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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

Cumulus Clouds and Their Modification

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Office
of the
Director
BOULDER,
COLORADO
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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

BOULDER, COLORADO

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Office of the Director
Boulder, Colorado
May 1972

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PREFACE

This review article, written mainly for the non-meteorologist, has been prepared as a chapter for a forthcoming book on Weather Modification, to be edited by Dr. Wilmot N. Hess.

The authors have decided to distribute a limited number of preprints in the present semi-final version for several reasons. The first is to solicit review and criticism from those with experience and expertise in the different aspects of cumulus modification, and the second is to discover how well the material serves its function of communicating to non-meteorologists, in a short course that one of us is teaching.

Joanne Simpson

Arnett S. Dennis

May 1972

ABSTRACT

The modification of cumulus clouds is discussed in the framework of their importance to the energetics and transports of the large-scale atmosphere, as well as that of their role in precipitation production and water management.

Present knowledge of cumulus physics and dynamics, and their interaction, is summarized, with emphasis on models and on the interaction of clouds in groups and populations. The various attempts at enhancing coalescence are described, including use of water spray, hygroscopic materials and electric fields.

About 40 percent of the material concerns seeding supercooled cumuli with Dry Ice and silver iodide, beginning with the basic principles and methods used. Distinction is made between the "static" and "dynamic" approaches. In the former, it is sought only to alter cloud microphysics by transforming a supercooled water cloud to one composed of ice, while in the latter, the latent heat of fusion is intended to increase buoyancy, invigorate updrafts and increase cumulus growth. Early "static approach" programs in Arizona and Missouri are summarized, but emphasis is placed on more recent programs, particularly those in the Great Plains (South Dakota) and in the tropics (Florida).

It is shown that while several types of randomized "single cloud" experiments have reached conclusive results regarding rain increases from seeding, as yet few or no multiple seeding or area experiments have reached a really satisfactory demonstration of increased rain from seeding.

Other cumulus modification methods, actual and potential, are summarized, including radiative alterations, (e.g. carbon black), boundary layer modifications (such as asphalt coatings) and fires. All of these methods are in their infancy regarding demonstration of success and usefulness.

Possible extended area and persistence effects of cumulus modification are suggested as well as potential ways of documenting these largely unknown interactions. The potential impacts of cumulus alteration on synoptic and larger-scale weather systems are speculated upon and the apparently most promising areas of future investigation outlined.

CUMULUS CLOUDS AND THEIR MODIFICATION

Joanne Simpson and Arnett S. Dennis

1. INTRODUCTION

Cumulus clouds (figs. 1-2) are of immense importance to man's livelihood and to his life. Firstly, they produce more than three-fourths of the rain that waters our planet, dominating even more strongly in the thirsty tropical and subtropical areas. Secondly, giant cumuli constitute the firebox of all severe storms, such as the hurricane, thunderstorm, hailstorm, tornado and squall line. Thirdly, cumulus clouds are a vital part of the machinery driving the planetary wind systems, and fourthly they act as a valve regulating the income and outgo of radiation from the earth.

While the atmosphere is fuelled by solar heating, the sun's energy is fed into it only indirectly, first being absorbed at the earth's surface and then supplied to the air from below, mainly in the form of gaseous water vapor. Cumulus clouds are the "converters" whereby the gaseous water vapor is condensed into liquid water droplets, turning "latent" heat into "sensible" heat which can be sensed by a thermometer and used to drive circulations. On the average, equatorward of about 38° latitude the planet earth receives more radiant energy than it loses, while polewards of 38° more energy is lost to space than that received from the sun. Since the 1930's, meteorologists have learned how the tropical driving circulation operates by means of thermally direct (Hadley) cells, with ascent concentrated in a narrow "equatorial trough" zone and mean sinking

Figure 1a. Typical trade-wind cumulus clouds. Oceanic clouds in "streets" lined up with the vertical wind shear.

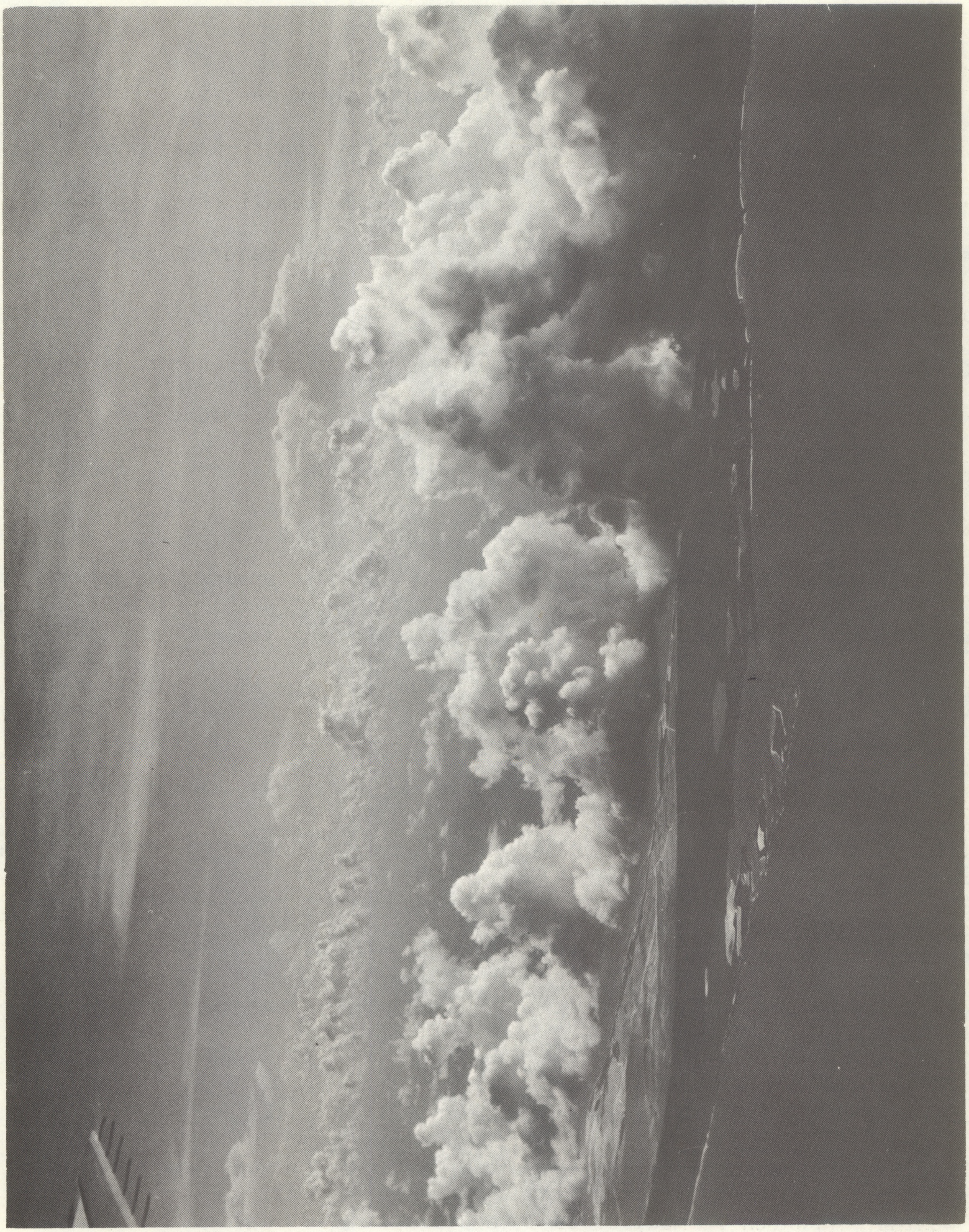

Figure 1b. Typical trade-wind cumulus clouds. Foreground: cumuli over a tropical island. Background: large cumulonimbus clouds. (Courtesy C. True.)

motion elsewhere. At high levels, the tropical cells export energy and momentum poleward to make up the radiation deficits and drive the circulations in temperate and polar regions.

Cumulus clouds form vital links in nearly every part of this engine. The water vapor fuel is mainly provided by the tropical oceans. Above these warm seas, growing day and night, trade cumuli (fig. 1) act as fuel pumps which carry the energy upward, releasing about 20 percent through local rainfall to drive the trade wind systems and making the rest available for these vast bands of easterlies to carry equatorward. In the "equatorial trough" the firebox function of the atmosphere is conducted by only 5000 to 15,000 giant cumulonimbus towers (fig. 2) concentrated in about 0.1 percent of the area.

These huge clouds are the cylinders of the heat engine, as well as a crucial part of its heat pump. Clustered into wave-like and vortical deformations of the flow, they raise and convert energy at a rate nearly one million times that of all the human power consumption in the world. The atmosphere, however, runs an inefficient engine. Only about 2 percent of this vast energy is actually utilized in driving winds; most of it is lost to space by radiation. The role of cumuli in global energy budgets is documented in more detail in Malkus (1962).

In temperate latitudes, cyclones drawing on the energy stored in air mass contrasts are a main driving mechanism in the planetary westerlies. At high levels, these winds snake around the globe in a wave pattern. With their instabilities, these westerlies govern the fluctuating weather in which so many of us live. Over the mid-latitude oceans,

Figure 2a. Cumulus clouds. Tropical oceanic "hot towers" in the equatorial trough zone.

Figure 2b. Cumulonimbus clouds. Clouds of a typical weak oceanic trade-wind disturbance, showing "orphan anvils." (Courtesy C.True.)

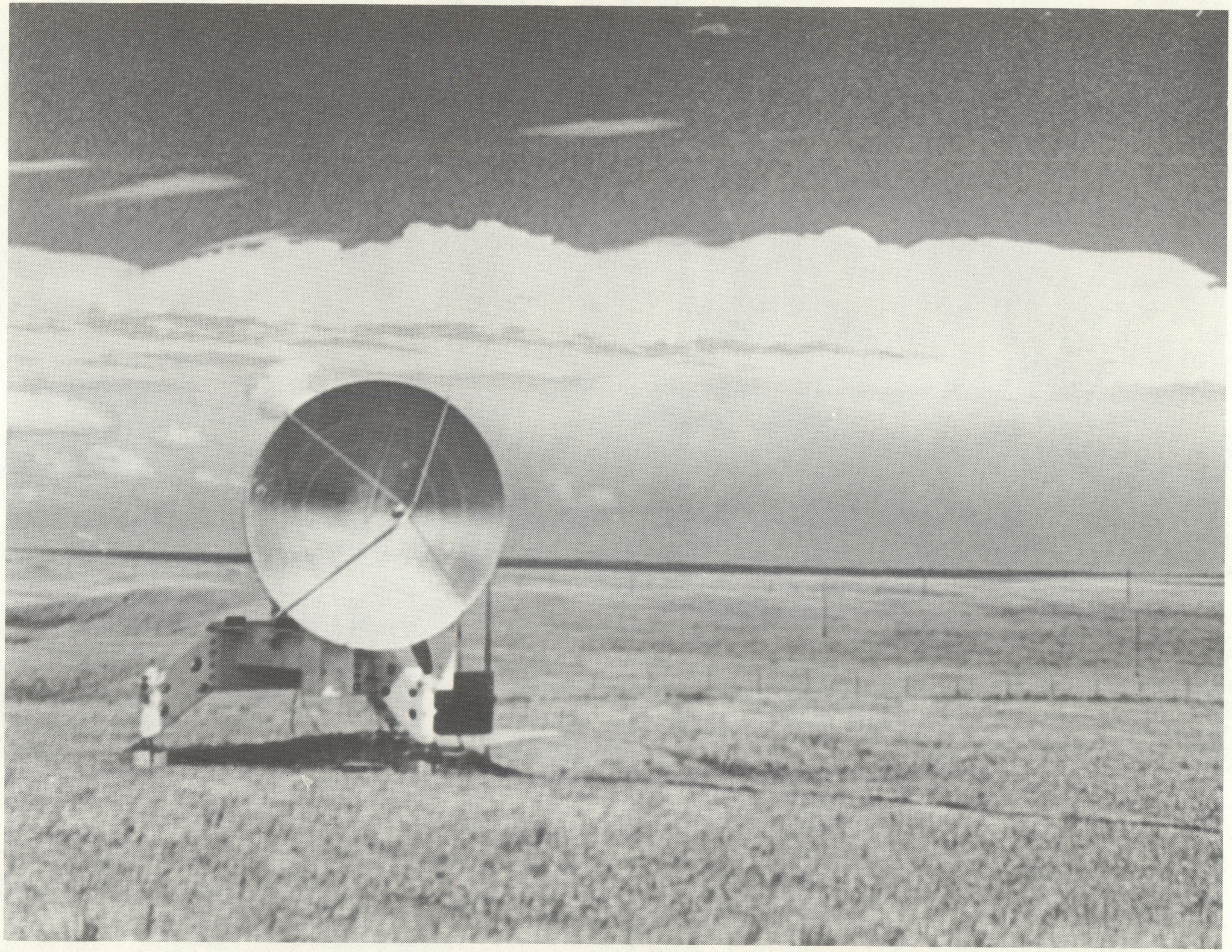

Figure 2c. Large, multi-cellular cumulonimbus cloud east of Rapid City, South Dakota. Antenna of 10-cm radar of National Center for Atmospheric Research in foreground. (Project Hailswath photo.)

cumulus clouds have been found to be a key in the occasional explosive deepening of winter storms, which often bear winds of near hurricane force. Their rapid deepening can trigger a major re-adjustment in wind pattern around a whole hemisphere (see Simpson, 1969).

It is clear from the foregoing that systematic modification of cumulus clouds holds enormous potential impact upon man and his environment. Significantly enough, cumulus clouds are one of the few geophysical phenomena upon which controlled experiments have already today led to definitive results, as we shall see later in this article. If we could indeed alter large numbers of these clouds controllably, a powerful tool is supplied for water management and to mitigate the disasterous destruction from severe storms. Reaching farther, cumulus cloud modification could conceivably trigger important changes in planetary circulations and if sustained, possibly might even bring about modification of regional climates.

What portions of these possibilities are near realization today, how much lies in the foreseeable future and what must be postponed to a later generation or put aside as sheer speculation? It is the purpose of this article not just to provide tentative answers to these questions, but to build sufficient scientific foundations so that the reader can evaluate their soundness and prospects for himself. To achieve this goal, it is essential to understand what is known and what is not known about cumulus clouds, and how modification experiments are carried on and evaluated.

Everyone knows that cloud modification has been a highly controversial topic since its discovery nearly thirty years ago. Cumulus experiments of the past decade have resolved part of this controversy and have revealed the most important single fact about cloud modification, namely that the modification potential depends upon the initial[1] conditions of the cloud-environment system. For example, seeding fair weather cumulus over the mid-latitude continents may give a quite different result from seeding similar looking cumuli over the tropical oceans. Furthermore, we shall find that even over the tropical oceans, different growth regimes can follow identical seeding procedures.

2. THE DYNAMICS AND PHYSICS OF INDIVIDUAL CUMULI

Cloud science began in the 1930's and has made fantastic strides since World War II. In its infancy, the microphysics and dynamics of clouds were mainly approached as separate disciplines and worked on by two different groups of researchers. Today they are progressively combining into one discipline, with the same workers contributing advances in both areas. Cloud physics or microphysics concerns the particles in a cloud, namely the condensation and freezing nuclei, the water drops and ice crystals, their origin, growth and behavior. Cloud dynamics deals with the relation between forces and motions in clouds, with the purpose of predicting and understanding the structure and life cycles of the updrafts and downdrafts.

In figure 3 we see a hierarchy of three important sizes of tropical cumuli. Naturally they come in all sizes, but we have just picked three

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[1] By "initial" conditions is meant those conditions prevailing at the time of the experiment.

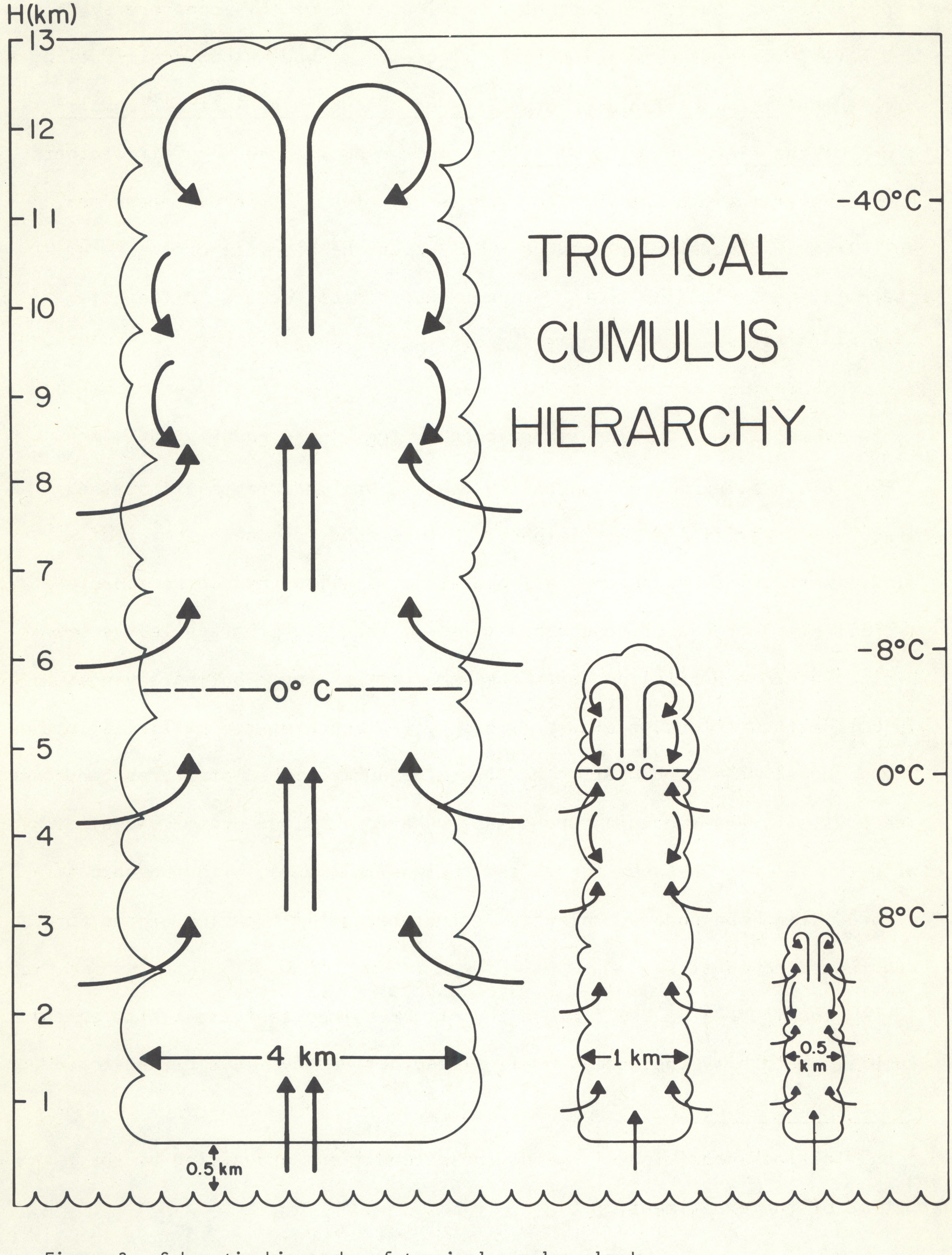

Figure 3. Schematic hierarchy of tropical cumulus clouds.

here to clarify the explanation. Aircraft studies have suggested that cumulus towers sometimes resemble a buoyant bubble or "thermal" or when more vigorous, a growing plume or jet. Both forms have a vortex-like internal circulation near the top. The energy driving the motions comes from the condensation of water vapor into liquid cloud drops. The cloud drops grow to 5-20 μm radius by the condensation process; the growth in radius slows down in direct proportion to the radius increase. For condensation growth a small supersaturation must be maintained by expansional cooling of the air in the updraft which serves to sustain it in the face of removal of vapor by the growing droplets. In the early stages there are normally between 20 and 2000 drops per cm^3 depending on the effective condensation nuclei (CCN) present and the updraft.

These nuclei, which should not be confused with freezing nuclei, are hygroscopic particles in the radius range 10^{-5} to 10^{-2} mm. At low levels over the ocean about 20 percent of these nuclei are sea salt. In continental air, the same number of salt particles constitute only 0.5-2 percent of the much larger total number of CCN's. The remainder are apparently ammonium sulfate and other primarily natural impurities, although smoke and man-made pollution can add greatly to their number locally. These may hasten or delay the initiation of rain, depending upon the size distribution of the polluting aerosol. For our purposes, the most important point is that these nuclei are usually five to ten times more concentrated over land masses than over the sea. Consequently, maritime clouds usually have only 20-100 drops per cm^3 among which to share their water, while continental clouds commonly have more than 500 drops per cm^3, making it much harder to grow rainsized particles and providing a self-enhancing feature for droughts, which may be more rarely found under marine conditions.

"Cloud-sized" condensation-produced droplets (5-20 μm) have negligible fall speeds relative to cumulus upcurrents and so are too small to come out of the cloud base as rain. Even a 40 μm drop falls at only 18 cm per second. Typical upcurrents are 2-3 m sec^{-1} in small cumuli, about 10 m sec^{-1} in medium ones and sometimes 20-40 m sec^{-1} or even more in the giants. Since the condensation process by itself would require more than the lifetime of a cumulus to produce a drop even as large as 40 μm, clearly cumulus rain requires additional mechanisms.

Most cumulus clouds evaporate without ever producing precipitation at the earth's surface. The fact that many convective clouds begin to dissipate at the time rain emerges from the base led to the idea that the clouds are destroyed by the precipitation forming within them; the "precipitation brake" is not fully understood but some aspects of it are discussed shortly.

A useful concept in studying the behavior of shower clouds is the "precipitation efficiency," defined here as the ratio of the mass of precipitation reaching the ground to the total mass of water vapor passing upward through cloud base. The precipitation efficiency (PE) is obviously zero in small non-precipitating cumulus clouds. It increases with cloud size, up to a point - other conditions being equal. A PE of ten percent has been quoted for small thunderstorms in the central United States and it exceeds 50 percent for some large thunderstorms. However, there is some evidence that clouds with updrafts in excess of, say, 25 m sec^{-1} are inefficient. The precipitation efficiency of an isolated hailstorm in South Dakota (fig. 2c) with a water vapor flux of five kT per second has been calculated at only three percent.[2] Considerable moisture is lost by evaporation at the edges of such a cloud in its downdrafts and often much of the condensed water is pumped away through a large anvil of mostly frozen particles streaming downwind from the cloud top (fig. 2b). The icy anvil evaporates much more slowly than the liquid portion of the cloud body.

We said that the cumulus engine is created and maintained by the release of condensation heating. To build up the science of cumulus dynamics we must find out just how the heat release drives the motions. Briefly, when the drops are formed, the release of latent heat (of condensation) makes the cloud air warmer than its surroundings and thus less dense, creating buoyancy. The buoyancy establishes and maintains the updraft, thus maintaining the slight supersaturation required to keep the condensation process going.

Like people, cumulus clouds have a life cycle. They are born, they grow up and eventually age and die, but unlike people, the fatter they are, the longer and more vigorously they live, and the taller they grow. Small trade cumuli like the ones on the right (fig. 3) usually enjoy an active lifetime or only five to ten minutes, while the medium ones thrive on the order of half an hour at most. The total amount of water vapor passing upward through the base of a small cumulus cloud may be one kT or less. A giant cumulonimbus in a hurricane or squall line can be active from one to several hours. It may process ten kT per second, or over 50,000 kT during its lifetime, while producing heavy rain, lightning and possibly hail. But at all times, natural existence is a

[2]One metric ton = 10^3 kg. Therefore, one kT = 10^9 g. An acre-foot of water weighs 1.23 kT.

desperate struggle for a cumulus cloud; its life is a precarious balance between the forces of growth and those of destruction. We have just described the buoyant growth forces. What are the destructive forces and how do they work?

The science of cumulus dynamics began in 1946 with the discovery of these resistive forces and their documentation by measurement. Prior to 1946 meteorologists had been largely unaware of interactions between clouds and their surroundings. Ignoring them, they had derived very beautiful stability criteria (called the "parcel theory") for cloud growth; these oversimplified criteria depend only upon the upward rate of temperature decrease (lapse rate) in the surroundings. The increased interest in tropical meteorology stimulated by World War II revealed that there was something drastically wrong with predictions that were made using "parcel" concepts.

Figure 4 illustrates the problem in terms of the cloud hierarchy shown in figure 3. According to the non-interacting parcel idea, cloud matter rises moist adiabatically and therefore all tropical clouds should penetrate into the stratosphere, topping at that level (about 100 mb or 54,000 ft in fig. 4) where "negative area" becomes equal to "positive area" on this thermodynamic diagram[3]. But in real life, only the fat giant clouds actually penetrate to the tropopause and these top at the

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[3]Called a "tephigram," a very valuable meteorological tool (see Hess, 1959 for explanation). Area is positive where the moist adiabat lies to the right of the environment sounding so that the cloud is warmer than its surroundings, is buoyant and would, without resistance, accelerate upward. Area is negative where moist adiabat lies to the left of the sounding.

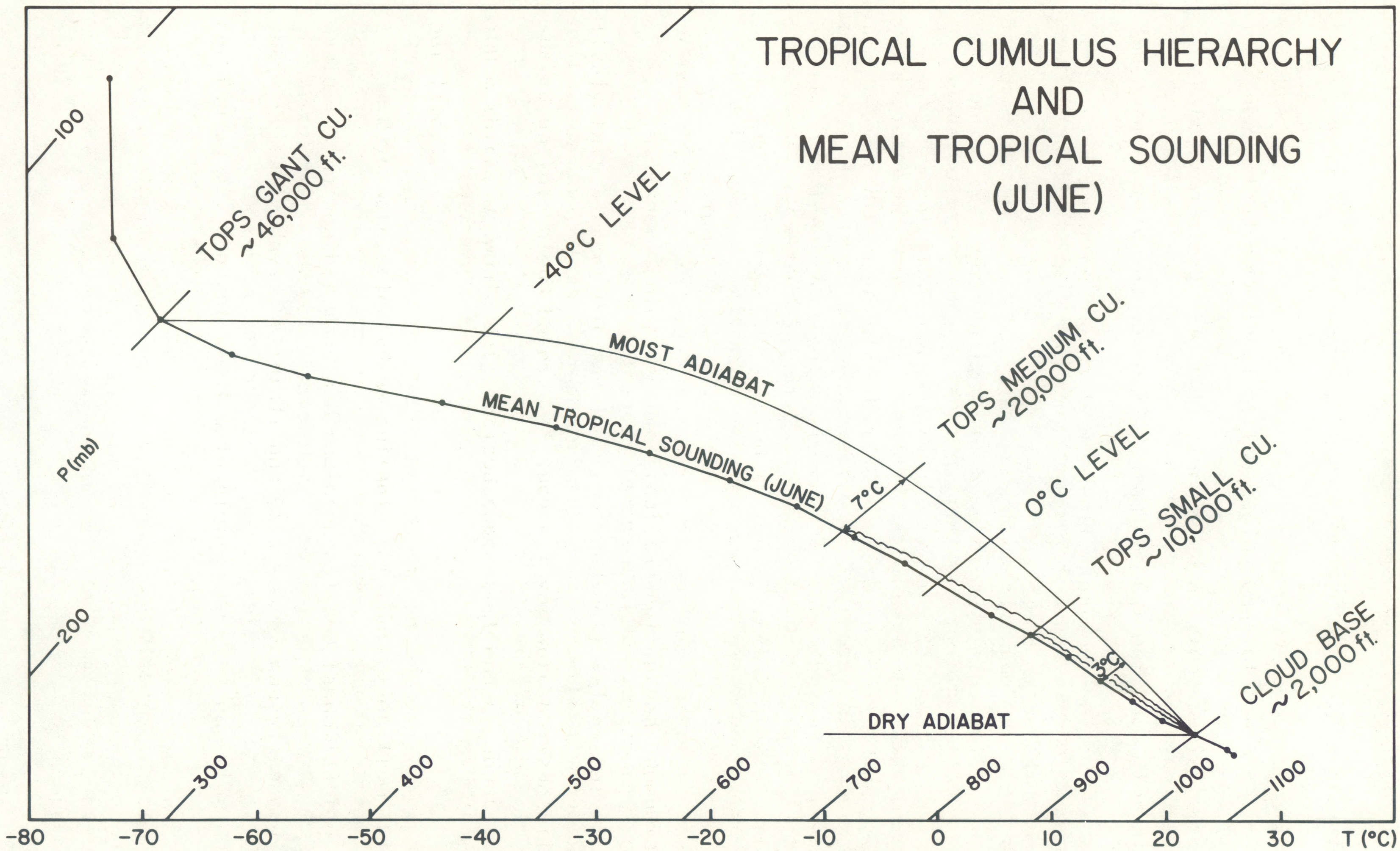

Figure 4. Tephigram illustrating temperatures inside clouds of tropical cumulus hierarchy in comparison with mean tropical sounding. The absciassa is temperature in °C; the slanted ticks are pressures in mb.

upper boundary of the positive area where theoretically their ascent rate should be highest. This observation suggests some kind of drag or friction force, in near balance with the buoyancy. An even more obvious deficiency of parcel theory is that most tropical clouds top out at heights between three to six km, at the very levels where the parcel buoyancy is greatest.

The advent of the research aircraft provided the solution to this paradox. For the small and medium cumuli, in-cloud temperatures measured closer to that of the ambient air than to those of the moist adiabatic ascent. Typical middle-sized clouds (center, fig. 3) had temperature excesses of only about 0.5 to 1.0°C, (corresponding to density deficiencies of only 0.2 to 0.4 percent) instead of the 3 to 7°C that would be experienced by a parcel rising moist adiabatically. Similarly cloud liquid water contents ran only about one to three g m^{-3} instead of eight to ten g m^{-3} predicted from the undilute parcel concept.

In 1946, the brilliant oceanographer Henry Stommel postulated that cumuli were "entraining" or mixing into themselves air from their drier surroundings. Using the newly available aircraft measurements of temperature and humidity made inside and directly outside of clouds, Stommel devised a mathematical and graphical method of computing the rate of entrainment (Malkus, 1954) which is expressed mathematically as 1/M dM/dz where M is the mass in the cloud element and z is the vertical coordinate. In small trade cumulus clouds (fig. 1) calculations from observations show that 1/M dM/dz is about 10^{-5} per cm. This means that the mass entrained is one in 10^5 cm or one km -- or that in one kilometer's rise, the cloud entrains into itself just about as much environment air as it originally contained. This large dilution with dry air drastically reduces the moisture life blood of the cloud, and thereby greatly cuts down its latent heat release and buoyancy.

Following the discovery of entrainment in 1946, the Woods Hole group made many advances in understanding entraining cumuli in a shearing wind field. By a "shearing wind field" we mean that the wind vector is varying with height in the atmosphere. The simplest case, common in the tropics, is that of a speed change only, with the wind strength increasing or decreasing upward while the direction remains unchanged. This situation is illustrated in fig. 5 (see Malkus, 1952, 1954). When the wind increases upward, the cumulus moves more slowly than the air surrounding it, because it is bringing up slower momentum air from below. When the wind decreases upward, cumuli will, conversely, move downstream faster than the wind. We were thereby able to explain why small clouds are so often not moving with the windspeed. In the case of large cumuli, there are additional, more complicated reasons why clouds move sometimes with a considerably different speed and direction from that of the wind.

We were also able to show with both theory and aircraft observations that the cloud entrains mainly on its upshear side (tail of white arrows) and it sheds moist air or "detrains" on its downshear side (head of white arrows). Thus, the cloud imparts its heat, moisture and momentum to its surroundings, a vitally important exchange which had been virtually ignored prior to 1946. A cumulus is not an inert entity, but rather a dynamic balance between rapid growth and equally rapid destruction. A component

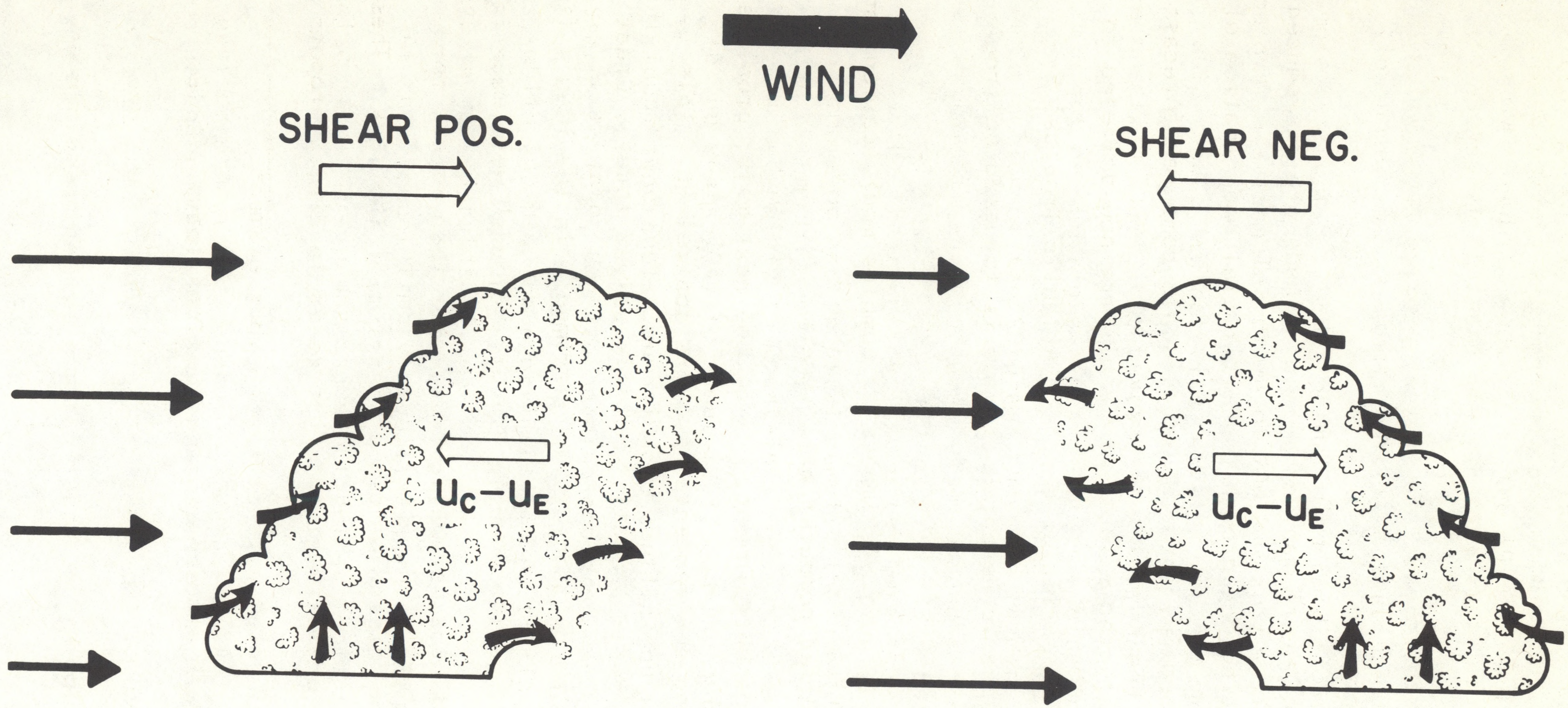

Figure 5. Illustration of how cumulus clouds lean with the vertical wind shear; on the left, the cloud velocity U_C is less than the windspeed U_E, while the reverse is true of the cloud on the right.

of its motion is often due to growth on one side and dissipation on the other. It is probably not an exaggeration to say that the discovery of entrainment revolutionized meteorology, because it enabled recognition of the role played by cumulus clouds in large-scale weather processes. Today we have advanced to the point where many effects of clouds are introduced into computer models predicting the growth and artificial modification of hurricanes and still very crudely, into the large-scale computer forecast models in daily use. In fact, the effects of cumuli are now believed to be so crucial that the main attention of the 1974 Atlantic Tropical Experiment of the Global Atmospheric Research Program is focussed on tropical cloud clusters to try to improve cloud process simulation in numerical prediction models. The large-scale impact of cumulus modification can then be explored with controlled computer experiments.

After the discovery of entrainment, one of the next major problems was to specify what cloud and environmental factors control it. This problem is by no means completely or satisfactorily solved today. Great progress on it was contributed by laboratory experiments in the 1950's (fig. 6), (Scorer and Ronne, 1956). Upside-down laboratory "clouds" were made in water tanks using miscible fluids very slightly denser than water, released from overturning a semi-circular cup at the top of the tank. These experiments showed that the entrainment rate decreases in direct proportion to the increase in horizontal size of the buoyant element.

In the case of the real atmosphere, observations leave little doubt that the giant cumulonimbi of figure 2 are diluting at a slower rate than are the tiny cumuli in figure 1, so the inverse dependence of

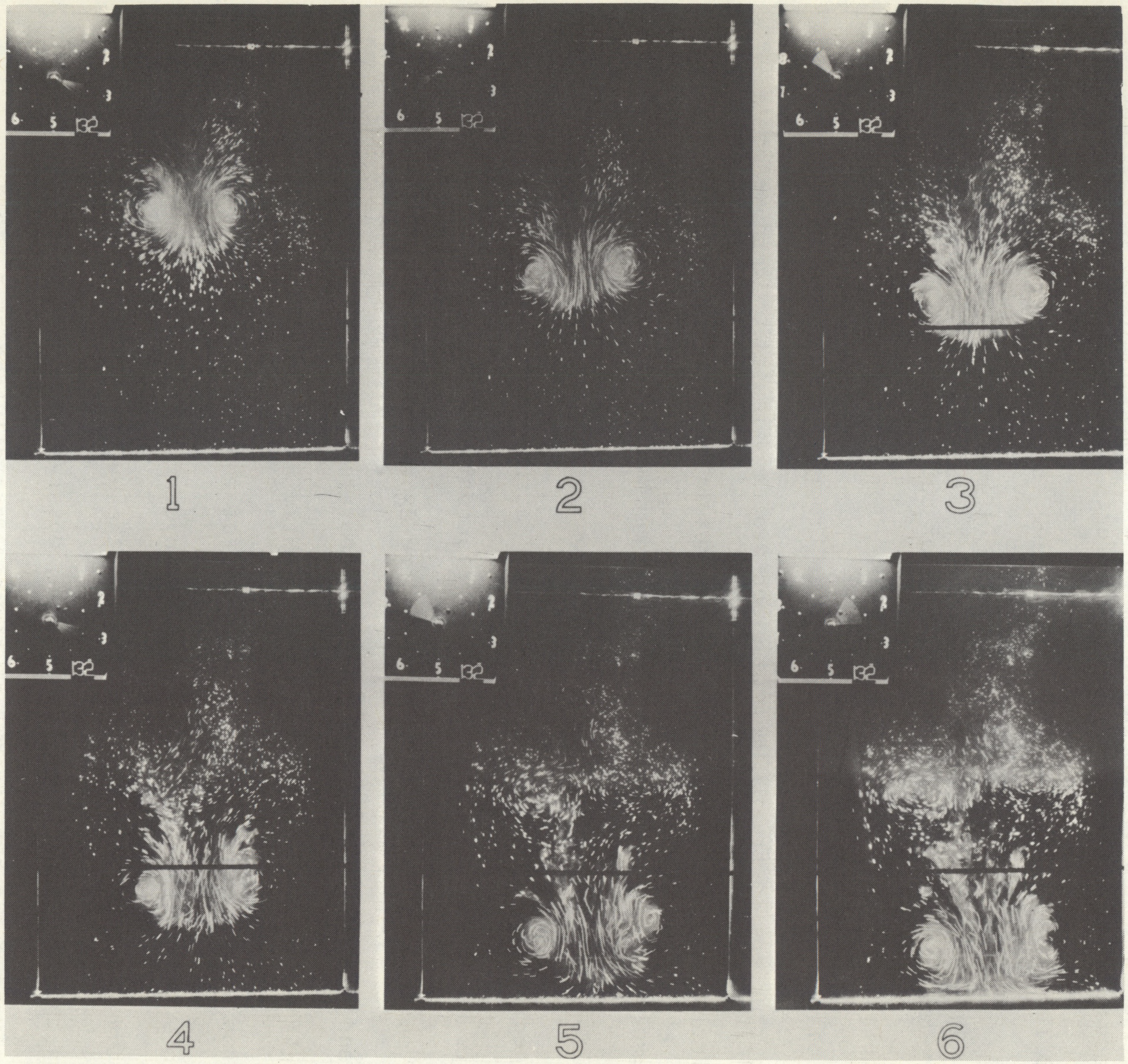

Figure 6. Development of laboratory tank "cloud" as a function of time. A blob of salt solution is released into a tank of pure water. The "cloud" being denser than its surroundings, moves downward. Its vortex-like circulation is made visible by neutral-density, white painted particles. (Courtesy Dr. Peter Saunders.)

entrainment on horizontal size is verified at least to first order. Now we can understand much better the cloud hierarchy of figure 3. Since the largest cloud shown has a diameter eight times that of the smallest, it will require eight km instead of one km to be diluted 50-50 with the surrounding air. Its central core is protected from the inroads of dry air by a much greater volume per unit surface area, and hence the tower can bulge upward through most of the whole depth of the troposphere before losing buoyancy. The "hot towers" performing the firebox function of the hurricane and equatorial trough zone are three to six km across (Malkus, 1960, 1962) and so can pump the sea-warmed surface air virtually undilute to the tropopause and sometimes even into the stratosphere. The factors controlling the diameters of cumulus towers are still not completely documented, except that we know that the big ones are found in those locations where the large-scale air flow is convergent, at low levels. In addition to entrainment, we will see that additional destructive forces are provided by the weight of suspended water substance and by downdrafts which may act to compensate the rising motions within the clouds. Cumuli may also be destroyed if their source of moist, low-level air is exhausted or cut off.

3. THE PHYSICS OF CUMULUS PRECIPITATION

To make rain, drops must become large enough to fall relative to the air (which in the cloud may be rising) and to last without evaporating from cloud base down to the ground below. In tropical and marine areas, with low cloud base and high humidity, drops with a radius of about 0.5 mm (terminal fall velocity about two m sec^{-1}) can survive, while in dry continental areas the minimum survivors must be about one mm in radius (terminal fall speed about four m sec^{-1}). To make a single one mm raindrop, it is necessary to combine the water from about one million 10 μm cloud-sized drops. How is this accomplished in nature and how could man change the process artificially?

Cumulus rainfall is formed by two processes, which commonly work together. One method of creating big drops is by collision and coalescence. This process is favored by a large dispersion or spread in the drop size spectrum, i.e. the coexistence of large and small drops. In tropical marine clouds, coalescence is often so effective that heavy showers fall from clouds only three to four km in thickness with tops well below the 0°C isotherm (usually between 4-5.5 km elevation in the tropics). In Florida, ten inches of rain in 24 hours has sometimes been dropped from cumuli that are totally "warm", i.e. above freezing. Many aspects of drop coalescence are still imperfectly understood; in marine clouds it may be initiated by giant sea salt particles.

The other precipitation-starting process, involving the ice phase, was discovered earlier and at one time was thought to be the sole rain-forming mechanism. In the free atmosphere, it is common for liquid water to exist at temperatures below freezing, that is in a "supercooled" state. In fact, at temperatures warmer than -40°C, it is necessary to have either ice particles or "freezing nuclei" to convert a supercooled water cloud into ice. Air-born substances which act as natural freezing nuclei have undergone extensive studies (Mason, 1971; p. 196). Certain earth-produced clays and dusts can initiate water-to-ice transformation at temperatures of about -9°C and colder. There is also increasing evidence that some man-made pollutants act as freezing nuclei.

At temperatures below freezing, the saturation vapor pressure over ice is less than that over water. Hence, whenever any ice particles come into being in a supercooled water cloud, they can experience a large super-saturation and thus grow rapidly. Their growth will continue as long as they coexist with liquid water drops, which will be evaporating as the ice-phase hydrometeors grow. When the ice particles attain a radius of several hundred microns, their terminal fall velocities are perhaps half a meter per second. Whether they melt or evaporate before reaching the ground is determined by the temperature and humidity of the air through which they fall.

While nature provides an overabundance of hygroscopic condensation nuclei to initiate cloud drops, she is stingy about freezing nuclei. Of these, about one per 100 liters[4] at temperatures of -2°C to -10°C is a typical concentration. As late as the 1950's, most meteorologists believed that many natural cumulus clouds which were growing would contain mainly supercooled water down to temperatures below -15°C (in the standard atmosphere the elevation of the -15°C isotherm is about 4.6 km). In the 1960's, scientists were surprised to find vast quantities of natural ice particles in relatively warm (-2°C to -10°C) clouds. Furthermore, their concentrations were often <u>three to four orders of magnitude higher</u> than the concomitant measured concentration of freezing nuclei, or one to ten ice particles per liter of cloudy air. This discrepancy suggests

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[4]A liter is 1000 cm^3.

either that our ice nucleus counters have problems or that there is a process of "ice multiplication" at work in some clouds. This exciting controversy is not yet resolved. Light is perhaps shed on it by the finding that the high natural ice levels are found mainly in marine or tropical clouds containing large drops and much less frequently in continental cumuli with very small drops, leading some scientists to postulate that "ice multiplication" is caused by the splintering of these large drops or by the shattering of ice dendrites with which they collide.

These findings have had enormous impact on modification experiments and their potential, as we shall elaborate later. In any case, the presence of ice hydrometeors in a cloud is of vital importance in several ways. Firstly, they serve as hail embryos, which can cause serious damage if they grow. Secondly, the formation of ice releases an additional latent heat - called "latent heat of fusion." Thirdly, most meteorologists believe that ice and water must usually co-exist in a cumulus to generate strong enough electric fields for lightning discharges.

The physics of cumulus particles is, of course, controlled by the dynamics of the cloud, in that it is the updraft that maintains the small but vital supersaturation required for hydrometeor growth. However, the microphysics has important feedbacks upon the dynamics, first through the release of latent heat - of condensation and sublimation or freezing when the ice phase appears. Another vital but less obvious feedback arises through the weight of the hydrometeors. The cloud buoyancy is reduced by the weight of the particles carried. To estimate the magnitude of this effect, one can use the relationship that one g m^{-3} of liquid water reduces the buoyancy as much as an 0.5°C decrease in cloud temperature. Since one gm m^{-3} is only a medium-sized water content and 0.5°C is often as large as the whole in-cloud temperature excess, it is clear that the weight of the hydrometeors is crucial in the dynamics of both the updrafts and the downdrafts in cumuli. If all the cloud drops remain small and cannot fall out, the cloud tower will be much more heavily loaded than if the rising air can shed some of the encumbrance by the formation and release of precipitation. On the other hand, updrafts in the lower portion of a cloud can be killed by the intrusion of heavy precipitation from above ("precipitation brake"). This effect can be intensified by the melting of ice-form precipitation. These factors frequently enter into determining the outcome of seeding efforts, as we shall see.

4. CUMULUS MODELS

The power and credibility of any weather modification effort is enhanced by many factors when a model exists prescribing quantitative relationships for the modified versus unmodified system. When we have a model, we are saying that we understand the important physics of the system and the causality of how the modification works. Furthermore, when a working model exists, generally it can predict the effect of the modification upon more than one measurable quantity, thus increasing our power to test the validity of the modification hypothesis.

Cumulus processes can be modelled by analogy in the laboratory or mathematically by solving a set of differential equations describing their behavior, so that the solutions prescribe the cloud properties as a function of space and time, given specified initial and boundary conditions. The equations, their physical background, and their solutions are what we commonly refer to when we speak of "cumulus models." A word of caution is in order here at the outset regarding all models of atmospheric processes. Firstly, we cannot yet formulate the exactly correct equations governing them. Secondly, even if we could, no foreseeable computers would be large enough or fast enough to solve them, and thirdly, even if the foregoing were realized, it would not be profitable to try to solve the exact equations precisely, because our measurements can never hope to be accurate enough to specify the "initial conditions" with commensurate precision. Hence all meteorological models are, and will remain, hierarchies of approximations and simplifications. Their adequacy must be judged by the degree to which they predict the phenomenon in question; the predictions must always be checked by measurements, which in their turn are never perfect.

In several important areas of cumulus modification it has been hypothesized that mainly the microphysics or particle structure is changed, and that alterations in the dynamics or motion field are sufficiently small and/or unimportant so that ignoring them will not lead to serious errors in model predictions. If this is justified, then the modellers' task is much less difficult than it is in situations where dynamic changes are involved or when dynamical-physical feedbacks strongly influence particle growth. Today, many meteorologists are coming to believe that we can advance little further, even in microphysical modification activities, without better understanding and modelling of the complex dynamical-physical interactions.

The pioneering modification experiments, however, were microphysical and based on models in which updrafts were held fixed and entrainment igonored. Beginning in the late 1940's, some rather beautiful mathematical models of cloud drop growth by condensation were developed, which started with a given realistic CCN spectrum. Not surprisingly by hindsight, these models failed to grow drops above about 20 μm in a cumulus lifetime, so that cloud physicists next introduced equations simulating further growth by drop collision and coalescence. By the mid-1960's these models had become very sophisticated and fairly realistic, despite virtual neglect of dynamics (Mason, 1971; p. 145-153).

Concerning the ice phase, vast amounts of work on crystal growth was done in laboratory cold chambers, but the application of the results to real cumuli must be made with great caution. In a supercooled cloud, ice particles may grow by collecting liquid drops (riming) or with less ease by collecting other ice particles. Furthermore, water drops can freeze directly by contact with a freezing nucleus. Even if updrafts are held constant and dynamical-physical interactions are ignored, accurate models of ice growth considering all relevant processes together are not yet available and even existing approximate models are ahead of our observational capability to test them. An unpleasant surprise derived from replication of ice forms in cumuli is that these are rather rarely beautiful crystals, but more often irregular and "junky" fragments. Moreover, many meteorologists are increasingly doubtful that dynamical interactions can be safely ignored in modelling the microphysics of ice clouds.

Concerning cumulus dynamics, models were virtually prohibitive prior to the introduction of the high speed computers in the early 1950's This is because the key processes are highly non-linear. The accelerations driving the motions are created by horizontal density differences, but in turn the densities are altered by the motions of the air and of the particles, which thus change the accelerations in a constantly operating "feedback loop."

The reason that computers permit, for the first time, meaningful approaches to this type of problem is as follows: the non-linear differential equations describing cumulus motions cannot be solved "analytically" by formal mathematics, but we can obtain "numerical" solutions in specific cases by feeding the equations into a computer, which then solves them by successive approximations or iterations, completing work in a few seconds which might take months to reproduce by hand.

Models of cumulus dynamics, after twenty years of hard labor, are finally entering the "pay off" stage. By this we mean that although their simulation of real processes is still very crude and very approximate, it has advanced to the stage that observational tests are meaningful. Some dynamic models are even already in real time use to guide the launching of modification missions and to select for seeding attempts those clouds and situations with favorable prognoses, as we shall illustrate in section 10.

Actually two classes of numerical models are under development to simulate cumulus dynamics. The more sophisticated and at first glance more rigorous approach is to take the complete hydrodynamic equations (of motion, energy, mass, etc.) and set them up in finite difference form, that is, divide up the space occupied by the cloud and its surroundings into a grid of discrete points separated by distances much smaller than the the cloud. Then the equations are solved by the computer in a series of finite time steps beginning with a prescribed "initial condition," which is usually no motion but a diffuse blob of slightly less dense air at the center of the grid. The density field then initiates motions and the computer prints out results for the "model cloud" every few minutes. The output at each grid point consists of velocity, temperature, water content, etc.

These are called "field of motion" models. The earliest and simplest one (Malkus and Witt, 1959) is illustrated in figures 7 and 8. It was two-dimensional[5] and modelled the early stages of a warm, dry "thermal" which resembles a cumulus tower without the effects of the phase change of water. Later workers have considered cylindrical and even three-dimensional geometries. Most important, they have lately simulated the condensation of water vapor into liquid and the transports of liquid and water vapor.

One of the outstanding pioneers in these models, Dr. Francis Murray, has just succeeded in modelling the growth and fallout of liquid precipitation and, with a colleague, is working on introducing the ice phase in the hope of being able to simulate seeding experiments. At the South Dakota School of Mines, simulated seeding experiments are being conducted

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[5]A two-dimensional model considers motions confined to a plane (fig. 7). The "cloud" is assumed to be of infinite extent in the direction into the paper - i.e. it is a long cloud line.

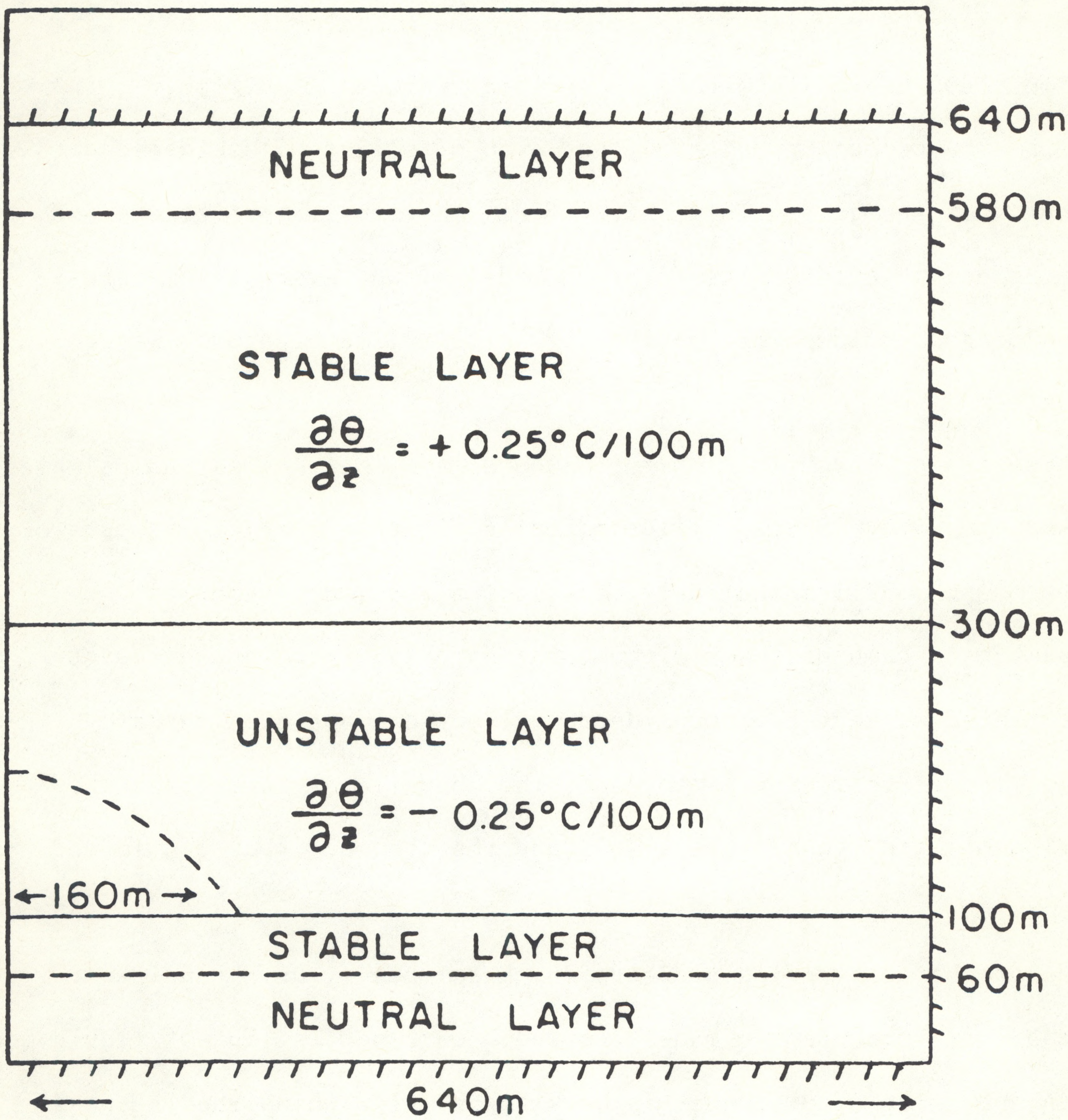

Figure 7. Framework for pioneering "field-of-motion" cumulus model. The initial density perturbation is shown by the dashed half semi-circle on the left (the other half is a mirror image). The space is divided into a 32 x 32 grid, with points separated by 20 m.

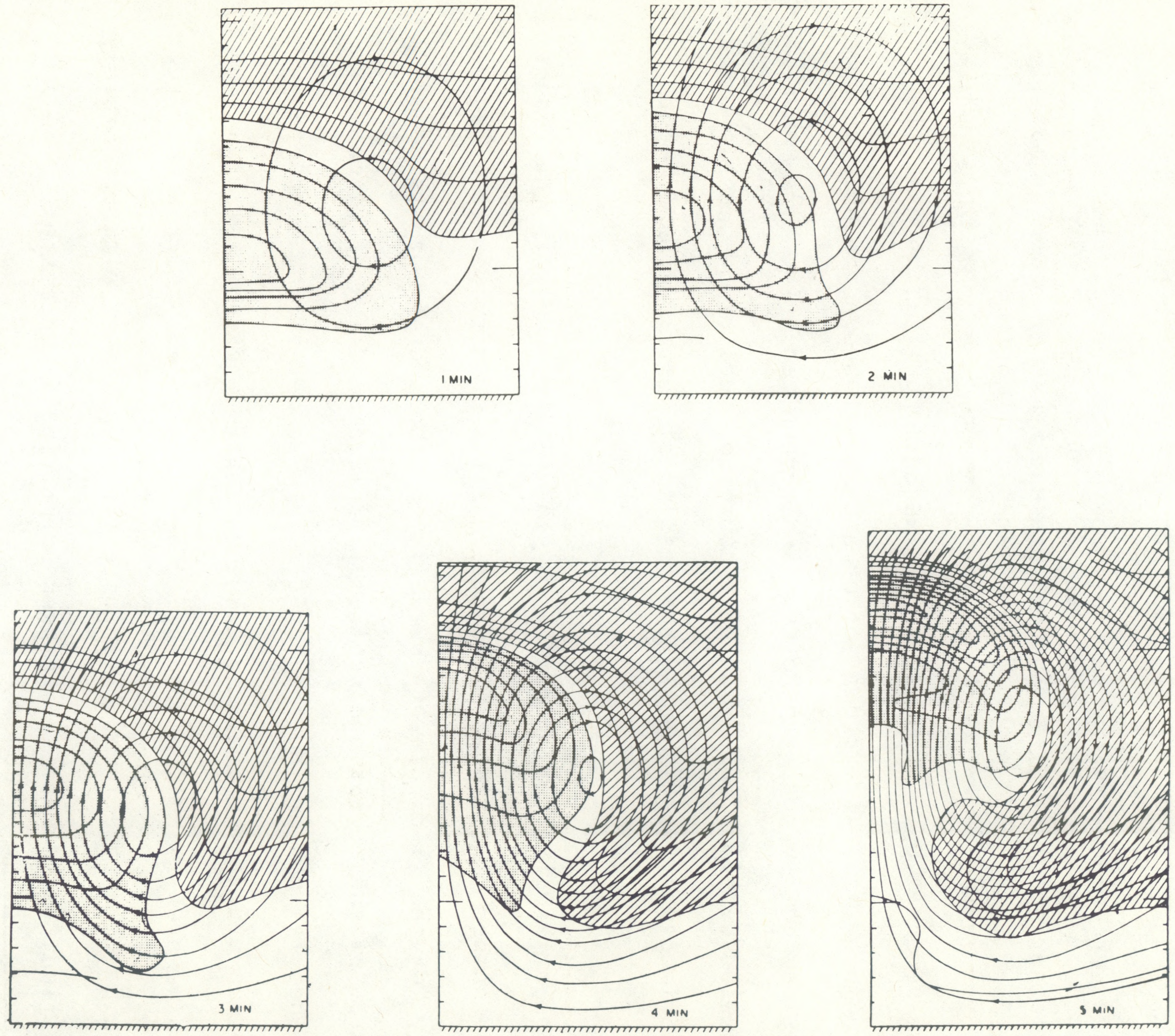

Figure 8. Results of solution in time steps of numerical "model cloud problem of figure 7, for the first five minutes of its lifetime. Note the "bubble-like" thermal which develops, associated with a vortical circulation. Potential temperature isopleths (interval of 0.1°C) are solid lines without arrows; the dotted region includes all potential temperatures higher than that characteristic of the lower neutral layer, while the hatched region includes all those more than 0.1°C lower. Lines with arrows are streamlines of the flow.

on a model of orographic clouds.

It must be emphasized, however, that existing dynamic cumulus models are forced to "parameterize" or oversimplify the governing particle growth. Introduction of all the exact equations for condensation, coalescence, freezing, riming, crystal growth, etc., etc., etc. would present staggering difficulties beyond present human or computer ability to cope.

The second type of dynamic models we call "entity" models. In these, a cumulus is likened to a jet or a plume, a buoyant bubble or some other physical entity that can be seen and recognized. The forms have been suggested by time-lapse[6] motion pictures of real clouds, by laboratory experiments (fig. 6) and by the results of numerical experiments (fig. 8).

A major simplification offered by the entity models is the reduction of the number of differential equations; the primary one to be solved is usually for the rise rate of the entity or the updraft at its core. Key features of the models are semi-empirical laws derived from measurements or theories concerning the entities; these permit the complete specification of every "parameter" in the equations except for the cloud properties we are trying the predict. For example, many current entity models are based on the inverse radius entrainment law. Although plainly oversimplified, these models have been surprisingly successful. Their

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[6]Motion picture frames are exposed at a rate of one frame every several seconds and projected at normal speed, that is 16 frames per second. This speeds up cloud processes, making them more clearly seen and understood. Quantitative time-lapse photography has been responsible for major advances in cumulus studies (cf. Malkus, 1952).

virtues and shortcomings will be described later in the framework of the modification experiments on cumulus dynamics, which stimulated their development.

To the theoretician, especially the purist, the "field of motion" models are more satisfying than the "entity" models since they apparently start from "fundamentals." Ironically enough, however, there are many difficulties with "field of motion" models which have so far greatly reduced their usefulness in field experimentation. Firstly, their results are painfully sensitive to the assumed form of the initial perturbation and to how the equations describing continuous fluid flow are expressed in terms of the points and spacing of a finite difference grid. Secondly, it is not clear that these models simulate entrainment even roughly correctly. This latter point depends upon how much of real entrainment is an ordered inflow into the cloud element, and how much is due to turbulent exchange of air at the cloud edges; this latter point is currently the subject of an interesting controversy. In the next decade we may look for the real "payoff" of field-of-motion models in cloud modification experiments; currently, only the one-dimensional models are in operational use.

5. CUMULUS GROUPS AND INTERACTIONS

A cumulus cloud rarely occurs in isolation. Nearly always, cumuli form in groups, lines, patterns and clusters, (fig. 1a, 9). Some of the most important effects of cumuli, such as heavy rains and severe weather, occur when two or more cumulonimbus clouds join forces to become a merged complex, or "merger." For example, in Florida a single isolated cumulo-

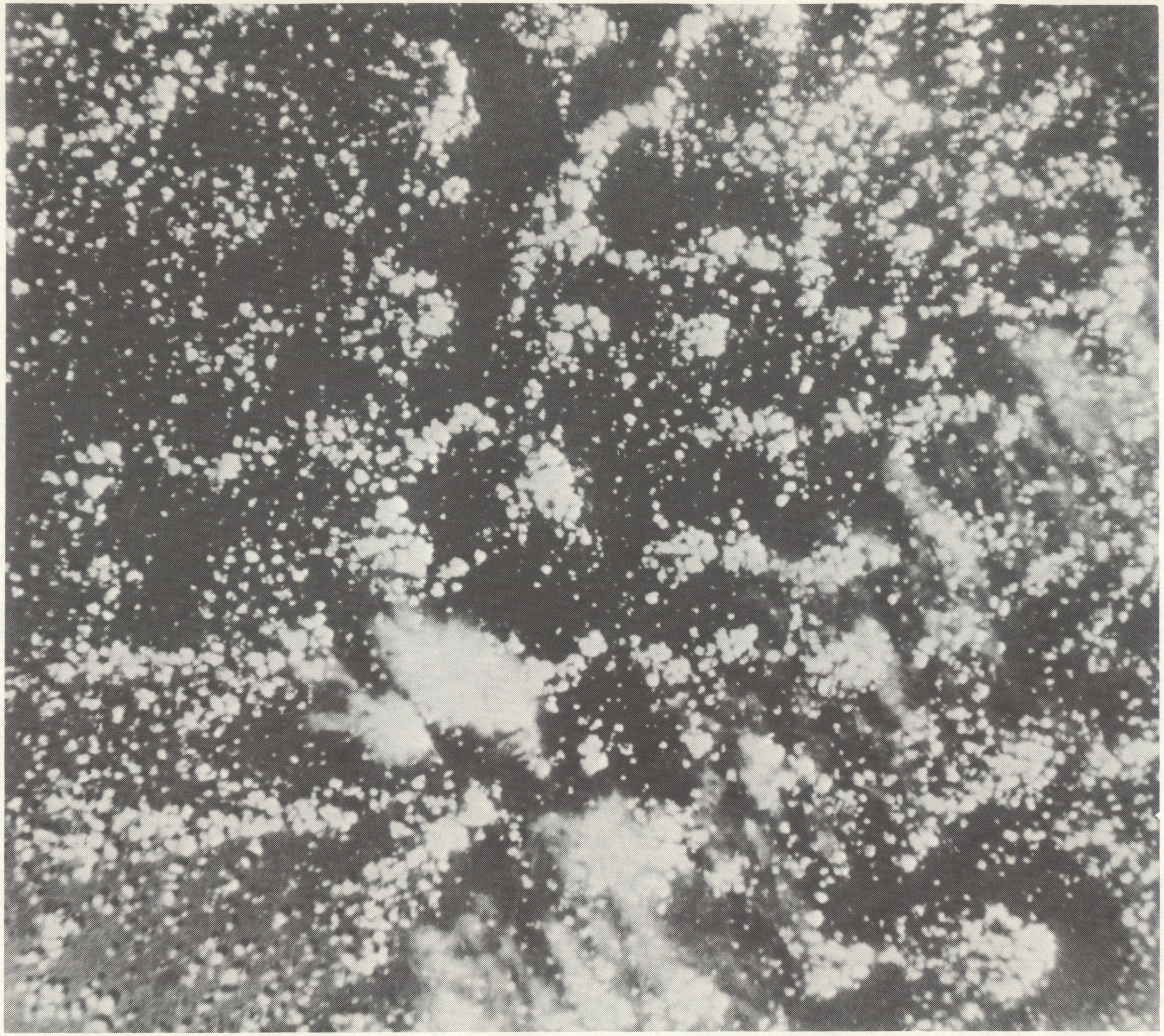

Figure 9. Photograph of polygonal pattern in tropical Atlantic cumuli (just east of Barbados) taken by the Apollo 10 astronauts in May 1969. The picture covers a width of about 200 km. (Courtesy J. Kuettner.)

nimbus thunderstorm may produce in its lifetime 200-2000 acre-feet of rainfall, while a merger of two or more such clouds often produces 5000-50,000 acre-feet!

Moreoever, some of us believe that nearly all large cumuli are formed by the merger of adjacent or successive smaller ones. Hence it is vital to study and experiment on cumulus interactions. Unfortunately, in 1972 we are no farther ahead in this task than we were in 1945 in treating individual cumuli. And the problem is at least ten times more difficult because it involves the meso-scale (10-100 km) of atmospheric phenomena, virtually unmeasured and unknown. Numerical models of cumulus groups and interactions are in their barely beginning stages.

Some study, with aircraft and satellites, has been devoted to the formation and patterning of oceanic cumulus groups. Over the tropical oceans, cumulus bases are found at roughly 600 m. The "subcloud" layer is neutrally stable and homogeneous, that is water vapor is quite evenly disbributed both in the vertical and horizontal. The vertical thickness of the homogeneous layer is often deformed upward, sometimes in a wave-like manner and in those regions where it extends above the condensation level[7] of the subcloud air, small cloudlets break out, mostly commonly lined up with the wind shear (fig. 1a). Causes of the vertical deformations of the homogeneous layer are not all well known or modelled; they are sometimes due to localized warm spots in the ocean and perhaps more commonly to patterns of convergence set up by uniform heating, surface

[7] The condensation level is the level at which surface air becomes saturated when lifted dry adiabatically.

friction and perhaps wave-like phenomena.

The most spectacular displays of oceanic cumuli are found in disturbances, both of the tropical variety (whose extreme form is the hurricane) and the extra-tropical frontal cyclone. In these regions, the cumuli are associated with lines or bands of strong convergence in the low-level wind flow - whether the clouds are the hen or the egg has not yet been resolved. One sign of a disturbance is the suppression of medium-sized cumuli, leaving only the very large and very small ones in the sky. The modification potential of cumuli almost surely varies between fine weather and disturbed conditions, an hypothesis of the utmost importance to be borne in mind throughout this discussion. Time-lapse motion pictures suggest that larger oceanic cumuli are built up by aggregation and conjunction of small cloudlets. At least until they reach the precipitating stage, individual oceanic cumuli do not have "roots" in updrafts or downdrafts extending below their bases. The mixed layer appears no different under cloud groups than in the intervening clear spaces. However, a major change comes about when a cloud reaches the shower stage and falling precipitation induces a strong cold downdraft which penetrates all the way to the sea surface. These downdrafts are of vital importance in accelerating sea-air exchange in tropical disturbances. They can both kill off the local cloud group and, if conditions are right, initiate a new one elsewhere. They are quite likely relevant in man's potential ability to change the atmosphere via cumulus modification, as we shall see later.

Over land, fair weather cumulus formation and patterning may be initiated by additional mechanisms. Mountains give rise to spectacular cap, roll and wave clouds, the modification of which is described elsewhere. Oceanic islands often give rise to photogenic cloud "streets" which will be discussed later in section 12. Coastal regions exhibit characteristic cumulus patterns; some are located in convergence lines associated with sea breezes or land breezes. These may be migratory or fixed in preferred locations depending on the large-scale air flow.

We still do not know what fraction of land cumuli are rooted in continuous ascending "thermals" which extend all the way up from the ground; if these prevail in the face of moderately strong winds, they must somehow migrate, although not necessarily with the windspeed, as we have seen.

Over continents, large cumuli are not as wholly confined to weather disturbances as they are over oceans; nevertheless, in extra-tropical regions, particularly over flat terrain, large cumulonimbi are primarily found in frontal and pre-frontal convergence lines. Again, it should be emphasized and will be illustrated that cumulus modification potential may be entirely different in disturbed and fair weather situations, and in disturbed situations the outlook may vary with the nature and structure of the disturbance. As modification studies continue it will be of utmost importance to specify the variation of modification results as a function of weather pattern and to document the fraction of all seedable clouds that are found in each type of weather pattern at each locality each month of the year. This vital work is in its infancy, as we shall see.

6. DESIGN AND EVALUATION OF CUMULUS MODIFICATION EXPERIMENTS

Two immense obstacles have opposed man's attempts to modify the weather. The first is the enormous amount of energy expended in natural atmospheric processes. A large thunderstorm releases as much energy as the fusion energy of a hydrogen superbomb, while even a moderate-strength hurricane converts through its cloud systems 400 bombs-worth in a single day. Hency puny man must seek an Achilles heel in the system, which when struck, can instigate a sizeable reaction from an energetically small trigger. Fortunately, we have seen that lives of cumulus clouds are a precarious seesaw between growth and destructive forces; recognition of this, in fact, let to the discovery of some of the triggers we shall describe.

A more serious obstacle, one which stands in the way of our sound evaluation and judgment of modification efforts, is the enormous natural variability in atmospheric phenomena. The most striking lesson these writers have learned from 30 years of cloud study is that a cumulus cloud can do virtually anything all by itself, without any interference by man. In a field of identical-looking cumuli, one or several can explode to thundering cumulonimbus, while the rest humbly die. Given two apparently identical convective storm systems, one can rain pitchforks, while the other, with indistinguishably similar looking clouds, remains dry.

High natural variability has at least two unfortunate consequences. The first is that the average layman grossly overestimates what has and can be accomplished in weather modification, particularly since the news media tend, for example, to play up those cases where floods follow cloud seeding. The second, and more crucial consequence as far as experiment design is concerned, is that we just cannot conduct a meaningful modification experiment without sound and rigidly enforced statistical controls.

"Eyeball" evaluation is of little value. A great deal of the unproductive controversy surrounding the modification efforts of the past two decades has arisen because people have kept making assertions like the following: "I just know the seeding was a success; the seeded clouds behaved very differently from the neighboring unseeded clouds - in fact, I just never have seen any clouds behave the way those seeded clouds behaved." The canny cloud expert will reply, "Just stick around for awhile, chum, and you'll see natural clouds behaving that way."

Seriously, what is the solution to this discouraging dilemma? In the current state of our knowledge, randomization is a most satisfactory procedure. That is, unknown to the experimenters, an honest coin must be tossed (or a sealed instruction opened) which says "treatment" or "no treatment" for the given experimental situation, be it single cloud, target area, or day. By this procedure we can obtain, with minimum bias, a treated and untreated sample of cases which can be compared by statistical methods to arrive at not only a quantitative assessment of the treatment effect, but equally importantly, an estimate of how confident we are that the measured differences between treated and untreated populations are due to the treatment and not due to chance fluctuations.

The importance of the above requirements can hardly be overemphasized. Nevertheless, there are some prominent scientists who have offered arguments that if one has a physical-numerical model, randomization of the experiment (which is costly in time and money) is not so necessary. In the millenium, when our models are very much better than they are today, this should be true. The astute reader who has studied section 4 will detect why, for the foreseeable future, this argument remains fallacious. All meteorological models today are based on chains of oversimplifications, assumptions and empirical laws. A little exercising on a computer with the best of these models will soon show that alteration of even a few of the key assumptions will often lead, with exactly the same initial conditions, to radically different predictions of a treatment effect! Therefore, our models must in fact, still be tested by the results of the experiments and so we cannot yet have full confidence, without randomization, that the model does indeed confirm any modification hypothesis.

At the risk of completely discouraging the reader, we must point out that the most impeccable randomization schemes can lead even the cautious experimenter to unjustified conclusions. For example, in a randomized cumulus seeding experiment in a target area, chance variations in rainfall just might cause the control days to average much wetter than the seeded days, or vice-versa. We say then that there were "uncontrolled background effects." This specter will raise its ugly head in many of the key cumulus modification experiments to be discussed.

How likely are "uncontrolled background effects" to mislead an experiment in view of the way that nature distributes rain? An interesting study by the Illinois State Water Survey (Huff, 1971) illustrates this point by a hypothetical five-year experiment on 116 summer convective storms of the U.S. Midwest. No seeding was really done, but half of the eligible days were put by random selection in a bin called "seeded." "Seeded" rainfall 50 percent greater than "nonseeded" rainfall would be expected in 14 percent of the experiments due entirely to natural fluctuations and a 20 percent "increase" would be expected in 30 percent of the "experiments." Other problems which can mislead the careful investigators with impeccable statistics will be discussed later in the experimental contexts in which they occur.

Therefore, detailed measurements of many quantities in both clouds and their environment, as well as data stratification, are generally required for meaningful approaches to modification.

Productive modification experiments are more likely if, additionally, backed by a model. An example of this situation are the single cloud experiments described early in section 10. In cases where we do not yet have a model, as in multiple cloud or area seeding experiments, we may hope that randomization and judicious statistical analysis lead us not only to evaluation of seeding effects, but to a start at modelling them.

But what can we do in those cases with or without any models where we cannot expect to live long enough to obtain an adequate number of randomized cases? In the latter part of section 10, on multiple cumulus seeding, and again in hurricane modification, we face such a prospect. Here the new techniques of decision analysis or Bayesian statistics are offered as a possible help in assessing the validity of the modification hypothesis. These techniques have the potential capability of using all our information about the experimental situation. They often can reach definite conclusions with fewer treated cases than can conventional statistical methods, <u>provided that the natural fluctuations in the</u>

system to be modified have been precisely documented. A disadvantage appears to be that the resulting probability for the validity of a modification hypothesis depends, at least to some extent, upon a subjectively assessed "prior probability" of its validity. Unfortunately, any subjectivity at all is a serious obstacle in the evaluation of weather modification experiments.

The design strategy of a cumulus modification experiment depends mainly upon what effect we desire, and then upon many other factors such as technique availability, possible side effects, and expense.

To date, most cumulus modification experiments, particularly in the United States, have been undertaken in an attempt to augment rainfall. There has also been extensive seeding to mitigate hail and lightning and to reduce the damaging winds in hurricanes. In the Soviet Union, some field efforts have been made to dissipate cumuli, such as by dumping powdered concrete into them. An important minority of cloud seeding experiments conceived were to alter either the dynamic growth or the radiative properties of cumuli; these are discussed in sections 10-12 of this article. To our knowledge, few meaningful efforts have been undertaken or seriously proposed to decrease cumulus precipitation, although such experiments could be valuable if they ever become feasible.

Nearly all cumulus experiments that have been actually and deliberately conducted so far have involved "seeding" the clouds with some kind of small particles. In some cases, the particles are dispersed from the ground, counting on air currents to get them into the clouds. In most of the others, aircraft are used to dispense the seeding materials. Aircraft seeding can be executed by flying with dispensing systems or generators upwind of the target clouds, by circling below cloud base and relying on updrafts, or by dropping materials from above directly into cloud top or by flying horizontally through the cloud. Seeding from ground generators has been going out of fashion in the past decade primarily because of the difficulty of reliably introducing enough material into designated clouds in designated areas and secondarily because of possible decay, contamination or undesired voyaging of the seeding materials. Aircraft seeding has been taking over because it affords accurate targetting and opportunity for measurement and observation. Aircraft are, however, rather costly for prolonged usage. For years, scientists in the Soviet Union have successfully seeded cumuli with artillery shells and rockets. Radar is used to determine the parts of the clouds to be seeded. This economic and quite possibly more effective technique might be useful in other nations, in those experimental situations where air traffic problems could be circumvented.

Next we will examine cumulus modification aimed at rain augmentation. Our emphasis will be mainly on experiments with strong scientific foundations, goals or results (although our omission of any experiment does not imply its lack of these). Purely practical modification work and that of the private or industrial sector is largely omitted from this article.

Rain augmentation in cumuli has been attempted in two ways, by increasing or accelerating the coalescence process and by initiating or increasing ice particle growth in the presence of supercooled water. In cumuli whose tops extend above the freezing level (roughly 4 - 5.5 km above sea level), these processes are virtually inseparable, although we must try, for explanation purposes, to separate them. Historically, ice phase seeding was discovered first and has been practiced more extensively. Here we begin with coalescence seeding for the sake of clarity and logical development.

7. CUMULUS MODIFICATION TO ENHANCE COALESCENCE

We have seen that the growth of cloud drops ($\sim$ 5-20 μm) to precipitation size (> 0.5 mm or thereabouts) by coalescence in cumuli is related to the updraft speed and dimension, to water content, cloud lifetime and to the initial drop size distribution, which in turn is controlled by the size spectrum of the condensation nuclei (CCN). Most favorable to growth by coalescence is the presence of large drops among much smaller ones - the large ones descend relative to the small ones and hence are able to collide with and "collect" them. Over the oceans, giant sea salt nuclei (one to ten μm in radius) are a major factor in setting off coalescence, contributing to the observation that marine cumuli rain more readily than their counterparts over land.

Beginning with one of the two great patriarchs of weather modification, Nobel Laureate Irving Langmuir, coalescence models attained by the late 1960's a high degree of sophistication, with two reservations. The first is that some factors controlling "collection efficiency" still must be determined empirically, and more important dynamic interactions and entrainment were left out. Early coalescence models were based on "continuous" collection or accretion, where a single large drop falls through a uniform distribution of water (the small drops). Later models treat the much more difficult subject of "stochastic collection" where the large drops are also permitted to collect each other.[8]

An exciting aspect of coalescence with possibly enormous impact upon modification is the so-called "Langmuir chain reaction." As raindrops grow large, they will become unstable and start breaking up. The size at which this break-up begins is not well known, but by the time drops have reached six mm diameter, the break-up probability is very high. Each fragment can in turn grow to break-up size and repeat the process. If the cumulus updraft is strong enough to sustain the near-breaking drops (nearly ten m sec^{-1} is the terminal velocity for a six mm raindrop) a rapid acceleration of rain growth would be possible. Both further modelling and further measurement work are required to ascertain the frequency and conditions for the natural occurrence of chain reactions and to assess man's chances of setting one off.

It seems plausible to hypothesize that the introduction of artificial precipitation embryos could shorten the time required for the appearance of rain and could sometimes increase the precipitation efficiency in short-lived clouds. Methods attempted for introducing artificial embryos have included the use of water spray and hygroscopic[9] powders and solutions.

Historically, many pioneering workers discussed and attempted water spray seeding in the later 1940's and early 1950's (see the biblio-

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[8]These models are just now being adapted for incorporation into dynamic models.

[9]Hygroscopic substances are those which attract water or encourage condensation of water vapor into liquid water upon themselves, at relative humidities that are less than 100 percent for pure water.

graphy in Braham et al., 1957). The first real landmark in controlled coalescence seeding, however, was established by a University of Chicago group under the leadership of three prominent cloud physicists, Byers, Braham and Battan. In 1953-54, they conducted an airborne water spray seeding experiment on warm tropical cumuli over the Caribbean Sea (Braham et al., 1957). Their avowed objective was "to obtain a more complete understanding of the fundamental processes which govern the formation of precipitation and not to carry out a series of 'cut and try' experiments aimed at determining the efficacy of cloud treatment." Using instrumented B-17 aircraft, they made both cumulus population censuses and individual case studies. In addition to vital background for their modification trials, these analyses still stand today as classical documentation on tropical marine cumuli.

Their randomization was by pairs and two different rates of water application were used, both with the spray drop size distribution carefully documented. The spraying aircraft penetrated within a few hundred feet of cloud tops. Tens of thousands of spray drops in the size range 100 μm to one mm in diameter were supplied to each treated cumulus for each centimeter of flight path. Evaluation of the onset time, endurance and location of precipitation echoes in both seeded and unseeded clouds was made using a vertically scanning three-cm radar mounted in the nose of the aircraft.[10]

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[10]The radar's sensitivity was maintained continuously at the same level for all observations.

When the seeding rate was 130 gallons[11] per mile, no effects were detected. But when the seeding rate was increased to one much greater than any previously attempted, namely 450 gallons per mile, precipitation echoes were both more probable in seeded clouds than in similar unseeded ones, and echoes also formed earlier in the seeded clouds.

With 63 properly selected cumulus pairs, the treatment increased the average probability of a precipitation echo within the cloud from four to 44 percent at the 95 percent confidence level (or as the statistician would say, at the five percent significance level). The average time for precipitation echo appearance was 6.4 minutes for the heavily treated clouds and 11.9 minutes for natural clouds. The confidence level that this difference was real is 0.999+, probably a record high for a cloud modification experiment.

We must emphasize, however, that back in the early 1950's, the Chicago group was not able to compare actual volumes of rain falling from the bases of seeded versus unseeded clouds. For many reasons, it would appear urgent to carry their work to this next stage. Although seeding rates of 450 gallons per mile were logistically awkward for the old-fashioned seeder aircraft, with today's C-130 (Hercules), that problem would be minor.

Costwise, this seeding method could, if established, be economic. We know now that a cumulus of the type they studied may rain five to 50 acre-feet in its lifetime, let us say 25 acre-feet. If the seeding should double the rainfall from this cumulus (Simpson and Woodley, 1971)

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[11]About 325,000 gallons = one acre-foot.

we would gain 25 acre-feet or an output of nearly one million gallons of water for an expenditure of about 1000 gallons. Financially, the greatest expense would be that of flying the aircraft, say $600 per hour, if heavily instrumented. At the standard price of $50 per acre-foot, 25 acre-feet of water is worth $1250. Hence by seeding five clouds per hour we would show a benefit-to-cost ratio exceeding ten to one! No chain reaction is required for the doubling of the precipitation by spray seeding, but merely the continuous coalescence growth of each spray particle under conservative assumptions.

But speculations concerning practicality aside, this type of experiment has and can further immeasurably enhance our understanding of cloud physics processes and modification potential. For example, the Chicago experiments were the first to show the vital fact that coalescence is a, if not the, main rain-forming process in almost all convective clouds. The impact upon modification of this discovery can hardly be overstated, as we shall see again shortly. Secondly, their tropical cloud censuses showed the further fact, suprising to many meteorologists in the 1950's, that by the time a marine tropical cumulus attains10,000 ft thickness, its probability of containing rain is 100 percent. This means that when we discuss modifying tropical marine cumuli, we rarely need to speak of starting or causing precipitation, but only of augmenting it. A tropical cloud failing to attain 10,000 ft thickness would usually process too little water to be worth modifying, except for scientific curiosity.

It has been mentioned that an alleged difficulty in the water spray approach to coalescence modification is that large quantities of water must be injected into clouds in order to produce significant effects. A way to mitigate this operational problem is to use hygroscopic materials as seeding agents. With these, calculations suggest that introduction of one kilogram of material into a cloud could result in the collection of five to ten kilograms of cloud water into artificial raindrop embryos.

One of the main materials used in hygroscopic experiments is fine powdered salt (sodium chloride). It is difficult to grind this material to a desired and controlled size spectrum and to prevent the particles from clumping before delivery. Introduction of many too-small condensation nuclei into the cloud would likely have an adverse effect on coalescence growth. Another method is to use sprays of such hygroscopic materials as ammonium nitrate and urea. This technique is alleged to have the advantage that a particle released may be small enough, say ten μm diameter, to be spread by small-scale turbulence and carried readily up to cloud base by thermals, and yet grow sufficiently as the relative humidity increases to be able to capture other cloud droplets when it reaches cloud base. However, it is not now known what the best particle size is, nor do we have the ready technology to control the spray output to conform to a specified optimum size. There still are unresolved questions about the efficacy of ground based generators in getting adequate amounts of seeding materials into cumuli.

Numerous salt seeding experiments were carried out during the 1950's, principally in the tropics, but also in Great Britain, France and the United States. Most were started by individual scientists or commercial firms and were short-lived and inconclusive; nevertheless there were some noteworthy pioneering efforts. Howell (1960) reports one of the earliest attempts to combine coalescence with ice phase seeding; he also introduces important concepts regarding the modification potential of groups of interacting cumuli. In one experiment in Pakistan, salt solution was sprayed into burners on the ground which vaporized it to produce fine salt particles to be carried upward by diffusion and thermals.

The first significant landmark in salt seeding was an experiment in northwestern India, reported by Biswas and collaborators in 1967 (Biswas et al., 1967). Statistical controls in the experiment were impeccable but, unfortunately enough, the results are still ambiguous. We shall see a similar unfortunate situation again in connection with one of the landmark ice-phase modification experiments. In the Indian experiment, the procedure provided for ground-based salt seeding in three climatologically similar regions surrounding Delhi, Agra and Jaipur. Control and target areas for each seeding day were defined as the 90° sector upwind and downwind, respectively, of the central seeding location in each test region, as determined from the mean wind at the 1.5 km level. Rainfall data were obtained from raingages within a 24-km radius of Delhi and within a 40-km radius of the Agra and Jaipur seeding sites. The data for the 867 test days suggest that the seeding result was highly positive, namely 40 percent increased rainfall, and statistically significant.

Seedable days were determined on the basis of forecast winds below cloud base and the actual or expected cloud cover and rain occurrence. All days with natural frequent or continuous rain were excluded from the experimental data, since warm cloud salt seeding from the ground was believed ineffective under such meteorological conditions. The experiment was randomized among the seedable days.

Hygroscopic particles were introduced at the ground either by spraying a salt solution of known concentration or by compressed air dusting of a finely powdered salt solution. It was estimated that with spraying, particles having dry masses of 4×10^{-10} to 10^{-8} g and diameters of seven to 25 μm are generated at the rate of 10^9 sec^{-1}. With dusting, the dispersal rate was near 2×10^{10} sec^{-1} of particles of mass 10^{-9} g, corresponding to a dry particle radius of about five μm. With either method, it would be amazing had more than a few grams of salt gotten into any one cloud.

The experiment was conducted in the Delhi region during eight monsoon seasons, in Agra during six seasons and in Jaipur during four seasons. Comparisons were made of the ratio T/C of rain in the target sector to rain in the control sector for seeded and for nonseeded days. Positive results were defined as a higher ratio for seeded days. The results were positive for 16 out of the 18 seasons at the three sites. For seedable days, the average increase in rainfall was calculated at 41.9 percent.

These results seem important. Parametric (t-test) and non-parametric tests appeared to validate the rain increase as real. However, a closer examination of the actual rainfall data shows that the differences in the total rainfall per station for the control areas upwind from the point of seeding (for all three experimental sites) for the seeded and non-seeded days is also positive and almost as large or larger than the difference between target and control area rainfalls for seeded days! Hence it is possible that the inferred "positive results" that arose might have occurred because of variations in rainfall in the upwind control areas and are not necessarily attributable to downwind seeding increase. It appears that an "uncontrolled background effect" may have been present. Again we see that impeccable randomization does not guarantee a meaningful modification experiment - to accompany statistics, we have a desperate need for physical and/or mathematical models to guide us, and for detailed measurements to enlighten the cloud processes at work.

At the South Dakota School of Mines an intensive coalescence modification program is under way, combining efforts to improve models together with field experiments. The modelling is still crude for the reasons discussed in section 4, but nevertheless, they have bravely attempted to address some of the most important questions regarding hygroscopic seeding. One of the most vital of these questions is whether and how seeding with hygroscopic materials could alter cumulus dynamics. The provisional answer is that dynamic effects associated with currently employed hygroscopic seeding agents are almost surely much smaller than those which can be produced by artificial ice nucleants introduced in some supercooled clouds (section 10).

The computer studies are now examining cloud particle growth in the framework of both the entity and field of motion types of dynamic model. Although this surely is a vast improvement over assuming fixed, non-entraining updrafts, some meteorologists question whether either the microphysical or the dynamical simulations are even now sufficiently close to nature to be reliable in coalescence modification work. With this reservation, the current models have confirmed the results of the earlier, more simplified ones. They suggest that artificial embryos of 20 to 100 μm introduced into the lower part of a continental cumulus cloud can lead to the formation of rain ten to 15 minutes before natural rain could form. They also show that large quantities of seeding agents, up to or exceeding 100 kg per cloud, are required unless a chain reaction can be initiated. These results suggest the desirability of experimenting with those cumulus clouds having updrafts strong enough to support a Langmuir chain reaction, and of specifying the conditions favoring chain reaction growth.

Consequently, the South Dakota hygroscopic seeding experiments have turned to vigorous convective clouds, using digitized radar as an important tool in evaluation (fig. 10). "Floating target" areas (see p. 107 for definition) are used which permit counting all the rain produced in the test cases while excluding that from other shower complexes occurring simultaneously, thereby greatly reducing the background variations.

Early results appear promising, in that first radar echoes in new cloud towers appear about 5000 ft closer to cloud base in salt-seeded cases than in no seed cases. Also, over the first three years of randomized trials, rainfall in the salt-seeded cases has run roughly 40 percent above that in the no-seed cases.

A tropical salt seeding program was conducted in 1968 and 1969 on St. Croix, V.I. by a group from the Pennsylvania State University. Interpretation of results has been hampered by incomplete data and the limitations of the cloud physics simulation in the current one-dimensional models. Many other programs on salt seeding have been recently undertaken,

Figure 10. Three-dimensional radar display with alphanumeric information generated by PDP-8 computer on Cloud Catcher Case 6B on 9 July 1971. Values of Z_e, the equivalent radar reflectivity factor, as computed at four levels in the storm, appear as mountains rising from a flat surface. Maximum value of Z_e noted by the computer at each level is printed out in dBz (dB with respect to one $mm^6 m^{-3}$). [The 3-D display was programmed in machine language by James H. Boardman.]

but remain inconclusive owing to lack of statistical controls. The factors determining the optimum amounts, and sizes, of seeding particles and the place and time to introduce them into cumuli are not yet firmly known. Some cumulus experts believe that improved modelling together with improved knowledge of cloud physics-dynamics are necessary prerequisites before large scale randomized hygroscopic seeding programs will be justified. Others believe in going ahead with the programs, designing them in such a way as to increase basic knowledge regardless of the practical success.

A quite different way by which cumulus coalescence might be modified is by means of artificial electrification. Interesting, but still inconclusive work toward this goal has been published, mainly by scientists at the Illinois State Water Survey.

Although natural cloud electrification is not well understood, both theoretical models and laboratory experiments suggest that collision and coalescence efficiencies can be increased by electrification. With this background, kilometers-long charged wires have been set outdoors to electrify fields of real cumuli.

The most advanced and best documented cumulus electrification experiments were conducted in central Illinois in 1960 and 1962. Corona discharges from a 130 km^2 network of seven high-voltage lines successfully electrified about 18 percent of the cumuli over the downwind target area. As anticipated, first precipitation echoes (from a calibrated three-cm radar) had a higher frequency downwind of the wires than upwind. Disappointingly, however, it was found that the downwind precipitation was less when the air was artificially ionized, but the sample was too small for statistical significance. This fascinating area of cumulus modification has not been pursued in recent years.

8. MODIFICATION OF SUPERCOOLED CUMULI BY ARTIFICIAL GLACIATION - METHODS AND BASIC PRINCIPLES

When cumulus clouds tower above the freezing level (about 4 - 5.5 km) much of their liquid drop content usually remains supercooled. Laboratory evidence suggests, however, that below temperatures of about -40°C, liquid drops will freeze "homogeneously", that is all by themselves without any foreign substances. So, if the cloud air is suddenly cooled enough, the cloud should glaciate.

This was the great discovery in 1946 by Vincent Schaefer when he first introduced Dry Ice (solid CO_2) into clouds, first in the laboratory and then in the real atmosphere. Dry Ice has a temperature of about -78°C. When small pellets of it are introduced into a supercooled cloud, the adjacent air is cooled below the critical threshold of -40°C and myriads of tiny ice crystals appear. The latest laboratory measurements indicate that one gram of Dry Ice can produce nearly 10^{12} (one million million) ice crystals in a supercooled cloud in the temperature range -2 to -12°C.

To deliver Dry Ice into a supercooled cumulus tower, it has been necessary to dump it into the top from aircraft, which is expensive. It is also necessary to have grinding apparatus to produce pellets of controlled size. The major advantages of Dry Ice relative to other artificial glaciation methods is that it works at warmer temperatures and evaporates well above the ground, having no residual which possibly could harm either people or the environment, or which could persist to accidentally seed clouds other than those intended.

The other main way to induce glaciation in supercooled clouds is by means of the introduction of artificial freezing nuclei. The first discovered and most widely used method is with silver iodidie (AgI). Silver iodide was originally found by Vonnegut because its crystal structure most closely resembles that of ice. The crystal structure of the much cheaper substance, lead iodide, is only slightly less close to that of ice; lead iodide has had widespread usage in the famous hail suppression experiments in the Soviet Union.

Silver iodide is nearly always introduced into clouds in the form of a smoke. From the outset, this method gained wide popularity, because ground generators could be constructed and operated very cheaply. With ground generators, however, it is both necessary and difficult to determine where the smoke goes and whether adequate amounts are entrained into the target clouds and reach levels having temperatures below about -4°C. Next, generators were affixed to aircraft. Most of these burn a solution of acetone and silver iodide, in combination with various iodine compounds. During the 1960's, pyrotechnic silver iodide generators were invented which have permitted the massive airborne seeding required to change cumulus dynamics (section 10) and to experiment on the modification of hurricanes.

There is a common, much oversimplified explanation of how silver iodide glaciates a supercooled cloud. It says that, because of the resemblance in crystal structure, the droplets in the cloud react as if the silver iodide particles were ice crystals, so that ice forms and grows on the AgI particles while the water drops evaporate, except those frozen by direct contact with silver iodide. Although it is reasonable to expect that the resemblance in crystal structure is vital, ice nucleation by silver iodide has been found to be extremely complex and has by no means been fully understood or optimized.

Silver iodide begins to be active as a freezing nucleus at -4°C. With most silver iodide mixes used for cloud seeding, the nucleation efficiency increases as the temperature decreases. That is, for each gram of silver iodide smoke in the cloud, we get larger numbers of active freezing nuclei at lower temperatures.

Laboratory tests suggest that at -10°C, 10^{12} - 10^{14} active nuclei per gram of AgI are achieved by currently used generators. It is still debatable, however, whether the laboratory conditions adequately resemble those in real cloud seeding experiments closely enough to be reliable. For this and other reasons, it has not yet been possible to fix firmly the optimum amount of silver iodide to use in each type of seeding experiment.

With most generators, the silver iodide smoke is not pure, nor is it in the form of single AgI crystals. Nucleation efficiency has been found to depend upon the method and temperature of burning and quenching, and upon the particle size spectrum and structure. It also may depend quite critically upon the nature of the impurities combined with the AgI and upon whether or not the particles are wetted. Recently, there has been evidence that in relatively warm supercooled clouds (down to about

-17.5°C) glaciation is mainly by contact and direct freezing of the drops, while at lower temperatures the more classical process of vapor diffusive growth upon the freezing nuclei predominates.

In laboratory experiments, sunlight has been shown to destroy the nucleation effectiveness of silver iodide, reducing it by an order of magnitude in one or several hours. Nevertheless, we must be concerned with its persistence and with the possible contamination of control areas, succeeding days and neighboring experiments. We must also be concerned with the amounts of silver, scavenged by seeded rain, that enters the soil and water bodies. In Canada, following massive seeding with pyrotechnics, concentrations of as high as four parts per billion have been found, ten km downwind from the seeding. Fortunately, this concentration is less than one-tenth of that deemed unacceptable for drinking water (U. S. Public Health Service). More tracings must be made, and also tests of potential effects upon plants and animals. A drawback of using large amounts of lead iodide, which is cheaper, is that lead is more toxic than silver.

A new frontier in cloud physics and modification is ice nucleation by organic compounds. Some of these have the ability to form hydrogen bonds with water and probably also have a molecular structure that is favorable to ice formation. Among those substances found most effective in the laboratory are phloroglucinol, metaldehyde and the fertilizer urea. The first two begin to nucleate at temperatures of -3 or -4°C and urea has been observed to cause glaciation at +6°C! This marvel is accounted for by the fact that urea dissolves readily in water and absorbs heat when it goes into solution and cools the solution significantly.

The Chicago group field tested phloroglucinol and urea on supercooled stratus clouds. For phloroglucinol, results were disappointing. The urea worked as well as Dry Ice; it is also undergoing preliminary trials as a coalescence enhancer in warm cumuli and warm fogs. In these ecology conscious times, the use of a fertilizer in weather modification offers considerable attractiveness.

The only organic substance so far tried in supercooled cumulus seeding has been metaldehyde, which appears also to exhibit favorable electrical effects. The results of exploratory airborne seeding on four days in Arizona were perhaps sufficiently encouraging to warrant a systematic randomized experiment in the near future.

Artificial freezing nuclei may have two classes of important modification effects on supercooled cumulus clouds. The first is to increase precipitation efficiency. The ice particles may grow at the expense of the water droplets acting as "precipitation embryos." Under favorable conditions these embryos may grow big enough to fall out as snow or rain. This is because of the lower saturation vapor pressure prevailing over ice at supercooled temperatures, as we explained earlier. For simplicity, we shall call the seeding concept based on this precipitation efficiency improvement alone the "static approach." The second class of possible effects are dynamic. In glaciating a water cloud, heat is released - the so-called "latent heat of fusion." Since the lifeblood of a cumulus updraft is buoyancy, or density deficiency relative to the surroundings, conceivably warming the cloudy air could decrease its density enough to affect its motions, that is alter its dynamics.

Seeding experiments using this concept are said to use the "dynamic approach." Even though effects due to the precipitation embryos produced are in nature often inextricably combined with the dynamic effects, for clarity we have separated experiments involving artificial glaciation of supercooled clouds into the two categories, depending upon which effects the investigators were seeking to produce.

9. SEEDING SUPERCOOLED CUMULI - STATIC APPROACH

Until the 1960's, virtually all operational supercooled seeding efforts and most randomized scientific experiments were focussed on increasing the precipitation efficiency; that is, they were based on the static approach. In those key experiments described in this section, it has been believed that dynamic effects were small and/or negligible. Reservations regarding this belief may arise in some instances.

Since a cumulus contains roughly 100 tiny droplets per cm^3, one million of them would occupy about ten liters of cloudy air. Their combined water content is required to build one raindrop. Therefore, we would need something like one artificial ice nucleus per ten liters of cloud air, or perhaps one nucleus per liter if we allow the rain embryos reasonable further growth by coalescence as they fall. Consider a seeding material that yields 10^{12} active nuclei per gram, such as Dry Ice or some silver iodide generators at supercooled temperatures of -6 to -10°C. Since the supercooled volumes of typical cumuli are in the range of one to ten km^3 or 10^{12} - 10^{13} liters, about one to ten grams of seeding material would be required for an individual cumulus.

Similar to other modification approaches, the randomized scientific experiments began here with single clouds and progressed to areas. For more certain targetting these experiments have mostly been conducted from aircraft, which greatly raises their cost. To be economic, most of the commercial seeding ventures of the 1950's used silver iodide ground generators.

In those days, a single burner emitted about 50 grams, or less, of AgI smoke per hour.[12] Under normal wind conditions the smoke might be spread over a triangular plume of 200 km^3 in the hour or so before sunlight could reduce its activity. With typical cumulus populations (active towers covering 0.5 to one percent of the area and living 15 minutes) four to eight per hour grow in the silver iodide infested plume and share whatever fraction of the 50 grams they can ingest. Direct verification of successful targetting into cumuli from ground generators is virtually lacking. As the freezing level is often more than 10,000 ft above sea level in summertime and tropical cumuli, the use of ground generators is nowadays limited mainly to mountains.

In the years 1947 to about 1953, non-randomized seeding experiments on individual supercooled cumuli gave conflicting results. In the U.S. Gulf States in 1949, Dry Ice seeding appeared to dissipate most of the clouds, while 100 Dry Ice experiments in Australia (1947-1951) were said to have increased rainfall.

At the present time virtually all meteorologists agree that statistical controls are a necessary but not sufficient condition for a mean-

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[12] The best modern ground generators' output of AgI smoke is up to 3500 grams per hour.

ingful cloud modification experiment. The additional physical and modelling requirements are only slowly being clarified as our basic knowledge of cloud processes inches forward.

In the United States the first randomized supercooled cumulus seeding experiment was conducted in 1954 by the Chicago group as a part of the same project that included the water spray seeding described in section 7. They rejected experimenting on tropical cumuli in the Caribbean, on the grounds that there natural precipitation was already highly efficient. They turned instead to continental cumuli in the central United States. However, the amount of Dry Ice (12 - 28 pounds per mile) and the flight patterns were selected in the hope of instigating dynamic effects as well as improving precipitation efficiency.

Because of suppressed weather, the cloud sample was small. The slightly higher tops and radar echo probability in the seeded clouds over the unseeded clouds failed to achieve statistical significance. The apparently greater success of a similarly designed non-randomized Australian experiment was attributed to the longer lifespan of the Australian cumuli. The relation of cumulus lifespan to modification potential is an important area that has progressed hardly at all in the intervening decades.

Isolated Australian cumuli were also the subjects of the only randomized "static approach" AgI seeding experiment with positive results, for which statistical significance was adequate. In 1964, 69 clouds were randomly treated with either 20 grams, 0.2 grams or 0 grams of silver iodide from airborne generators flown at cloud base. Precipitation was measured from the numbers and sizes of raindrops recorded by a foil impactor flown in a criss-cross pattern by the same aircraft.

When cloud top temperatures were warmer than -10°C, or when natural rain fell within 30 km of the seeded clouds, no effects of seeding were detected. When cloud top temperatures were below -10°C and there was no nearby rain, clouds seeded with the larger amount rained, on the average, four times more than unseeded clouds (160 acre-feet versus 40 acre-feet unseeded). No significant dynamic effects were detected. However, some cloud physics experts discount the results of this experiment on the grounds that foil impactor measurements are unlikely to adequately represent the total precipitation from a cumulus. The reason is that in one run through a typical cloud this device samples only about one cubic meter of air in a very thin "tunnel", less than 15 cm^2 in cross section. On the other side, an identically designed experiment in Rhodesia also gave positive significant results. In the latter, the foil impactor measurements were backed by those of a scoop collector.

The static approach to cumuli was next applied to randomized airborne seeding upwind of target areas of hundreds or thousands of square miles. By hindsight, we can see that this step was taken without adequate resolution of the isolated cumulus problem. Cumulus group and area seeding is always hugely more difficult and complex than that involving single clouds, because cloud interactions and the meso-scale of atmospheric motions (10 - 100 km) become involved. The latter is the least well-measured and understood scale of motion in the atmosphere.

Two intensive and still controversial area experiments were performed in the United States, namely that by Battan and collaborators

(Battan et al., 1960) on orographic cumuli in Arizona (in 1957-60, 1961, 1962 and 1964) and Project Whitetop by Braham and collaborators on non-orographic cumuli in Missouri (in 1960-1964). Both projects included important measurements upon the clouds and their environments, particularly emphasizing radar.

In the Arizona orographic cumulus experiment, airborne seeding was conducted upwind of a 400 sq mi target area, with a generator emitting about 1000 grams of AgI per hour. Randomization was by pairs of successive days chosen by their suitability for convection. Seeding began about noon and continued for two to four hours. Evaluation (by raingages) was made by examining the precipitation quantities which fell between 1300 and 1800 hours local time.

In Program I (1957-1960) the seeding aircraft was flown at the -6°C level (18-20,000 ft). The density of the gage network was about one every 13 sq miles. In the first two years, seeded days experienced moderately more rainfall than did the unseeded days, a difference which reversed in the second two years. The overall difference between seeded and unseeded days was negative but not statistically significant.

In Program II (1961, 1962 and 1964) the seeder aircraft was flown at altitudes just below cloud base and the density of the gage network was nearly doubled. The rainfall result was again negative. Seeded days averaged 30 percent less rainfall than unseeded days, which again was not statistically significant. A careful study of the radar data showed, however, that on seeded days in both programs more clouds developed precipitation echoes than on unseeded days. This result was significant, leading the experimenters to conclude that the silver iodide seeding may have influenced the precipitation-initiation process.

The Arizona data have been subjected to considerable later scrutiny by other investigators, with apparently conflicting results. A famous statistician asserts that he has found significantly less rainfall on seeded days at a location 65 miles away from the seeding, when the prevailing wind had a component in that direction. On the other hand, a Pennsylvania State University group of meteorologists claim to have detected an "uncontrolled background effect" by means of a one-dimensional "entity" type cumulus model. They found that the model calculated systematically less vertical cumulus development on control days than on seeded days. Even if only tentative, this result may be important since the main conclusion drawn from these experiments by their senior scientist was that the dynamics of cumulus updrafts are much more important in controlling their rainfall than is their microphysical structure.

Project Whitetop is the most famous, most controversy-provoking and most carefully studied weather modification experiment that has yet been conducted. Topnotch cloud physicists were involved together with topnotch statisticians. The plan was carefully designed and executed. The data have been painstakingly analyzed for seven years, leading to significant advances in cloud physics. Nevertheless, the deduced seeding effect was negative, beyond reasonable doubt, and the possible explanatory hypotheses may ever evade firm proof.

The Whitetop "research area" was a circle of 60 mi radius (about 11,300 sq mi) centered at the three-cm radar. The airborne seeding was done near cloud base level at the upwind edge of the area. The seeder aircraft flew along a 30 mile line lying at right angles to the wind. The burners released up to 2700 grams of AgI per hour, for six hours prior to and during the daily convection period.

The smoke was envisaged to spread downwind across the research area and to mix vertically forming a "plume" (fig. 11). The plume was defined as that area downwind of the seeding line which was encompassed by the most divergent wind directions between the seeding level and 14,000 ft. The investigators recognized that the entire plume might not be uniformly seeded, but assumed that no seeding material would invade the "out of plume" area.

The experimenters assumed that the AgI spreads downwind as a relatively thin blanket not far from the seeding level except where it is sucked up into cloud bases. If such a layer were horizontally uniform, 100 m thick, we would get in-cloud concentrations of about two particles per liter.

Days were selected as suitable for convection from objective criteria (using weather maps and rawinsondes) and randomization was within these suitable days. Rainfall analysis was by gages, spaced roughly one per 250 sq mi. Recent studies in Florida raise a question concerning whether such a sparse network can accurately depict cumulus rainfall.

The main result of Project Whitetop was that on seeded days the rainfall was much less than on non-seeded days, both in and out of the plume and increasing downwind after the cessation of seeding. The statistical significance of these results is too clear to permit an easy

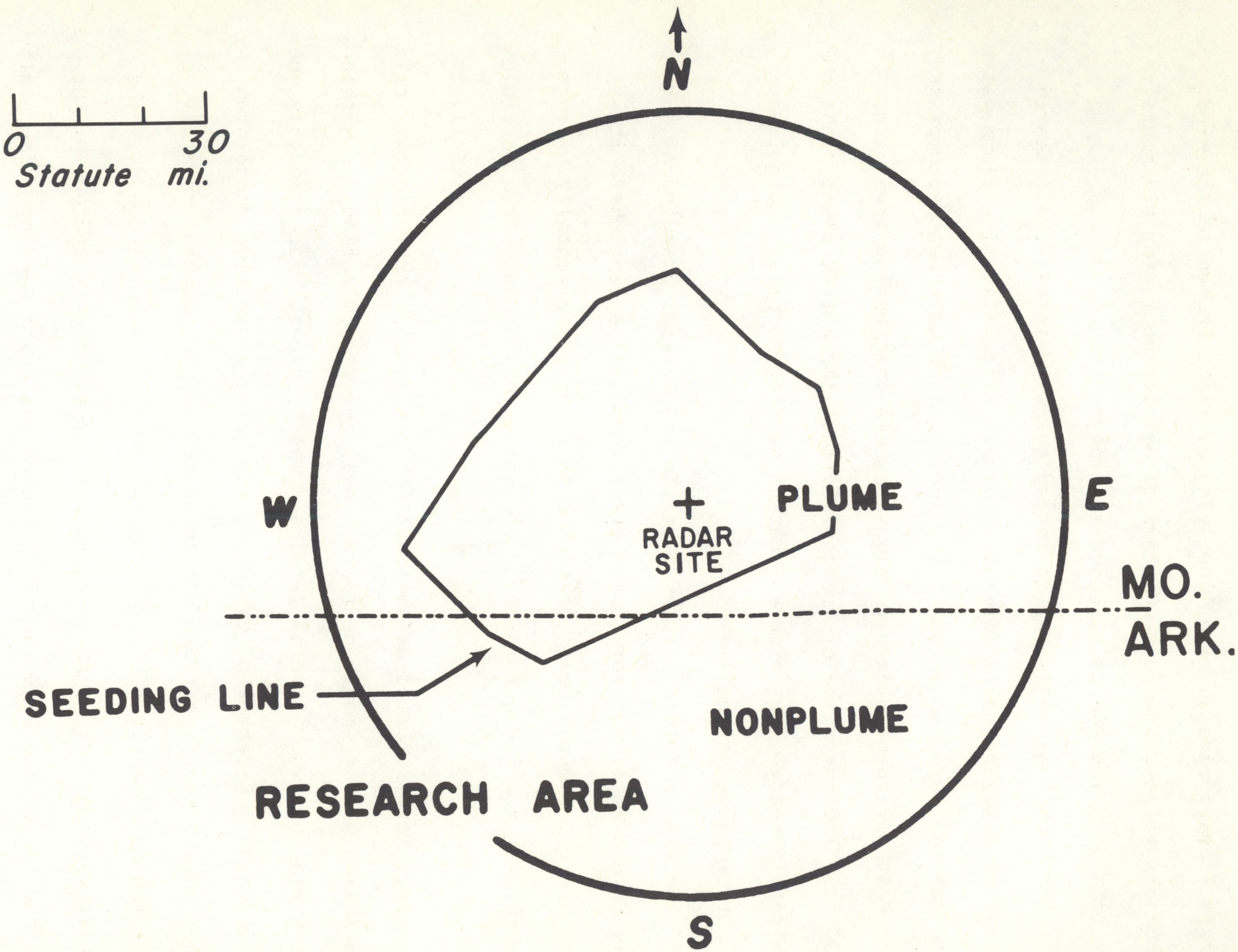

Figure 11. The project Whitetop research area, radius 60 mi. The seeding line is the heavy line at the left, while the calculated plume is the solid outline.

dismissal. It was learned, however, that despite impeccable randomization procedures, the non-seed days were rainier than the seed days, as evidenced from upwind and before-seeding records. This type of imbalance is called "an uncontrolled background effect"; such problems must be carefully watched for in all modification experiments.[13]

After subtracting the uncontrolled background effect, the overall negative treatment effect in the plume area was calculated to be rainfall decreases of 24-30 percent over the 11 hours of the experiment and 43-74 percent in the five hours immediately following seeding! "Out of plume" rainfall decreases on seed days were suspected, but could not be clearly separated from the uncontrolled background effect.

Another equally important result was that the seeded days can be stratified into days with large rain excesses relative to control days and more days with large rain deficiencies relative to control days. The days on which seeding apparently increased rainfall were those on which echo tops were restricted between 20,000 and 40,000 ft and days with wind directions from west through north. The days on which seeding apparently decreased rainfall were those having echo tops above 40,000 ft and days with south winds. Further, on the south wind days there is evidence of large rainfall decreases outside the research area to the west which amounted to 57 percent in the 11 hour experimental period and 71 percent during seeding hours!

Important results emerged from Whitetop. The first was re-confirm-

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[13]An uncontrolled background effect in the opposite sense apparently worked in the Indian salt seeding experiment (section 7).

ation of the predominance of the coalescence process in rain formation in the supercooled Missouri cumuli. The second was the surprising finding of large quantities of natural ice in warm (-2 to -10°C) supercooled cumuli. As many as one to ten natural ice particles per liter were measured and about one-third of the small unmodified cumulonimbi appeared to completely glaciate naturally in five to ten minutes time. Braham suggested that the surprisingly large natural ice quantities were associated with the freezing of the large drops formed by coalescence, which might shatter or otherwise initiate an ice multiplication process.

The large amounts of natural ice in the Whitetop cumuli led some scientists to the belief that seeding such clouds would be futile or worse. In fact, the apparent negative seeding effect obtained by project scientists was attributed by some people to "overseeding." "Overseeding" means the introduction of too many ice particles among which the available water must be shared, preventing any from growing large enough to precipitate. If this theory were correct, the west to north wind clouds should have contained less natural ice, a now untestable postulate in keeping with the more continental origin of those air masses. There was also some evidence of stronger cumulus updrafts on those occasions, probably related to lower static stability. The events in Whitetop may never be explained to everyone's satistaction.

In a review of the world-wide application of the static approach to seeding cumuliform clouds to produce rain increases, there appears to be only one type of situation where positive significant results have been obtained. The successful trials have been confined to seeding convective storms in California, Switzerland and possibly elsewhere. These weather systems are quite different from fields of towering white cumuli superimposed on a blue sky. Furthermore, in these stormy situations dynamic effects and important cloud interactions cannot be precluded. Dynamic effects are next examined, first in their least complicated context.

10. DYNAMIC SEEDING OF ISOLATED SUPERCOOLED CUMULI

So far, we have discussed cumulus modification in terms of altering just the cloud particles, namely just the microphysics. Nearly always these efforts have been attempts to increase precipitation efficiency. That is, from the given amount of water vapor entering the cloud by ascent through its base, a greater fraction would be (hopefully) caused to fall to the ground as rain, over that which would have fallen naturally. However, in the 1950's while scientific and practical applications of static seeding were in progress, many meteorologists increasingly contended that the strength, size and duration of the vertical air currents, namely dynamics, has a far stronger control on cumulus precipitation than does their microphysics.

To illustrate the importance of dynamic control on cumulus precipitation, let us return to figure 3 and compare the precipitation from each of the three typical clouds. The upward flux of water vapor through cloud base may be calculated from the formula:

$$\text{Flux (vapor)} = \rho q A w \Delta t \qquad (1)$$

where ρ is the air density in grams per cm^3, q is the specific humidity of water vapor in grams of vapor per gram of moist air, A is the cloud base area, w is the average updraft velocity through cloud base and Δt is the lifetime of the updraft. Typical values of these properties and the resulting fluxes and rainfall, with varying precipitation efficiencies are shown in table 1.

Table 1. Rain from Cumulus Clouds (fig. 3) as a Function of Precipitation Efficiency

	Big Cloud	Middle-sized Cloud	Little Cloud
Air density $\rho(g/cm^3)$	$\sim 10^{-3}$	$\sim 10^{-3}$	$\sim 10^{-3}$
q(g/g)	18×10^{-3}	18×10^{-3}	18×10^{-3}
$A(cm^2)$	50×10^{10}	3.14×10^{10}	0.78×10^{10}
w(cm/sec)	200	100	50
Δt(sec)	3600	1800	600
R (100%PE) kt	6480	101.8	4.2
R (50%PE) kt	3240	50.9	2.1
R (10%PE) kt	648	10.2	0.42

Table 1 shows forcefully that a giant cumulonimbus with even one percent precipitation efficiency brings down more rain than does an ordinary warm cumulus with 100 percent precipitation efficiency. Could we deliberately make giant cumuli from small ones? If so, why did meteorologists not follow this avenue from the outset of seeding, rather than devoting decades attempting to manipulate just the precipitation efficiency? The answer to this paradox is complex. It is partly historical, illustrating the principle that for a feasible weather modification experiment, theory (and/or model) and technology must meet, together with motivation and economics.

Invigorating cumulus updrafts by artificial glaciation was originally suggested by Langmuir and was almost certainly produced in some of the pioneering Australian experiments, in which large amounts of Dry Ice (10-150 lbs) were dumped into individual cumuli. Notwithstanding, in 1958 the prospect of artificially altering cumulus dynamics was dismissed as impossible by a famous cloud physicist (McDonald, 1958). The concept arose again in 1963 in a context which was, except for technology, completely apart from weather modification.

Since the end of World War II, the senior author and colleagues had been attempting to model the dynamics of a single cumulus, with the dream of someday incorporating the interactions of the droplets with the updrafts. To test and improve the crude early beginnings, an elderly amphibious aircraft was instrumented and flown into hundreds of tropical oceanic cumuli (Malkus, 1954) and artificial "clouds" were created and measured in laboratory tanks (fig. 6). By the late 1950's access to a primitive electronic computer permitted the first non-linear "field of motion" cumulus model (figs. 7 and 8) which used some of these observations to grow a simulated cloud from an initial density perturbation in a resting fluid.

Based on all these results together came the breakthrough by Levine (Malkus, 1960), namely the framework of a relatively tractable one-dimensional "entity" model. This model simulated the rising phase of an individual cumulus tower. The achievement of this breakthrough was twofold; firstly, the rate of rise of the tower was expressed by a relatively simple ordinary differential equation, whose components could be specified (after many assumptions and parameterizations) from knowledge of cloud base conditions and an environmental sounding of temperature and humidity. If necessary, the equation could be solved by hand integration. Secondly, when the equation was solved for the height of cloud tops (defined as the level where the rise rate goes to zero) and internal tower properties, the results were sufficiently realistic to compare favorably with aircraft and photographic observations.

Using evidence from the laboratory and computer, as well as time-lapse pictures of real clouds, Levine hypothesized that the internal motions in a cumulus tower resemble those of a spherical vortex. This hypothesis permitted him to adopt the classical rate of rise equation for a buoyant vortex to a cloud tower, namely:

Vertical Acceleration = Buoyancy - Drag

$$\frac{dw}{dt} = w\frac{dw}{dz} = \frac{gB}{1+\gamma} - \frac{1}{M}\frac{dM}{dz}w^2 \qquad (2)$$

where w is the tower ascent rate, t is time, z is height, g is the acceleration of gravity, B is tower buoyancy, γ is the so-called "virtual mass" coefficient and $1/M\ dM/dz$ is the entrainment rate, or the dilution rate of the cloud's mass with the outside air as it rises (see p. 16 and discussion).

Buoyancy is reduced and drag is created by entrainment. Buoyancy dilution is maximum at low levels in warm air masses (where the specific humidity difference is maximum between saturated cloud air and unsaturated surroundings). In tropical cumuli this eating away of cloud fuel is the predominant effect of entrainment. Once the entrainment rate is specified, we are well on the way to solving (2) for the rate of rise w (zero at maximum level achieved by the tower) and other cloud properties as functions of height z. The solution applies just to the rounded cap as it rises, as if the observer were riding with the tower; later one-dimensional models treated "steady state" profiles and time-dependent plumes.

The postulate regarding entrainment dependence is crucial, because it permits solution of the equation. Most existing one-dimensional models are based on the inverse-radius entrainment law, namely:

$$\frac{1}{M}\frac{dM}{dz} = \frac{2\alpha}{R} \qquad (3)$$

where R is tower radius and α is the coefficient of proportionality, derived empirically from measurements in the laboratory and, very roughly, on real clouds. When entrainment is better understood, more accurate relationships may be substituted for (3) in the models.

Cloud buoyancy is cut down not only by entrainment, but also by the weight of the liquid or solid particles - that is, the water drops, ice crystals, hail stones, etc. that it carries. A typical modest water content of one g m^{-3} can subtract more than the equivalent of 0.5°C from the buoyancy, which is small cumuli and near cloud tops is often as large as the entire buoyancy. Thus, if any precipitation falls out of the tower as it rises, we must be able to specify the amount that leaves in each height step in order to calculate the remaining weight of water substance. This requires a precipitation growth and fallout scheme in the model, an example of which will be outlined shortly.

One remaining parameter needs specification before solution of

(2) is possible, namely the "virtual mass" coefficient γ. In rising laboratory plumes, this fictitious buoyancy reduction occurs because the ascending tower must push aside the surrounding fluid as it rises. No direct verification of this effect has been possible with real clouds. Steady state models, therefore, assume $\gamma = 0$ and the EML[14] series discussed here use the laboratory value for the spherical vortex, namely 0.5.

The calculation is best understood if we make the entrainment calculation first, directly after specifying the cloud radius R. With an environment sounding, entrainment can be then computed either graphically or by machine and its output is the cloud temperature and humidity at each level (assuming in-cloud saturation) and the amount of water vapor condensed into liquid. After applying the precipitation fallout scheme, we then compute cloud buoyancy and integrate (2) upward in a "marching" scheme, assuming a small value of w (say one half to one m sec^{-1}) at cloud base. When w goes to zero, the tower has achieved its maximum height.

In early trials of the model on natural tropical clouds, we either assumed no precipitation or assumed that a fixed fraction of the condensed drops fell out in each height interval; that fraction was adjusted to give agreement with the very fragmentary cloud water measurements then available. Despite these oversimplifications, valuable insight into relationships between cloud top heights, dimensions, buoyancy, temperature and water content were obtained. It became clear, for example, that if the middle cloud in figure 3 had its buoyancy increased by 50-100

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[14]EML = Experimental Meteorology Laboratory, NOAA.

percent, it could (under many tropical conditions) grow as tall as the big cloud on the left.

In 1961, the invention of pryotechnic generators (at the Naval Weapons Center) of silver iodide enabled massive seeding from aircraft, and hence modification experiments on tropical hurricanes could be seriously undertaken. We saw that this exciting invention could also readily supply a cumulus with one ice nucleus for every one of its cloud drops and rapidly release the latent heat of freezing.

In figure 3 the middle cumulus has about 300×10^{15} supercooled cloud drops[15] (one ice particle per liter is still only one for each 100,000 drops). From a one-kilogram pyrotechnic (efficiency $\sim 10^{13}$ ice nuclei per gram at -10°C) we get 10^{16} ice nuclei, or more than enough to rapidly glaciate the cloud. Freezing 1.5 - 3.0 grams water per kilogram of cloudy air, a typical liquid water content, would raise the cloud temperature by 0.5 - 1.0°C due to the heat of fusion and about 0.8 - 0.9°C more due to the vapor deposition occurring when we proceed from water to ice saturation.

Our modelling experience led us to seize upon the pyrotechnics as a tool to make a real-life experiment in cumulus dynamics and as a marvellous opportunity to test our model. The idea behind the experiment is illustrated in figure 12. When the latent heat is released rapidly by AgI seeding at or just above -4°C level, cloud temperature excess and buoyancy is increased. In the natural cloud, the figure shows the latent

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[15]Assuming 100 drops per cm^3 and a supercooled volume, $V = A\Delta Z = \Pi R^2 \Delta Z \simeq 3 \times 10^{15}$ cm^3 where ΔZ = 1 km vertical thickness above 0°C.

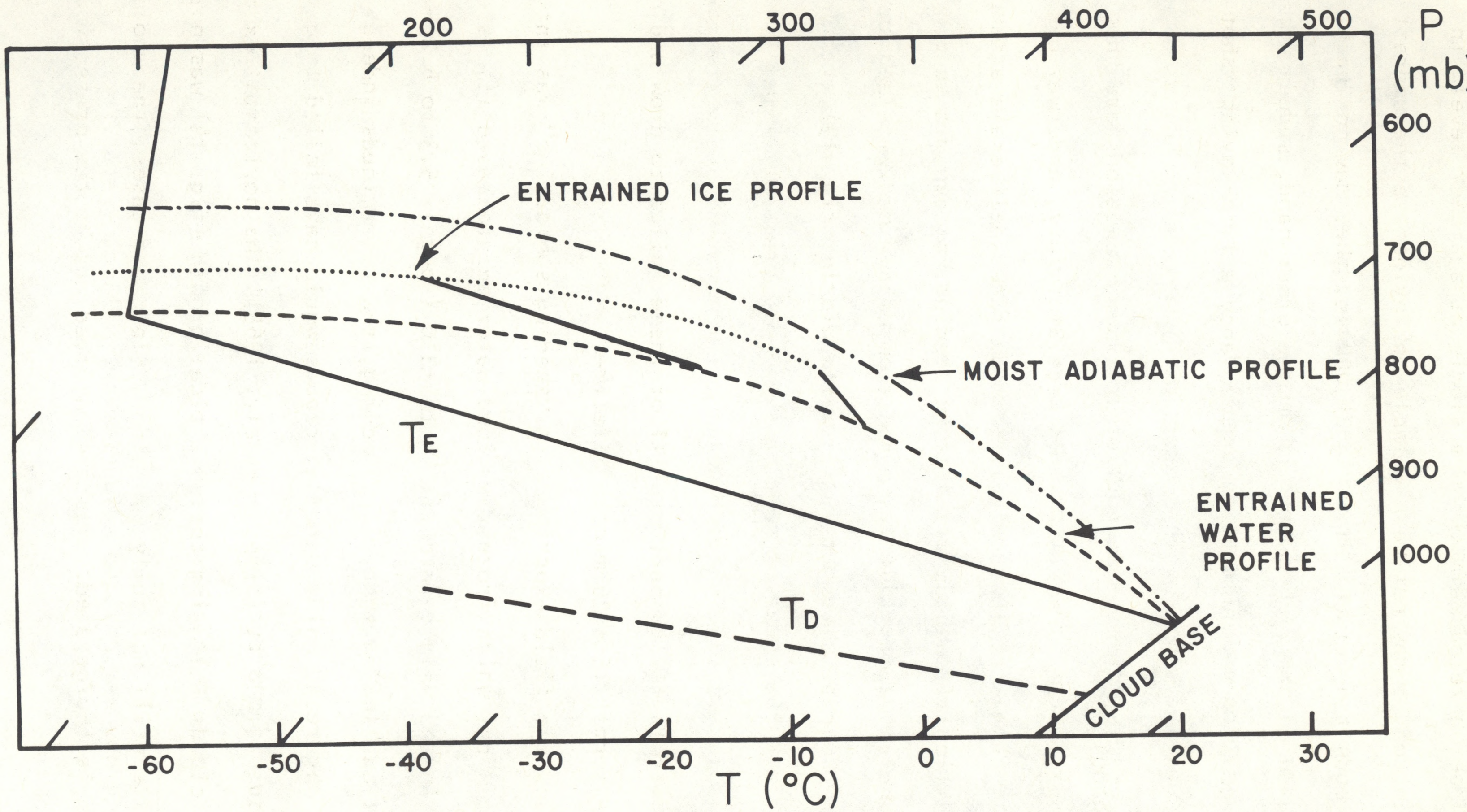


Figure 12. Tephigram illustrating the principle upon which dynamic cumulus seeding is based. The environment actual and dewpoint temperature are given by the solid (T_E) and dashed (T_D) lines, respectively. The warming due to freezing is shown by the slanted solid lines; the lower right-hand one is postulated to be the effect of seeding. The upper part of the curve for the seeded cloud is thus to the right of and hence warmer than that of the natural cloud, whose heat of fusion is realized more slowly and at a higher level. The abscissa is temperature in °C; the slanted ticks are pressures in mb. (Courtesy J. McCarthy.)

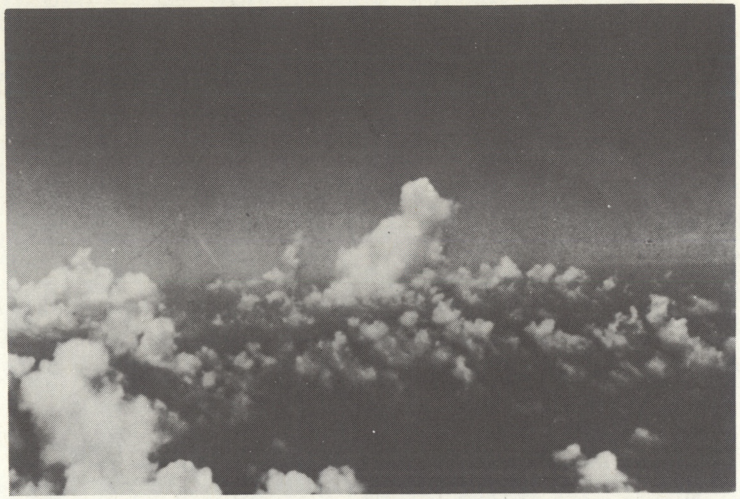
heat of fusion being released much more slowly at a higher level; in real clouds most of it may not be available to invigorate the updraft. If the real clouds top between about 18-24,000 ft, they may not be high enough to draw on natural freezing, but on the other hand, sudden artificial freezing could give their dwindling buoyancy a life-saving "shot in the arm."

In August 1963, four days of cumulus experimentation were "bootlegged" as a part of the practice for Project Stormfury, underway over the ocean south of Puerto Rico; thus began the first deliberate attempts at the modification of cumulus dynamics by seeding, or dynamic seeding.

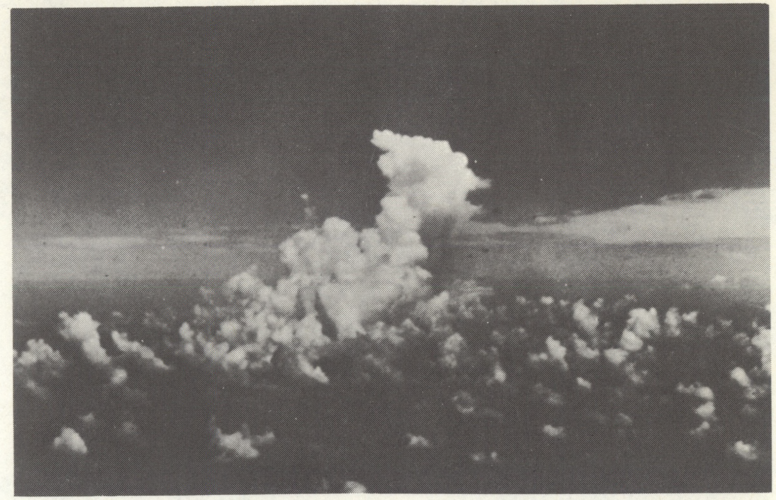
Pryotechnics were dropped into the tops of six medium-sized supercooled cumuli. Four of these exploded spectacularly (fig. 13), first about doubling their height and then expanding horizontally into a giant long-lived cumulonimbus. There were four initially similar looking cumuli selected as controls for comparison; all of these failed to grow and dissipated in the normal 15 - 20 minute lifetime.

Following the field experiment, a "seeding subroutine" was introduced into the model which froze the cloud water and released its latent heat linearly in the height interval -4 to -8°C (roughly 5.3 to 6.2 km). These calculations showed that, with seeding, the test clouds indeed could have grown as observed, while unseeded clouds would have failed to grow much above about 20,000 ft (Simpson et al., 1965). The horizontal expansion of many seeded clouds following their vertical growth (fig. 14) was not predicted and is still not fully explained. In these cases, the whole updraft system is invigorated. Factors involved may be the protection

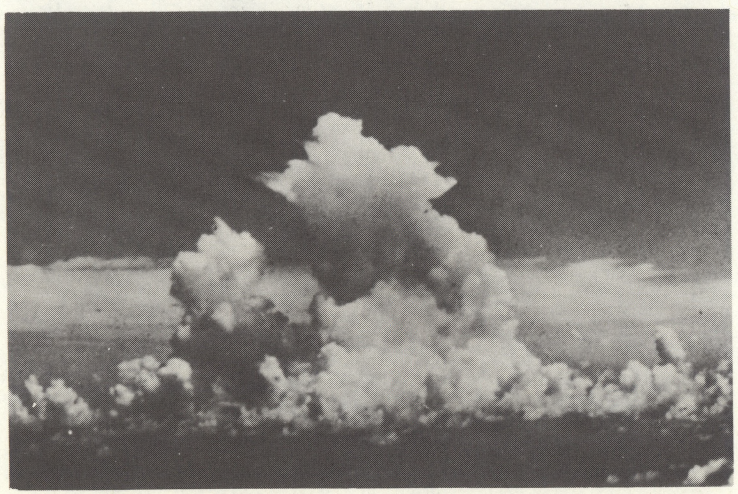
Figure 13. "Explosion" of a tropical cumulus following seeding.



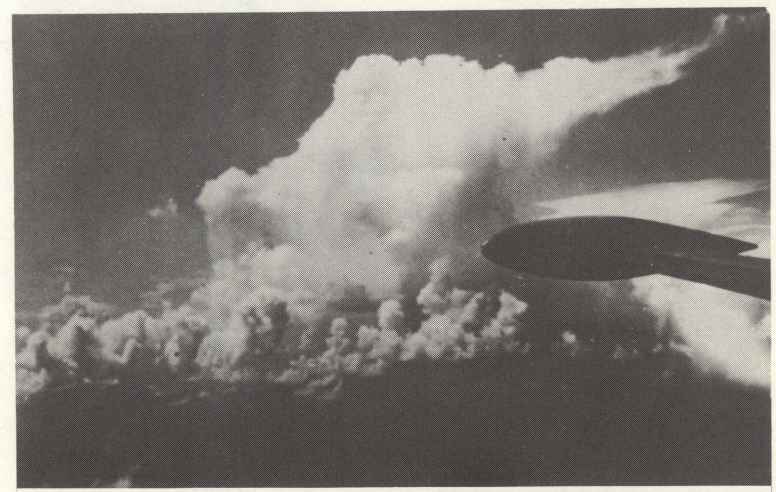
a. Cloud at seeding time, top about 7.5 km.



b. Cloud nine minutes later.



c. Cloud 19 minutes after seeding.



d. Cloud 38 minutes after seeding with top at about 12 km. It is now a full blown cumulonimbus.

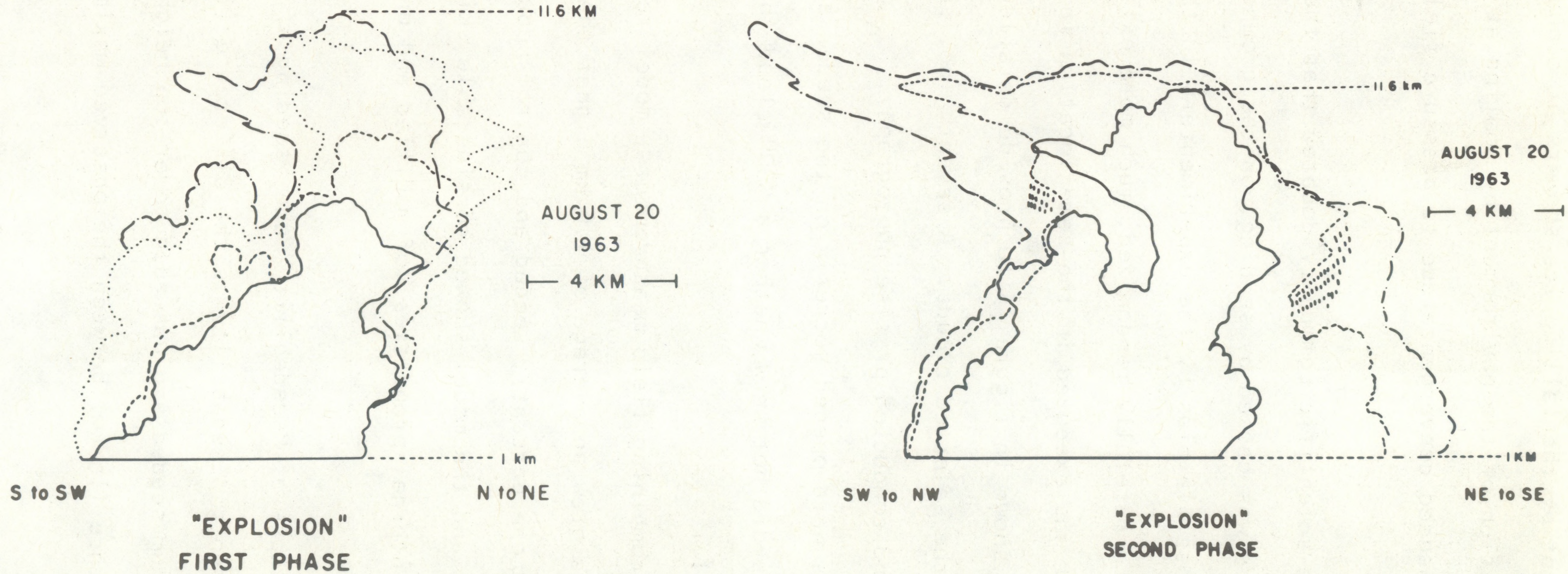


Figure 14. Growth of the cloud of figure 13 following seeding. Constructed from a series of photographs made at known distances and directions from the cloud.

afforded against entrainment by the falling ice showers at cloud edges and a possible destabilization of the environment by cooling at the melting level, and perhaps enhanced convergence due to pressure field alterations.

Many members of the scientific community doubted that the enormous growth of the seeded clouds was caused by seeding, on the grounds of high natural variability and possible bias by the experimenters in their cloud selection. Consequently, a carefully randomized, much more extensive dynamic seeding experiment was executed in the same location in 1965. Six aircraft were used as shown in figure 15 to provide detailed "before and after" depictions of the selected clouds. A seventh (not shown) directed the rest by radar and conducted precise photography.

Sealed instructions were opened secretly on the seeder aircraft so that project scientists did not know whether a "GO" cloud they selected was seeded or a control.

Analysis was made combining field measurements, model results and statistics. Seeded clouds grew an average of 1.6 km higher than controls (significance better than one percent), seeded and control populations were distinctly separate, and the model showed considerable skill in predicting top heights and internal properties of modified and unmodified clouds.

The important concepts of "seedability" and "seeding effect" were defined with this experiment. Seedability is the difference (in km) between the predicted maximum seeded and unseeded tower top heights. Seeding effect is the difference (in km) between the observed maximum top

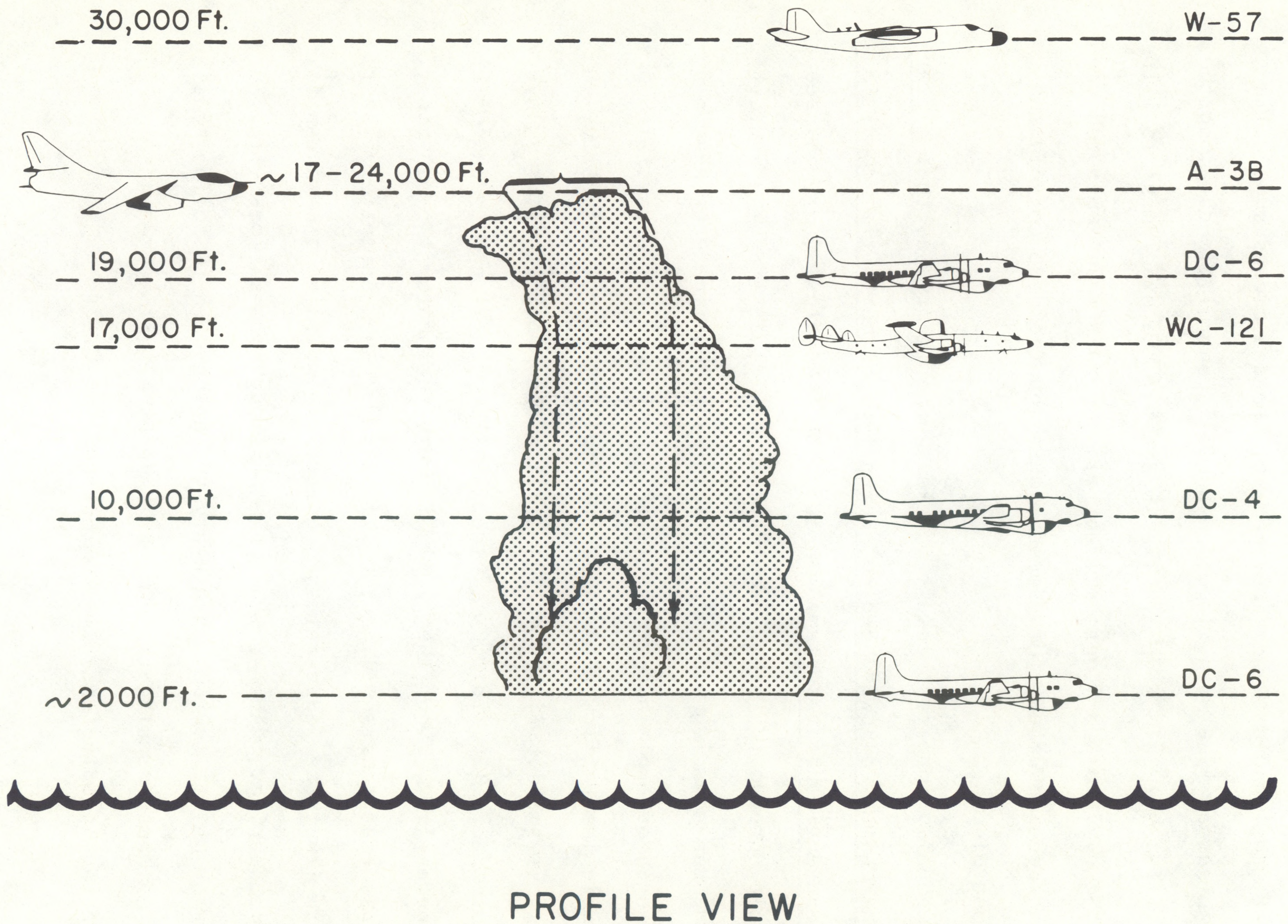


Figure 15. Field design of single cumulus airborne pyrotechnic seeding program. Pyrotechnic generators are dropped at 100-m intervals in bracketed zone. The vertically stacked aircraft are heavily instrumented; they make one cloud penetration prior to seeding and several afterward. The seeding decision is not known to the scientists so that seeded and control clouds are studied identically.

height and the predicted unseeded top height. Seedability is illustrated in terms of the model in figure 16. Figure 17 shows the relationship between seedability and seeding effect for the 1965 seeded and control clouds. If model and data were perfect, all seeded clouds should lie along the diagonal line with slope one and all control clouds along the horizontal line with slope zero. The success of the experiment is illustrated by the 0.97 ($p < 0.5$ percent) correlation coefficient between seedability and seeding effect for seeded clouds and the zero correlation for the controls.

An equally important result of these experiments was that <u>different growth regimes followed seeding, depending on the initial conditions of the cloud-environment system</u>. In addition to explosive growth, seeded clouds could undergo two other growth regimes, illustrated in figures 18 and 19. We can now diagnose which regime will predominate by examining the soundings, as explained by figure 20. On rainy, humid days with a deep unstable layer (fig. 20a) all cloud radii will grow naturally, so seedability is small. Figure 20b illustrates the small stable dry layer in mid-troposphere (20 -26,000 ft) that limits natural growth and offers maximum seedability. When the air is too dry near natural cloud tops, the rising seeded towers will cut off (fig. 20b); when adequate moisture is present with these lapse rates, spectacular explosive growth can follow dynamic seeding. Under dry, stable or drought conditions (fig. 20c) the inversion may be too strong and dry for any growth to follow seeding, or in the extreme, cumulus tops may be suppressed below the -4°C level, eliminating AgI seeding potential altogether.

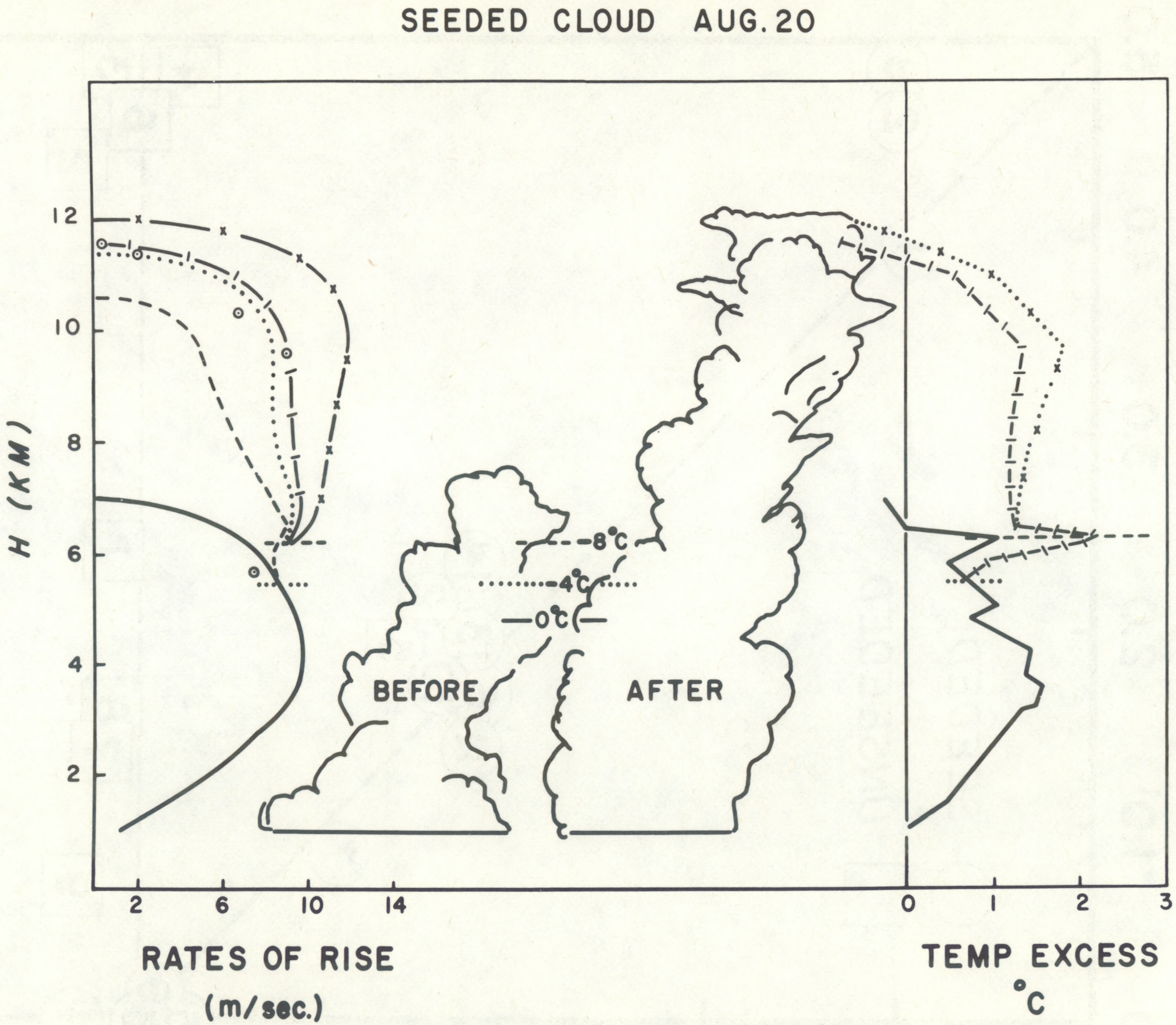


Figure 16. Some of the one-dimensional model results applied to the growing tower of the seeded cloud illustrated in figures 13 and 14. Curves show the rise rate (left) and temperature excess (right) of the tower as it rises through a given level H, the left scale, in km. Unseeded properties are shown by solid lines. Various seeding subroutines (see table 3) are being tested with the upper curves. Circles are the photographically measured rise rates of the actual cloud tower. Note the increase in temperature excess caused by the seeding, which leads to the taller growth of the seeded model cloud.

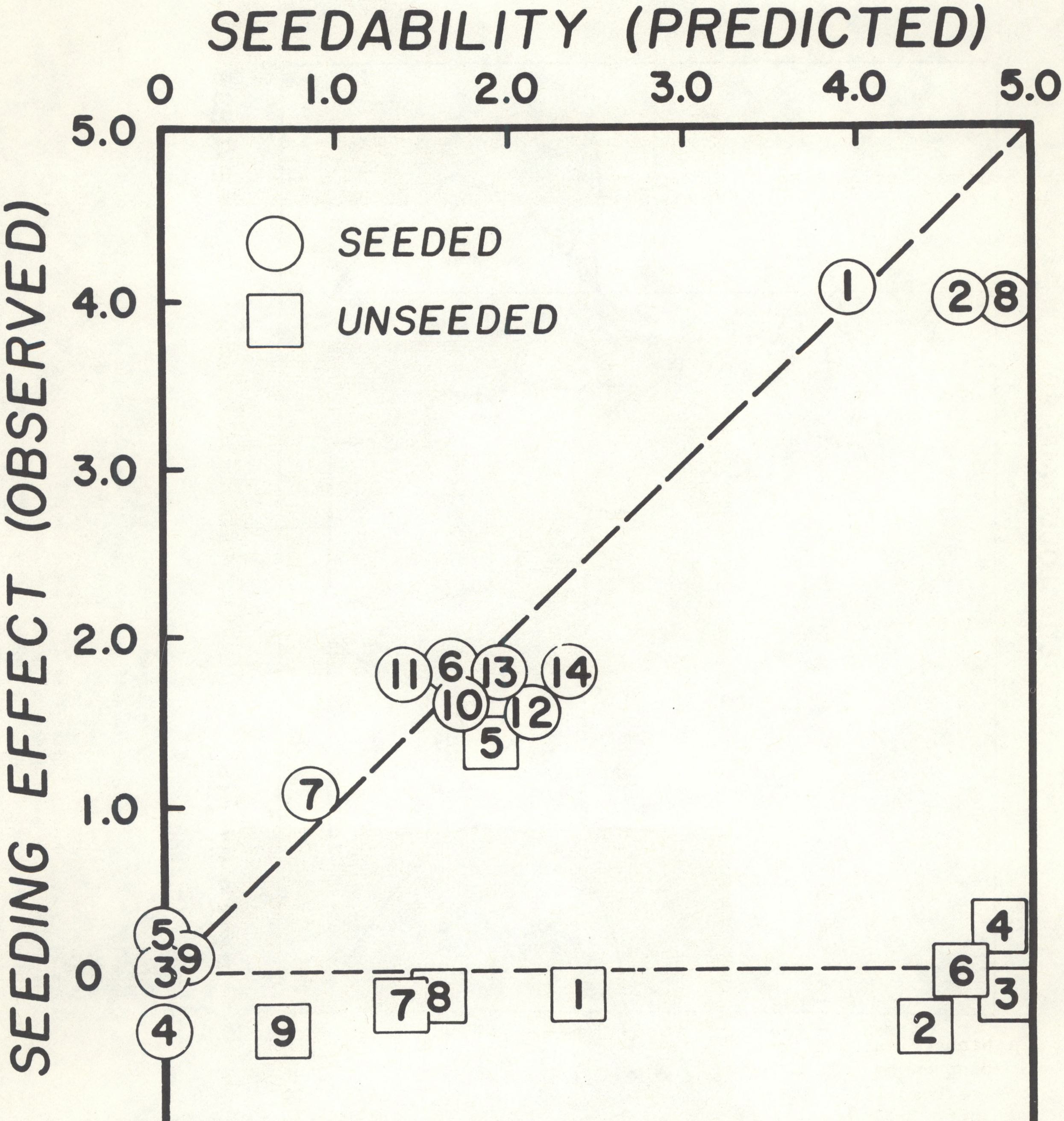
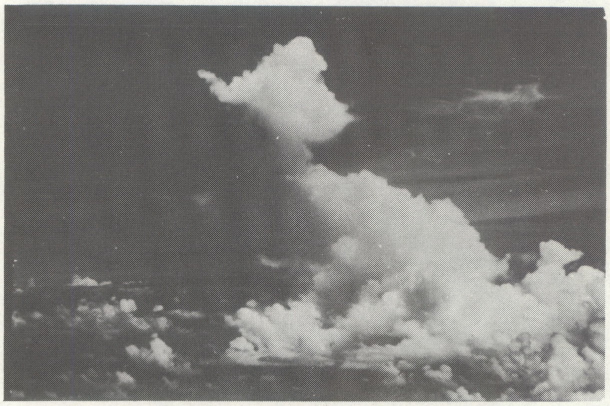


Figure 17. Seedability versus seeding effect for the 14 seeded (circles) and nine control (squares) clouds studied in 1965. Note that seeded clouds lie mainly along straight line with slope one (seeding effect is close to seedability) while control clouds lie mainly along straight horizontal line (showing little or no seeding effect regardless of magnitude of seedability). Units of each axis in km.

a. Cloud at seeding time

A.

b. Ten minutes later



B.

c. Eighteen minutes after seeding, when tower has reached 11 km and cut off.

C.

Figure 18. Photographs illustrating "cut off tower" regime which often follows dynamic seeding of a single cumulus (see fig. 20b).

Figure 19. Typical "no growth" regime. At 12 minutes after seeding, cloud looks unchanged except that the top has glaciated.

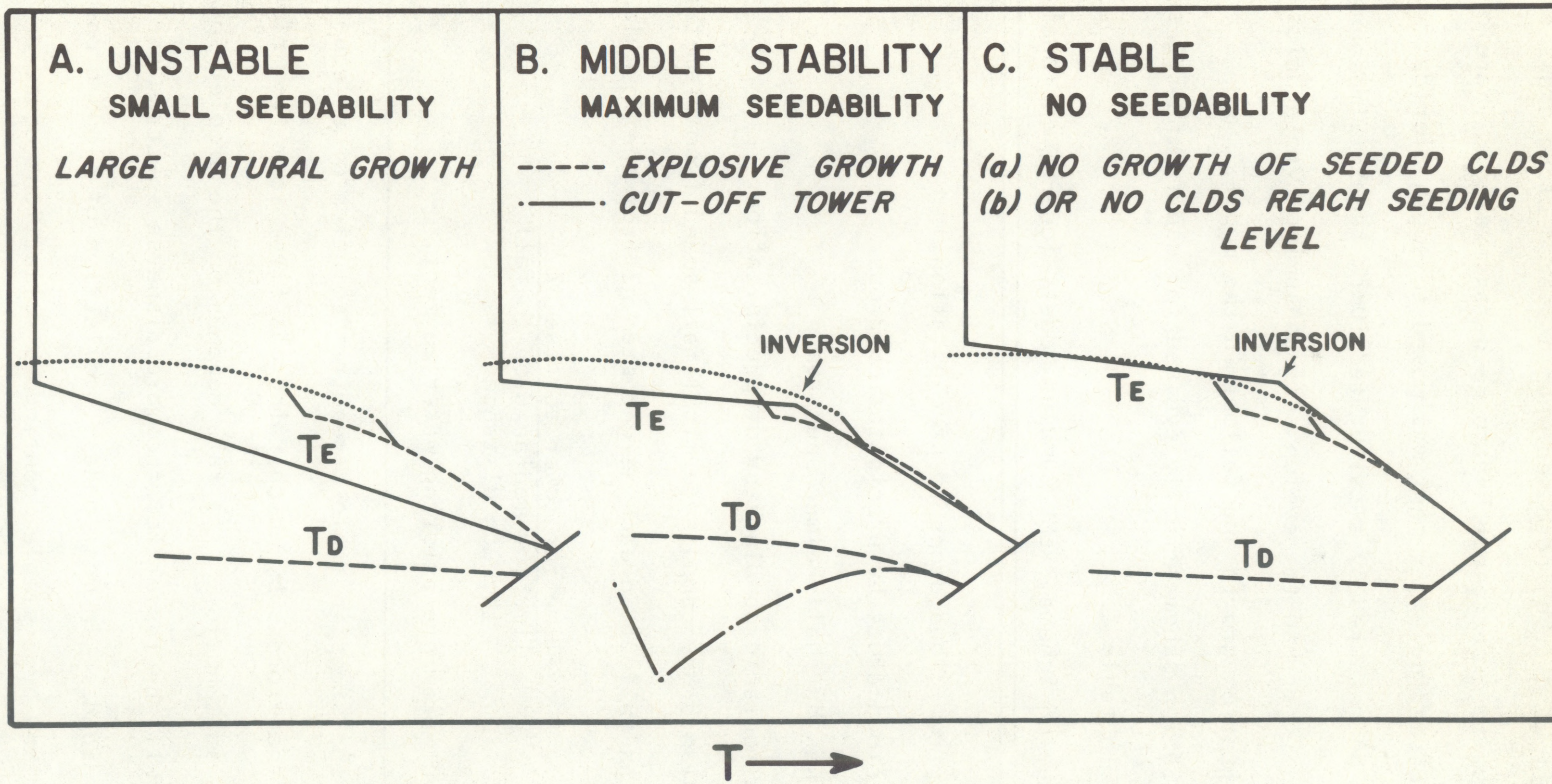


Figure 20. Soundings illustrating the characteristic environments for the four main growth regimes of single cumuli following dynamic seeding. (Courtesy J. McCarthy.) a. Unstable. All cumuli grow whether seeded or not. b. Inversion in mid-levels. Unseeded cloud tops there; increased buoyancy enables seeded tower to grow past inversion and reach unstable region above. T_D dashed, enough moisture for explosive growth. T_D dash-dotted, dry mid-layer, cut off tower regime probable. c. Dry, inversion conditions characteristic of tropical droughts. Either seeded clouds fail to grow following seeding or tower does not reach the -4°C level.

That rainfall should be increased when a seeded cloud grows explosively seems logical to expect, but had to be demonstrated. Therefore, in 1968 the dynamic seeding experiment was moved to south Florida, where the rainfall could be measured by a calibrated 10-cm. radar (Simpson and Woodley, 1971). We first had to develop self-consuming pyrotechnics and to simulate precipitation growth and fallout in the model.

The precipitation scheme finally evolved for use in the EML series models is outlined in table 2.

Table 2. Precipitation Scheme - EML Cumulus Models (one-dimensional)

1. Autoconversion from cloud drops to precipitation.
2. Collection of cloud drops by precipitation drops.
3. Precipitation has Marshall-Palmer spectrum.
4. Compute volume median drop diameter of precipitation.
5. For volume median drop, compute terminal fall speed from diameter.
6. Compute fraction fallout in each height step ΔZ from the formula

$$\text{Fraction Fallout} = \frac{\text{Time for tower to rise } \Delta Z}{\text{Time for median drop to fall through distance R}}$$

7. Subtract fallout from pre-existing water content.

Each of the steps in table 2 requires solution of an equation. Autoconversion is the process by which raindrops first form from cloud drops, or on giant salt nuclei. Its rate depends on the droplet spectrum at cloud base and will be faster for the more disperse spectrum and larger drops in maritime clouds. In most models, collection of cloud drops by raindrops is described by a simple "continuous collection" equation, where the rate of growth of rain water depends on the mass of rain water, the mass of cloud water and a collection efficiency near unity; sophisticated "stochastic collection" equations are being put in the more advanced models.

The Marshall-Palmer precipitation spectrum simply says that the distribution function of raindrop size is linear on semi-logarithmic paper, with drop number in each size category diminishing with size; the slope of the line is determined by the rain water content. The spectrum assumption has verified well by foil impactor samples in active towers. Once the spectrum and water content are specified, the volume median diameter follows; from this the terminal velocity is computed from an empirical equation. It should be emphasized that this model calculates only the precipitation growth in and fallout from a single cumulus tower; no existing cumulus models can yet adequately calculate the total rain reaching the ground from an entire cloud or cloud system.

A precipitation scheme requires a more sophisticated "seeding subroutine." The current EML version is shown in table 3.

Table 3. Seeding Subroutine - EML Cumulus Models (one-dimensional)

Define "slush" region as occurring between -4°C and -8°C in seeded cloud. All listed changes proceed linearly in this interval.

1. Fusion heat release of 60% total liquid water content at -4°C.

2. Proceed from water to ice saturation.

3. Proceed from water to ice hydrometeor spectrum (still Marshall-Palmer with different slope for same mass of water substance).

4. Ice collection efficiency remains one.

5. Reduce terminal velocity of ice precipitation to 70% of that of droplets of same mass.

Fortunately, cloud top heights are insensitive to the assumptions in table 3, since several of the latter are not founded on adequate observations. For example, we know little about ice spectra, collection efficiencies and terminal velocities in tropical clouds; these depend upon whether the ice particles are snowflakes, hail embryos, junk ice fragments or some mixture. The icing levels in large cumuli pose severe hazards to aircraft and further, the instrumentation problems raise extremely formidable obstacles to recording the needed data.

In 1968 and 1970 randomized dynamic seeding experiments on single clouds in south Florida reconfirmed the 1965 results on cloud growth. More important, they showed conclusively that the rainfall from the seeded clouds greatly exceeded that from the controls. The rainfall increase was proportional to seedability.

In this experimental series, the model was run in real-time in advance of launching the experimental aircraft. On days of poor seedability, namely wet conditions with excessive natural growth (fig. 20a) and dry suppressed conditions with no expected seeded growth (fig. 20c), missions were not usually launched, avoiding the "dud" cases of 1965 and saving expensive aircraft time.

Altogether 52 "GO" clouds were obtained, 26 seeded and 26 controls, on 19 operating days. The total rainfall from each cloud was evaluated by radar. The radar calibration was checked against raingage records for each of the two years. The cloud base echoes were planimetered (fig. 21) to get the rain in each ten-minute period in each contour interval and then summed. The average rainfall difference between seeded and

EXAMPLE OF CLOUD BASE ISO-ECHO CONTOURING
CLOUD 6, MAY 16 1968

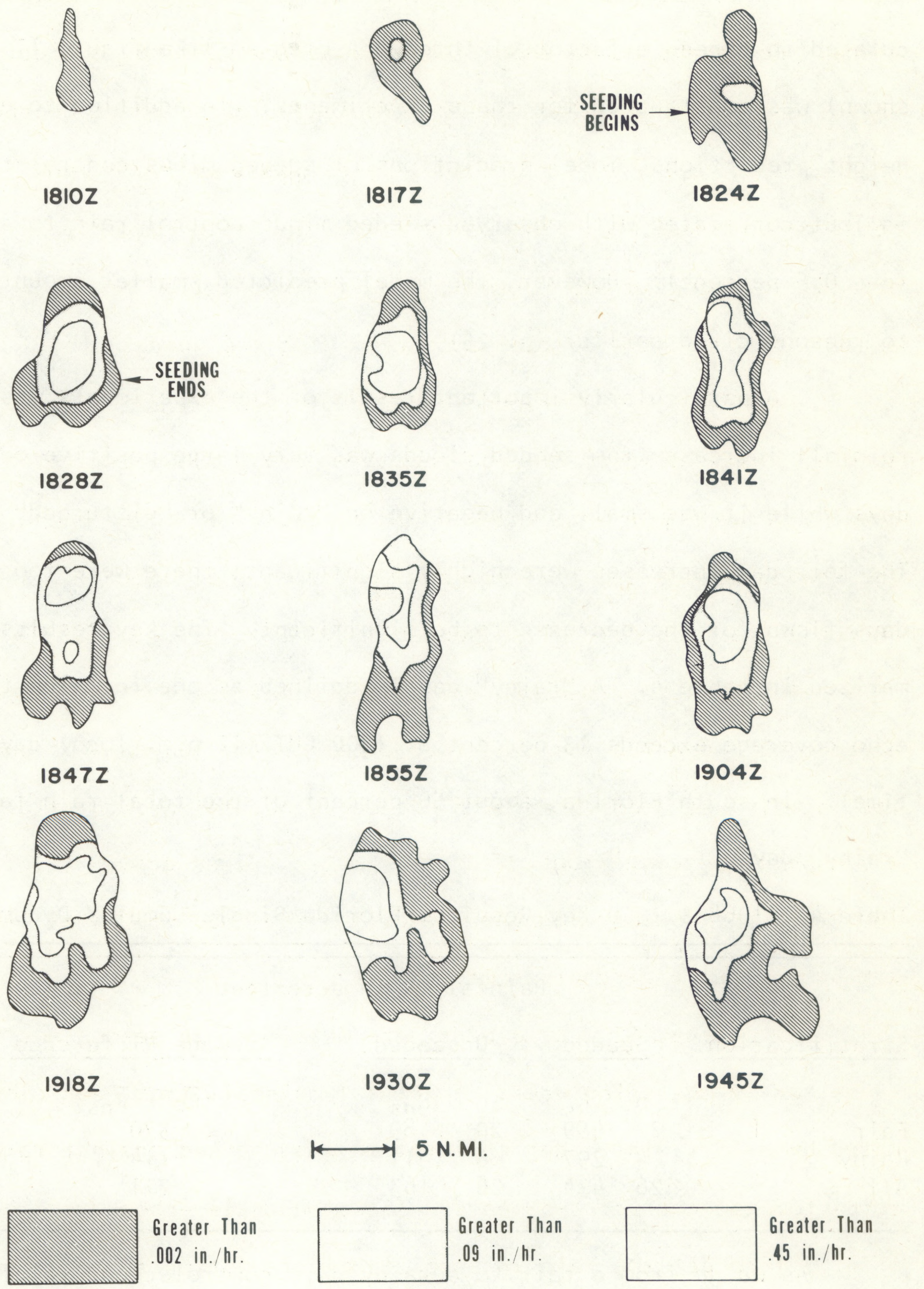


Figure 21. Contoured cloud base echoes showing (below) equivalence of contours to rainfall rate obtained from radar calibration. Area within each contour is measured and summed over time to give rain volume falling from cloud base.

control clouds was 271 acre-feet, significant at better than the five percent level. The single cloud seeding effect on precipitation was calculated to exceed a factor of three. A diagram like figure 17 (not shown) was constructed for these experiments. In addition to excellent height predictions, model predictions of seeded minus control tower rain fallout correlated with observed seeded minus control rain to above 0.9 ($p < 0.5$ percent). However, the model predicted smaller amounts owing to reasons cited earlier (p. 25).

A particularly important result of the experiments was that the rainfall increase from seeded clouds was very large positive on "fair" days while it was small and negative on "rainy" or "disturbed" days. The fair day increases were highly significant; there were too few rainy days flown for the decrease to be significant. The key results are summarized in table 4. A "rainy" day is defined as one in which the radar echo coverage exceeds 13 percent at 1800 GMT (12 p.m. local daylight time). In south Florida, about 50 percent of the total rain falls on "rainy" days.

Table 4. 1968 & 1970 Key Results, Florida Single Cumulus Dynamic Seeding

Rainfall R in acre-feet

Stratification	Seeded		Unseeded		Average Difference
	n	$\overline{R}_s$	n	$\overline{R}_{ns}$	$(\overline{R}_s - \overline{R}_{ns})$
Fair	22	459	20	89	370
Rainy	4	297	6	411	-114
All	26	434	26	163	271

As we go from a fair to a rainy day, control cloud rainfall increases greatly, as expected, but seeded rainfall also decreases. Careful case studies showed smaller horizontal expansion and shorter lifetimes - that is, weaker "explosions" of seeded clouds on rainy "socked in" days. The reason is not yet clearly understood.

Figure 22 shows an empirical relation between seedability and seeded rainfall increase in south Florida. The seedability threshold for rain increase is at about 1.3 km. Owing to a small sample, this graph should not be taken seriously; it shows, however, what can perhaps eventually be done to learn about rain augmentation potential from dynamic seeding for a given area. Maps of seedability as a function of location and season have been made with the one-dimensional models and the library of radiosonde observations for each station. Needed to accompany these maps are radar population studies showing the time distribution of seedable clouds, as done by EML for south Florida.

The silver iodide seeding experiments conducted in the Northern Great Plains by the South Dakota School of Mines and Technology for the U.S. Bureau of Reclamation (Dennis, 1970) have followed a different pattern from those of the Experimental Meteorology Laboratory, but the results of the two series of experiments are consistent if allowance is made for the differences in airmass and cloud characteristics in South Dakota as compared with Florida.

The one-dimensional steady-state cloud model developed at Pennsylvania State University has been adapted for use in the Northern Great Plains experiments by Mr. John Hirsch. Hirsch has modified the handling of the water substances to include solid precipitation (graupel). Precipitation fallout is treated after the methods developed at the EML.

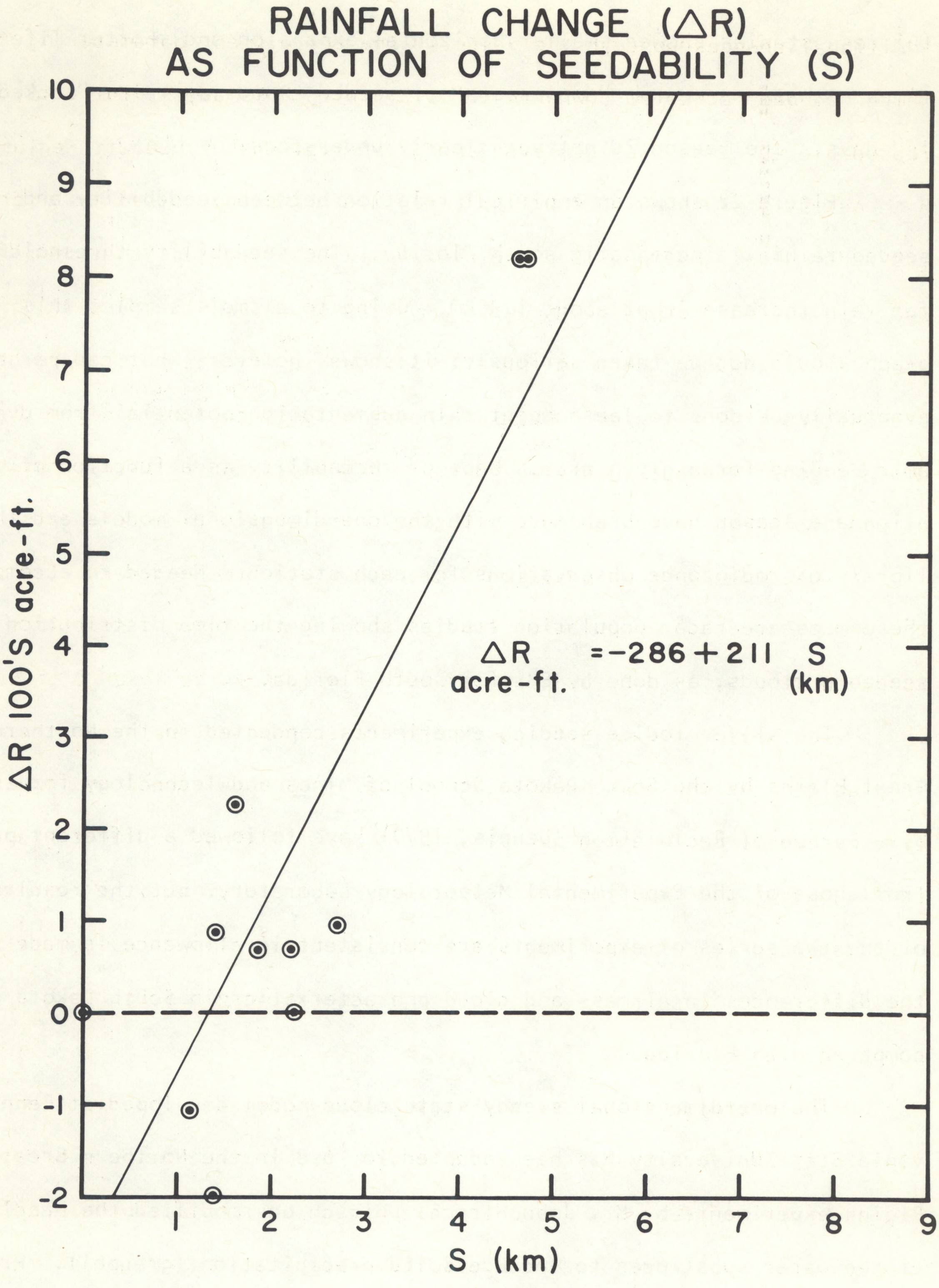


Figure 22. Empirical relation between rainfall increase ΔR (100's acre-feet) and seedability as tentatively established for south Florida. Note the rainfall decreases apparently associated with seedabilities (S, in km) of about 1.3 km or less. Different empirical S-ΔR relationships may be applicable in other areas and/or other weather conditions.

Additional changes concern the value of the entrainment parameter α, which has been adjusted downward to 0.15. With this adjustment to α, reasonable agreement was achieved among observations of updraft radius R_o, updraft profile, and cloud top height. This study, based on aircraft and radar data, re-emphasized the previously observed fact that updraft radii in the Northern Plains can be as small as one-tenth the radii of the visible clouds. Because updraft radii are difficult to measure, the present practice is to use observed shower heights to determine initial updraft radii, rather than vice versa. This approach yields estimates of updraft speeds which compare favorably with aircraft measurements.

The atmosphere on unstable summer days over the Northern Plains does not feature the weak inversions around six or eight km sometimes observed in Florida. Originally it was thought that the absence of such inversions would make it difficult to increase rainfall by dynamic seeding, as it precludes the spectacular explosive growth situations sometimes encountered in the tropics. However, as modeling and radar studies continued, it was realized that increases in cloud height of a few hundred meters are possible and might have significant impact upon total rainfall. It is an interesting point that such increases in cloud height are almost impossible to document. The natural clouds on a given day over western South Dakota may have tops ranging all the way from five to 15 km above sea level, and the detailed observations which would be necessary to predict a cloud top to within 500 m appear prohibitively complex and expensive. Nevertheless, the associated potential rainfall increase is worth pursuing.

The best data on dynamic seeding in the Northern Plains come from a comparison of the silver iodide seed and no-seed cases of Project Cloud Catcher in 1969 and 1970. This was a three-way randomized experiment (no seed, silver iodide, salt) using floating target areas and has already been mentioned in connection with hygroscopic seeding. The hypothesis governing the silver iodide seeding was that it could stimulate cloud development by latent heat release and thus increase rainfall through intensification and/or enlargement of updrafts feeding the cloud. However, silver iodide seeding was conducted at moderate rates of only a few hundred grams per one-hour test case to minimize possible reduction of precipitation efficiency by cloud glaciation at warm temperatures. The objective was to move the region of cloud glaciation, which normally occurs in cumuli of western South Dakota in a non-linear fashion between about -20 and -40°C, down to the -5 to -25°C region. This "light" seeding treatment has been simulated in the Hirsch model and shown to have significant dynamic effects, although not as great as those produced by massive seeding. Most clouds in the area with natural tops seven to ten km above sea level show some additional growth (in the model) as a result of light AgI seeding, with a typical increase in cloud height (seedability) being 500 to 1,000 m. As radar estimates of total rainfall versus maximum observed echo height for shower complexes in the area have shown that the rainfall roughly doubles for every two km increase in height, the predicted increases in cloud height would produce substantial increases in rainfall, provided the natural height to rainfall relationship was maintained. This would require maintaining precipitation efficiency and relationships such as height versus cloud diameter and height versus cloud lifetime. The precipitation processes within the model are being refined in the hope that they will ultimately provide reliable estimates of precipitation efficiency in both seeded and natural clouds.

Analysis of the taped radar data suggests that the silver iodide seed cases of Project Cloud Catcher so far have yielded roughly 40 percent more rainfall per test case than the no-seed cases. While the 40 percent apparent increase in rainfall is not yet statistically significant if only the radar rainfall estimates are considered, confidence in the correctness of the seeding treatment is increased by a study which shows that first echoes in clouds seeded with silver iodide tend to appear near the -8°C level and significantly closer to cloud base than in unseeded clouds.

It is tempting to ascribe the apparent rainfall increases to increases in cloud height. While the best indication of the 40 percent increase comes from a covariance analysis utilizing maximum observed radar echo height as a predictor, which would suggest that the rainfall increase is related to an increase in precipitation efficiency rather than cloud height, most of the test cases consist of a succession of cloud towers and the seeding treatment is aimed at introducing silver iodide into new towers as they appear around existing showers. It may be that the dynamic effects are occurring in these cloud towers, which increase in size and total rainfall production without necessarily increasing the height of the tallest cloud occurring during the one-hour test case. In this connection, the existence of multiple cells within most South Dakota thunderstorms is relevant. However, there are alternative explanations for the apparent rainfall increases so that conclusions regarding the mechanisms responsible for them are only tentative.

Dynamic seeding experiments on single cumuli have been executed in Pennsylvania, Arizona, Australia and Africa, with similar results to those in Florida. These experiments in cumulus modification have been both unusual and satisfying because it has been possible to achieve significant positive results on two variables (vertical growth and precipitation) with a relatively small sample of cases. The experimentation has also been productive of advances in understanding and modelling cumulus processes. But what of the practical usefulness of this work? Can we hope, for example, to apply it to water management economically? Can it be applied in other areas of weather modification than water management?

In considering the rain augmentation problem, suppose that by flying two aircraft in tandem we could seed ten cumulus clouds in a daily operation (a reasonable goal). If the figures in table 4 can be applied, we might expect to gain 2700 acre-feet of water. At the rate of $50 per acre-foot[16] this would be a benefit of $135,000. If the aircraft were well instrumented and flew ten hours all told at $600 per hour, and if AgI pyrotechnics are expended at $14 each, the benefit-to-cost ratio would exceed 18. Could we reasonably expect to find ten isolated seedable cumuli in a day over a needy watershed? What of possible side

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[16]The approximate cost of municipal water in Florida

effects? And most important of all, will there be cloud interactions, will these help or hurt us, or does the answer depend on both the context and the experimental approach? These questions are examined in sections 11 and 13.

11. CUMULONIMBUS MERGERS, DYNAMIC SEEDING OF MANY CUMULI OVER A TARGET AREA AND APPLICATIONS

From Project Cloud Catcher in South Dakota and from natural cloud studies in Florida, it was discovered that merged systems or "mergers" produced much more rainfall, by an order of magnitude, than the sum of their component clouds (figs. 23-24). Radar measurements showed that a single merger may produce 5000-50,000 acre-feet of water, compared to 200-2000 from the vigorous isolated thunderstorm.

Can mergers be induced by dynamic seeding? If so, can multiple cloud dynamic seeding lead to rain increases over sizeable areas without adverse side effects? In taking the step from single to multiple cloud experiments over whole areas, the scientific problems become more difficult by at least a factor of ten. As we saw in section 6, natural rain variations are so great that seeding effects must be large to be distinguishable by conventional statistics even with 100-200 experimental cases. Cloud interactions and meso-scale motions (ten to 100 km in size) allow greater natural variations and may also permit seeding effects to propagate in space and time.

Cloud group modelling is in its early infancy. At EML, a three-dimensional model with the shape of south Florida has been devised which predicts areas favorable for convection arising from interaction of the

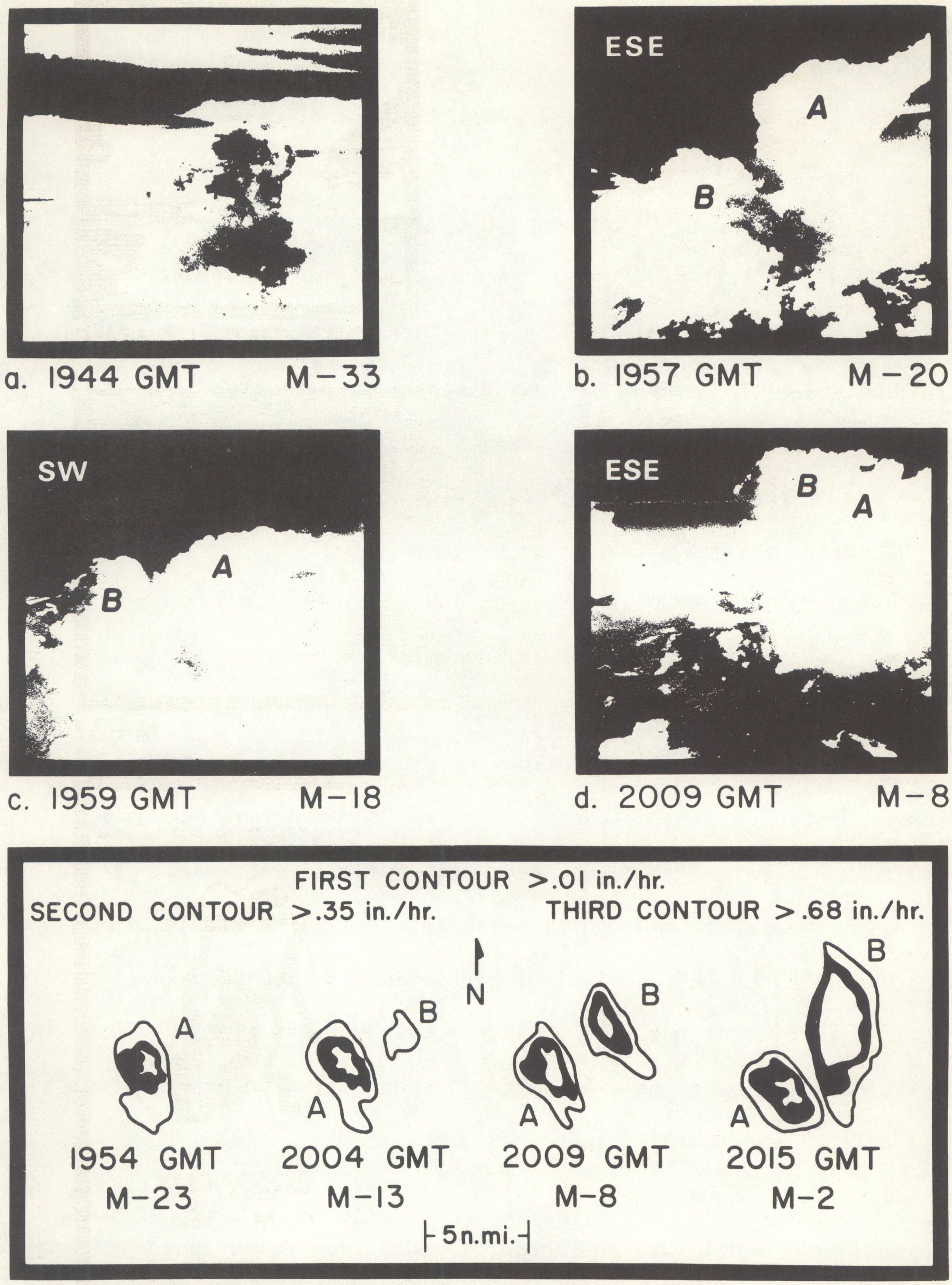

Figure 23a. Photographic and radar documentation of a merger. Cloud A is seeded and B is not. Top -- photographs before merger. Camera direction in upper left. Below -- Radar echoes before merger. M is time of merger. Times in minutes relative to merger time.

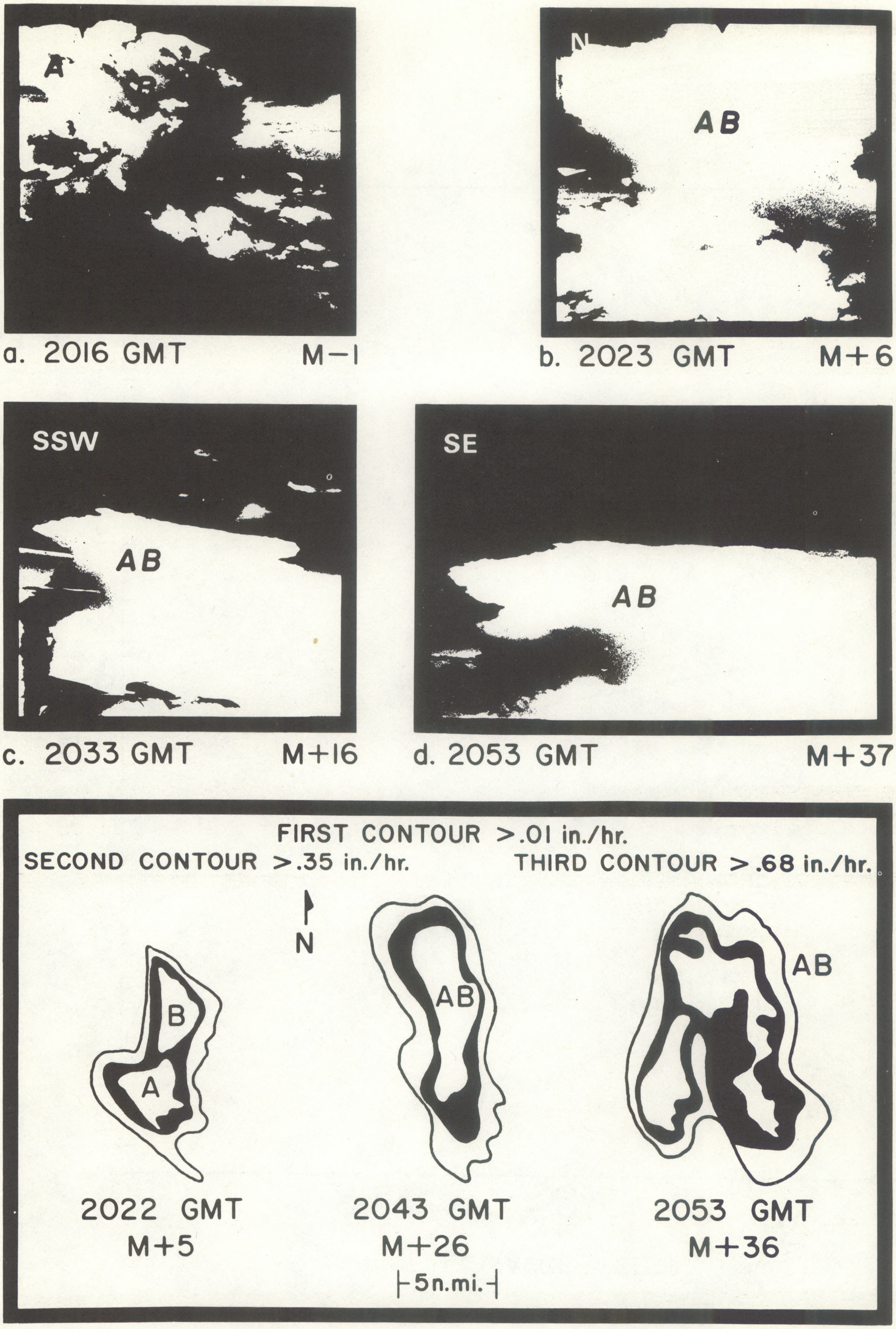

Figure 23b. Photographic and radar documentation of a merger. Cloud A is seeded and B is not. Top -- photographs after merger. Note giant system at M+37. Below -- radar echoes after merger.

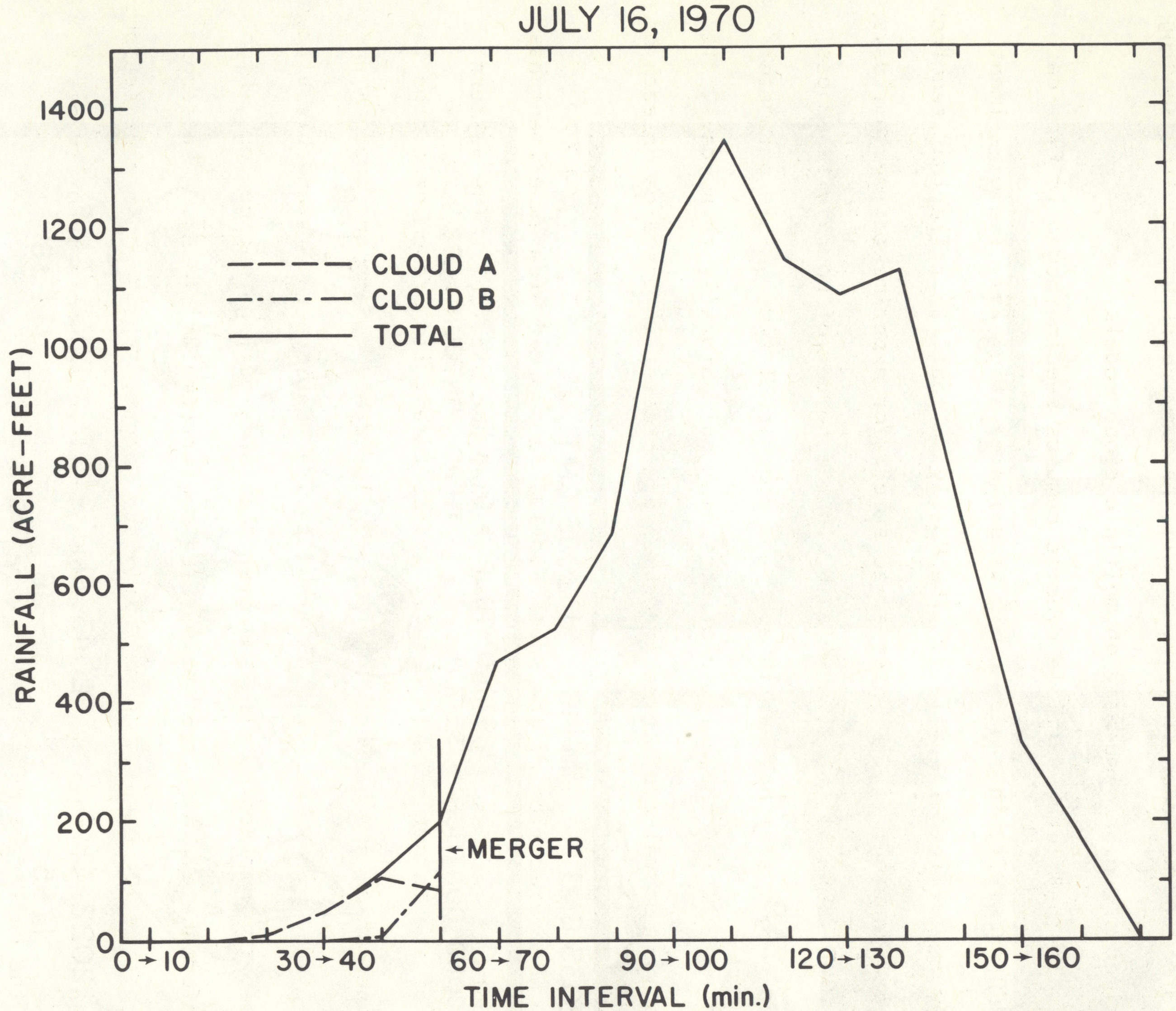

Figure 24. Precipitation history of cumulonimbus merger shown in figure 23. This system produced about 9000 acre-feet of rain in its lifetime. Rainfall is plotted against time. (10-minute intervals relative to seeding cloud A.)

heated boundary layer over the peninsula with the larger-scale flow. Similar to the early stages of modelling single cumuli (figs. 7 and 8), the model is "dry" so far. While the initial steps toward introducing moisture will be taken in 1972, it will be many years before area seeding experiments can be simulated on multiple cloud models.

In the field, multiple dynamic cumulus seeding began in Florida in 1970 and 1971, in a 4000 n mi^2 target area (fig. 25). The experiment design is outlined in table 5. The "daily suitability criterion" requires some explanation. It is intended to select for experimentation fair days with high seedability S (in km). N_e is the number of hours with echoes in the target area between 10 a.m. and noon local time. This parameter is introduced for the purpose of screening out naturally rainy days. It has a maximum value of three if echoes are present in the area on each of the three hours.

The execution of the south Florida randomized area experiment has encountered serious obstacles, some of them sociological. The western half of the target area is heavily agricultural; its predominant crop is tomatoes which are harvested during April and May. Rain on tomatoes during harvest ruins the fruit, so that the farmers are understandably bitterly opposed to any seeding programs over that area during that period, which is unfortunately also the optimum season for cumulus clouds. The second best period for cumulus, namely July and August, is also hurricane season, during which the NOAA seeding aircraft are involved on a priority basis with the hurricane modification experiments.

Owing to these difficulties, only 13 "GO" days have been obtained

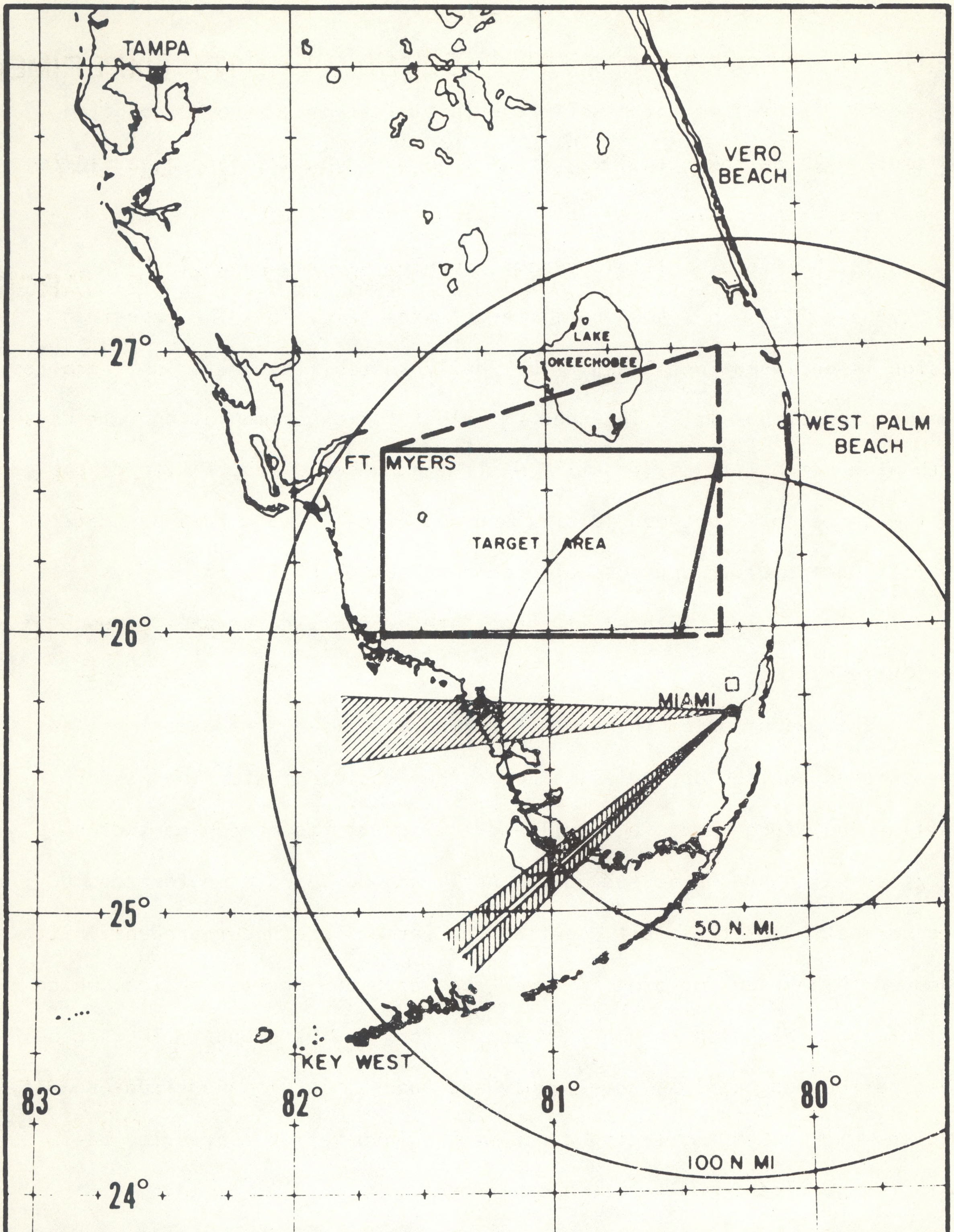

Figure 25. EML area in south Florida for randomized multiple cumulus seeding experiments. 1970 area solid outline; 1971 area dashed outline. Shaded regions are "blind cones" of the University of Miami 10-cm calibrated radar.

Table 5.

DESIGN OF FLORIDA MULTIPLE CLOUD SEEDING EXPERIMENT

FIXED TARGET AREA — RANDOMIZATION BY DAY

↓

CONTINUOUS UM/10-cm RADAR SURVEILLANCE OF TARGET

↓

DAILY SUITABILITY CRITERION } $S-N_e \geq 1.00$? NO → NO OPERATIONS

YES

↓

TARGET SUITABILITY } SUITABLE CLOUDS IN TARGET ? NO → RETURN TO BASE

YES

↓

RANDOMIZER DETERMINES SEEDING DECISION

↓

CARRYOUT SEEDING INSTRUCTION

↓

ACCEPTABILITY CRITERION } 6 SEEDED CLOUDS OR EXPENDITURE OF 60 FLARES ? NO → NO AREA ANALYSIS

YES

↓

DO AREA ANALYSIS

in the randomized area experiment in 1970 and 1971, seven seed cases and six controls. Since with this limited sample there is no immediate hope of evaluating the seeding effect over the whole target area, an intermediate goal has been established, namely first evaluating the seeding on "floating targets." The floating targets consist of all cloud echoes that have undergone seeding penetrations[17] and all those echoes merging with them. The total target rainfall thus consists of that from the floating targets and that from the unmodified clouds that also happens to be in the target area.

Results of the first two experimental years are shown in table 6.

The average floating target rainfall for the seven seeded cases is 2.6×10^4 acre-foot, while it is 0.67×10^4 acre-foot for the five fair control cases, which is smaller by nearly a factor of four. Is this difference significant? With conventional statistics (Mann-Whitney-Wilcoxon test) the difference is significant at the ten percent level using a one-tailed test; this result says that we do not have a large enough sample to conclude safely that the seeded-control difference is not due to chance. Using Bayesian statistics and one dangerous assumption, we can estimate the floating target seeding effect and its significance. With these data only, the probability that it exceeds zero is 98 percent, the probability that it exceeds two is 66 percent, while the probability that it exceeds 3.3 is about 50 percent. The dangerous assumption lies in asserting that we have accurately specified the unmodified floating tar-

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[17]Whether it was actually a seeded or control day was unknown to the scientists and aircraft flights were conducted identically (and the seeding button pushed) on both types of occasions.

Table 6. Dynamic Cumulus Seeding in Florida - Randomized Area Experiment. 1970-71 Floating Target Analysis

Date	Action	FT Rainfall acre-ft $\times 10^4$	Rank	FT Depth in.	FT Mergers
1970					
6/29	S	0.16	12	1.29	3
6/30*	NS	3.08	--	2.72	9
7/2	S	1.11	5	1.28	6
7/7	NS	0.78	8	1.04	6
7/8	S	8.96	1	2.49	18
7/8	S	4.56	2	4.39	12
1971**					
6/16	S	0.23	11	1.66	1
7/1	NS	0.26	10	1.02	6
7/12	NS	0.35	9	1.31	4
7/13	S	1.58	4	2.49	11
7/14	S	1.66	3	1.23	7
7/15	NS	0.96	7	1.68	8
7/16	NS	1.00	6	2.07	8

* Rainy day, discarded from sample

** Adjusted values of rainfall. Radar-raingage comparisons made in both years indicated that in 1971 the radar rainfall was underestimated by 1.75 relative to 1970. Ranks are not changed by the adjustment.

get rainfall distribution using just the five control cases (and some other knowledge gained from single cloud studies). The next step in this experiment must be an accurate determination of these natural fluctuations. Then, unless our present assumptions are grossly in error, about a dozen more seeded cases should be adequate to demonstrate conclusively that the seeding effect for floating targets is positive, and about 25 cases to show that it exceeds a factor of two. The last column in table 5 offers further encouragement, in that the correlation between number of mergers experienced by the floating targets and their rain production is 0.9. The demonstration of this relation supports the physical hypothesis behind the experiment, namely that dynamic seeding can promote merger and thereby enhance cumulus rainfall, as does a high and significant positive correlation (0.74) between floating and total target rainfall.

Regarding total target rainfall, we encounter a more sticky ball of wax. The specter should be clearly raised that we could find large positive effects in floating target areas and simultaneously find the effects in a larger fixed target area incorporating the floating ones to be undetectable or even negative.

The area experiments of the South Dakota School of Mines and Technology have been underway for several years. The Rapid Project from 1966 to 1968 utilized a randomized crossover design with north-seed and south-seed days on target areas of 700 sq mi each. The days were stratified in advance in accordance with the synoptic situation, with the principal distinction being between shower days and storm days. Shower days were characterized by a moist unstable atmosphere, but no "trigger." Storm days were characterized by similar conditions plus a trigger (positive vorticity advection at 500 mb), which generally led to widespread convective activity, sometimes organized in squall lines.

Seeding was conducted principally from aircraft with generators releasing roughly 300 gm AgI per hour. The project design differed from the Arizona and Whitetop experiments in that seeding was conducted only when supercooled clouds were present and then in updraft areas below cloud base.

The Rapid Project is apparently the only one to date on convective clouds yielding evidence of increases in average rainfall under any predetermined set of conditions throughout a designated target area. Quite good evidence for such increases was obtained from the shower days, with suggestions that the rainfall may have been increased by a factor of two or more on such days (table 7). Rainfall was quite scarce on shower days and calculations show that the apparent increase was equivalent to the production of a single shower of a few hundred acre-feet over the seeded target area on each shower day. At some stations the statistical difference between north-seed and south-seed days, as evaluated by a rank test, proved significant at the five percent level.

The results on storm days were mixed and pose interesting questions. On storm days with northwesterly winds aloft the data suggested a decrease in total rainfall (table 7). On storm days with southwesterly winds the data suggested rainfall decreases in the areas where the seeding was accomplished and possibly even upwind of such areas, but substantial increases in rainfall about 20 miles downwind of the silver iodide release

Table 7. Average rainfall per gage per test case (in mm) and seed/no-seed ratios in target area for all days of given type on the Rapid Project

	SW Flow	NW Flow
SHOWER DAYS		
North Area, Seed N	0.99	0.92
Seed S	0.69	0.64
Seed/No-seed ratio	1.4	1.4
South Area, Seed S	1.8	1.1
Seed N	0.30	0.10
Seed/No-seed ratio	6.0	11
STORM DAYS		
North Area, Seed N	2.2	0.89
Seed S	2.8	4.3
Seed/No-seed ratio	0.78	0.21
South Area, Seed S	2.4	1.4
Seed N	3.0	3.2
Seed/No-seed ratio	0.80	0.44

areas. There was also evidence that hail was suppressed, but throughout the surrounding region rather than in the seed target itself. Concerning these paradoxes the experimenters reason, "Effects in the unseeded target would not require physical transport of the seeding agent from one target area to the other. A decrease could arise for example, from widespread subsidence related to the intensification of convection in the seeded target area." Dennis and Koscielski (1969) have coined the term "dynamic contamination" to cover these and other possibly even more subtle effects of seeding upon the surrounding regions not necessarily reached by the seeding agent.

A further two year randomized experiment over a larger target area of 5300 sq mi in northwestern South Dakota has not resolved the various possibilities. In that project the target area and two smaller control areas to the south and west were instrumented with about 100 rain gages. Randomization was imposed by reserving two days of every eight-day time block during the two summers as no-seed days. The radar and rainfall data collected were compatible with any or all of the following postulated effects:

1) An increase in cloud heights in the target area.

2) A shift toward lighter rains in the target area achieved either by initiation of light showers or by suppression of heavy rainfalls, or both.

3) A decrease in rainfall in the control areas, due mainly to a decrease in the number of rainfall events.

Additional analyses utilizing hourly rainfall observations at 130 stations in South Dakota, North Dakota, and eastern Montana have shown that the area of rainfall deficiency on seed days in the target and control areas was actually part of a large area of deficiency extending over much of the three states and, furthermore, that the rainfall deficiency on seed days existed from 0200 local time onward, or for six to ten hours before any seeding was undertaken. This is another example of an uncontrolled background effect dominating the outcome of a randomized experiment. However, the failure of the evidence for a rainfall suppression effect to stand up under close scrutiny in this case does not mean that the possibility of such an effect can henceforth be ignored.

This and another type of dynamic contamination has been observed by EML scientists in Florida. The second type occurs when a huge cumulonimbus anvil, from a seeded or natural cloud, extends over the target area. A single anvil may cover thousands of square miles and its shadow completely wipes out the cumulus activity below by cutting off solar radiation.

The possibility of "dynamic contamination" is of utmost importance in weather modification. Firstly, it renders the randomized crossover target procedure suspect and possibly untenable, since even clouds over a control area upwind of a seeded area could be dynamically or thermally influenced by the seeding. Secondly, it raises the specter of extensive downwind, large-scale and persistent effects of seeding, which are considered in section 13.

With these vital questions unanswered, disastrous and damaging droughts have forced dynamic seeding into attempted practical applications prior to the establishment of the required sound scientific foundations, posing serious moral dilemmas to the scientists involved.

In the winter and spring of 1971, south Florida experienced a record drought. By April 1, the water deficit exceeded three million acre-feet. Drinking supplies for the coastal region were threatened by salt water intrusion, while raging grass and muck fires in the Everglades compounded the already severe damage to plant and animal wildlife. At the request of the state government, NOAA-EML undertook a dynamic seeding program from April 1 - May 31 in two target areas, including the largest possible fraction of the important watersheds consistent with avoiding most of the tomato harvest.

Additional precautions were undertaken to avoid potential severe weather side effects of cumulus invigoration and merger. In Florida, virtually all severe weather such as squalls, lightning, hail and tornadoes are associated with cumulonimbus mergers. Severe weather is increasingly likely with increasing instability and vertical wind shear. Criteria were evolved which required removing seeding areas farther upwind of populated areas as these parameters increased, halting seeding altogether if actual warnings were likely to be issued by the Weather Services.

Important scientific and practical benefits were apparently gained from the program, although the latter cannot be confirmed without resolution of the seeding effect in the randomized area experiments. Firstly, within the 61-day operational period during a prevailing severe drought, 21 days presented seedable clouds in the target area. Due to aircraft limitations, only 14 days were actually seeded, which, however, exceeded the anticipated number. Secondly, frontal cumuli associated with dissipated fronts were found to be highly seedable. One such merger alone produced in excess of 50,000 acre-feet, or more than 25 percent of the seeded cloud rain for the whole experiment. Since most cumuli in Florida's dry periods and seasons are associated with old cold fronts, this result is very encouraging, with the reservation that these situations are also those most prone to severe weather.

Rainfall from all seeded clouds in the program was assessed (from radar and raingage records) to be more than 180,000 acre-feet. Using floating target, single cloud, modelling and other criteria, a conservative estimate of the rain added by seeding was 100,000 acre-feet. Although this amount is a real "drop in the bucket" compared to the several million acre-feet shortage, there is little doubt that the $165,000 program had a benefit-to-cost ratio considerably exceeding ten. The factor would be 32 if $50 per acre-foot (municipal water price) is used for the value of the water produced, which is admittedly a poor measure.

Even if much of the seeded rain evaporates without direct usage by man or the ecology, any rain at all can be of immeasurable value in breaking the vicious self-aggravating cycle of a tropical drought. Firstly, the rain washes the excessive number of cloud condensation nuclei out of the air and dampens the ground so that fewer particles go aloft to divide the precipitable water into such a large number of small drops that none can fall as rain. EML studies show that burned Everglades vegetation particles serve as very active CCN's. Secondly, cooling the ground and wetting the lowest air works against another major drought-maintaining factor, namely the 3000-5000 ft rise in cloud base from coastal to inland Florida which sets in as the normal swamps become dry. Model calculations show that raising the cumulus base is a most effective way of reducing their rain potential. Thus, even evaporating seeded rain can result in increased rain production from later natural clouds. Finally, in 1971 rain from seeded clouds extinguished more than 26 Everglades fires, on the one occasion when a seeded merger delivered 50,000 acre-feet.

Despite the uncertainties related to dynamic contamination and other unknowns, the state of South Dakota has launched an operational program of weather modification to increase rainfall and suppress hail from summer convective clouds. Impetus for the program has come from the research results obtained at the South Dakota School of Mines and Technology and from a target-control analysis of about 25 project seasons of commercial seeding programs in the state. Most of these projects were conducted with aircraft releasing silver iodide in updraft regions below cloud base. The target-control analysis has suggested an overall positive effect of roughly ten percent of the expected rainfall over the 25 project seasons. Results for individual seasons vary considerably and results for the individual months range from "decreases" of perhaps 50 percent to "increases" of as much as 100 percent. These results are not surprising in view of the large natural variability of rainfall in the region.

The South Dakota state program is operating in only two or three project areas in 1972, but is expected to spread to cover most of the state within one or two years. Seeding will be conducted from aircraft burning pyrotechnic devices and will be guided from radar equipped field offices. Weather forecasts and cloud model predictions to guide seeding attempts will be provided from the School of Mines in Rapid City, which has access to a time-share computer network operated by the U. S. Bureau of Reclamation as part of Project Skywater. Associated economic and sociological studies will be undertaken by university groups throughout the Northern Great Plains region, while experimental seeding programs under Project Skywater are expected to continue in the Rapid City area and in western North Dakota.

To combat droughts in the Philippine Islands, Okinawa and Texas, airborne dynamic seeding programs have been undertaken. The experimenters claim success mainly based on visual observations. In Africa, several water management oriented dynamic seeding programs are under way. Some of these are beginning by constructing the optimum scientific foundations, namely randomized single cloud experiments, closely based on radar measurements and modelling.

12. ARE THERE OTHER WAYS THAN SEEDING TO MODIFY CUMULI?

So far all cumulus modification approaches discussed in this article have involved "seeding" with some sort of small particles. Seeding with Dry Ice or silver iodide is effective only on supercooled clouds, which in tropical air masses means cumuli reaching at least 14,000 ft. The main coalescence seeding methods mentioned, whether hygroscopic or water spray, act to increase precipitation efficiency. As we saw, "warm" clouds which do not naturally reach above the freezing level usually do not yield very much water, even if 100 percent efficient. Moreover, all the aforementioned modification methods require pre-existing cumuli to be modified. We want now to inquire whether there may be cumulus modification methods involving techniques other than seeding. In particular, it would be valuable to know whether "warm" cumuli might be dynamically invigorated, whether existing cumuli could be artificially dissipated and whether and how man might create cumuli out of a clear sky and if he could do this, whether he could induce the formation of precipitating cumuli.

At the outset it is necessary to point out that all other modification approaches than seeding are at most in their early infancy, few have been attempted for operational or practical purposes and, in fact, none have reached the scientific stage of the successful or conclusive randomized experiment. Some have not even been attempted in the field and so far exist only as numerical model calculations or as promising ideas.

The most advanced of these methods involves altering the radiative properties of cumuli; so far carbon black has been the substance used. Some theoretical and experimental work was done developing this approach in the 1950's, which was dropped in a promising stage. The carbon particles were dispersed from an aircraft into its exhaust wake. Typically, about five pounds of material, particle size of about 1-0.1 μm diameter, if totally de-agglommerated, gives a concentration of 100-100,000 particles per m^3 in 2.2 km^3 of air. Calculations based on the radiative properties of the material, the sun, the cloud and the air mass indicate that the cloudy air would be warmed 0.2-0.4°C per minute while losing 0.03-0.1 gm m^{-3} of liquid water in the same time interval with an average one percent solar absorption per m^3.

Carbon black experiments were conducted both to dissipate cumuli and to invigorate them. In the dissipation experiments, the carbon black is dispersed on the edges and outer surface of the cloud. An exploratory dissipation experiment was run on eight warm cumuli in Georgia in 1958 by a group at the Naval Research Laboratory (NRL) (maximum top height 12,000 ft). All eight clouds were reported to have dissipated in five to 24 minutes after treatment with one and a half to six pounds of carbon black. The experimenters brought out the following points:

1) All except one of the treated clouds were vigorously growing when treated.

2) There was some indication that increasing the amount of carbon increases the dissipation rate.

3) Flight through some similar cumuli without dropping carbon produced no noticeable results; the mechanical action and exhaust wake of the aircraft above had no apparent effect.

4) There was some indication of grayish virga forming below the treated clouds.

Clearly, cumuli this size usually dissipate naturally in five to 24 minutes so that no firm conclusions could be drawn without a randomized experiment. A sequel non-randomized dissipation experiment in New England and the tropics (by another group) gave less apparently successful results; many of those clouds treated were stratocumulus.

When carbon black is used in an attempt to invigorate cumuli, it is released in the main updraft. The NRL group conducted a randomized carbon black experiment for invigoration in the Bahamas in the late 1950's. The material was introduced either one-third or two-thirds of the way from cloud base to top. Calculations for these experiments showed that the carbon black heating effect should be as great well within the cloud as on its periphery, owing to multiple reflection of the incoming solar energy by the droplets. A basic hypothesis of the experiment was that the added buoyancy from the heating would accelerate the condensation process enough or more than enough to compensate the droplet evaporation due to warming.

Although the cloud sample obtained was too small for definite conclusions, the experimenters were encouraged by their visual observations of increased growth and precipitation in many of the treated cases. Further experiments, also inconclusive, were conducted by NRL in Louisiana with apparently greater success on continental than maritime cumuli. With the progress in cumulus modelling in the past decade, these experiments could profitably be resumed, perhaps using now-available dyes which have the desired radiative properties, but which are less messy and less polluting than carbon black.

As part of the experimental series described above, carbon black was dispersed near the natural condensation level in clear air, with the purpose of inducing cumulus formation. On four out of five occasions using one and a half pounds of dry powder, a small cumulus formed. On the one unsuccessful try, the carbon black package may not have opened. A sixth attempt used six pounds of carbon black in five gallons of water. In this case, a one-mile line of cumuli formed along the track, 3000 ft in thickness. Although critics concluded that the five gallons of water themselves, finely dispersed in saturated air, would result in a visible cloud, it seems unlikely that this factor alone could build the cloud thickness to 3000 ft.

Small cumulus clouds have also been successfully produced in clear air by the introduction of salt particles. The physics behind this approach is that due to its hygroscopicity, water vapor condenses on salt particles at relative humidities of only 80 to 90 percent. Considerable theoretical work and thermodynamic calculations preceded the experiments illustrated in figure 26, undertaken over the ocean near Hawaii. Dry particles of sodium chloride, in the size range 0.5 to 20 μm in diameter, were dropped from a light aircraft into moist air at altitudes of 400-500 m, just below natural cloud base level, but far away from any pre-existing clouds. Discharge rates from each 400 kg load were adjusted to produce salt concentrations in the air of 40 mg kg^{-1}, with the purpose of releasing the latent heat in about 10^7 kg of air as a result of condensation of water vapor on the salt. Forty-one inexpensive experiments (about $250 each) in the air with a relative humidity of 80 to 90 percent showed that the salt-laden air was warmer than ambient by an average of 0.35°C. Results suggested that unsaturated air, heated internally in this manner, may under certain conditions rise to the lifting condensation level and become visible as a small cumulus. From the salt concentration and size spectrum it was calculated that these artificial clouds would contain about 300 droplets per cm^3 and hence would be less likely to form precipitation than their normal marine counterparts, even if they were able to grow.

While initiation of small cumuli by salt and/or carbon black can be of great value scientifically in studying convective processes, these cloudlets are most likely to begin and end their lives as small, "single-bubble" puffs, of extremely limited vertical development, unless the environment were on such marginal equilibrium that one warm puff could trigger a sustained convective plume.

Figure 26. Small cloudlets produced by dumping powdered salt from aircraft near cloud base level over the ocean off Hawaii. (Courtesy A. H. Woodcock.)

Deeper, more sustained cumuli have been created in clear air, at very much greater cost. Nearly every visitor to the tropics has seen a medium-sized, grayish-brown cumulus topping the smoke from a sugar cane fire. This principle has been utilzed for deliberate weather modification in the famous "météotron" by Dessens, father and son. Their observations of African brush fire clouds indicated that, for a good-sized cumulus to form, the energy released must be comparable to that received from the sun, namely of the order of 10^6 kilowatts per square kilometer. The energy must be immediately available and ready for application when the meteorological situation favors the triggering of convection, such as that in the humid equatorial zones under conditions of light winds. The first météotron was built at the University of Clermont, France, in 1963 at a cost of about $100,000. It consisted of 100 fuel oil burners situated in a circle of 250 m in diameter which together consumed a total of one ton of fuel oil per minute! Many artificial cumulus clouds were produced, two of which gave rise to substantial downpours. In the Sahara desert, the météotron was unsuccessful. The artificial clouds dissipated from the base upwards and never lasted more than three minutes. In 1966 a météotron was constructed in Cuba, but we have been as yet unable to find any reported results.

Nature herself often performs cloud modification experiments which man can, if he is sufficiently ingenious, sometimes model, comprehend and simulate under conditions in which the results might usefully be applied. Among the most fascinating natural cumulus experiments are those performed by heated islands surrounded by ocean (fig. 1b). "Streets" of cumuli, often precipitating, frequently extend downwind of small (50 - 100 km^2) tropical islands for 100 km or more.

As a means toward understanding convection processes, models and observations of air flow over islands began in the early 1950's (Malkus, 1952). In those pre-computer days, the equations had to be solved analytically so linear models had to be used. This limitation meant that the island-induced motions were required to be small relative to the imposed basic air current, and hence precipitation could not be treated. Among the important early results was demonstration of the equivalence between flow over a heat source and that over a mountain; the linear models permitted calculation of the height of the "equivalent mountain" from the island surface temperature excess and assumed low-level mixing processes. The tiny flat tropical island of Anegada (about 18 by 4 km) was found to correspond to an "equivalent mountain" of 600 m height, assuming 3°C temperature excess. "Hotspots" in the ocean, only about 0.5°C in amplitude, had "equivalent mountains" of more than 200 m height and were often observationally associated with cloud streets.

Inspired by these studies, Black, a products engineer at a major oil company, suggested simulating a heated island by an Anegada-sized asphalt coating on the ground, in order to induce rain-producing cumuli in needy tropical and subtropical areas. Asphalt coatings commonly show midday temperature excesses above 11°C over grassy surroundings, and maintain a sizeable temperature excess for about 20 hours out of the 24. Thermal mountains of 1000 m or more were calculated to correspond to asphalt coatings of reasonable length ($\sim$20 km). Ingeniously, Black estimated the potential benefits from the excess rain associated with actual tropical mountains of similar heights to his heat mountains (as much as 50 cm per year). If the asphalt coating is assumed to require renewal each five years, the excess precipitation would be induced at $9 per acre-foot, with a benefit-to-cost ratio exceeding five, the value depending on how water cost is assessed.

Political and financial obstacles have so far prevented actual execution of this experiment. Nevertheless, the idea has stimulated profitable discussions, modelling advances and field studies of natural islands. Black and his associates have developed a three-dimensional, steady-state, dry, non-linear numerical model, with the interesting result of two helical downstream vortices. An important joint observational-modelling study of Grand Bahama island (130 km length by 10 km width) by the University of Miami meteorologists has given some very pertinent and exciting results. Among these are:

1) A two-dimensional, moist, time dependent model, with simulated precipitation (similar to table 2) predicts that even a very small island, with only two km extent in the direction of the wind, can produce precipitating cumuli.

2) Grand Bahama temperature excess was measured (with a radiation thermometer) as 6°C; this was the temperature amplitude used in the model.

3) In three case studies with surface and aircraft measurements of temperature, humidity, wind, cloud formations and rainfall, model predictions were found to agree well with observations. On fair days with light winds, heavy showers are predicted and observed over the island,

but not over the surrounding oceans. Showers begin at the lee shore and propagate upwind (figure 27) owing to evaporational cooling of the surface and lowest air by precipitation.

A very significant result of the Grand Bahamas study is illustrated in figure 28 showing the changing streamline pattern over the island as daily heating develops. Note the confluence zone which develops by 1400 hours local time, parallel to the island outline. This confluence line is firmly associated with the cumuli and propagates upwind with them. On days of strong winds which do not develop deep island cumuli, this confluence line fails to form. Relevant to many other cumulus modification efforts, to induce cumuli deep enough to rain it is believed that convergence of moist subcloud air at and below cloud base must be established and maintained; otherwise, a single puff or thermal only is likely to appear, as in the salt experiments shown in figure 26.

Another significant result of the same program concerns the feedback control of the precipitation on the life cycle of the disturbance. On the heavy shower day illustrated, cooling due to the rain itself began rapidly to kill the island heating by 1500 hours local time; the disturbance had completed its own destruction by 1800 hours.

The asphalt-island experiment would be of great value scientifically regardless of its success in producing rainfall. However, since it will cost in the neighborhood of four million dollars to execute properly, some cautions are in order to achieve optimum usefulness. Firstly, studies of the island of Barbados and others at the University of Wisconsin suggest that the momentum transfer from the heated surface is crucial in

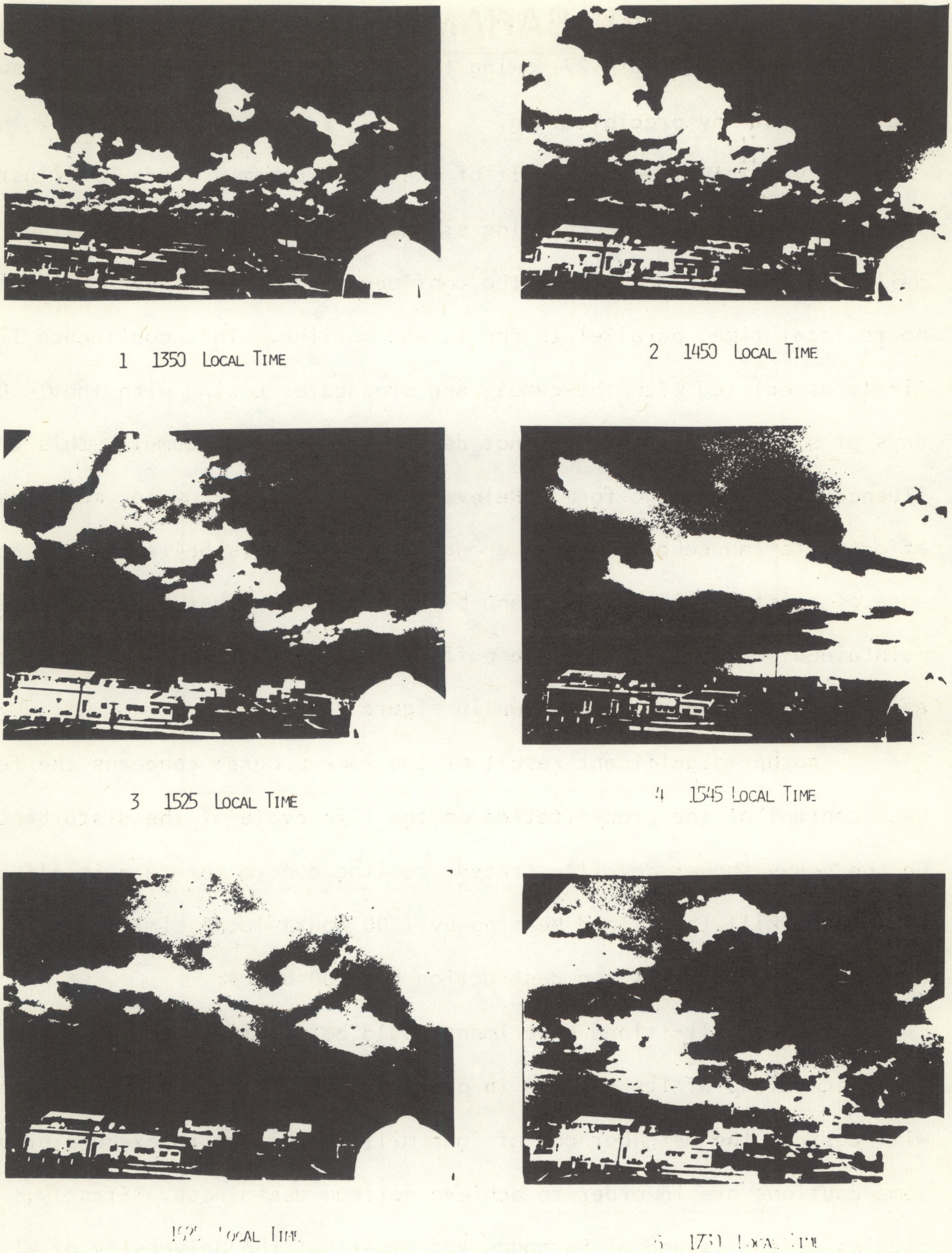

Figure 27. Photographic series illustrating the heated island effect on rainfall, Grand Bahama Island, August 27, 1970. The camera was pointed east, along the long axis of the island. The prevailing flow was from right to left across the photographs, so that the leeward edge of the island is on the left. Note the upwind propagation of the disturbance, which clears between 1545 and 1730 local time. (Courtesy C. Bhumralkar.)

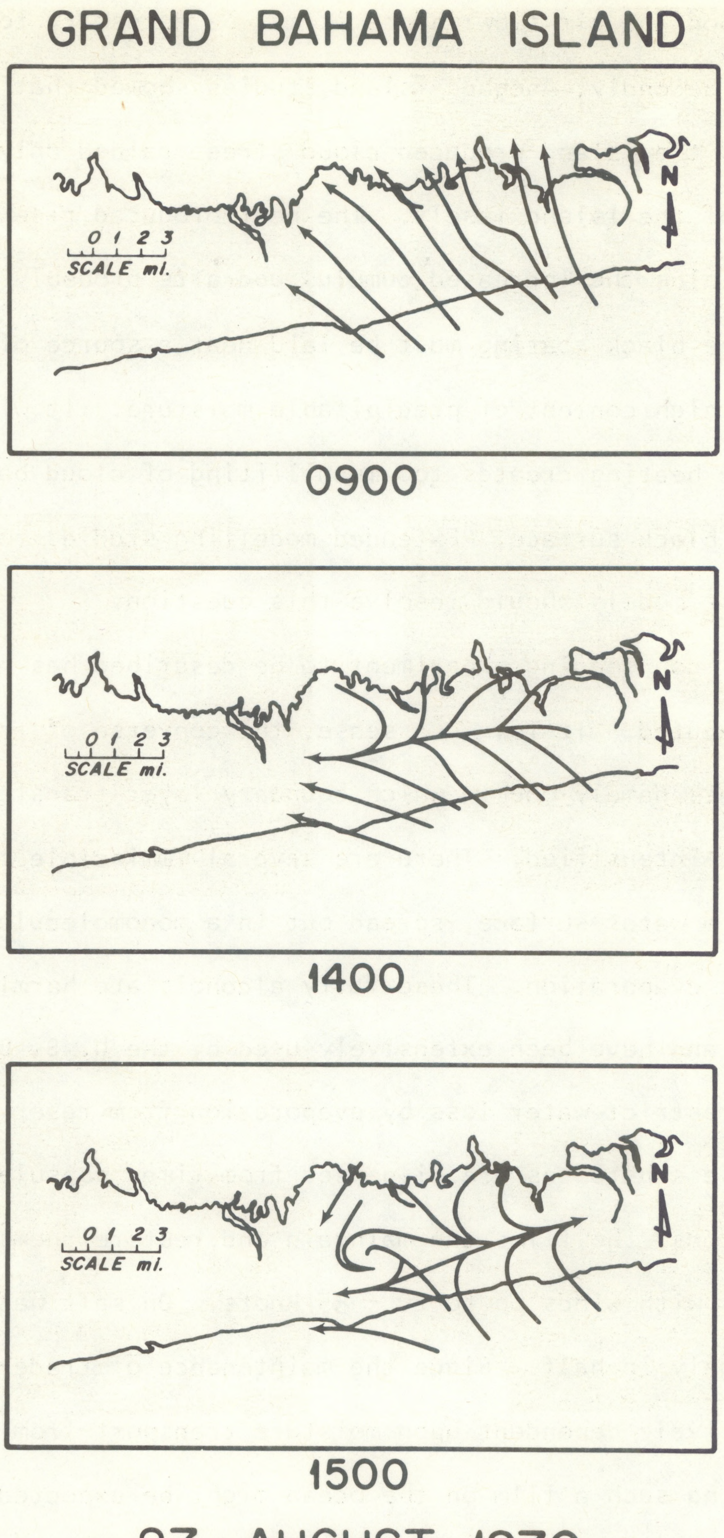

Figure 28. Streamlines of the lower airflow over Grand Bahama corresponding to figure 27. Note the confluence line (associated with the showering cumuli) which propagates upwind. (Courtesy C. Bhumralkar.)

its influence upon the air flow; hence it may be necessary to leave the asphalt rough. Secondly, Anegada island studies showed that on a typical undisturbed day, the island-produced cloud street rained only over the ocean downwind of the island itself. The heat-produced rise in cloud base over the island plus the increased cumulus updrafts probably were a factor. Clearly, the black coating must be laid near a source of moist maritime air with a high content of precipitable moisture. It will be unfortunate if the heating creates too much lifting of cloud bases over and downwind of the black surface. Extended modelling studies to three-dimensional moist models should resolve this question.

The final non-seeding experiment to be described has neither been modelled nor executed. It is, in a sense, the converse of the heated island experiment, namely one in which boundary layer transfers are inhibited rather than intensified. There are several immiscible fluids which, when applied to a water surface, spread out in a monomolecular layer and strongly inhibit evaporation. These fatty alcohols are harmless to man and the ecology and have been extensively used by the U. S. Bureau of Reclamation to restrict water loss by evaporation from reservoirs.

When these substances are dispensed from timed capsules (similar to some medications) the films can maintain and restore themselves on large reservoirs with winds up to 20 - 35 knots. On salt water, they cut evaporation roughly in half. Since the maintenance of trade-wind cumulus groups is sensitively dependent upon moisture transport from the sea surface, spreading such a film on the ocean might be expected to suppress cumuli and effect major changes in the boundary layers in sea and air simultaneously. This would be a scientifically valuable, but expensive and logistically difficult experiment. While it might not have direct practical applications in fine weather, it could eventually be enormously valuable in hurricane modification experiments, since a necessary condition for intensification of these storms has been shown to be local evaporation from the sea (Malkus, 1962).

Many other cumulus experiments have been suggested, ranging from introducing rice as artificial hail embryos, to altering radiation balances over substantial areas with plastic bubbles (impregnated with substances of selected radiative properties) dispensed from aircraft exhausts. Until the relevant modelling, motivation and technology come into closer juxtaposition, for the time being these are omitted from the discussion.

13. EXTENDED AREA AND PERSISTENCE EFFECTS.

POTENTIAL IMPACTS OF CUMULUS MODIFICATION.

Whether or not cumulus precipitation can be artificially increased over target areas a few hundred or a few thousand square miles in extent is still unresolved. It is even more unresolved whether attempts at cumulus modification within such target areas have extensive effects <u>outside</u> the target areas and possibly persisting for hours, days or even months beyond the cessation of the treatment.

Some meteorologists have argued, without concrete evidence, that when we increase the rainfall from a cloud or cloud group that we must be "robbing Peter to pay Paul," namely that rain must be decreased elsewhere. Others have argued, lacking convincing evidence, that man can willfully increase the total amount of rain falling on the earth's surface. Surely this is one of the most important unanswered questions in precipitation management. In the realm of cumulus modification, it is a question for which not even tentative answers exist; what follows in this section is therefore highly speculative.

In the silver iodide seeding of winter orographic and convective storms, however, in the mountainous far west of the United States, persuasive evidence does exist for sizeable downwind effects. Apparent 50 to 100 percent increases in rainfall on seeded occasions have been found 80 to 150 miles downwind of seeding sites. In Project Whitetop, on the other hand, there were apparent extended area and persistent rainfall decreases of as much as 90 percent reaching 120 miles downwind of the seeding and persisting five hours after its cessation, particularly on the south wind days. In Australia modification experts have claimed that positive effects of seeding on rainfall have persisted even from one year to the next! Persistence was deduced to explain the decrease with time of the ratio of seeded-to-control rainfall in some single targets, and in some pairs of targets where the randomized crossover design was used. Still other scientists have argued for seeding effects on rainfall upwind of seeded areas.

Extended space and time effects of cloud modification need not be confined to rainfall, but could affect radiation and energy budgets, momentum transports, boundary layer processes, severe weather manifestations, wind circulation patterns, etc., etc. If any of these prove real or even plausible, they constitute simultaneously an exciting, in some instances useful but also potentially hair-raising, aspect of weather modification, involving unbelievable avenues for legal and sociological complications, as well as scientific controversy. For example, conceive of the interstate fracas which could break out if it were believed that a seeding project in Colorado changed the rainfall in parts of Nebraska, or of the international fracas if such an extended area effect were alleged to cross national boundaries in the troubled Middle East!

In cumulus experiments, what could be the possible causes of extended effects in space and/or time? These might include, but need not be confined to, the list in table 8.

Table 8. Possible Causes of Extended Space and/or Time Effects

1) Physical transport of the seeding agent

2) Physical transport of ice crystals produced by a seeding agent

3) Changes in radiation and thermal balance, as for example, from cloud shadows or wetting of the ground

4) Evaporation of water produced

5) Changes in the air-earth boundary, such as vegetation changes over land or changes in the structure of the ocean boundary layer following cloud modification

6) Dynamic effects

   a. Intensified subsidence surrounding the seeded clouds, compensating for invigorated updrafts

   b. Advection or propagation of intensified cloud systems which subsequently interact with orography or natural circulations

   c. Cold thunderstorm downdrafts, either killing local convection or setting off new convection cells elsewhere

d. Extended space-time consequences of enhancement or suppression of severe weather owing to cumulus modification

e. Alteration, via altered convection of wind circulation patterns and/or their transports which could interact with other circulations, perhaps at great distances

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We shall consider these possibilities in the order listed.

Attempts to trace silver iodide crystals or specially introduced tracer compounds such as indium trichloride through convective cloud complexes have yielded some unexpected results. Experiments in Illinois thunderstorms and Alberta hailstorms have found tracer compounds precipitated to the ground in regions not anticipated from available wind observations. So far, the distances involved have not exceeded 100 km.

The importance of the transport of silver iodide to regions downstream of the target area and its persistence are reduced by the decrease in AgI effectiveness as an ice nucleant, at the rate of about one order of magnitude per hour. Decay is more rapid than this in direct sunlight and sometimes slower under cloud conditions or at night. At night, one could anticipate ice-nucleating activity from silver iodide crystals released 100 - 200 km upward from an observation site, particularly with dynamic area-seeding experiments in which tens of kilograms of AgI may be released in a day's work.

Ice crystals produced by silver iodide (or Dry Ice) could conceivably be carried for very long distances by upper winds before falling into supercooled clouds to act as nucleating agents. In both tropics and temperate latitudes "orphan anvils" from natural cumulonimbus clouds are found several hundred miles and many hours from their site of origin. Figure 29 shows an extensive anvil streaming out from an exploding seeded cumulus in Florida, a not uncommon event with a strong jet stream over the seeding area.

In addition to their nucleating potential, "orphan anvils" could have important radiative impacts. Where solar radiation striking the ground directly maintains convection, as over Florida in summer, the shade of a single anvil often wipes out cumuli over a sizeable fraction of the southern peninsula extending outward in any direction from the target area, depending on winds aloft. Over tropical oceans, convection is maintained around the clock by the warm ocean, so that shutting off incoming solar radiation does not suppress cumuli. There the anvils could be most important in reducing the outflux to space of infra-red radiation from the surface.

Under inflow conditions this protection could lead to local warming from reduced radiation losses in the high troposphere. Some hurricane experts have suggested that the anvil canopy may play an important role in the warming required to transform a mild cold core tropical disturbance into the warm core necessary for further intensification. Although strong vertical wind shear is inimical to hurricane development, it frequently prevails in the early stages and is removed just prior to the critical deepening. A vital question is whether extensive anvil covers may be induced artificially.

Evaporation of water and/or wetting of the ground produced by seeding could have many different, possibly interacting, effects depend-

A.

B.

Figure 29. A Florida seeded cloud with a long anvil, May 27, 1968. A. Seeded cloud six minutes after seeding. B. Same cloud one hour and 44 minutes after seeding. Note long anvil extending more than 80 miles to eastward.

ing upon the locale of the seeding and the initial conditions of the system. In droughts, we have suggested how cloud base could be lowered and CCN production suppressed by these mechanisms. Over a heated island, cooling of the ground by precipitation was found to destroy the island effect. Evaporation of falling rain is a major factor in starting and maintaining the thunderstorm downdraft, while wetting of the ground can change the soil and vegetation, etc. The latter effect is postulated by some Australian scientists as a possible cause of year-to-year persistence in rainfall increases from seeding.

While extended space-time dynamic effects of cumulus modification are potentially complex, widespread and subtle, the writers believe they have observed many of those listed, in their own dynamic cumulus seeding experiments in Florida and South Dakota. The first one, namely compensating subsidence, is believed to be a main way in which we may be robbing Peter to pay Paul. However, no one yet knows how to specify where the compensating subsidence will occur; its location and local strength almost surely depend on the meso- and larger scale wind patterns and their convergences. Even where we have observed cleared out areas surrounding seeded complexes, we cannot be sure whether Peter has been robbed of more or less than Paul has been paid. Preliminary radar results in Florida do not indicate compensating rain decreases surrounding seeded complexes.

In Florida, we have rather clearly documented the propagation of seeded cumulonimbus complexes out of the target area and their interaction with the coastal seabreeze, to produce heavy rainfall at least 50 miles away from the seeding site up to five hours after seeding had ceased. If the seeding did indeed cause the observed explosive growth of the original seeded clouds, the extended space and time effects follow. More explicitly, we may alternatively postulate that the seeding was a necessary, but not sufficient condition to cause the observed chain of events, or better perhaps, that the extended effects could be triggered by the seeding because of the special initial conditions of the cloud-environment systems.

The effects of cold cumulonimbus downdrafts to suppress or propagate convection have not yet been explicitly studied in connection with modified cumuli. However, they are becoming documented in connection with natural cumulonimbi. Since in the tropics no observable differences have been detected between cumulonimbi whose stature has been brought about by dynamic seeding and those created by nature, cold downdrafts could quite probably play a role in extending the effects of cumulus modification experiments.

Cumulus modification has also been attempted to suppress lightning and hail. It has been alleged that under some conditions, inducing cumulonimbus growth by dynamic seeding could result in severe weather phenomena that might not have occurred had increased cloud growth and merger not been induced. The alteration, either way, of hail or lightning, could quite possibly give rise to extended effects. Hail swathes can be as much as 20°C colder than their surroundings and persist for two to 24 hours. Lightning sets off extensive forest fires and perhaps more subtle electric effects in the air, which could effect future condensation, coalescence and even cumulus dynamics.

The items from table 8 discussed so far are mainly extended space-time effects on the meso-scale. Many of them have been deduced from statistical analyses and raingage records only, with an unfortunate lack of direct evidence regarding cloud processes. New tools such as tracer techniques, infra-red photography, radars and satellites must be adapted to document the large scale effects of modification. At EML, considerable promise is found from calibrating enhanced satellite photographs with radar to measure precipitation changes over extended areas, including oceans. Meso-scale modelling is in its infancy and must be pushed hard to the point where it can be used to supplement the most sophisticated statistics and observations.

Next we must proceed to the last topic in table 8, namely the vitally important possibility of the effect of cumulus modification upon synoptic and larger-sized circulations in the atmosphere (Simpson, 1970). Firstly, both types of hurricane modification experiments are based on the postulate that we can alter the storm scale of motion by massively seeding hurricane clouds. This postulate is based on nearly two decades of hurricane research in which the role of cumuli in driving and maintaining the hurricane motions has been well documented. Results of full-scale field experimentation to date warrant some optimism that a storm-sized system may be markedly changed by means of cumulus modification.

Another promising but untried area lies in the "explosive" deepening of middle-latitude oceanic cyclones. This very sudden intensification of winter storms often occurs in the Gulf of Alaska and off continental east coasts. An important factor in the deepening process appears to be sea-air heat flux, coupled with increasingly tall cumulus convection. In fact, when the cumuli remain stunted, satellite studies indicate that deepening fails to take place.

If the seedability in some potential deepening situations were to prove adequate, the explosive development of the storm could possibly be induced artificially. But why would anyone wish to consider such an experiment? The reason is that explosive deepening of marine cyclones, particularly in the Gulf of Alaska, has been found to trigger major changes in the entire wind circulation pattern over the whole northern hemisphere. Other "teleconnections" between local triggers and hemispheric circulation adjustments are becoming subjects of serious investigation.

In pursuit of the possible effects of cumulus modification upon really large, namely planetary scale, circulations, we use the vast progress of the last decade that has been made in documenting the role of cumuli as both combustion cylinders and fuel pumps in many large-scale circulation branches, particularly in the tropics.

The primary, newly gained knowledge that renders questioning the role of cumulus modification here meaningful, rather than ridiculous, is the concentration of the cumulus function. Studies of the atmosphere's firebox, namely the equatorial trough zone (Malkus, 1962) has shown that its entire vertical transport and heat release function is carried out by a few thousand (5000 - 15,000) cumulonimbus hot towers active at one time around the globe, mainly clustered in vortical disturbances and/or over continents. In tropical storms and disturbances, the firebox function is conducted by 100 - 400 active hot towers occupying two to four percent of the storm area. Identification of these towers has now been made possible from satellite pictures using simple enhancement techniques. The role of cumuli in large-scale flows is threefold:

1) Latent heat release by precipitation, which provides (by warming) the pressure gradients that drive many wind systems

2) Radiational (discussed earlier)

3) Vertical transports of heat, moisture, vorticity and momentum

4) Possible creation of relative vorticity and/or its re-orientation from a vertical to horizontal plane

It is therefore clear that a successful outcome of area seeding to increase cumulus precipitation is not necessarily required (except for item 1) for cumulus modification to affect large-scale flows.

Since large-scale general circulation models are relatively advanced and even now include many parameterized effects of convection, it would be interesting and important to inquire with them what impact an increase in the number and intensity of hot towers would have on the Hadley cell and how the large-scale circulations would be affected by various estimated possible artificial changes in cumulus processes. The modelling limitations discussed in section 4 must be kept in mind and they suggest at this time that most proposed experiments should be confined to a computer.

One must inquire, furthermore, whether the circulation would respond to the imposed changes stably or whether an unstable response might be triggered. As an example of a stable response, a simple analytic model (Malkus, 1962) showed that the poleward portion of the trade-wind circulation tends to restore itself when the convective heat release (i.e. precipitation) is increased. The theory predicts that the increased heat release leads to increased downstream acceleration of the trades, resulting in increased divergence and subsidence, hence shutting off the convection and reducing its rainfall.

As we approach the equator and in disturbances, an unstable interaction between convection and the flow has been postulated to occur sometimes. This mechanism has been christened CISK, namely "conditional instability of the second kind." It means "cooperation" between cumulus convection and larger-scale circulation which can take place when the low-level flow possesses cyclonic vorticity. If this prevails, the boundary layer flow is convergent. Convergence in low levels intensifies cumulus convection and intensified cumulus convection, as we saw, can lead to increased cyclonic vorticity and so forth in a mutually accelerative cycle. The effects of convection in this cycle are believe to be partly thermal and partly dynamic. CISK models, with and without cloud modification, should be achievable in the near future.

Lastly, we should consider another direct dynamic effect of cumuli on planetary circulations not yet included in most large-scale numerical models. Gray has emphasized the role of these towering clouds in the vertical flux of horizontal momentum. Other researchers have shown that vertical momentum fluxes in the tropics are important in driving the circulation of the Hadley cell, which in turn supplies mid-latitudes, partly through direct infusion by the subtropical jet stream. It is thus not inconceivable that massive modification of equatorial cumuli might one day change the weather in middle America. More important than this speculation is that we are gaining the means of testing it.

In reaching this point, we have in a sense brought cloud modification in a full circle, from the pioneering days of Schaefer and Langmuir. A quarter century ago, Langmuir postulated that seeding clouds in New Mexico affected the subsequent weather in Boston. His suggestion met with violent reactions from many meteorologists ranging from bitter hostility to angry ridicule. Today, enough about the atmosphere, the role of cumuli, and modification potential has been learned so that the wise meteorologist neither asserts nor ridicules anything. On the contrary, he inquires how adequate understanding and documentation can be gained to formulate and test hypotheses meaningfully.

14. CONCLUSIONS AND OUTLOOK

After 25 years of effort, the promise and excitement of cumulus modification are great, while the concrete accomplishments are modest. Definitive sound results are confined to single cloud experiments, in two or perhaps three physical classes. These are water spray seeding, dynamic seeding of single supercooled clouds, and possibly static seeding of single supercooled clouds, if one can rely on the foil impactor to represent cloud base rain.

In dynamic seeding, randomized single cloud experiments gave definitive results for both cloud growth and volume of rain falling from cloud base, in Florida confidently related to a threefold increase in single cloud precipitation reaching the ground. In spray seeding, the definitive results involved the frequency and early initiation of rain echoes within cloud but treatment has not yet been related to rain volume falling out.

Major advances in cumulus experimentation and in confidence in their results have derived from the development and use of numerical models. Despite their imperfections and the criticisms incurred, one-dimensional cumulus models originated the concept and exploitation of dynamic "seedability." They have provided virtually priceless criteria for launching and evaluating seeding missions; they provide unique means for quantitatively examining physical-dynamical interactions; they have provided pioneering classifications of seeding climatologies and, last but not least, they serve both as springboards and test beds for more advanced and sophisticated modelling efforts.

Concerning area experiments on cumuli, none have yet attained definitive positive results, although one (Whitetop) involving the static approach, appears to have obtained negative results. However, the apparent rainfall increases at four to five Rapid Project stations (on shower days) were significant at the five percent level and may indicate some real area effect, even if only a redistribution between the two targets.

Extended space and time effects of cumulus modification are likely to exist, but their nature, magnitude, extent and functional dependence await documentation, which will require modelling advances and detailed measurements combined with judicious applications of statistics.

Our most important conclusion is that cumulus modification depends on not only the amount, nature and method of the treatment, <u>but also on the initial conditions of the cloud-environment system</u>. The identical treatment may lead to entirely different results even in the same target area, depending on the initial cloud circumstances and the prevailing weather. Data stratification and probably detailed documentation of cloud behavior will be necessary to unravel causality. The returns from blind statistics applied to masses of averaged raingage data have probably diminished to zero or lower. As a corollary, one of the most futile questioning methods in weather modification seeks "yes or no" answers, such as "does seeding cause rain increase?"

Reviewing this article reveals that many promising approaches to cumulus modification were begun and then dropped, such as spray seeding, electric charge application, carbon black and asphalt ground coatings. Why? Ostensibly, lack of financial support is offered as the reason, but this is only part of the story.

Paradoxically, large and expensive area seeding programs for operational purposes continue, while sound scientific foundations for them are not only incomplete, but are advancing at a snail's pace. Why? One reason for the dichotomy is that many decision makers, under pressure from the public, act over-optimistically regarding what is known to be achievable with modification, while many fine scientists are either completely pessimistic - or for other reasons do not wish to become involved with modification. Much scientific talent has either shied away from the field or has been driven from it, owing to bitter controversy, the mixture of political with scientific rationale for decisions, the pressure to deliver results with insufficient knowledge and the actual stigma that has attached itself to virtually every scientist who has touched the subject. Fortunately, the latter aspect of the climate has been improving slowly over the past five years, so that some brilliant and eager young people are now entering the field full time.

The total support for cumulus modification has indeed been pathetically small. Today in the United States the funding probably does not exceed five million dollars annually, with perhaps one quarter of that beggarly sum devoted to operational or semi-operational programs.

In contrast, it is clear from this article that virtually all of the major advances in cumulus modification have originated from scientists primarily involved in basic research. Most of the breakthroughs, or their necessary backgrounds, were not at first intended to apply to modification at all, but had the purpose of advancing man's knowledge of cumulus processes. And yet resources devoted to advancing the basic physics and dynamics of clouds, and to learning more of the role that these clouds play in atmospheric processes are not growing, but are probably suffering retrenchment!

These writers believe that the optimal way to reach useful cumulus modification is to devote resources, increased by at least tenfold, to a judicious balance between basic research and controlled experimentation, in the field, in the laboratory and on the computer. The experimentation is likely to reach economic application faster and more firmly if it is mainly devoted to establishing sound causality, understanding and prediction, using ingenuity to exploit all potentially practical avenues that will naturally arise in the course of conducting good science.

Accompanying these efforts, a vigorous public education program isrequired so that the democratic decision process when focussed on modification, is based on sound and realistic appreciation of the options involved.

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