapor content of the air that enters the cloud is high enough, the liquid-water content developed by vertical motion may be adequate to produce shower precipitation in warm clouds—that is, in clouds in which no supercooling occurs.

If, however, the air that enters the cloud is sufficiently low in moisture content, when the cloud base is high, temperatures throughout nearly all the cloud may be below freezing. Such a cloud could not produce perceptible rain on the ground if all the cloud drops froze immediately upon reaching 0°C, because "drop" growth by coalescence would not take place. The small frozen drops of such a cloud would not accrete ice by sublimation at moderate temperatures below freezing because of competition by a large-particle population for the limited supply of water vapor at the reduced temperature. The supply of water drops that, supposedly, freeze without supercooling would be maintained if the temperature of the cloud base were above freezing.

It is fortunate that clouds in arid lands supercool and that nature has not provided appreciable numbers of sublimation or freezing nuclei which are effective in the temperature range 0° to −15°C. If some act of man or nature were to provide such nuclei, generally dispersed and in sufficient numbers, we would not have thunderstorm precipitation in New Mexico. Fortunately, it would be difficult, if not impossible, to artificially overseed to the extent of producing complete glaciation. It is expected, however, that a more moderate treatment would modify the development of the cloud.

The effect of nucleating all clouds in the arid southwest would be to initiate light precipitation which would evaporate into the lower air. Heat would be transferred to the high atmosphere, the distribution of water through the vertical section would be changed, and possibly the flow of surface heat into the atmosphere would be increased. The important effects would be changes in the water and temperature structure, in rainfall to the ground.

It should be emphasized that the consequences here indicated do not depend on the existence of a particular precipitation mechanism in nature. They depend only upon the condition that precipitation occurs when clouds of marginal liquid-water content are sustained in a supercooled condition.

Warm-cloud precipitation is another matter. Such clouds play the usual role in the heat-flux system, but processes which might enhance or inhibit their development are quite different. It is clear, however, that any influences which would lower the potential "hills" against energy storage might reduce the probability of tropical storms.

In 1953, Langmuir published a report on an extended series of periodic seeding experiments (Project Cirrus) carried out in New Mexico. His report shows a high correlation of this seeding with rainfall and other weather elements in the Middle West. (A portion of Langmuir's summary is quoted in an appendix to this article.)

Conclusions

If the arguments that I have given are valid, it is conceivable that the rainfall periodicity observed by Langmuir and the temperature anomalies at high altitudes that he reported might have resulted. One question remains: "Is the effect large enough to be so dramatic in its consequences?" It appears that the least we can do is to try to answer this question. After all, there is a strong "statistical" argument for trying this experiment again. What is more important, perhaps, is the fact that the Project Cirrus report appears to be in accord with physical facts as currently interpreted.

Whatever may be the future course of testing the responses of the atmosphere to our manipulative efforts, we should look to the energetics of the system for understanding. Modifying the energy configuration will be the basic approach to changing the performance of the atmosphere.

Appendix

Some readers may wish to review the findings in Langmuir's report on Project Cirrus, part II, entitled, "Analysis of the effects of periodic seeding of the atmosphere with silver iodide," issued in May 1953 (*2*).

The first three chapters of the report contain introductory statements related to the general question of cloud seeding, and the second part of the report (chaps. 4 to 12) contains a vast amount of statistical information bearing upon what Langmuir interpreted to be "widespread effects from the seeding of cumulus clouds." Since this report had a limited circulation, I think it appropriate to quote from the summarizing statements (pp. 339, 340).

> Starting 6 December 1949 and continuing until 2 July 1951, a total of 82 weeks, about 700 grams of silver iodide per week was dispersed as a smoke from one ground-based generator in New Mexico operating on a prearranged seeding schedule designed to introduce a 7-day periodicity into the rainfall over large areas.
>
> Chapters 4 to 12 are devoted to an analysis of the 7-day periodicities shown by the daily Weather Bureau data on rainfall, upper air temperatures, and pressures over the United States. The rainfall data were analyzed for 36 "cycles" of 28 days each. For the upper air temperatures, the analysis covered the whole northern hemisphere for twenty consecutive 28-day cycles starting 18 September 1949.
>
> The cumulated evidence presented in these chapters constitutes a proof of the Seeding Hypothesis, according to which localized periodic seeding with only two pounds of silver iodide per week has produced profound periodic changes in weather at distances that extend many thousands of miles from the point of seeding.
>
> These weather modifications were not small nor were they difficult to detect. For example, over areas of more than one million square miles during the first 140 days of periodic seeding the average rainfall on Mondays or Tuesdays was 3 to 10 times as much as on Saturdays or Sundays.
>
> The 7-day periodicity in upper air temperatures extends with large amplitudes throughout the whole troposphere, up to 40,000 feet altitude, and often covers many millions of square miles.
>
> These periodic changes are of such extremely high statistical significance that to prove the existence of widespread effects of periodic seedings statistical methods are not needed; the effects are obvious by mere inspection.
>
> The onset of the periodic changes in rainfall, upper air temperatures, and pressures occurred suddenly within two weeks after the start of the periodic seedings and ended suddenly within two weeks after the periodic seedings stopped, 82 weeks later.
>
> Although after August 1950 periodicities of large magnitude often occurred, they tended to become somewhat sporadic in time and in location because of the masking effect of the rapidly increasing nonperiodic commercial seeding operations in the western states, which often amounted to from 50 to 100 times as many generator hours as were used by Project Cirrus. . . .
>
> Although widespread modification of weather by seeding has been proved, its mechanism is not yet understood. The situation is much like that in the germ theory of disease. We know that diseases may frequently be produced by single bacteria, but we do not yet understand essential elements in the mechanisms, such as the actions of toxins, antibodies, the nature of various types of immunity, etc.
>
> The upper air pressures and temperatures and especially the waves in the westerlies and the jet streams are known to be related to subsequent rainfall. The existence of widespread effects of seeding proves that *rainfall* is one of the most important factors that determines the subsequent upper air phenomena, such as the waves in the westerlies and the location of the jet stream.

At this date one might add the following comments.

It is unfortunate, perhaps, that Langmuir, throughout the course of the work treated analytically in chapters 4 to 12 of the report, assumes the attitude of a statistician and thus denies himself and his readers the privilege of considering a causal treatment of the possible physical processes involved, as they may have occurred to him.

The early history of Langmuir's important contribution to this field, as summarized in the first three chapters of the Project Cirrus report, tends to direct the critical reader to conclude (i) that silver iodide dispersed in relatively small quantities in New Mexico remained active in the atmosphere for several days, (ii) that it was conserved and transported to the Middle West, and (iii) that by direct seeding action there it produced anomalies in the atmosphere.

Thinking of the process as delayed direct action caused some critics to dismiss the entire matter with the statement, "Utterly fantastic." Certainly there was good cause, even as early as the time of the seeding on which Langmuir reported, to believe that the relevant properties of silver iodide were not conserved in the atmosphere. In addition, widespread seeding operations in New Mexico performed by commercial seeders at approximately the time of the Project Cirrus periodic seeding produced little or no additional precipitation from local clouds. Indeed, some local residents have contended that the year of this widespread seeding activity was the dryest in New Mexico since 1873. It is not unreasonable, therefore, to ask how silver iodide transported to the Ohio Valley could make rain there when it had been unable to do so at the place of injection.

Another criticism which warrants consideration developed from the fact that "periodic" rainfall in the Middle West continued after termination of the "periodic" seeding with which it has been correlated. It is true that nearly all of New Mexico, as well as many parts of Arizona and west Texas, was covered by commercial cloud-seeding programs involving the injection of silver iodide during the time when the large periodicities were observed. We must weigh against this information the criticism that the periodicities in rainfall persisted after the termination of the seeding in Project Cirrus.

Langmuir, in his talk at the meeting of the National Academy of Sciences dedicating the Knolls Laboratory in Schenectady, suggested the possibility that there was a period of resonance of about 7 days in the circulation system with which he was concerned. "It looks to me," he remarked, "as though the atmosphere needs to be stimulated about once a week." Other investigators have found evidence suggesting a 7-day period, or harmonics thereof, since Langmuir's report appeared. [One recalls also the folk saying of the Middle West, "If it rains on Easter Sunday, it will rain on the following seven Sundays" (*3*).]

Let us assume that such a tendency to resonance is inherent in the system and that the period is about 7 days. Two additional facts should be considered. First, commercial cloud seeders do not seed clouds when none exist; even the most avid engineers gave up that practice early in the game. Second, it makes no difference whether seeding is done every day or only on days when there are clouds; the only possible effect that silver iodide can have on the atmosphere occurs when, and only when, supercooled clouds exist. Indeed, the effect such seeding would have would be roughly proportional to the amount of supercooled clouds. It would seem, therefore, to make no difference whether this peculiar type of resonance stimulation is periodic or not, since the feedback will be appropriately adjusted.

Whether the periodic seeding happened to fall in just the right phase relationship or whether such "controlled" seeding was the factor which established the phase relationship remains to be determined. It would appear that the existence of a tendency to resonance in this type of atmospheric response might make it unnecessary to pick out the right starting time or to choose a particular frequency schedule in order to produce excitation.

These arguments have been presented in an effort to develop further interest in Langmuir's Project Cirrus report and to suggest the desirability of making further tests to resolve the very important questions raised.

Notes

1. The earth receives, on the average, 0.5 calorie per square centimeter per minute in the form of radiant power from the sun. Approximately 35 percent of this radiation is reflected directly back to space, leaving a net budget of about 0.33 calorie per square centimeter per minute, which amount eventually must be reradiated to space if the earth's temperature is to remain "constant." In the meantime, 0.11 calorie per square centimeter per minute is used to evaporate water into the atmosphere (on the average, 100 grams per square centimeter per year, or about 2×10^{-4} gram per square centimeter per minute) and 0.2 calorie per square centimeter per minute is reradiated at reduced temperature without perceptible participation in the energy budget of the atmosphere as a whole.
2. *General Electric Research Laboratory Rept. No. RL-785* (1953).
3. I have been reminded that a very significant 7-day cycle is our schedule of living, which might, it has been contended, "culturally" induce effects on the weather. Although such action might invalidate Langmuir's primary conclusion, it would not necessarily invalidate the arguments in this article. Actually, "cultural influences" dictated the choice of a 7-day seeding schedule—compliance with the regular working week is urged by business managers and comptrollers. The question of starting on a particular "working day" is, of course, another matter.