7 August 1964, Volume 145, Number 3632 SCIENCE

Modification Experiments on Tropical Cumulus Clouds

"Exploding" cumulus clouds by silver iodide seeding is used as a controlled experiment on their dynamics.

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Cloud modification was initiated in 1946 when Vincent Schaefer (*1*) scattered dry ice into a supercooled, stratocumulus deck, transforming the seeded path into falling snow. Then his colleague Vonnegut from the General Electric Company (*2*) demonstrated that silver iodide, probably because its crystals resemble ice, was as effective and was much more practical and economical to administer wholesale to clouds. Inspiring their work was the guidance of Nobel prize winner Irving Langmuir, who made extensive calculations of the seeding effects (*2a*).

In those days it was believed that natural rain was produced when supercooled water clouds turned to ice (*3*); this was thought to be the main if not the only way that cloud particles could grow large enough to fall to the ground. It was also thought that most clouds remained highly supercooled bunches of small droplets (10 to 40 microns in diameter) because of deficiencies in the number of "freezing nuclei." The introduction of dry ice or silver iodide could thus, by changing a water cloud into ice, provide the previously lacking means of making cloud particles grow sufficiently large to precipitate. So man appeared, hopefully, to be on the threshold of artificial rain production and perhaps of even more grandiose modifications of his atmosphere.

After nearly 20 years of serious cloud-seeding efforts in many parts of the world, the results are highly controversial and largely disappointing. One of the contributing reasons is that another natural rain-producing mechanism, requiring neither supercooling nor ice, has been identified. It has been learned that cloud drops can often grow to rain size (diameter > 200 microns) by collision and then "coalescence," and an uncertain, but doubtless large, fraction of the world's rain is made in this way.

Does this mean that the rainmakers' apparent failure is irremediable? What can we learn from their failure? Is there any way that man can employ cloud seeding for some useful purpose? In our study we seek to use seeding as a purely experimental tool: to illuminate the processes in individual cumulus-type clouds and to find out quantitatively, by a combination of theory and measurement, what seeding in fact does to a cloud.

Early Cloud Studies

While the rainmakers were dispersing silver iodide into broad "target areas" many miles on a side, using precipitation statistics to test their results and thus requiring several years to obtain significant findings, other meteorologists were, quite independently, trying to understand and design models of the dynamics of cumulus clouds.

Following World War II, the instrumentation and calibration of aircraft for penetrating clouds and recording their motions, temperatures, and moisture distributions led to a rapid increase in understanding which reached a maximum rate in the mid-1950's. One of several such aircraft programs was carried out by Joanne Malkus and her colleagues at the Woods Hole Oceanographic Institution, in Massachusetts. The Woods Hole group found that the tropical oceans, where cumulus clouds are produced with reasonable regularity and uniformity, provide a reliable laboratory for experimental studies of their mechanisms of growth (*4*). The aircraft measurements revealed the main forces at work in the formation of cumulus clouds, and rudimentary models of their circulations were made, by means of mathematics and, later, high-speed computers (*5*).

Briefly, it was learned that cumulus clouds, like people, go through a life cycle; they are born, grow to maturity, age, and die. Unlike people, however, the fatter they are the longer they live, and the taller and more successfully they grow. Most common are the "trade cumuli" (small clouds in photographs on cover). With heights and widths ranging between 0.5 and 1.5 kilometers, these are vigorous only for about 5 to 20 minutes. In contrast, the giant towers of tropical storms are 3 to 5 kilometers across, they flourish for a half hour or more, and their tops may reach into the stratosphere, at heights of about 15 kilometers. One of these clouds releases, in condensation heat, as much energy as the fission energy of several Hiroshima bombs. The patterning of tropical oceanic clouds and their relationship to large-scale atmospheric motions has been described in *Science* (*6*).

Large or small, all cumulus clouds undergo a terrible struggle for exist-

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ence, a marginal battle between the forces of growth and those of destruction. A cloud can grow if the condensation of its water vapor into drops is rapid enough so that the release of latent heat keeps it warm, or buoyant, relative to its surroundings. The main destructive force is the "entrainment" of cool outside air, of low humidity, which lessens the buoyancy of the cloud and, through drying, chokes off its condensation potential. Entrainment is largely a process of turbulent mixing, and thus is very difficult to model mathematically or on the high-speed computer. Current efforts are being guided to some degree by laboratory experiments; the applicability of such experiments is, however, limited by the reduction in scale and by other problems, such as the difficulty of simulating condensation. Obstacles of this sort increasingly hindered progress in cloud studies, and after the late 1950's a breakthrough in cumulus dynamics (*7*) was badly needed. The way in which cloud motions determine the sizes of cloud drops and, in turn, the way in which the growth of drops affects the cloud motions are still difficult and unsolved aspects of the problem. It is necessary to understand this linkage in order to evaluate and exploit cloud-modification possibilities, as our work shows.

Bases of the Modification Effort

That entrainment is the main brake against the growth of cumulus clouds is simply illustrated. At heights of 4 to 8 kilometers a nonentraining tropical cloud would be warmer than its surroundings by 3° to 4°C, and it would thus experience an enormous upward acceleration (10 to 15 cm sec^{-2}). An entraining cloud is only about 0.5° to 1.5°C warmer than its surroundings, and its relatively low buoyancy is nearly balanced by drag and the weight of suspended water drops.

In such a marginal situation the testing of cloud theories by direct measurement is difficult, since all forces must be determined very accurately when a small residual spells growth or death. We postulated (*8*) that the rate of entrainment was inversely proportional to cloud diameter, but the complex turbulence precluded development of a detailed model, and the rigorous observational conditions made it hard to test properly or further develop our simplified model.

Paradoxically, this very difficulty—the slight difference between the forces that cause growth and those that cause disintegration—makes drastic cloud modification a possibility. A hair-trigger balance can, potentially, be upset even when man's fund of energy is puny as compared to that of a cloud. If a cumulus could be warmed by only about 0.5° to 1.5°C by freezing supercooled water at a critical stage, its growth forces could be doubled, and a failing cloud could be given a potent "shot in the arm." As little as about 1.5 to 5.0 grams of supercooled water per kilogram of cloudy air would provide the needed fusion heating. Fragmentary aircraft measurements obtained earlier suggested that this much supercooled water might be available in those tropical cumuli which reach heights somewhat above the freezing level (about 4.8 km).

But the bridge between possibility and actuality is often lacking, particularly in large-scale geophysical problems. Here the chasm appeared almost too formidable to be spanned. First we required a method of directly introducing large quantities of silver iodide into still-living clouds, and clouds seldom wait patiently. Second, we required a way of measuring the cloud structure before and after the seeding and comparing these results with measurements of identical unmodified clouds. Already it appeared that coordinated use of several specially equipped aircraft would be needed. Meteorological work with a single instrumented aircraft is a house of cards, which can be collapsed by the malfunction of just one in a myriad of components. But cloud seeding and measurement from several coordinated aircraft has rarely been attempted.

As is so often the case in science, the bridge design used had been developed in quite a different context. Robert Simpson, after years of hurricane research (see, for example, *9*) had developed a hypothesis that the circulation in these storms might be measurably reduced by the release of fusion heat in the huge cumulonimbus towers surrounding the "eye." The preliminary results from Hurricane Beulah (1963) have already been described briefly in *Science* (*10*). These experiments were facilitated by the use of pyrotechnic silver iodide generators developed by Pierre Saint-Amand of the Naval Ordnance Test Station at China Lake, California. His bomb-like devices (see cover) are dropped from aircraft at special intervals. They create a dense sheet of silver iodide smoke extending down to the ocean, and in seconds fill a cloud with a vast number of large silver iodide particles.

Testing the pyrotechnic generator technique and testing some links in the hurricane hypothesis (*11*) was the practical motivation which provided the logistic support for our primary scientific objective—a two-pronged experiment in cumulus dynamics in which we would (i) try to relate cause (seeding) and consequence quantitatively and (ii) use modified versus unmodified cloud to test the various assumptions and facets of our cumulus model. Progress in such testing is immeasurably accelerated by the existence of the near-balance in natural clouds, which is readily upset.

Experiment Design

The key features of the operational concept are shown in Fig. 1*a*. A "test cloud" is chosen from a group of clouds whose tops naturally reach heights of 6 to 7.5 kilometers. At these heights towers have temperatures below −4°C (about the highest temperature at which silver iodide is effective), but they are not yet cold enough for much of their water to have formed ice naturally; natural ice formation may become important above about 8 kilometers, but knowledge is currently lacking on this vital point.

The idea is, first, to get the two observing DC-6's through the chosen cloud to record the "before" picture of its structure, then to send the seeding plane (a Navy A3B) across the cloud top and have it drop its "bombs" at intervals of 100 meters or less. The cloud is thus filled with large silver iodide particles in amounts ranging between 2 and 200 particles per *cubic centimeter*.

During the seeding, the two DC-6's perform a 180-degree turn and retrace their course, making a series of four or five penetrations of the cloud to measure changes in temperature, liquid water content, and density of active freezing nuclei for about 30 minutes after seeding. Meanwhile a W-57 aircraft at 9 kilometers makes similar measurements. In addition, a Navy photographic plane makes passes at 10 kilometers, recording the cloud growth and the time at which the cloud top crosses the plane's level—an important check upon calculations to follow.

So far, five coordinated aircraft have been mentioned. As a minimum requirement for success, the first three of these must have near-perfect timing. The key aircraft which makes this coordination possible is not shown in Fig. 1*a*, but its track appears in Fig. 1*b*, a plan view of the experiment. This is the "command aircraft," a Navy Super-Constellation (WV-3) of the type used in the coastal airborne early warning service. It carries 3- and 10-centimeter plan-position radars, a height-finder radar, and an essential individual called the "flight controller," who directs the detailed movement of each aircraft, directing it relative to the cloud by use of his radarscope. Unquestionably, the Navy's experience in executing complex multi-aircraft maneuvers made possible an experiment which otherwise would have remained a theoretical meteorologist's daydream and a practical meteorologist's nightmare.

We rode in the command aircraft, selected the clouds, and, after checking their heights on radar, gave the "go ahead" signal. From there on, the experiment was in the controller's hands; we were free to observe and take carefully timed photographs as the command plane followed a box course clockwise at a known distance (50 to 75 km) from the selected cloud.

Overall Results

The aircraft were based in Puerto Rico and were able to range over the entire Caribbean Sea seeking suitable clouds. By some miracle the operation was successfully carried out on all the 4 days on which it was attempted, in August 1963. Altogether, 11 clouds were studied. Six clouds were seeded and five "controls," in the same location and growth phase, were penetrated and observed. All the control clouds died within the normal life span of tropical cumuli. Of the six seeded clouds, one was seeded after it had collapsed at a height below 3 kilometers (at temperatures above freezing); in one other case the procedure was perhaps improperly carried out, as the cloud had already achieved a height of 9 kilometers when it was seeded. Both these "failures" occurred on the same day (19 August).

The four properly seeded clouds "exploded" after seeding—that is, they behaved in the abnormal and spectacular fashion shown in the cover photographs. The explosion consisted of two phases. The first was a vertical growth of the seeded tower, the test cloud becoming 3 to 5 kilometers taller than it was when seeded and that much taller than neighboring and control clouds (Fig. 2, *a* and *b*). This first phase lasted 9 to 14 minutes, ending when growth of the seeded tower was stopped in the layers of stable air up near the tropopause.

Then a second and quite unexpected growth phase set in. The cloud body expanded horizontally to more than twice its original diameter (Fig. 2, *c* and *d*), regenerated internally, and put forth new towers; in two cases a whole line of lesser clouds formed, extending for about 100 kilometers. The second phase lasted at least 20 to 30 minutes; generally the aircraft's fuel supply dwindled before that of the seeded clouds did. Such a prolongation of the cloud's normal life cycle causes it to release additional condensation energy equivalent (at a conservative estimate) to the energy of one or two Hiroshima bombs. If the explosion can be definitely attributed to the seeding, this is quite a return for 30 kilograms of silver iodide (about 25 bombs per cloud). To our

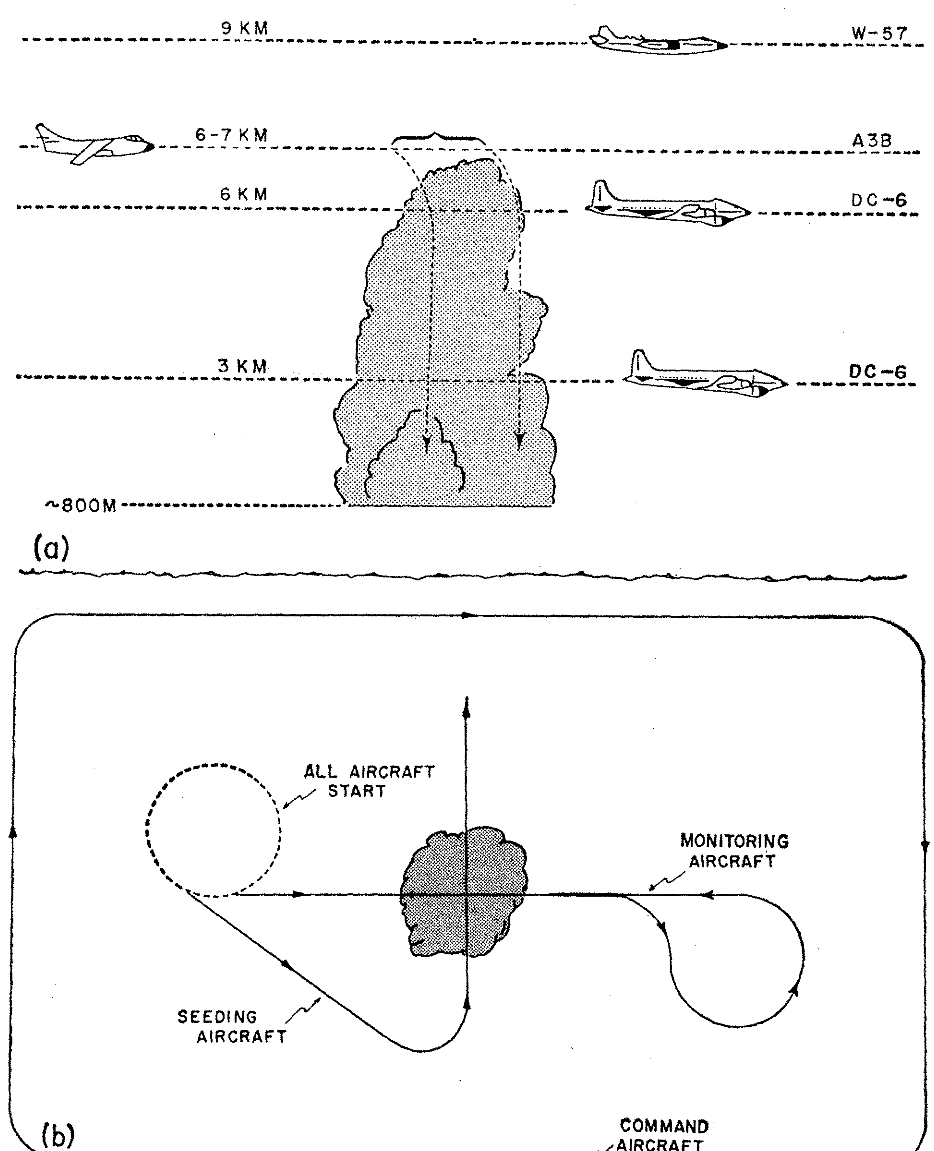

Fig. 1. Experiment design. (*a*) Profile view. The two instrumented DC-6's penetrate the test cloud about 3 minutes before the Navy A3B drops the pyrotechnic generators along the bracketed part of the path near the cloud top. Then the DC-6's make four or five more traverses through the cloud after seeding. The instrumented W-57 penetrates the growing tower after it reaches a height of 9 kilometers. (*b*) Plan view. Dashed circle shows initial deployment of all aircraft (except command aircraft). Seeding aircraft crosses the cloud, making a drop after the first pass by monitoring aircraft.

knowledge, similar cumulus explosion by seeding has been achieved a few times previously—for example, by Kraus and Squires (*11a*), but soundings and cloud measurements have not been available to establish quantitative causal relations.

The Cloud Model

Our purpose in using a mathematical-numerical cloud model in conjunction with this experiment is twofold: (i) to establish beyond reasonable doubt the cause-and-effect relationship between seeding and explosion; (ii) to test and develop cloud modeling in the dual context of normal and highly abnormal cloud.

The experiment, to a degree, met the test of reproducibility. Yet the two clouds of Fig. 2 (and two others not shown) could be freaks of nature, or conceivably, they might have exploded naturally without the introduction of silver iodide. On 17 August, no oceanic clouds were growing above 7.5 kilometers, but clouds of large diameter over the islands and over the distant continent were attaining cumulonimbus stature without seeding. On 20 August, also, cumulonimbi were sprouting over the land, and on that day some of the oceanic clouds of larger diameter were attaining heights of 10 to 12 kilometers unaided. In science, there are two ways of testing a causal relationship—by physical laws and by statistics. The latter method is usually resorted to when the applicable physical laws are not known; it requires a very large sample of observations. Our experiment was neither sufficiently randomized nor reproduced often enough to demonstrate the causal relationship statistically. Fortunately, simplified physical laws governing cloud growth have been formulated. These laws still contain some arbitrary assumptions and inaccurately known parameters, but we compensate for these by means of multifold "control" calculations, widely varying each assumption at each stage.

Our cloud model is here applied only to the vertical or first phase of explosion. It is based on the "spherical vortex" model of a cloud tower, a model developed and tested some years ago by Levine (*12*). Levine showed that if the cloud tower has an internal circulation like a vortex

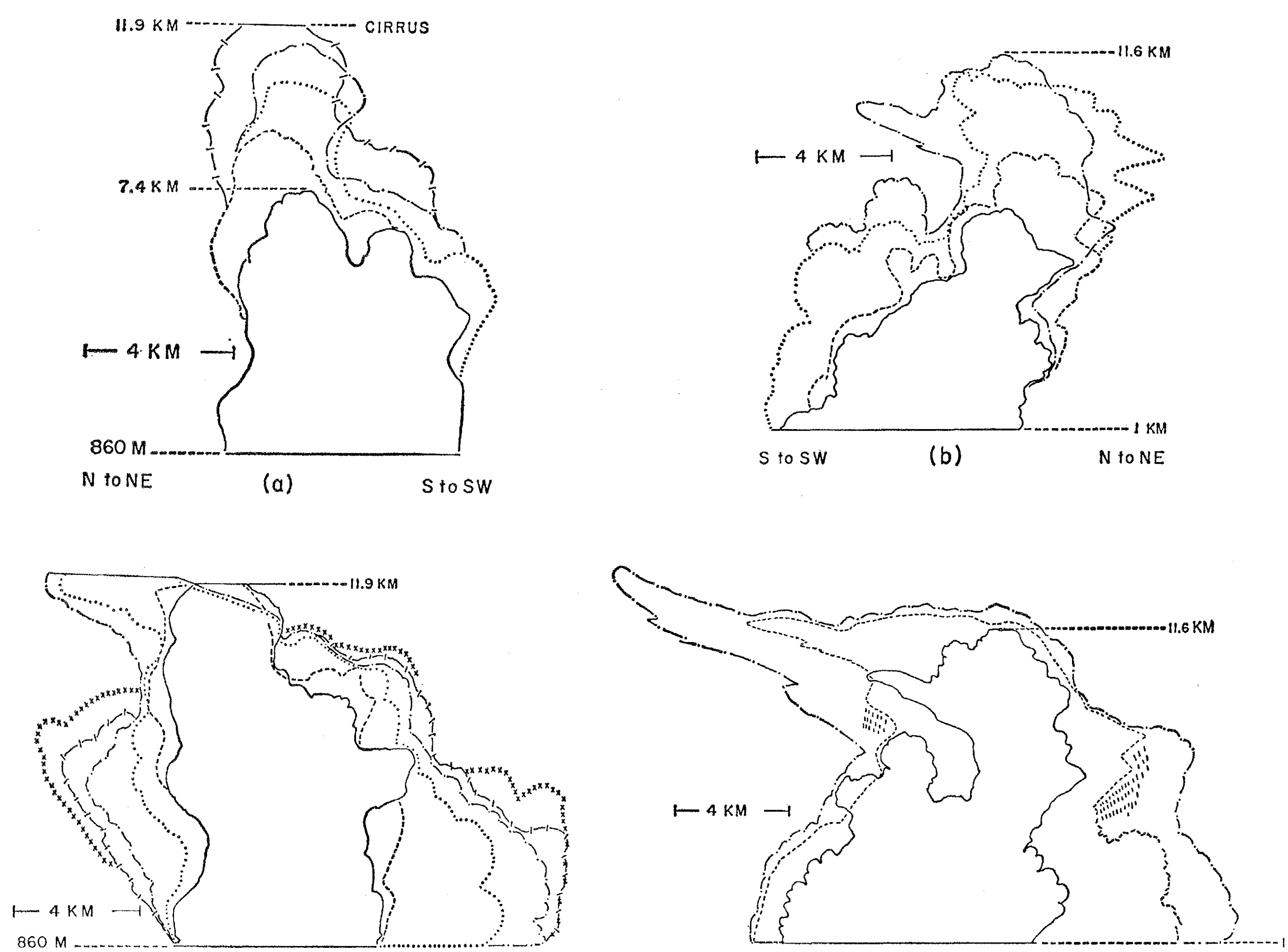

Fig. 2. Profiles of two seeded clouds, showing the two phases of the "explosion" after seeding. The profiles were traced from projected 35-millimeter slides taken from the command aircraft. The scale was obtained from radar photographs which give the aircraft's distance from the cloud. Vertical rise rates (used later to test the cloud model) were also measured from the radar photographs. (*a*) Seeded cloud on 17 August, first phase (first interval, 4 minutes; later intervals, 3 minutes). (*b*) Seeded cloud on 20 August, first phase (see cover, top photographs) (first, third, and fourth intervals, 4 minutes; second interval, 5 minutes). (*c*) Seeded cloud on 17 August, second phase (intervals, 3 minutes). (*d*) Seeded cloud on 20 August, second phase (see cover, bottom photographs) (first interval, 21 minutes; second interval, 4 minutes). Dashes denote ice crystal showers.

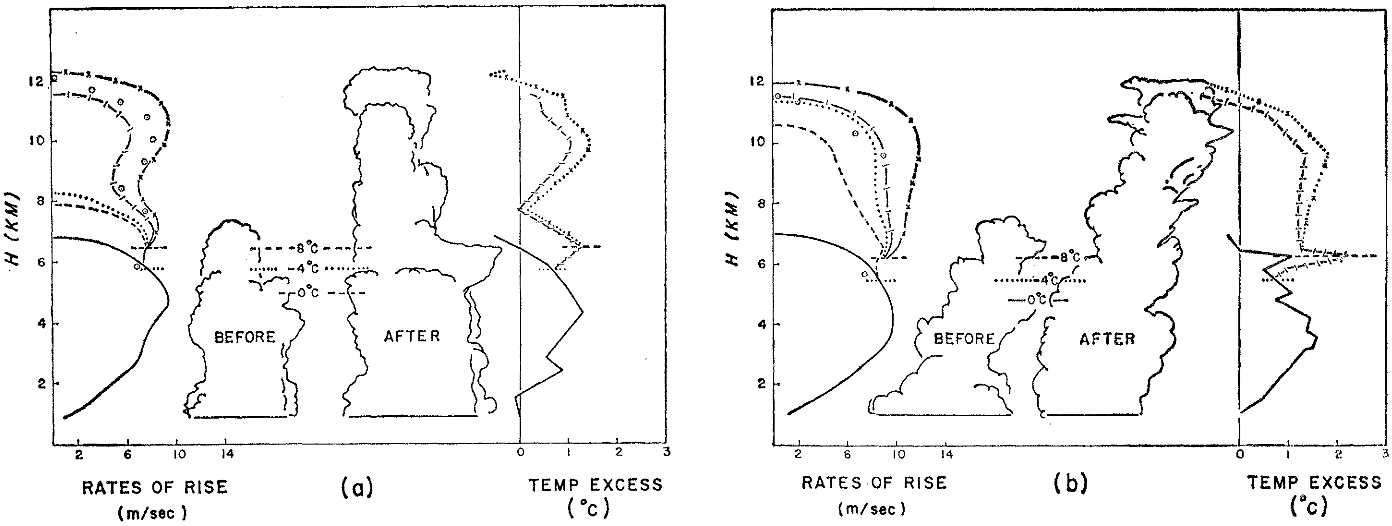

Fig. 3. Comparisons of seeded clouds and theoretical-numerical model. (*a*) Cloud of 17 August. (*b*) Cloud of 20 August. Cloud outlines are drawn schematically to resemble photographs; tower heights and widths are drawn to scale; temperatures shown are in-cloud temperatures. Vertical scale, height above sea level (in kilometers). Rate-of-rise curves (left) are computed from the model, as described in text: (solid curve) before seeding; (dashed curve) after seeding, fusion heating only; (dotted curve), after seeding, fusion heating plus tower expansion of one-third; (dashed curve with bars) after seeding, fusion heating plus three-fourths of condensate dropped; (dashed curve with ×'s) after seeding, fusion heating plus tower expansion plus three-fourths of condensate dropped. (Circles) Actual rate of rise measured from photographs. Cloud-temperature excess (right) computed from entrainment calculation and from observed tower diameter at time of seeding: (solid curve) temperature before seeding (checked by DC-6 measurements); (dashed curve with bars) temperature after seeding, with no tower expansion; (dashed curve with ×'s) temperature after seeding, with tower expansion of one-third. Fusion heat was released at cloud heights in the range between dotted and dashed horizontal lines, which represent cloud temperatures of −4° and −8°C, respectively.

(or smoke ring), a relatively simple, tractable form of Newton's second law of motion can be applied to predict its rate of rise as a function of height, given only the conditions at cloud base, the cloud diameter, and the vertical distribution of temperature and humidity in the ambient air (called the environment "sounding"). Later workers (*13*) showed that an equation of the same form is applicable also to plume or jetlike cloud towers.

In words, this equation may be stated as follows:

Vertical acceleration =
buoyancy force minus drag forces (1)

If we can specify the force terms on the right, we can integrate or solve this equation for the vertical velocity, using the electronic computer if necessary. We attempt to predict thereby the rate of rise as a function of elevation for unseeded as compared to seeded clouds. The height at which the rate of rise becomes zero gives the position of the vortex center when growth ceases (the cloud top is about 1 km higher).

If the cloud suffered no entrainment and carried no water or ice particles, its buoyancy would be immediately deducible from the input information. In a real cloud, however, buoyancy is reduced by entrainment of cool dry outside air and by the weight of the sustained drops or ice crystals. The drag forces consist of the momentum loss due to entrainment and probably also of an aerodynamic drag due to displacement of air around the rising tower. Whether this latter drag exists and, if it does, how great it is are questions which cannot be answered merely by observing natural clouds; repeated experiments such as ours may provide the answers to these important questions.

If we know what fraction of its air the cloud is entraining from outside for each kilometer it rises, we can readily compute, by means of Stommel's method (*14*), the reduction in buoyancy, the total amount of water condensed, and the drag due to entrainment. We can, further, set an upper limit to the aerodynamic drag by moving around the tower the fraction of the displaced air that is not entrained—that is, by taking that fraction of a solid sphere's aerodynamic drag.

The basic postulate of our model is that the entrainment rate is an inverse function of cloud diameter—namely,

$$\text{Entrainment per 1-km rise} = \frac{K}{D} \qquad (2)$$

where D is the cloud diameter and K is the constant of proportionality. The availability of measurements, obtained over many years, of natural cloud buoyancies and diameters made possible a "calibration" of K in Eq. 2. A value was obtained that was within the range determined in laboratory experiments (*15*).

Thus the first step in our cloud procedure is clearly specified. We take the observed cloud diameter and calculate the before-seeding temperature profile of the cloud, then check this against the measurements obtained from the DC-6. In all cases the laboratory value of K gave cloud temperatures within 0.1° to 0.2°C of those observed. Next we wish to substitute our results in Eq. 1 and solve it, but one uncertainty remains. How much of the condensed liquid water, of known amount, is carried up with the tower and how much falls out? In the calculations based on observations of clouds before seeding or of clouds that were not seeded, we arbitrarily took a value of ½ and obtained results that compared favorably with measurements from the DC-6's (whose instrument underestimates, if anything). Since the upper-level aircraft (the W-57) was unable to obtain water measurements during these experiments, we tried, in our calculations, various fractional values for liquid-water content and

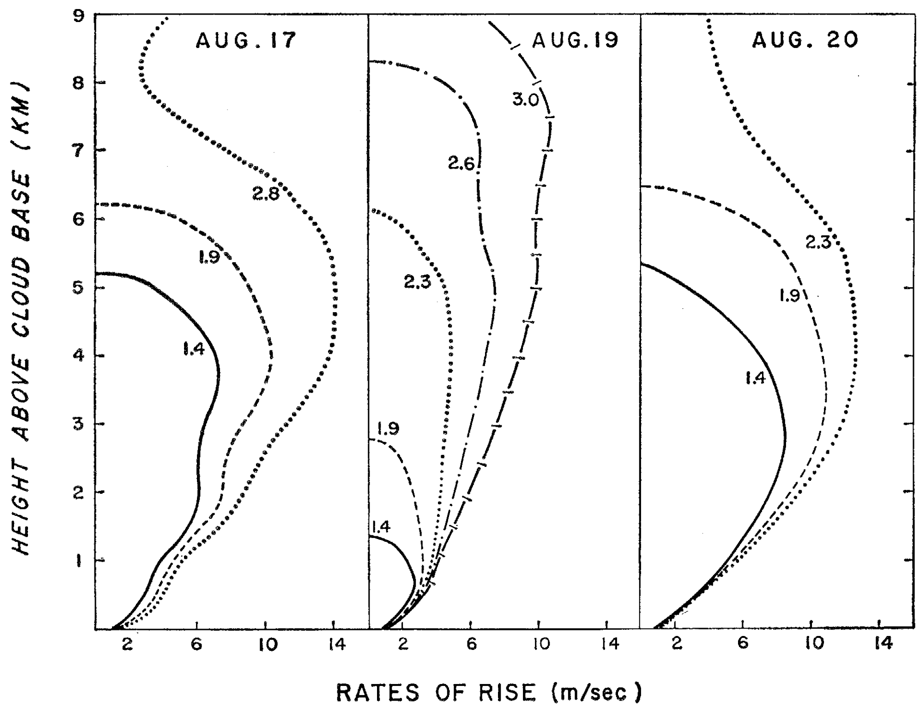

Fig. 4. Vertical rise rates for a group of unseeded, unfrozen clouds of various diameters on 3 of the 4 experiment days. Vertical scale, height above cloud base (in kilometers). The value beside each curve is the diameter (in kilometers) of the cloud tower.

compared each result with observations for the seeded clouds.

The rest of our procedure can best be explained by discussing the results. Figure 3 shows these for the seeded clouds of Fig. 2, *a* and *b* (17 and 20 August, respectively). Both test clouds had an original tower diameter of 1.7 kilometers. The origin of the solid "before" curves should be clear. The temperature excess is computed by means of Eq. 2 and Stommel's method and then checked against the measurements from the DC-6's. The rate-of-rise curve is obtained by substituting, in Eq. 1, the result of the entrainment calculation and integrating on the high-speed computer; retention of half the condensed water is assumed. The results are tested against observed cloud-top heights and against rise rates computed from the photographs.

The calculations for the seeded clouds are made by introducing the following modifications. The retained water is frozen at temperatures between $-4°$ and $-8°C$, and the heat of fusion is added to the cloud air linearly between those levels, with the little evaporation required to keep the cloudy air saturated. Then the entrainment calculation proceeds (upward from the $-8°C$ level) as before. There are two alternative curves for temperature excess after seeding; the curve representing higher temperatures shows the excess when the diameter of the seeded cloud had expanded by one-third (measured). The rate of rise is then obtained, as before, by computing the new buoyancies from the new temperature excesses and substituting them in Eq. 2. There are four rates-of-rise curves for the seeded cloud—two for the expanded and two for the unexpanded tower. In each case the curve representing the higher rate results from the dropping out of three-fourths of the condensate after seeding. This trial was suggested by the DC-6 pilots' report of very heavy precipitation following successful seeding. In each case the curves for the situation in which precipitation was higher (dashed line with vertical bars, or curve of $\times$'s) show a more rapid rise and greater heights attained than the curves (dashed and dotted) for the situation in which half the condensate is retained after seeding; these distinctions are especially marked for 17 August (Fig. 3*a*), the date on which this difference is critical. Plainly it is important to our knowledge of cumulus dynamics, as well as to practical cloud-modification endeavors, to resolve the controversy of whether seeding does or does not lead to increased precipitation.

The excellent agreement between observed and computed rise rates and heights of modified and unmodified clouds strongly suggests that the model is workable and, perhaps even more important, that seeding in fact caused the cloud to increase its height so drastically. However, the clinching evidence remains to be introduced. It is necessary to show that unseeded clouds could not have attained the observed heights naturally. Concomitantly, it is necessary to show that no reasonable, or even unreasonable, alterations in any of our assumptions could alter this conclusion, theoretically permitting an unseeded cloud to grow as high as the clouds we seeded and observed.

The first necessary step is illustrated in Fig. 4. Here we present rise curves for a hierarchy of computed cloud sizes, using the modeling assumptions described. Let us look first at the days on which attempts at cloud modification were successful, 17 and 20 August. On both these days clouds in the size range near that of the test cloud (1.4 to 1.9 km in diameter) terminate at heights near or below 7 kilometers, with temperatures higher than $-10°C$. There appears little chance that such clouds will "run away" unaided. (Our diameter measurements of 1.7 kilometers are accurate to better than 10 percent.)

Under the conditions of 17 August, clouds 2.8 kilometers across will grow naturally to great heights, as did the large ones over land. Under the conditions of 20 August, slightly smaller clouds (only 2.3 km in diameter) will grow by themselves; some oceanic clouds of this size indeed did so. We seeded one of these and have analyzed the results elsewhere (*16*). On both these days on which modification attempts were successful, there was an atmospheric "lid" on clouds of a wide spectrum of sizes—a stable, dry layer imposed at heights 1 to 3 kilometers above the freezing level. In contrast, on 19 August, the day on which seeding was unsuccessful, conditions were quite different, as the middle graph of Fig. 4 shows. A very narrow range of cloud diameters reached heights of 6 to 7.5 kilometers, and with such low velocities that rapid collapse is certain. The slightly larger clouds which attained these heights with adequate speeds were bound to run away spontaneously; these points were painfully brought home by our experimental difficulties.

Only one loophole still remains:

Could there have been, in our model, "overdrag" of the clouds in the test range, and could such clouds, with less drag, have grown to great heights naturally? Only if this possibility is clearly negated can we say that the need for sudden release of the fusion heating—the basic cause-and-effect relation—has been demonstrated beyond reasonable doubt.

For this important reason a wide variety of "control" calculations were undertaken; only a few of the key ones can be summarized here.

Control Calculations

The most crucial and most arbitrary assumption in our work concerned the fraction of the condensed liquid water retained in the model cloud. The skeptic might argue that if this fraction were much lower in the real cloud, two bad results, from the standpoint of cloud modification, might ensue: first, the reduction in weight could cause the unseeded cloud to explode, and second, the reduction in freezable water might diminish the seeding effect to insignificance.

D. A. Andrews tested these questions in modeling studies based on assumptions of various water contents before and after seeding (*17*). The surprising result was that wide variations in retained water made little difference in the crucial features of the cloud's behavior. Part of this result is illustrated by curve *B* of Fig. 5, which represents the way in which the unseeded cloud of 17 August would have behaved had it retained only one-fourth of its condensate. The value of ¼ is unrealistically low, giving less than 1 gram of cloud water per cubic meter—well below the DC-6's estimate, which is always low. Even so, the unseeded drier cloud (curve *B*) grows but little higher; the environmental control dominates. Furthermore, when seeded, the cloud of curve *B* grows nearly as high as the one of Fig. 3. We have not shown cloud *B*'s "after-seeding" curve, but its loss of water and hence of fusion heating is compensated by its higher ascent rate when seeded.

However, the controversial aerodynamic drag remains—could reducing it permit an unmodified cloud to run away? We removed this drag altogether and repeated every calculation; a telling example is the dotted curve of Fig. 5. The calculated rise rates are now much higher than the observed rates, but still unmodified clouds not only fail to run away, they even fail to reach altitudes above 8 kilometers or temperatures below $-10°C$.

Conclusions and Future Outlook

We believe that the series of control calculations establishes, beyond reasonable doubt, the causal relationship between seeding and the observed explosive cloud growth which followed. These calculations, however, can do much more for cumulus dynamics—in conjunction with future, repeated experiments. This potential is suggested in Fig. 5. Although large variations in amount of suspended water and in drag do not spell the difference between explosion and early death of the cloud, they do make a difference of about 5 meters per second in its rise rate (an increase of more than 50 percent); this is measurable even by rather crude methods.

Figure 5 thus shows that if we could exactly determine a cloud's water content, which could be done with existing instrumentation, we could find indirectly the aerodynamic drag, which cannot be found directly with existing instrumentation. This is an important step in cloud modeling, a prerequisite for understanding and predicting the behavior of natural clouds and for designing new experiments that will eventually yield practical benefit.

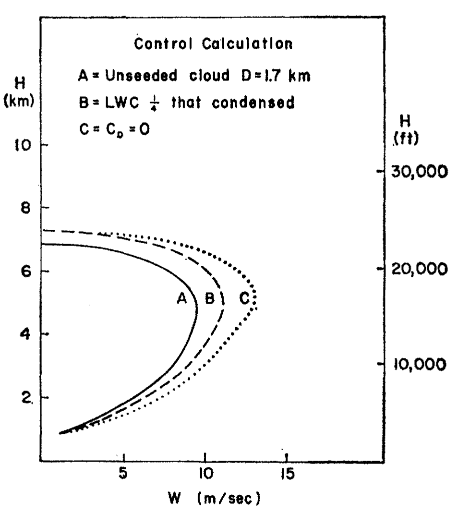

Fig. 5. Example of one of many "control" calculations, with variation of parameters and assumptions, used in the cloud model, as applied to the cloud of 17 August before seeding. Vertical scale, height above sea level (at left, in kilometers; at right, in feet). (Curve *A*) Rise rate for unseeded cloud of Fig. 3*a* with half the condensate retained and with aerodynamic drag exerted by air not entrained (drag just under half that of a solid sphere of the same diameter). (Curve *B*) Rise rate for the cloud with only one-fourth the condensed water retained (that is, condensate of < 1 g/m^3) and with aerodynamic drag retained. (Curve *C*) Rise rate for the cloud with aerodynamic drag reduced to zero and half the condensate retained.

This experiment has barely scratched the surface; its repetition, with a number of improvements, is mandatory. Selection of clouds for seeding and for control should be randomized. Better measurements of humidity and water content from the observing aircraft are necessary, as well as frequent sampling of hydrometeors to determine types and particle sizes. We must learn more of the natural freezing behavior of tropical oceanic clouds.

The second (horizontal) phase of the cloud explosion is exciting and potentially perhaps even more important than the first (vertical) phase. We have just begun to study the second phase. During it, the aircraft measurements showed a doubling or tripling of cloud buoyancy and an *increase* in the content of supercooled *liquid* water (despite the dense showers and the proliferation of a myriad of ice crystals inside and outside the cloud), suggesting dynamic invigoration of the whole convective machinery (*16*).

For practical weather modification, this second phase could prove the most significant, since giant clouds are the combustion cylinders in hurricanes and in the equatorial "firebox" of the global air circulation (*18*). The cirrus sheets these cumulonimbi produce are important in the radiation budget of a region. But many experiments beyond this one must be made, many times over, before extrapolation to the practical or to the large scale will be possible. In fact, it should be emphasized that the experiment described, as compared to most weather modification schemes that have been talked about, is ultramodest in purpose, limited in scale, and not yet practical in aim or result—and yet it is at the outer limit of man's present scientific and operational resources.

The important conclusion, of course, is that such an experiment can be made: a real atmospheric phenomenon is at last subject to a relatively controlled and theoretically modeled experiment. It has long been deplored that the earth sciences, in contrast to physics, must be observational rather than experimental sciences. Here meteorology is taking the first small steps toward becoming an experimental science, which it must become if man is ever to exert real control on his atmosphere. Fortunately, the first step has been made with cumulus clouds. These are of vital importance to man in themselves, a key part of the larger-scale atmospheric machinery, and a prototype of the widespread geophysical phenomenon of thermal convection.

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19. Our colleague, Captain Max Eaton (U.S. Navy) made this study possible by his efficient direction of the vital part of the operation contributed by the U.S. Navy. We are deeply grateful to the crews of the Navy's VW-4 Squadron and the U.S. Weather Bureau's Research Flight Facility, who went far beyond the call of duty in carrying out the experiment. The analysis of results was mainly carried out under the National Science Foundation's grant No. GP-1158 to the University of California, Los Angeles. This article is University of California (Los Angeles) Department of Meteorology paper No. 106.

CURRENT PROBLEMS IN RESEARCH

Enzymatic Alteration of Nucleic Acid Structure

Enzymes put finishing touches characteristic of each species on RNA and DNA by insertion of methyl groups.

P. R. Srinivasan and Ernest Borek

Nucleic acids, both RNA and DNA, contain several minor components in addition to the four main bases of their primary structure. In the DNA of bacteria the minor component is 6-methyladenine (*1*) and in that of plants and animals it is 5-methylcytosine (*2*). The presence of methyl derivatives of the bases has also been reported in ribosomal RNA, but the compounds have not as yet been characterized. In transfer RNA, on the other hand, no fewer than ten methylated bases have been demonstrated (*3*). In addition, transfer RNA contains an unusual riboside, pseudouridine, a compound in which the ribose is attached to carbon atom 5 of the base (*4*) (Fig. 1).

The presence of methylated bases in nucleic acids has, until recently, presented several paradoxes. In the first place, no monomeric methylated precursors were ever found within any tissue examined. Moreover, it was difficult to visualize how transfer RNA, which contains ten different methylated bases and pseudouridine, could be derived by complementary alignment from DNA, which contains but one methylated base. Indeed, the Watson-Crick hypothesis for the replication of DNA itself, or for its transcription into transfer RNA, offers no mechanism for the determination of the sequence of methylated bases in a nucleotide chain.

All of these paradoxes were resolved by the discovery, in our laboratory, of enzymes, which activate transmethylation, at the polymer level of the previously formed transfer RNA. This work revealed the mechanism of insertion of the methylated bases into both RNA and DNA. The bases are methylated *after* the formation of the polymeric nucleic acids.

These conclusions were made possible by an unexpected observation made 10 years ago (*5*) on an anomalous attribute of the auxotroph *Escherichia coli* $K_{12}W6$. This organism is unique among amino-acid-requiring microorganisms in that RNA synthesis continues during starvation of its essential amino acid, methionine, whereas in every other auxotroph RNA synthesis ceases in the absence of an essential amino acid.

Recently Stent and Brenner (*6*) have made an important contribution to the genetics of *E. coli* $K_{12}W6$ by demonstrating that the relaxed control over RNA synthesis in this organism is due to a genetic aberration which can be transferred during conjugation. The appropriate amino-acid-requiring recombinants accumulate RNA in the absence of any requisite amino acid.

Examination of the RNA which accumulates during methionine starvation revealed no moleculear species different from those found in normal microorganisms. However, we observed a profound alteration in the structure of the newly formed transfer RNA. It lacked the methylated bases, including thymine. This finding pointed to the possibility that methionine is the source of methyl groups for all of the methylated bases in RNA. This could be anticipated in part, for methionine, or rather its activated derivative S-adenosylmethionine, is the methylating agent in most biological reactions. However, that the thymine of RNA should stem from this source was completely unexpected. It had been unequivocally established earlier, by Kornberg and his associates, that the thymine in DNA is a product of a different reaction: a condensation of a

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