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Experimental Meteorology[1])

Survey article

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As basic research along the frontiers of science advances, there are few of the natural sciences which do not receive careful scrutiny. As each study expands, it encounters the borderlines of related phenomena which often become so completely inter-related that it is difficult to determine where one ends and the other begins.

This is particularly true when the study involves a subject such as the earth's atmosphere and the physical processes which occur within a few hundred miles of its surface.

The general subject I should like to discuss at this time involves an area of even shallower depth with few, if any, of the problems to be considered involving a region exceeding ten miles above the earth. Despite this relatively narrow zone in the physical dimensions of the earth, the problems encountered are of considerable magnitude and of a nature which, if we are to approach their solution with any hope of success, must employ as many scientific techniques as possible.

As in any pioneering venture, success is much more likely if the investigations are carried out with enthusiasm, imagination, and an active curiosity and without too much regard for older theories or prejudices.

The role of clouds in the hydrologic cycle

In considering clouds and their formation due to the interactions between air, water, and sunlight, we have the essential constituents of an important mechanism for the release of energy on the earth. The water molecule is the basic unit in this energy transfer system, since the water involved is continually passing through the closed cycle of evaporation, condensation, and precipitation—the sequence starting again by evaporation.

Because of its physical nature, the lower atmosphere serves as a vast reservoir for water. A relatively high concentration of water vapor may be stored in the form of gaseous molecules before condensation forms. In fact, even

[1]) This paper has been approved by the National Military Establishment and also by R. W. SAROW (August 15, 1949). It has been presented before United Nations Conference on the Conservation and Utilization of Resources (August 19, 1949).

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when this occurs, the small size of the condensed droplets often permits the atmosphere to support this additional moisture for a considerable time—often long enough, in fact, for the cloud thus formed to evaporate into warmer or drier air. It is in this manner that large air masses become modified. Warm and moist maritime air encountering colder, drier continental air mixes with it at the contact interface and thus changes the nature of both air masses.

In addition to forming clouds, water molecules in the very low levels of the atmosphere often condense as frost or dew. This is really a precipitate but, except in regions where it is common, is not of great economic importance since much of it soon evaporates again. Where cloudless skies occur and dew deposits are common, they may constitute an important source of moisture on the earth. Improved methods for enhancing this precipitation by artificial means is an important problem that should receive more attention.

The presence of clouds in the atmosphere tends to decrease the flow of energy from the sun to the earth, since most clouds absorb much of the visible and near infrared radiation of the sun. Even a thin layer of clouds reduces insolation (incoming solar radiation). At night, however, the presence of clouds provides an insulation blanket and slows down the loss of heat from the earth to outer space.

When a cloud forms in the atmosphere, the amount of heat released to the air amounts to about 580 calories per gram of condensed water. This energy may be considered lost insofar as the water resources of the earth are concerned if the cloud evaporates before it is precipitated. Not until precipitation develops in the clouds as snow or rain and then falls to the earth may we consider the hydrologic cycle completed and the maximum energy recovered. Extremely complex relationships in this respect result from the interaction between the seasonal changes of temperature and humidity, variations in the wind, the effect of topography, land use, and similar factors, all of which exert an influence on the delicate balance existing between the sun, the atmosphere, water, and man's welfare.

In discussing experimental meteorology, I would like to limit my consideration to experimental studies in the lower ten miles of the atmosphere and with air samples ranging in volume from a few cubic millimeters to several hundred cubic miles.

Among the interesting problems related to the atmosphere which require a solution is a logical and comprehensive understanding of precipitation processes. That there is more than a single mechanism involved in the formation of snow and rain as precipitation is now becoming well recognized. It was only a few years ago, however, when heavy rain was only thought of [1][1]) as necessarily preceded by the initial formation of snow.

[1]) Numbers in brackets refer to References, p. 227, ZAMP I/4.

It seems to me that when we consider the economic aspects of precipitation processes, it is important to evaluate not only the quantity of moisture that reaches the earth but also the related effects, such as winds, lightning, hail, intensity of the precipitation, and the related amounts of sunshine.

If any of these factors can be modified artificially, even to a limited degree, it is of great importance that every feature of the modification should bear careful scientific scrutiny.

While it is true that it is relatively easy to assign a definite value to an inch of rain on a square mile of newly planted seed corn; ten thousand acre feet of water added to an irrigation reservoir; two feet of snow on the upper drainage basin of a stream used for power purposes; or to supply a large metropolitan district with adequate drinking water, it is nevertheless of great economic importance to evaluate weather phenomena. The loss in timber resources and recreational areas occasioned by fires started by lightning storms; the devastation resulting when high local winds flatten banana plantations; the bruised fruit or smashed vegetables following an intense hail storm, and the muddied streams and eroded farm lands left in the wake of a torrential rain all serve as examples of the by-products of unstable cloud systems which occur in the atmosphere.

Most cloud systems are examples of colloidal instability. Many of them rigorously follow the reactions which have well known counterparts in colloid chemistry. In most instances, where colloidal instability occurs, it is possible to shift the system to a more stable form by the proper and judicious use of chemical or physical reagents or reactions.

Even though glycerine and boric acid, for example, can exist as supercooled liquids in a relatively stable condition, methods are known whereby they can be changed to their less common, though more stable, crystalline form. The water in cloud systems also has a tendency to develop supercooling as a common characteristic.

Cloud types to be considered

Before going into a detailed description of this interesting phenomenon, it will simplify the discussion to establish a certain terminology at this time. The clouds which we shall refer to consist of the three common forms—cirrus, cumulus, and stratus. The many variations in which each of these may be classified will, in general, be neglected for, although they are very important from the standpoint of the genetic development of a weather pattern, these variations are not of prime concern in relation to the subject under consideration. A physical feature of great importance, however, is the freezing level in the atmosphere and its relationship to the clouds under discussion. In general, the temperature in clouds follows the wet adiabatic lapse rate with the temperature lowering with increase of altitude at the rate of about 2·1° C (3·8° F) per 1000 feet at 0° C (32° F). With relation to the freezing level, we shall be dealing with clouds existing under one of three temperature conditions. The term *warm cloud* shall be used to designate a cloud of liquid water droplets warmer than 0° C (32° F). A *cold cloud* shall then designate a cloud of liquid water droplets colder than 0° C, while a *cool cloud* will be a cloud extending above and below the freezing isotherm, thus combining the features of *warm* and *cold* clouds. The term *cool cloud* may thus designate a cumulus cloud, cooling according to the wet adiabatic lapse rate and thus becoming colder with increase of altitude, or it may be used to describe a more stable stratus cloud extending through an inversion and thus inverting the normal temperature sequence. These various cloud conditions are illustrated in Fig. 1.

The amount of condensed water in clouds

The variation in the amount of condensed water vapor in natural clouds covers a considerable range. In general, it is lowest in cirrus and highest in cumulus, with stratiform types intermediate. The temperature of the source air is the major factor governing the limit to the amount of moisture which may appear in clouds from condensation. Table 1 (p. 176) shows the amount of gaseous water vapor which may be contained in saturated air of different temperatures.

This difference in the amount of water which may be held as a gaseous vapor at different temperatures is the direct cause of cloud formation in air cooled by radiation, convection, or advection.

The size and size distribution of the cloud droplets contained within such clouds is also a variable involving many complex relationships. Cloud studies have now progressed to the point [2] where limiting values may be given in sufficient detail to be quite satisfactory. These are assembled graphically in Fig. 2.

As might be expected, the lowest values in condensed water occur in cirrus clouds as ice crystals, the intermediate values in stratiform clouds, while the highest liquid water contents and particle sizes are found in towering cumulus type clouds.

The degree of turbulence in clouds

Studies of turbulence and convection in clouds show that of the three general types under discussion in this paper, only the cumulus type exhibit turbulence and convection of high order. While it is true that vertical velocities of a considerable degree may sometimes occur in stratus clouds subjected to orographic or frontal lifting, i. e., displacement due to the encounter of the cloud with a land barrier or an air mass having a different density, such effects are of a temporary nature and generally fail to produce marked changes in the nature of the cloud. It is likely that vertical velocities in stratus clouds rarely exceed 2 m/s. The vertical velocities in cirrus clouds are even lower, since they generally form at very high altitudes and in relatively stable air. Cumulus clouds, on the other hand, contain high velocities which may exceed 20 m/s in towering cumulus. Even in relatively small cumulus, 1 km in thickness, vertical velocities of more than 3 m/s often occur.

Liquid water content and particle size are physical features of clouds which are not affected by the location of the freezing level, except as they may be a function of the absolute humidity. High values of particle size and liquid water content may occur at temperatures far below the freezing temperature. The factor which affects the liquid water content of a particular parcel of air is the initial saturation temperature and its final temperature. If, however, in reaching this final temperature, the cloud particles have grown so large that the effect of gravity on them is great enough to overcome the vertical air velocity of their surroundings, the liquid water content may become lower. By a somewhat similar process, the liquid water content of a given air sample may be temporarily enriched by an invasion of falling precipitation from depleted clouds above. These are features of old clouds and are of much importance in reaching a proper understanding of precipitation processes.

Types of nuclei in the atmosphere

In understanding the structure of natural clouds, it is of much importance to consider the initial formation of the cloud particles. All of the features of this phase of cloud physics are not understood, although rapid advances are underway. Three types of nuclei are of importance—*condensation*, *sublimation*, and *freezing*.

Condensation nuclei

If ordinary atmospheric air is saturated with water vapor and then suddenly cooled, a cloud appears consisting of small water droplets. The number of droplets which form is directly related to the effective condensation nuclei present in the air before cooling occurred. If these observations are made using an enclosed chamber, and its temperature and humidity are adjusted so that the cloud droplets reach the bottom of the chamber before they evaporate, it is an observable fact that successive expansion cycles fail to produce a new cloud unless a higher expansion ratio is used at which time effective nuclei serve as centers of condensation.

It is a well known fact [3] that condensation nuclei are formed in great quantities by many processes. Fine, hygroscopic salt particles, which become airborne as waves and bubbles break at sea, seem to be an important source of very active condensation nuclei. The smoke from forest fires, and most other burning processes, produces vast quantities of condensation nuclei which permeate the atmosphere to a thickness in excess of a mile. In some industrial regions, these particles become so numerous that they form a dense pall of smoke and fog which restricts visibility to a fraction of a mile.

If air samples are used from industrial regions or other places where the foreign particle concentration in the air is high, a dense cloud is observed in the cloud chamber containing from 10^4 to 10^5 particles per cubic centimeter. On mountain tops, at sea, or at higher levels of the atmosphere, the number of effective nuclei may drop to values of only a few hundred per cubic centimeter. It can easily be shown that the preponderance of such particles continue to serve as water drop nuclei to a temperature of $-38\cdot5°$ C. Supercooled clouds of this temperature can easily be formed, even when the concentration of nuclei is as high as $10^5/cm^3$.

Sublimation nuclei

Among the foreign particles carried in the dust of the air are certain special forms which in a proper environment serve as sublimation nuclei. These become active in the formation of ice crystals at specific temperatures below 0° C and in air supersaturated with respect to ice but not necessarily saturated with respect to water. Fig. 3 shows typical results observable with samples of natural soils and similar materials. Many of these were gathered in regions where extensive dust storms are common occurrences.

It is perhaps of considerable significance that very few particles have been found which serve as effective sublimation nuclei at temperatures warmer than about $-12°$ C. No observational evidence is known of snow storms starting in clouds warmer than this temperature.

A study of considerable significance in relation to the occurrence of sublimation nuclei in the natural atmosphere has been made on Mt. Washington during the past eighteen months. Every three hours, day and night, in conjunction with the regular weather observations, the number of sublimation nuclei in a typical air sample are determined as part of our Project *Cirrus* weather research studies. The cold chamber method [4] is used in making these observations. The results are summarized in Table 2 (p. 176). This indicates that the level of sublimation nuclei in the atmosphere is generally very low throughout the year. The highest level observed during approximately 4500 observations is 10 per cubic centimeter. In contrast, the level of condensation nuclei at the same time would show values ranging from 10 to 10,000 times greater.

While sublimation nuclei in the natural atmosphere may apparently have a number of different molecular properties, there is one pure chemical compound which to date has not been equalled in its effectiveness as a foreign particle ice nucleus. This is silver iodide, a hexagonal crystal which is almost identical in its crystalline structure to that of ice.

Work in our laboratory [5] and in the field is actively underway evaluating the effectiveness of silver iodide as a sublimation nucleus under various atmospheric conditions. To date, it appears to have exceptional value for cloud modification where dry ice cannot be used. One of its most important applications may be to inoculate clouds from ground generators placed in such a manner that the submicroscopic particles are carried up into the clouds where they will become active at temperatures colder than $-5°$ C, the threshold of activity of silver iodide smokes. Further details in relation to silver iodide will be given in a subsequent section of this paper.

Freezing nuclei

Only brief mention will be made of freezing nuclei at this time, since not much is known about them. It is apparent, however, that they seem to possess somewhat different properties than sublimation nuclei. Where the latter permit the formation of ice crystals by the direct deposition of water molecules from the vapor to the solid phase, freezing nuclei appear to initiate the freezing of supercooled water droplets [6]. It is apparently due to the presence of freezing nuclei in bulk water that leads to the crystallization of water in the temperature range of $-6°$ C to $-20°$ C under conditions when care is exercised to prevent the seeding of the water by frost crystals deposited just above the water meniscus on the container. It might be that the presence of certain water insoluble sublimation nuclei are partially responsible for the development of snow in cold and cool clouds at temperatures below $-12°$ C when they come in contact with supercooled cloud droplets and cause them to freeze. It is a matter of observation that a considerable number of snow crystals have as a nucleus what appears to be a cloud droplet such as shown in Fig. 4.

Causes of natural precipitation

The ice crystal process

Since 1933 when BERGERON proposed [1] a mechanism for the formation of rain by the initial development of snow in the upper parts of cool clouds, it has been generally accepted that heavy rains could only be accounted for in this manner. Experiences during the past war, especially in tropical regions, convinced fliers and some meteorologists that another mechanism could also lead to the formation of heavy rain. Such precipitation was often observed to fall from warm clouds.

BERGERON's theory proposed that the difference in the saturation vapor pressure with respect to ice and water would lead to the preferential growth of an ice crystal at the expense of the cloud droplets in its vicinity. Without doubt, this process is of major importance in the middle latitudes.

The vapor pressure differential process

Another precipitation mechanism parallel in some respects to that of BERGERON has been proposed by PETTERSSEN [7]. This would account for the development of rain drops in clouds due to the difference in temperature of small rain drops falling into a warmer environment, the difference in saturation vapor pressure of water at two temperatures producing a differential growth in a manner akin to that of the ice crystal effect. A variation in temperature of 0·01° C at 25° C would lead to the same differential as that which produces the optimum condition for the growth of snow crystals.

While this mechanism would lead to a logical development of rain drops, it is not easy to explain the method which starts the process. From a theoretical consideration, it is difficult to account for the early increase in size of the cloud particles from their relatively stable dimensions. LANGMUIR's [8] calculations suggest that it is impossible to maintain the necessary temperature difference between small particles long enough for some of them to grow large enough to start falling away from the others. From the experimental studies in our laboratory, high velocities and large temperature differentials fail to demonstrate this growth mechanism, although it is extremely easy to illustrate the ice crystal effect.

The salt nuclei process

It is quite possible that the mechanism of natural rain formation in warm clouds is intimately related to the presence of certain hygroscopic nuclei in the air.

WOODCOCK has obtained experimental evidence recently [3] that there are considerable numbers of large salt particles present in air over the sea in the trade wind area. Salt particles as large as 2×10^{-11}g were collected by him at altitudes ranging from a few meters to a kilometer above the sea surface.

A recent series of observations [9] by our Project *Cirrus* Group in the vicinity of Puerto Rico showed that rain developed in extremely thin clouds below the trade wind inversion at temperatures of +8° C. Light rains were measured coming from clouds whose measured thickness was less than 300 feet. Fig. 5 shows a photograph of precipitating warm clouds. An estimate of the rainfall rate calculated from the observed rate of collection in flight showed that it would be approximately 0·05″/h. A similar measurement of a thicker cloud 2000 m (6500 ft.) in vertical thickness showed a rain water content falling from the cloud into the sea at the rate of approximately 25 mm/h (1″/h). The coldest part of this warm cloud had a temperature of +8° C.

Such amounts of rain from relatively thin clouds are rarely observed over continental America and obviously require a mechanism for rain formation different than the ice crystal effect.

While studying clouds in Puerto Rico, we also made some rough observations on the concentration of condensation nuclei in the air. Invariably, with air coming in from the sea, the levels were extremely low, the number rarely exceeding 200/cm³. Similar observations have since been made off the New England Coast. In this latter case, however, the concentration jumps to high levels within a few miles of the coast as the high levels inherent to continental air raise the concentration to between 10^3 and 10^5/cm³.

The experimental evidence thus far known seems to be compatible with the view that the salt crystal nuclei are extremely effective centers for rain formation. Due to their hygroscopic nature, they have considerable mass even before a normal cloud forms. Due to the larger size of these particles, there will be a tendency for them to start falling within the cloud at a different rate than the small droplets in their vicinity, thus gathering in by collision more and more of them. In this way, rain would form quite readily, and if the cloud had a vertical thickness of a kilometer or so, the particles could easily reach the maximum size that may fall without breakup. In addition to the growth by collision as the drop became larger, it might also add to its growth by the vapor pressure differential which, in the early stage, would be somewhat enhanced because of its salt content and in the later stages by the difference in temperature as the colder drop fell into warmer rising air.

Man's efforts to produce rain

Down through the ages, man in various ways has tried to get rain, prevent hail, and eliminate lightning. These efforts have ranged in method from ceremonial sacrifices to rain gods to spraying electrified sand and dumping such things as liquid air and dry ice to "cool the air". Since 1875, the literature is replete with pamphlets, books, patents, and popular stories giving reasons why such methods should be successful or detailed arguments to show that they could not possibly be effective.

During the past thirty years, several methods have been tried to modify atmospheric conditions which have claimed to make use of scientific principles. Most prominent of these have been the activities of BANCROFT and WARREN using electrified sand and VERAART using dry ice.

The electrified sand was used with the hope that the charged particles would attract oppositely charged cloud droplets and thus form rain drops. While considerable interest was displayed in these activities, the plan was doomed to failure because of the tremendous quantities of materials required, and the relative unimportance of the results obtained.

The next experiments which attracted considerable attention were centered on the claims of VERAART [10] of Holland who dropped dry ice from an airplane to affect clouds. A study of his theories and practices suggests that he was merely putting into practice methods proposed by GATHMANN [11] in 1891.

The effects expected from the introduction of dry ice into the atmosphere was to reduce the temperature of the air to either form clouds where no clouds previously existed or to augment the amount of condensed water already existing as a cloud with the expectation that it would produce precipitation of the cloud.

In his use of dry ice, VERAART proposed using very large quantities of this material. He apparently failed to recognize the importance of the effect of dry ice in supercooled clouds and, consequently, missed the chance to use this material in an effective way.

In 1938 FINDEISEN [12] in concluding an important paper entitled, *Colloidal Meteorological Processes in the Formation of Atmospheric Precipitation*, made the following prophetic statement:

"The recognition of the fact that quite minute, quantitatively inappreciable elements, are the actual cause setting into operation weather phenomena of the highest magnitude, gives the certainty that, in time, human science will be enabled to effect an artificial control on the course of meteorological phenomena. It would be going beyond the limits of the present work to discuss in detail the possibility of exercising a kind of technical control over the course of weather conditions. From the considerations under survey here, we have now come to quite new points of view on this. It can be boldly stated that, at comparatively moderate expense, it will, in time, be possible to bring about rain by scientific means, to obviate the danger of icing, and to prevent the formation of hailstorms. Through the energy transformations thus secured, various other weather phenomena (e. g. temperature, wind) will be brought under a certain kind of control, which perhaps never, in a direct manner, could, to an appreciable extent, be acted upon in the atmosphere. The colloido-meteorological investigations, by themselves with the only assistance of research work on the means to get some control over the weather factors, have opened up a new field for their efforts. They obviously only can solve those various problems with the close assistance of aerology."

In recognizing the possibility of modifying unstable cloud systems, FINDEISEN pointed out the tremendous energies that might be released when the proper type of "seeding agent" was discovered and properly used.

It is now believed that methods are now available to profoundly modify cloud systems and thus realize some of the effects predicted by FINDEISEN.

A study of the literature shows that at least one person observed that ice crystals could be produced in air supersaturated with respect to ice if the air was locally cooled to a very low temperature [13]. The significance of this observation as it might be related to meteorology was apparently not considered by ADAMS.

Meteorological studies at the General Electric Research Laboratory

In 1946, after spending the previous three years studying the nature of snow storms and aircraft icing, the writer [14] described some laboratory experiments concerning the seeding of supercooled clouds with dry ice. He pointed out the important relationship between this effect, and the modification of supercooled clouds in the natural atmosphere.

On November 13, 1946, the first experiment with seeding supercooled clouds in the atmosphere was accomplished, producing results which had been anticipated on the basis of the laboratory results. A four mile cold cloud was profoundly modified within a few minutes by dispensing 6 pounds of crushed dry ice into it. The cloud, which was supercooled to a temperature of approximately $-17 \cdot 5°$ C and which before seeding showed no sign of ice crystals, was completely changed to snow within five minutes after seeding.

Subsequent experiments in the fall and winter [15] of 1946 included the initiation of a snow area in the Hudson and Champlain Valleys of New York, the modification of a supercooled valley fog which initially reduced the visibility to a remarkable degree, the production of snow showers from cold stratocumulus, and the production of extensive grooves and holes in a solid deck of stratus clouds.

In addition to these flight experiments in the natural atmosphere, the laboratory studies which had started in 1943 in the General Electric Research Laboratory were carried out on an increased scale during the fall and winter of 1946–7.

These experiments pointed the way for further scientific work which would require extensive facilities. The General Electric Company is not in a position to supply such facilities and, consequently, a contract was initiated with the Army Signal Corps. This contract is a joint Army, Navy, and Air Force instrument wherein the General Electric Company provides scientific and technical guidance as consultants and the Government carries out all experiments other than those done within the General Electric Research Laboratory. This activity is identified as "Project *Cirrus*" and is administered by a Technical Steering Committee consisting of representatives of the Army, Navy, and Air Force. Dr. IRVING LANGMUIR and myself act as scientific consultants to this Committee.

At the present time, the Operations Group of Project *Cirrus* uses a flight facility at the General Electric Flight Test Hangar at the Schenectady County Airport which includes two B-17s, one PB4Y-1, one JRB, and one L-5 and the necessary pilots, mechanics, cameramen, aerologists, and technicians to carry out flight operations for studying the various phases of the precipitation process.

The formation of a supercooled cloud

It is a simple matter to form a supercooled cloud [16]. A chamber having dimensions of approximately 30 cm wide, 50 cm long, and 40 cm deep is quite suitable for cloud experiments. Means should be provided to cool the air in the chamber down to a temperature of at least $-25°$ C, if possible. The walls of the chamber should be painted black or lined on sides and bottom with black cloth, such as velvet. Illumination may consist of a flashlight or similar type of focused light beam. With the chamber[1]) cooled below ambient room temperature, a cloud may be formed within it by the introduction of moist air. Within a few seconds after condensation occurs, the droplets reach the temperature of the chamber. Under ordinary laboratory conditions, the cloud droplets reach a diameter in the range of 10 to 25 μm and a concentration of 200 to 1000 per cubic centimeter. Occasionally, a few ice crystals appear in the chamber if the temperature is colder than $-10°$ C. Generally, however, this is a transient effect with rarely more than 1 crystal/cm^3 forming. The supercooled cloud droplets persist until the air is no longer supersaturated with respect to water. During this period, a wire or miniature propeller will be coated with ice if rotated within the cloud. Eventually, it disappears, the droplets slowly settling to the bottom of the chamber or evaporating onto the frosty walls.

Such relatively stable supercooled clouds can be formed to a temperature of nearly $-39°$ C. If, however, the temperature is reduced below this value, it is impossible to form a supercooled cloud!

The formation of condensation nuclei

In most air samples likely to be used in laboratory experiments, there is no lack of condensation nuclei. Concentration ranging between a thousand and a million per cubic centimeter are normally observed. If the level is low, it may be increased by burning a bit of charcoal, striking a match, heating a nichrome filament, sparking a Tesla coil, or atomizing a salt solution. In fact, some very striking experiments may be carried out to demonstrate the optical effects possible with variations of type and concentration of condensation nuclei.

The formation of sublimation nuclei

To demonstrate the presence of natural sublimation nuclei in the air under laboratory conditions is not easy. Sometimes the free air contains relatively

[1]) A very convenient type of chamber is a 4 cubic foot home freezer, although it is possible to conduct effective experiments with much cruder apparatus if necessary. Two galvanized tubs separated by a water–ice–salt solution may be quite adequate for short experiments.

high concentration with the number occasionally reaching 10 particles per cubic centimeter. However, under ordinary conditions, the concentration seems to range between 50 and 500 per cubic meter. Under such conditions, a few particles will be seen in the beam of a light directed into the cold chamber containing a supercooled cloud.

As indicated in an earlier chapter, certain clays and other mineral dusts serve as effective sublimation nuclei at definite temperature ranges below 0°C. A given sample my be evaluated by using particles of such a size that they readily form an aerosol. Shaking a box containing the sample while held in the chamber will produce a cloud, since the fine particles will float out of the container. The particles, if effective as ice nuclei, will become coated with a frost layer if the air is supersaturated with respect to ice. This normally occurs within 30 s. They become visible as twinkling crystals if allowed to grow and generally form asymmetrical crystals unless the initial particles are smaller than 1 μm in diameter. Methods already described in detail [16] may be used to study such particles.

The role played by silver iodide serving as a sublimation nucleus is outstanding. It may be introduced into the air some distance away from the laboratory and still have an appreciable effect in the laboratory if the air trajectory is favorable. A few simple laboratory experiments will be mentioned. A wire filament dusted with a few minute particles of silver iodide will, if heated in air supersaturated with respect to ice, produce many millions of ice crystals. The particles formed in this way are submicroscopic with many less than 100 Å in diameter. By drawing an arc with a pure silver wire using either a Tesla coil or by momentarily shorting the leads of a dry battery with a silver wire, a smoke of silver particles may be introduced into the cold chamber. In a supercooled cloud formed subsequently, no ice crystals will be observed if iodine vapor is absent. If, however, a small iodine crystal is then passed briefly through the chamber, large numbers of ice crystals will be seen to form in the wake of the crystal within the supercooled cloud. A still simpler means of demonstrating the silver iodide effect is to place a few particles on the end of a match which will be volatilized as the match is ignited, thus producing many nuclei.

As shown [5] by VONNEGUT, the nature of silver iodide smokes in forming sublimation nuclei seems to be related to a probability function which has a fairly high temperature coefficient. Thus, at a temperature of $-6°$ C, some sublimation nuclei will appear. At $-10°$ C with all other factors the same, many more particles will be observed in the same unit time. Space does not permit a detailed discussion of the interesting relationships which have been found. The original reports and papers of VONNEGUT should be studied carefully if plans are contemplated to use this material for laboratory or field experiments.

Establishment of Project Cirrus

Early in 1947 under the direction of Dr. IRVING LANGMUIR assisted by the writer, a much more extensive cloud studies program was initiated by the Research Laboratory under the sponsorship of the Army Signal Corps, the Office of Naval Research, and the Air Forces. Under this arrangement, a temporary flight facility was established at the General Electric Flight Test Hangar at the Schenectady County Airport which, at the present time (year of 1949–50), includes 2 B-17s, 1 PB4Y-1, 1 JRB, and 1 L-5 and the necessary pilots, mechanics, cameramen, aerologists, and technicians to carry out flight operations for studying all phases of the precipitation process.

Project Cirrus and experimental meteorology

Project *Cirrus* is a fundamental research study of the physical and chemical processes which occur in the lower atmosphere and produce clouds, snow, rain, atmospheric electricity, and associated phenomena.

One of the major activities of Project *Cirrus* is in the field of experimental meteorology. In this respect, observations and experimental studies are made with cloud systems having volumes ranging from less than one to more than several hundred cubic miles. The limitations in size are related primarily to available cloud systems and the physical conditions required for each particular experiment.

These studies are planned and carried out insofar as possible as laboratory type experiments. Each operation is planned to supplement others previously accomplished so that some features are checked as new aspects are under exploration. Insofar as possible, controls are maintained so that comparative evaluations may be achieved.

The major objective in this particular phase of our study has been directed toward the detection of unstable atmospheric conditions which develop in the atmosphere and often persist for some time. When such conditions are discovered various "triggering" actions are then applied in an attempt to shift the system to its more stable form. Such modifications of clouds often involve the release of tremendous quantities of energy. As pointed out recently by LONGLEY [17], the energy release following the condensation and subsequent fall of one inch of rain on one square mile of the earth is equivalent to $1{\cdot}7 \times 10^{12}$ erg. For comparison purposes, this is about twice that of the energy said to be released by an atom bomb of the type dropped on Hiroshima. Although much of this energy is released as the cloud forms, unless it is precipitated on the earth in an effective and useful way, it may be regarded as lost energy insofar as the earth and its water resources are concerned.

Evidence is now accumulating which shows that under certain conditions it is feasible to initiate the precipitation cycle artificially in some types of cloud systems so that their increased output forms a valuable addition to the natural resources of the earth.

Before going into a discussion of this fascinating subject, it may be in order to review briefly the operational facilities and procedures which we are now using in our basic research and studies of clouds and the atmosphere.

These activities may be divided into three major parts: (1) laboratory research; (2) field studies; (3) flight operations.

Laboratory research under Project Cirrus

The main laboratory studies are conducted at the new General Electric Research Laboratory building at the Knolls in the lower Mohawk Valley in eastern New York. Complete facilities for physical and chemical studies with many unique features are available in this laboratory. Part of the laboratory in use includes a weather observatory equipped with standard, as well as special, meteorological instruments, radio communications, a small wind tunnel, and a complete photographic dark room. In addition to the laboratory areas, excellent shop facilities are available including the services of skilled technicians for special developments in mechanical and electronic instrumentation.

In addition to these facilities, meteorological observations of a specific nature are carried on by special observers at the Mt. Washington Observatory on the summit of Mt. Washington in the state of New Hampshire. This mountain observatory, at an elevation of 6288 feet above sea level, is world famous for its exceptionally severe weather, especially high winds and extended rime storms produced by supercooled clouds sweeping over the mountain. Besides having projects carried out by Observatory personnel for Project *Cirrus*, the research facilities on the mountain are always available to members of Project *Cirrus* for testing instruments and studying various types of natural orographic clouds.

In addition to the experimental research activities at the Research Laboratory, an important phase of the laboratory program is the analysis of flight data by photogrammetric methods and detailed studies of meteorological conditions present during the experiment. Considerable space in the laboratory is used for these purposes, and at least one person spends full time on this activity.

Field studies under Project Cirrus

Supplementing experimental research in the laboratory, the Research Group is involved in a considerable variety of field studies ranging from a study of the effect produced in the atmosphere by ground generators dispensing silver iodide smokes, detailed observations of various types of natural rain and snow storms, studies of the development of all types of clouds using lapse time motion pictures, determination of the concentration of condensation and sublimation nuclei which occurs in the atmosphere, and activities of a similar nature dealing with weather phenomena associated with the formation of clouds and the subsequent development of precipitation. Many observations are made in regions other than eastern New York. For example, cloud studies have been conducted by one or more members of the Research Group in northern Idaho, Wyoming, and other parts of the Northwest, Florida, Puerto Rico, various parts of New England, and Central America, particularly in Honduras. It is of great importance that cloud systems in various parts of the world be studied and their local peculiarities understood, since it is quite obvious that large differences exist in clouds, not only in their general development and life cycles but even in their microstructure. Until these variations are better understood, it will be impossible to draw general conclusions about them.

Flight operations by Project Cirrus

At the present state of our knowledge of clouds, it is of great importance that the general structure, as well as the microstructure, of clouds be explored by going into them. This may be accomplished to a limited degree by observing them at a mountain observatory using the summit as a stationary probe to study their structure as they pass by the station. The information gained in this manner is of great value but does not provide much data on convection, turbulence, and three dimensional structure which is of basic importance in studies of clouds in the free atmosphere.

The only method now reasonably satisfactory involves the use of one or more aircraft which can probe clouds at various levels and in doing so, register on automatic instruments some of the properties characteristic of the clouds explored. Good photographic techniques are of extreme value in this respect because of the complexity of clouds and the rapidity with which they change some of their features. It is impossible to obtain a satisfactory record by visual observation alone.

In this respect, some of our seeding techniques are of unique value since, for the first time, they provide a method of marking a cloud that will persist for a long time and may be seen for large distances. By taking consecutive pictures of a cloud area marked in this way, much information may be obtained during periods of an hour or more which shows the various mechanisms that are of importance in the formation and dissipation of clouds.

To carry out such a flight program effectively requires much organization and specialized training of the personnel engaged in the work. The planes involved must have a considerable amount of workable scientific equipment especially suited for meteorological studies. In addition, it is of great importance that a special schedule is followed in reporting the results of each experimental flight study.

A typical flight operation of Project Cirrus

It may be of interest to describe a typical experimental flight study conducted by the Project *Cirrus* Flight Operations Group. For this example, Flight 83 will be described since it was a two plane operation employing both dry ice and silver iodide in the seeding operation.

At 1500 on the previous day, the weather group assigned to Project *Cirrus*, comprised of Navy personnel, notified the Chairman of the Operations Group that the synoptic situation suggested the strong possibility that a suitable supercooled deck of stratus clouds might be expected the next morning. An alert was sounded, crews were assigned duties, and tentative plans set for 0900 take off in the morning using two B-17 planes.

Early the next morning, a check on the weather developments showed that the forecast was good, and each member of the flight group carried through his assigned duties prior to take off. These duties included, besides normal preflight preparations, such extra things as cleaning the windows used by the photographers, crushing and packing the dry ice in canvas bags, loading the silver iodide dispenser with fragments of impregnated charcoal, loading and checking the photopanel camera for operation, checking the operation of the automatic recording instruments, and making sure that the inking pens and charts were ready for operation.

Except for the preparation of the silver iodide and dry ice and their dispensing mechanisms, the above special activities were required for both planes.

On B-17 No. 5667 used as the seeding and probing plane, a crew of ten men were assigned for the operation including:

1 Pilot
1 Co-pilot
1 Navigator
1 Flight Controller (alternate)
1 Photographer
1 Technical Observer
1 Aerologist
1 Radio Operator
2 Flight Mechanics

On B-17 No. 7746, the photographic and observation plane, a crew of seven men included the following:

1 Pilot
1 Co-pilot
1 Flight Controller

1 Photographer
1 Aerologist
1 Radio Operator
1 Flight Mechanic

Just before take off, both flight crews assembled for a briefing at which time a brief description of the proposed flight was given by the Flight Controller, including the general objectives of the operation. After take off, the planes were to rendezvous over the Albany Radio Range at approximately 20,000 feet. When the rendezvous was accomplished, the planes would again check radio contacts and proceed together to a position about 30 miles NW of the range with the seeding plane holding a position on top of the stratus deck, the photo plane climbing but maintaining visual contact with the lower plane.

From his vantage point in the photo plane, the Flight Controller sized up the situation as favorable for a "Figure Four" seeding pattern using $^1/_2$ pound of dry ice pellets per mile of flight with a short seeding with silver iodide. He then ordered the preparations to start for dispensing the silver iodide charcoal since the seeding flight would start within a few minutes. The proposed "Figure Four" flight plan as suggested by the Research Group and adopted by the Operations Group is shown in Fig. 6.

As soon as the order to seed was given, the seeding plane went into its pattern, flying several hundred feet above the top of the slightly ragged top of the stratus deck putting out dry ice pellets for five miles, after which for one mile no seeding agent was used. The order to dispense the small burning charcoal fragments producing silver iodide was then given. About 20 seconds was required to dispense the silver iodide particles. Another one mile gap without seeding was next ordered, after which time dry ice seeding was again started and continued at the rate of ½ pound per mile until the "Figure Four" was outlined. Following this, a single dry ice pellet drop was made bracketed by a line of continuous seeding parallel to the first leg of the four pattern.

Throughout all of the seeding operation, the photo plane was cruising at 21,300 feet. For the first time, the seeded track immediately behind the seeding plane was photographed. Fig. 7 illustrates one of several remarkable photographs obtained at this time showing the speed with which the dry ice effect spreads in the wake of the seeding plane.

Shortly after take off the photopanels in both planes were started. Each panel holds the following instruments:

Rate of climb
Air speed
Altimeter
Bank and turn

Compass
Clock
Counter
Battery of station indicator lights

Automatic photographs are obtained of this instrument panel every 55 seconds while, in addition, whenever any one of four other switches at various positions are tripped an additional picture is taken. This permits the photographers, the aerologists, the flight controller, special observers or those with special assignments, such as dispensing the seeding agent, to produce a special record of any operation he might make individually as part of the flight operation.

After the seeding flight was completed, plane No. 5667 was directed by the Flight Controller to obtain low level photographs of the developing seeded pattern and, in addition, to probe the infected area to observe optical phenomena and other features that might be of interest. Fig. 8 illustrates typical photographs obtained from this plane. Since the flight was made over mountainous terrain, it was decided to forego a descent through the deep trough cut by the ice crystals. After 30 minutes of probing studies and low level photographic coverage, it was released from further cooperative observations by the Flight Controller. A total of 24 photographs were taken at various altitudes up to 3000 feet above the cloud deck.

Meanwhile, plane No. 7746 was cruising above the seeded track taking still photographs and a few moving pictures. This continued for a period of 40 minutes during which time a total of 48 photographs were obtained. Figs. 9 and 10 are typical photographs taken during this period. By this time, the Flight Controller decided that an adequate set of photographs had been obtained since the pattern was beginning to deteriorate and no new phenomena were in evidence. It should be mentioned at this point that throughout the observation flight, the entire crew in plane No. 7746 were on oxygen since the flight occurred at an altitude of 21,300 feet. The flight was then terminated with both planes heading for the base where they landed at about 1130. Thus the operation required a total flight time of approximately 150 minutes, about 40 percent of this time being employed in the experimental studies.

Procedure for reporting on an experimental flight study

The procedure now in use by the Flight Operations Group to effect a close relationship with the Research Group may be divided into four stages.

The preflight briefing – This involves the development by the Research Group of a series of experiments required to provide specific data on certain types of clouds. These requirements are studied by the Operations Group and adopted to flight procedures. A Flight Controller is designated who is directly responsible for the carrying out of the complete experimental flight. Personnel are kept on the alert for suitable cloud systems whenever the aerologists report suitable conditions within 200 miles. As soon as reasonable assurance is at hand that the type of clouds needed may be found, the planes take off, approach the system, and then follow through according to the briefing plan.

It is of great importance that the Flight Controller has several alternate plans for immediate substitution in the event that the cloud system is somewhat different than expected from the reported synoptic situation. He must have the ability to size up the situation while approaching the experimental area and thus take advantage of whatever cloud system is found.

The preliminary report – Within an hour after the flight is completed, a brief report is transmitted to the Research Group by the Flight Controller which summarizes the results as observed and the general data obtained. This includes enough detail so that it is possible for the Research Group to determine immediately whether there is need for another flight to supplement the data obtained.

Detailed flight report – A more detailed report including copies of all the raw data, all logs and notes of observers, and contact prints of still photographs obtained are supplied to the Research Group within two days. Following a review of the contact prints, the Research Group orders enlargements of all photographs which appear suitable for analysis.

Final report – Within a week or two, all supplemental data not available at the time of the second report, reduced data from the photopanel, enlargements of selected prints, moving picture film and a meteorological analysis of the weather preceding, during, and subsequent to the flight study are supplied to the Research Group to aid in the analysis. The detailed analysis of the flight is then scheduled with relation to other flight operations under study. The summary of this work is subsequently published in an Occasional Report of Project *Cirrus*.

It should be pointed out at this time that the above procedure is carried out beyond the third and fourth stages on only those operations where the accumulated data is reliable and has sufficient detail to warrant spending the time involved in carrying through a complete analytical study.

Types of cloud seedings used in Project Cirrus operations

Two types of cloud seeding as related to flight studies shall be discussed at this time—the formation of ice crystals in supercooled clouds and the development of a chain reaction in cumulus clouds using large water drops.

The dry ice effect – When solid carbon dioxide is introduced into a supercooled cloud in the atmosphere, enormous quantities of ice crystals form and produce profound changes in the cloud by the mechanism explained by the

BERGERON-FINDEISEN theory. Crystals may be produced in such large quantities that it is sometimes possible to create conditions unlike those which occur naturally in the free atmosphere.

As mentioned earlier, it is extremely uncommon to find any ice crystals forming in natural clouds until some region has a temperature of −12° C. Since the introduction of carbon dioxide ice (henceforth called dry ice) will produce ice crystals at any temperature below 0° C, many cloud systems that would not shift to snow naturally may be affected by this type of artificial inoculation.

The enormous numbers of snow crystals produced in this manner also allow us to modify unstable supercooled clouds in several ways which rarely, if ever, happen in nature. For example, it is possible by artificial means to shift all of the condensed water in a massive supercooled towering cumulus cloud to snow crystals in considerably less than five minutes. A similar cloud by natural processes normally requires an hour or more to reach the same condition and even after that time, might not be completely modified. The quantity of dry ice required to accomplish artificial modification is insignificant, since, as pointed out in previous papers [14], one gram of dry ice is capable of producing at least 10^{16} ice crystals. Fig. 11 is a photograph showing the cloud of ice crystals that trail from a single piece of dry ice falling through air. Laboratory experiments show that tremendous numbers of ice crystals stream from a small pellet as it falls through the air. In order that these crystals become effective, they must form in air colder than 0° C which is supersaturated with respect to ice. By flying above or through the cloud, dry ice particles having sizes ranging from 1 to 20 mm in diameter fall down or are carried aloft, depending on their size and the turbulence in the clouds. Natural convection and turbulence of cumulus clouds, augmented by the heat released by the change in phase from water to ice, assist in causing the rapid infection of a large region of the cloud system. Experiments show that if a concentration of crystals exceeding about 50 per cubic centimeter is present, the supercooled cloud thus infected is completely evaporated in less than 10 s. With a concentration ten to twenty times more than this, the competition between particles for the available cloud water is so great that none of the particles grow as large as the original supercooled cloud droplets. As a result, the cloud is "overseeded" and becomes extremely stable. Such overseeded clouds rapidly lose their convective activity and become very stable and persistent. Examples of overseeded clouds may often be seen to form naturally when cumulus clouds pass through the transition temperature of −39° C. Fig. 12 illustrates a typical cloud of this sort. This generally occurs at altitudes of 28,000 feet to 32,000 feet, the results appearing as anvil tops or as long streamers of cirrus clouds drifting across the sky in the tropopause region of the atmosphere. These overseeded effects, however, are rarely, if ever, observed in the natural atmosphere at warmer temperatures unless the clouds are seeded artificially or at times when natural seeding takes place due to the entrainment of snow crystals carried down from higher altitudes through stable air.

Since it is demonstrable that cold clouds may be overseeded, it follows that lesser amounts may be introduced as desired. This makes it possible to produce many interesting effects in cold and cool clouds. For example, it is feasible to seed and dissipate clouds at specific altitudes above the freezing level in the atmosphere and thus prevent the development of large vertical thicknesses of supercooling. In this way, thick supercooled clouds cannot form. Consequently, the sudden release of a large amount of energy necessary to produce thunderstorms and similar disturbances may be checked or at least reduced in intensity.

On the other hand, if it is desirable under certain conditions to go to the other extreme and attempt the release of the maximum amount of energy possible from a particular cloud system, this may be accomplished also. For this to be successful, it is necessary to wait until the maximum vertical development occurs at which time the cloud is seeded in such a manner that the optimum number of crystals are introduced to cause a rapid shift from the water to the ice phase and, at the same time, obtain the most effective particle size to initiate rapid precipitation. By properly carrying out such operations, it might at times be possible to release enough energy to break through inversions limiting the vertical development of the clouds.

The development of Precipitation by water seeding – LANGMUIR has proposed [8] a mechanism for initiating precipitation in cumulus clouds. The method involves the introduction of relatively large water drops into clouds having the following properties:

(1) They must be actively growing cumulus clouds having vertical thicknesses greater than 1–½ km.

(2) The upward vertical convection in some region of the clouds must exceed 2–½ m/s.

(3) The droplets in the cloud must have a diameter of 15 μm or more.

(4) The average liquid water content of the clouds should exceed 2·7 g/m^3.

Field studies show that most actively growing cumulus clouds having a vertical thickness of 1–½ km possess the other characteristics mentioned above.

When water drops larger than 0·01 cm diameter are introduced into a region of the cloud having strong upward convection, they sweep up the smaller droplets in their path as they are carried aloft. Most of this coalescence occurs on the under-surface of the drop since the cloud droplets move faster than the larger droplets and are thus intercepted and collected. When the growing drops become so large that the pull of gravity exceeds the vertical lift of the air current, the drops begin to fall and sweep up even more cloud particles in their path. In addition, the falling drops by virtue of their lower vapor pressure grow by diffusion since they are continually invading air that is warmer than the residual temperature of the falling drops. When the drops reach a weight of about 0·5 g, they are no longer spherical but are flattened out in the peculiar manner shown in Fig. 13. Such drops are potentially unstable and become susceptible to break-up. A small shearing force of the kind common to turbulent air is all that is required to shatter the drops into two or more smaller drops. BLANCHARD's experimental studies [18] in our laboratory show in a very elegant manner the limiting conditions of stability which restricts the size of falling rain drops.

If a growing rain drop in a cumulus cloud breaks apart before reaching the level from which it started growing, the mechanism constitutes a chain reaction. Thus one drop produces two or more; these droplets passing through the same cycle produce two or more, and within a very short time, many millions of particles have developed from the initial drop. If, for example, such an unstable drop breaks into five droplets (a common occurrence as seen in BLANCHARD's experiments), it requires only 10 cycles for more than 2 million new drops to form.

The effects which may develop from water seeding of cumulus clouds – Under most conditions, the introduction of large water drops into a convective cloud exceeding these critical dimensions might be expected to do no more than initiate a chain reaction within the cloud which would lead to its dissipation.

Since this mechanism is a mechanical one and is not related to a change in phase, no energy release is effected and, consequently, one would not normally expect anything to happen, save the disappearance of the cloud.

If, however, the precipitation develops as a chain reaction so that heavy rain forms on one side of a large convective cell, the down drafts might be so strong that an upward counter current is produced. If the air is unstable, this upsurge of air may lead to a local convergence which would certainly produce more precipitation than would normally result by the mere dissipation of the treated cloud.

The normal effect, however, which seems to be most commonly experienced when clouds are seeded by water is dissipation. This is an important feature, however, since even supercooled clouds may be affected in this manner. In respect to the dissipation of clouds, it should be emphasized at this point that many large clouds dissipate naturally, especially when the air aloft is dry. The best way to evaluate such results is to become familiar with the growth and disappearance of clouds by the use of lapse time moving pictures. Successive pictures of clouds taken by a movie camera at 2–½ second intervals and then viewed at the normal rate of 16 per second, speed the apparent development of clouds by a factor of 40 fold. A familiarity of cloud development gained in this manner permits the observer to make a critical evaluation of results which follow seeding operations.

Table 1

Mass of water vapor in saturated air (from Smithsonian Tables)

Temperature °C	Amount of water vapor in saturated air g/m³
30	30·039
20	17·118
10	9·330
0	4·835
−10	2·154
−20	0·892

Table 2

Concentration of ice nuclei in air of Northeastern U. S.
(January 1948 to September 1949 [3 hourly observations])

Number of ice nuclei per cubic meter of air	Number of observations during 18 months period
1×10^0 to 1×10^2	1194
1×10^2 to 1×10^4	1294
1×10^4 to 5×10^5	1757
5×10^5 to 1×10^7	295

(Received: October 1, 49.)

(To be continued in ZAMP I/4)

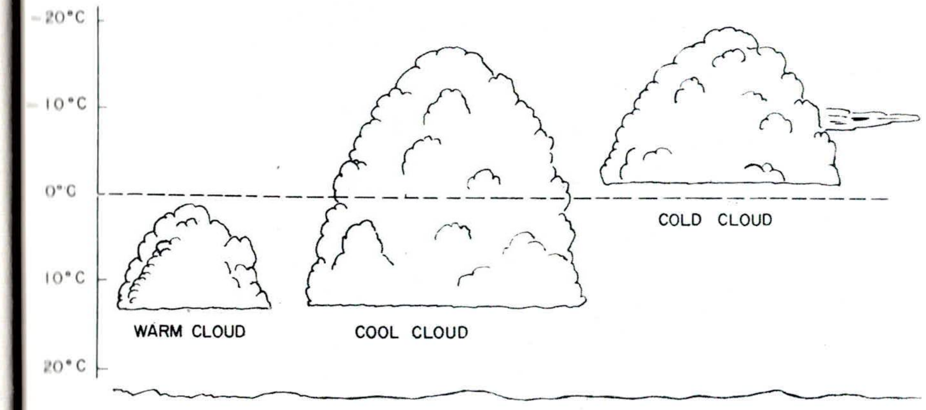

Fig. 1. Temperature relationships in warm, cool, and cold clouds.

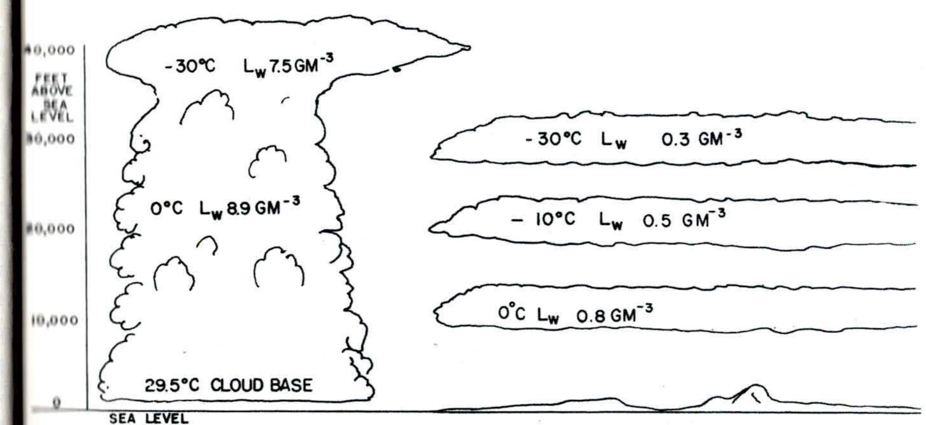

Fig. 2. Approximate maximum values of the liquid water content of supercooled cumulus and stratus clouds at several temperatures.

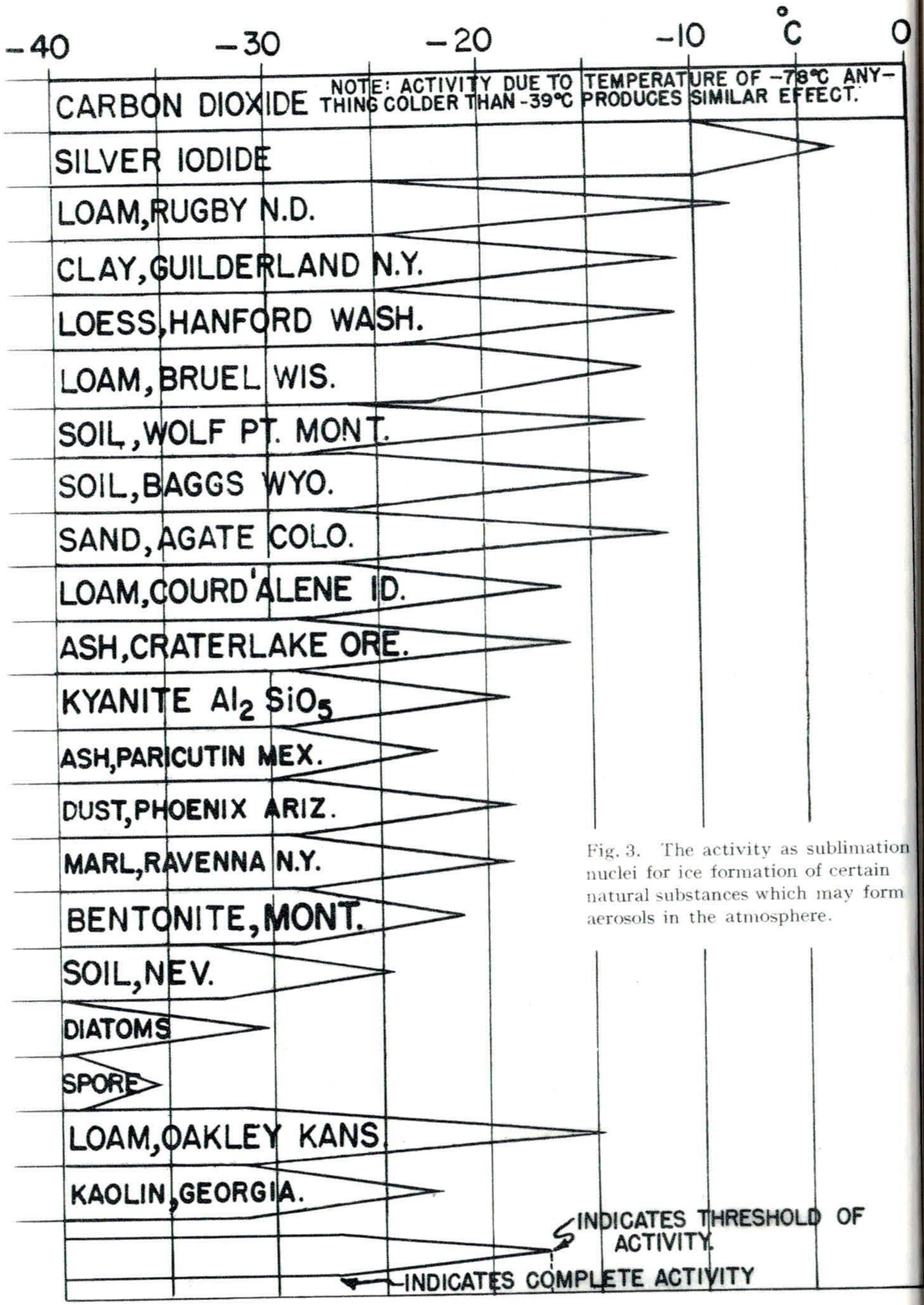

Fig. 3. The activity as sublimation nuclei for ice formation of certain natural substances which may form aerosols in the atmosphere.

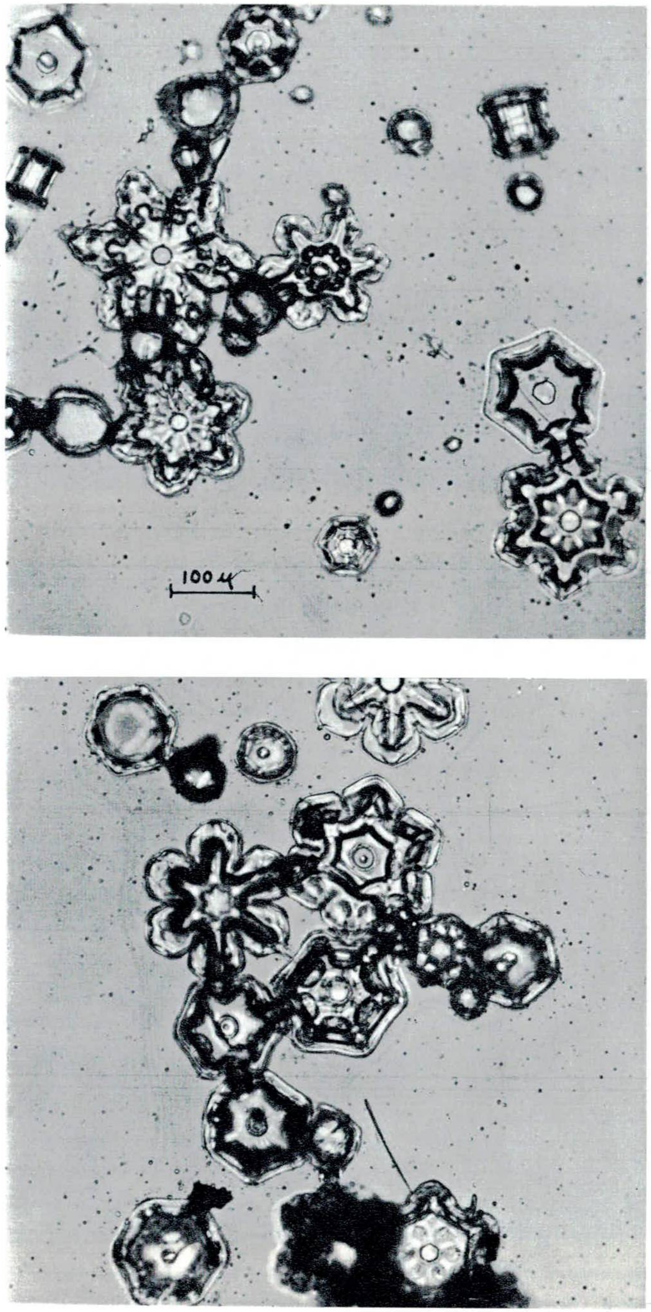

Fig. 4. Photomicrographs of replicas of snow crystals formed on frozen cloud droplets.

Fig. 5. Rain showers from warm tropical cumulus cloud without appreciable vertical development.

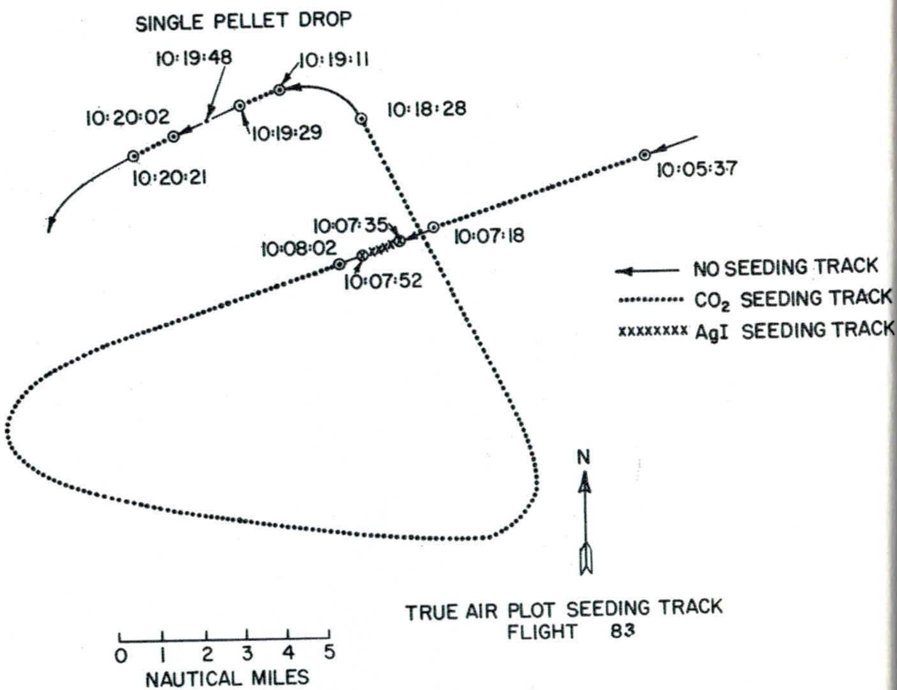

Fig. 6. Seeding pattern used in Flight 83, Project *Cirrus*.

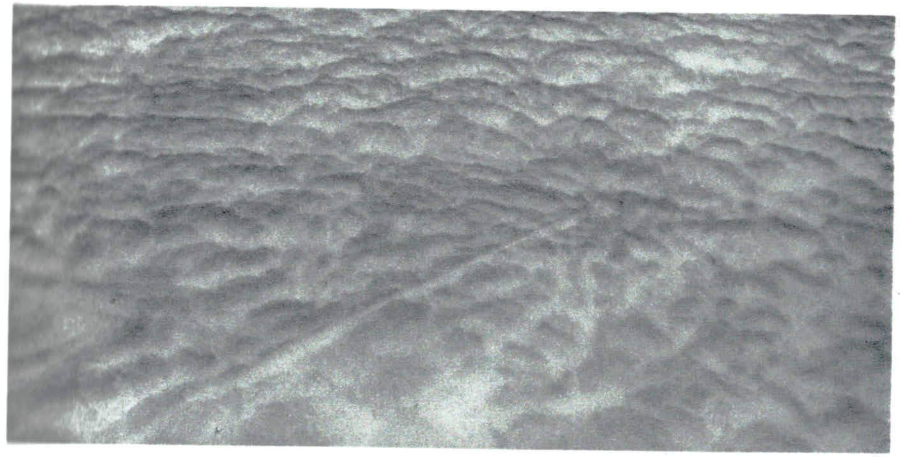

Fig. 7. View of rapidly spreading seeding track behind plane dispensing dry ice. Seeding plane several hundred feet above cloud deck. (Official Photo, Signal Corps Engineering Laboratory.)

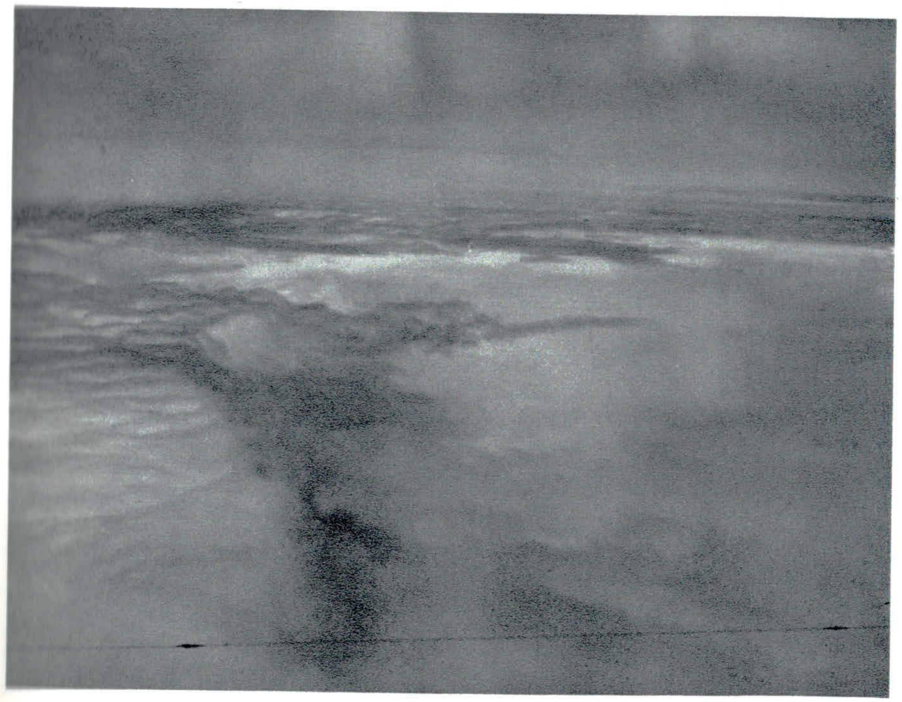

Fig. 8. View of subsiding area of snow crystals produced by dry ice seeding, Flight 73, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

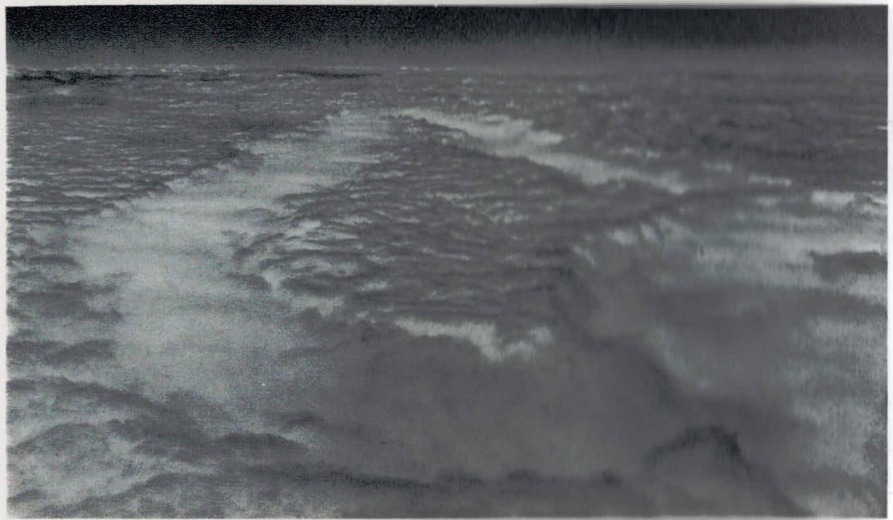

Fig. 9. View of "Figure four" seeding, Flight 83, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

Fig. 10. View of "Figure four" pattern from near apex, Flight [illegible]. (Official Photo, Signal Corps Engineering Laboratory.)

Fig. 11. Ice crystals streaming from pellet of carbon dioxide ice.

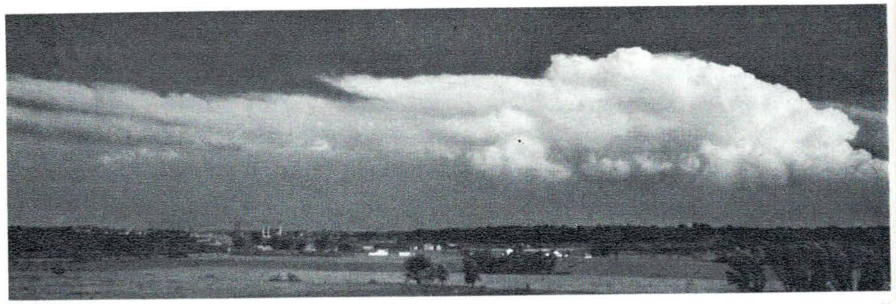

Fig. 12. View of cumulus cloud generating large quantities of ice crystals. Streamers of "false cirrus" produced by successive build-ups of cumulus.

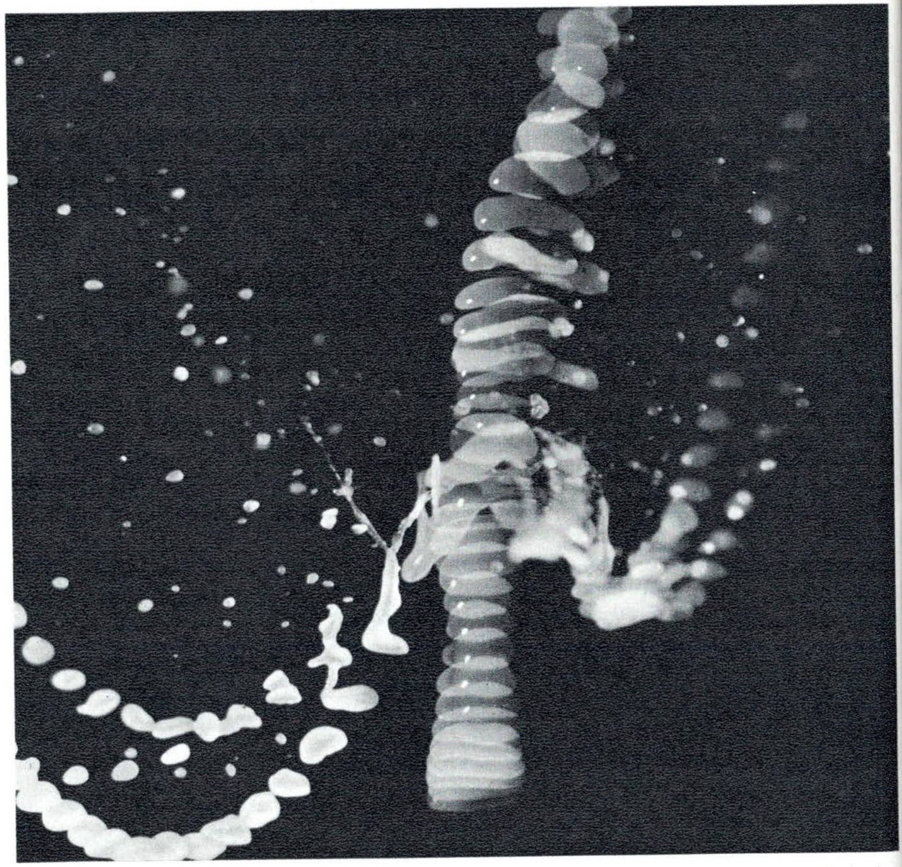

Fig. 13. The oscillations and breakup of a single large drop of water floating in air having a velocity equivalent to the terminal velocity of the drop. Illumination with high intensity stroboscopic light. (General Electric Research Laboratory Photo.)

The application of seeding methods to clouds of various types

The modification of orographic clouds

The modification of orographic clouds by seeding methods presents a particularly intriguing possibility. These are clouds which form as moist air is forced to rise as it encounters a barrier such as a mountain range. In rising, the air expands and cools as its pressure decreases. If the amount of cooling drops the air below the dew point temperature, a cloud forms.

Under many conditions, the clouds formed by orographic processes are cool or cold clouds, especially in the wintertime or when towering cumulus develop over certain mountain peaks or ridges.

The condensed water in orographic clouds in the wintertime is not very high, since it rarely exceeds 1 g/m^3. Such clouds, however, are very common in mountainous regions and often form continuously for many days. Even a cursory study of them reveals that relatively little precipitation reaches the earth from them except as rime deposits on trees and rocks or in the form of scattered snow crystals. Under most conditions observed on mountains in the northeastern United States, snow crystals do not form in sufficient numbers to use up the available supercooled cloud droplets. Consequently, only a small fraction of the clouds which form in this manner are precipitated. If techniques can be devised to cause a widespread and effective precipitation of such clouds, the depth of the snow pack in the vicinity of mountains might be markedly increased. Such a result would be of much importance since the snow pack on mountain slopes is of great importance in stabilizing the streams which flow from such regions.

The use of ground generators using silver iodide smokes is one way in which orographic clouds might be seeded. Unless such clouds form at relatively low temperatures, however, this seeding material will not be of much importance since temperatures below −10° C are necessary if an efficient production of nuclei is to occur. The concentration of nuclei must be of the order of 50 to 100 per cubic centimeter where the vertical rise of the cloud is rapid if the available cloud droplets are to be converted to snow. Whether particles of this concentration will subsequently grow large enough to form precipitation is a question which is answered best by experimentation with varying types of clouds, temperatures, wind velocities, and vertical accelerations in mountainous regions. Such particles will probably grow large enough to fall to the earth's surface if the cloud beyond the mountain summit is of sufficient thickness to sustain the growth of the particles until they become large enough to precipitate. In many instances when orographic clouds have temperatures of −10° C or colder, the liquid water content of the clouds is so low that it is questionable whether the precipitation initiated with silver iodide would be economically feasible.

The production of ice crystals in orographic clouds by the use of dry ice, liquid carbon dioxide, or similar methods requires that the crystals be introduced into air supersaturated with respect to ice. In addition to this requirement, it is also necessary that the seeding be a continuous operation. This imposes rather severe limitations on the sites where such experiments may be carried out effectively. For this reason, it is at present questionable whether a feasible method is known for carrying out the seeding of relatively thin and cold orographic clouds on a scale that would have economic importance.

A method might possibly be developed, however, making use of the riming nature of cold clouds so that very weak rime feathers are formed which continually shed tiny ice fragments into the wind. That this might be feasible is suggested by the fact that small rime fragments form a considerable percentage of the ice particles observed in the air during an icing storm. If the source of these particles was better understood, a more effective way of forming them in larger quantities could probably be developed which might not require more than the planting of certain types of sub-alpine trees or the construction of man-made structures in strategic regions on the upwind region of the mountains.

The production of regions of ice nuclei in the sky

It sometimes happens that large snow storms from low, cold clouds are started and kept going by their contact with a thin layer of middle or upper clouds, such as altostratus or cirrus. CONOVER has described [19] an interesting case of this kind.

It is a fairly common experience to note examples of the seeding of lower clouds by cirrus crystals. This latter type of observation may be deduced by

a study of the snow crystals reaching the ground during a snow storm. This condition generally produces stellar snow crystals with cirrus type hexagons in the center. This is illustrated by Fig. 14 which shows a few samples of crystals which grew in this manner.

The production of specific regions in the free atmosphere containing high concentrations of ice nuclei or potential ice nuclei is now an interesting possibility. Cold middle clouds, even though having no appreciable moisture, may be used as "holding reservoirs" to store ice crystals until they come into contact with lower clouds of greater thickness or are entrained into cool or cold cumulus. An example of this type of seeding is contained in the seeding operation during our high level study [20] of Hurricane King on October 13, 1947. A relatively thin layer of stratus clouds covering an area of nearly 300 square miles was transformed to snow crystals. The subsequent fate of these ice crystals is still a moot question, but if a considerable region of them was entrained into the lower levels of a line of towering cumulus observed during the flight located in the southeast quadrant of the storm, the entrainment of these snow crystals might have exercised a profound effect on the subsequent development of these cumulus.

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

It will take much careful study to establish methods for utilizing this type of seeding. Eventually, it may become one of the most important of all.

A discovery that would have great importance in this respect would be a stable sublimation or freezing nucleus which would be effective at a temperature within one or two degrees below 0° C. It is obvious from the observations made thus far that natural nuclei of this kind are rarely, if ever, formed. It thus remains for us to find or develop a substance in the laboratory which will fit the requirements.

The modification of stratiform clouds

The widespread modification of stratus clouds by artificial means is possible at the present time whenever such clouds are supercooled. Under such conditions, the clouds may be further stabilized by overseeding them or their precipitation may be accomplished by using an optimum number of ice nuclei. This latter result is achieved by using only enough ice nuclei to cause the cloud particles to evaporate completely as they condense onto the crystals thus formed which then grow large enough to fall as snow.

Typical results obtained in seeding cold stratus clouds are shown in Figs. 15, 16, 17, 18, 19, and 20.

Stratus clouds may be seeded by flying 30–100 m above them and dropping dry ice fragments ranging in size from 0·1 to 1 cm diameter at the rate of approximately 250 g (½ pound) per mile. Except with clouds thicker than 2 km (6500 ft.), the use of more than one pound of dry ice per mile will tend to produce overseeding.

Besides seeding stratus clouds from on top, it is also possible to seed them effectively by flying through them as well as by flying at the cloud base. At this lower position, however, there is no need of using large fragments since the dry ice is only effective in air supersaturated with respect to ice. A zone below the cloud base equivalent in depth to approximately 10 m per degree centigrade below freezing will support the formation of ice crystals formed with dry ice. Thus, if the temperature at the cloud base is −10° C, a distance of 100 m below the cloud will become filled with ice crystals if dry ice fragments are sprinkled or liquid CO_2 is sprayed into that region.

The modification of supercooled ground fogs

While warm ground fogs formed by advection or radiation may only be modified at present by heating the air to cause its evaporation, supercooled ground fog formed in a similar manner may be modified and even dispersed if care is exercised to prevent overseeding.

In order to disperse a cold fog of this sort, it is necessary to use up the available condensed water by seeding with only enough ice nuclei that the crystals grow large enough to precipitate. An average concentration of about 20 ice nuclei per cubic centimeter is about the number required to produce this effect.

If higher concentrations are used, there is a real danger that the density of the fog will actually increase, thus reducing the visibility to a remarkable degree. Since most ground fogs rarely contain more than 200 particles per cubic centimeter, it is a simple matter to produce 10,000 per cubic centimeter of ice crystals in the same volume of air. This not only reduces the visibility but also makes the fog considerably more stable due to the very small particle size and the further removal of moisture from the air.

Very peculiar optical effects occur in an overseeded cold fog. The outline of objects near the limit of visibility become extremely fuzzy and of an unreal appearance. In addition, the light scattered in the fog has a peculiar bluish cast due to the Rayleigh scattering from particles small with respect to the wavelength.

The prevention of the formation of ice fog is another possibility that may be attained by the proper manipulation of seeding techniques. By introducing an optimum number of sublimation nuclei into the air in regions where such fogs are troublesome, it may be possible to continuously remove the moisture

from the air which is responsible for the formation of this interesting but often troublesome type of ground fog.

The ice crystals generated in the vortices of airplane propellers plus the moisture added to the air by the combustion exhaust of the plane are the effects which generally lead to the formation of ice fogs at airports.

Whether the removal of supersaturation with respect to ice by seeding methods will be of sufficient magnitude to prevent ice fogging effects produced by plane operations can be determined most conclusively by actual experimentation.

The modification of icing clouds for the protection of aircraft

This effect suggests an interesting possibility—the elimination of icing clouds in the vicinities of airports and along heavily traveled air lanes. There is no question about being able to accomplish the modification. The problem which exists at present is whether or not it may have a practical application.

Low clouds which restrict the visibility for landing approaches around airports, thick clouds in which planes must cruise as they wait for permission to land, and thick clouds which might deposit a serious icing load on a plane as it tries to climb up through them—these comprise hazards to safe plane operations. Whenever such clouds are supercooled, they may be profoundly modified as shown in Figs. 21 to 24. The practical and economic importance of such operations can only be determined after detailed studies are made in regions where such problems are thought to exist.

The simplest means for carrying out such cloud modification operations is to employ a plane well equipped for flying under serious icing conditions. Such a plane would be assigned the job of patrolling the air lanes, reporting weather and cloud conditions and whenever serious supercooled clouds occurred, would carry out seeding operations. A more direct means for protecting individual planes may be the use of projectiles for modifying the cloud directly ahead of a plane. This hardly seems practical for peace time operations, however, since a considerable hazard is involved in shooting anything into clouds.

Perhaps the most serious limitation to this use of cloud modification is the fact that at the present extent of our knowledge icing clouds are nearly unpredictable. The indefinite persistence of such clouds because of their unstable nature is the feature that will probably prevent any effective use of this application of cloud seeding within the near future.

In flying through a supercooled cloud, the airplane itself may produce a fairly effective modification since the vortices which form at the trailing edge of the wings and particularly from the propeller tips form large numbers of ice crystals as the expanding air in the vortex cools below −39° C. Laboratory studies of this effect indicate that as many as 10^{12} nuclei per cubic centimeter may be formed in this manner. It is significant that when aircraft icing studies are carried out in supercooled clouds, it is difficult to obtain an accumulation of ice on the plane by making successive passes through a particular cloud. After the first traverse, the icing property of the cloud is radically changed, and it is often impossible to find any supercooled cloud in a region where heavy icing was present a few minutes earlier.

The modification of orographic thunderstorms

An extremely important type of orographic cloud is the towering cumulus. In most mountainous regions, certain peculiar topographic features combine to favor the local formation of clouds. At certain seasons of the year, the clouds generated by these "cloud breeding" regions develop into such large cumulus that they become thunderstorms. Such storms once formed often become detached from their site of development and produce violent disturbances. This aspect of these clouds will be discussed in a later section.

Since orographic cumulus formations are common in specific regions [21], they provide nearly ideal conditions for research studies and the evaluation of various techniques in experimental meteorology.

It may be possible that silver iodide seeding from ground generators would be particularly useful in modifying orographic cumulus to prevent their growth into thunderstorms. By determining the air trajectory from the ground into the cold part of the cloud, potential ice nuclei may be sent aloft by a very simple procedure. Since silver iodide particles become quite effective in the region between −12° C and −16° C at which temperature the largest differential exists between the partial vapor pressures of water and ice, it is quite possible that such clouds could be profoundly modified by permeating their general area with effective ice nuclei. If subsequent experiments indicate that it is important to seed such clouds at a temperature only a few degrees colder than the freezing point (0° C), it may become necessary to use dry ice dispensed from planes or carried into the clouds by free balloons or projectiles.

The pioneer work, however, must be accomplished using, if possible, both ground observation stations and aircraft. Aircraft alone must be used if the nature of the region precludes the use of ground stations.

The potential precipitation contained in clouds

From quantitative considerations, it is obvious that unless convergence of moist air occurs during the development of clouds and precipitation, the amount of rain or snow that may reach the ground is at best of minor importance in relation to the water resources of the earth. For example, a cloud having a vertical thickness of 2 km and an average liquid water content of 1 g/m³ would produce only about 2 mm of rain if completely precipitated.

With towering cumulus, however, having a vertical thickness of 5 km and an average liquid water content of 3 g/m³, the precipitable water is more than ½ inch. Since such clouds are potentially unstable, the sudden conversion to rain might also lead to a local lifting of moist air which could produce even more precipitable water. Such clouds may often be seen to form and dissipate without producing any precipitation. It is for this reason that careful studies should be conducted to learn everything possible about the physical and colloidal properties of towering cumulus.

The modification of towering cumulus

As indicated in the last paragraph, the cloud structure of great economic importance is the towering cumulus. While such clouds often are produced by orographic lifting, they also form over flat country at times when the atmosphere is conditionally unstable. Differences in ground heating and contact effects between warm and cold air along frontal systems often lead to the formation of large regions of such cloud structures. If local conditions permit the continued development of such storms within two to five hours, they may develop into thunderstorms. Dangerous and often deadly lightning strokes, torrential rains, destructive winds, and sometimes hail and tornadoes are the end products of such developments.

Invariably such storms in their formative stages are characterized by a high liquid water content, strong vertical velocities, and supercooled clouds whose vertical thickness may exceed 5 km before many ice crystals form.

This large volume of supercooled cloud is invariably observed during the initial stages of a thunderstorm and must, to a large extent, be responsible for the sudden outbreak of such storms once their growth exceeds a critical stage. The large degree of instability due to supercooling may be altered within a few minutes as ice crystals invade the cloud. The large amount of energy released in this process provides additional impetus to the vertical development of the storm. The rate at which this shift in phase takes place is one of the important variables determining the subsequent progress and development of the storm. Since under some conditions, the increase in temperature alone may exceed 3° C, the total amount of energy released in this manner is of tremendous magnitude. In a relatively small storm, it may be equivalent to that released by several atomic bombs.

It is the presence of thick supercooled clouds which raises the distinct possibility that profound changes may be induced in cloud systems which are growing into thunderstorms.

Since the high, vertical thickness of a supercooled cloud seems to be a basic requisite in the formation of a thunderstorm, it may be quite feasible by proper seeding methods to prevent this phase from developing.

The manner in which this seeding is done may produce a wide variation in the end results obtained. By seeding each cumulus tower with large numbers of crystals shortly after it rises above the freezing level, the cloud would be continuously dissipated and no extensive regions of supercooled cloud could develop.

On the other hand, it might be desirable to seed such clouds to realize the maximum possible energy release. This presumably would involve seeding each cumulus tower just previous to the point of its maximum development. If this could be done effectively, it might be possible to build the storm into a much larger one then would develop under natural conditions.

The prevention of hail by seeding methods

Of considerable economic importance is the possibility that hail storms might be prevented by seeding techniques. Hail is believed to form under conditions of strong vertical convection in cumulus clouds having a high liquid water content but low concentrations of ice nuclei. With relatively few active nuclei within supercooled clouds at temperatures between −5° C and −20° C, hail particles may grow very rapidly by the difference in the partial vapor pressures of water and ice aided by the agglomeration of relatively large supercooled water droplets.

If large numbers of ice nuclei were present, the competition for available water would be so keen that no particles could grow very large. The importance of silver iodide for this type of modification is obvious since it might be practical to use ground generators positioned in such a way that these sublimation nuclei would be carried into the clouds by entrainment. Since silver iodide particles become quite active at temperatures colder than −10° C, this substance should be quite valuable for this application if a reliable technique can be developed to get the nuclei into the critical regions for it to be effective.

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

To accomplish the desired results, it may be necessary to build up a concentration of nuclei of the order of not less than 100 per cubic centimeter in all the air likely to be involved in forming the cloud. With efficient generators, this should be possible using approximately 100 mg of silver iodide for one cubic kilometer of air.

The apparent limitations to the modification of cloud systems

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

Foremost of these is the factor of cloud size and type. Certain clouds, such as the fair weather cumulus (*cumulus humilus*), have such a small volume and restricted area that, even though they are easily modified when supercooled, their total liquid water content is inconsequential. As pointed out in a previous section, even clouds of considerable vertical thickness contain but relatively small amounts of condensed water. Another complicating factor is that the air below larger clouds is sometimes so dry that a considerable amount of precipitation evaporates before it reaches the ground.

Another type of cloud which is difficult to modify is the warm ground fog formed by radiation or advection. Such fogs are often extensive and of considerable economic importance, especially from the standpoint of airplane traffic control. The natural structure of a fog precludes any simple method of modifying it. Generally, the vertical thickness is not more than a hundred meters or so with a cloudless sky above. This rules out the modification from above by forming precipitation in higher clouds to "rain out" the fog. On the other hand, supercooled ground fog may be modified and, in some cases, dispersed by the intelligent application of presently known methods of infecting the atmosphere with seeding agents.

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

A typical drought condition of this type occurred in New York state between June 1 and June 25, 1949. A dome of high pressure of great stability developed over the northeastern part of the United States and resisted the encroaching movement of a cold front to the westward. This high became stagnant for nearly a week and then slowly moved eastward causing the persistent movement of fairly moist and very warm air from the south. Cumulus clouds occurred with increasing frequency after a week of nearly cloudless skies but were restricted in their vertical development by a layer of dry air existing between 8,000 feet to 16,000 feet where the temperature ranged from +8° C to −6° C and the mixing ratio fell from 6 g/kg to less than 1 g/kg of air. The cloud structure was mostly of a diurnal nature with the nights being cloudless, while the greatest development occurred toward evening due to the convection produced by the sun.

On the evening of the fourteenth day, a few widely scattered and very local showers occurred coming from single cloud systems. Fig. 25 illustrates a cloud which produced a brief shower as it passed across a strip about two miles wide by ten miles long. The cloud dissipated in about an hour, the average amount of rainfall within this area being considerably less than 0.05″—scarcely enough to lay the dust. If a number of clouds of this kind formed rain in succession, the accumulated moisture might be of importance. Unfortunately, the development and dissipation of this cloud required nearly two hours and eventually, reduced the cloud cover to zero since the heating effect of the sun needed for this type of cloud formation was no longer present due to the late hour of the day.

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

An interesting and valuable analyses of the relationship of cloud types and systems and the possible effect which might be produced in them by artificial seeding operations has been presented recently by BERGERON [22]. Papers of this kind are of the utmost value, especially when they consider and evaluate the results of laboratory and field operations. It is the feeling of the writer, however, that such evaluations must be limited at the present time to a consideration of the cloud systems in regions of the world familiar to the observer. Generalization without observational data may raise obstacles which are not truly valid.

A series of experiments [23] carried out in Ohio by a group associated with the United States Weather Bureau have reported results which they have interpreted as of doubtful economic importance. A study of the results which they describe could be interpreted with a more optimistic viewpoint as confirming many of the claims made thus far by other workers in the field.

In view of the present relatively crude techniques and rapid advances now being made in the field of experimental meteorology, it may be wisdom to refrain from making world-wide generalizations until more experimental and observational data becomes available.

The research related to experimental meteorology which is underway in such places as Australia [24], South Africa [25], Hawaii [26], Canada [27], and Honduras [28] are typical examples of the attitude which is necessary to gain

a proper perspective of the possibilities and limitations of cloud modification in various parts of the world.

Acknowledgments

The size and scope of many research projects at the present time makes it difficult, if not impossible, to adequately define and give credit to those responsible for the success of a project. A well coordinated team of enthusiastic workers becomes more and more a necessity. Because of their interrelated responsibilities, it is nearly impossible to place credit where it is due.

This is particularly true with respect to Project *Cirrus* which enjoys the cooperative effort of members of the Army, Navy, Air Forces, as well as the General Electric Research Laboratory.

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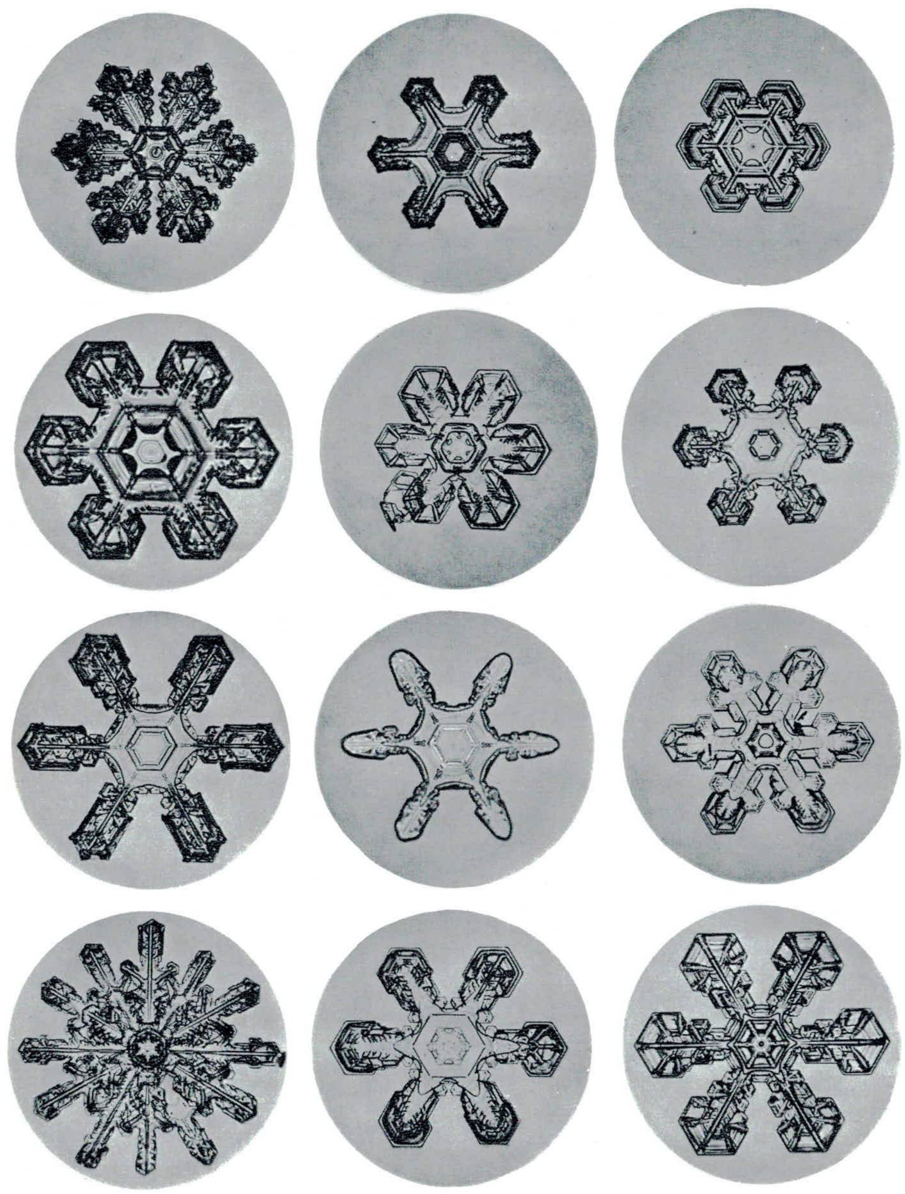

Fig. 14. Photomicrographs of stellar crystals formed on cirrus type hexagons

Fig. 15. Portion of 15 miles long "L" pattern produced with about 1-½ pounds per mile of dry ice which resulted in overseeding effect. Note reflection. Flight 3, April 7, 1947, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

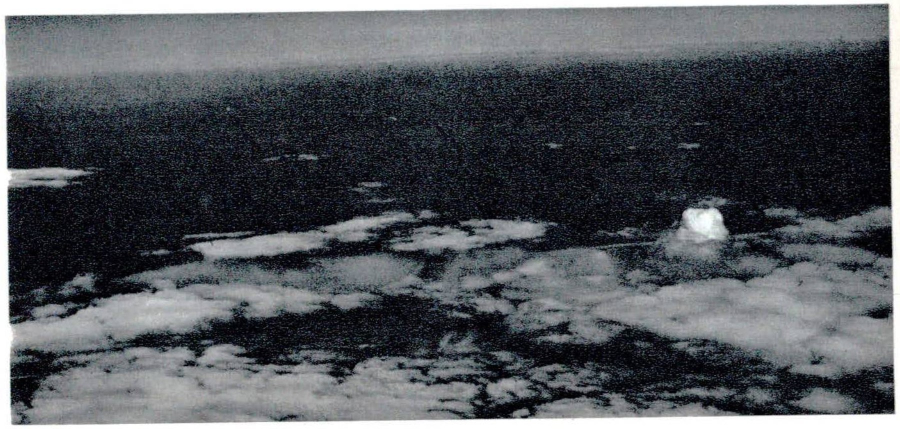

Fig. 16. Remnants of six separate spot drops of 1-½ pounds of dry ice. These six ice crystal clouds persisted after all other supercooled clouds dissipated. Flight 23, April 29, 1948, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

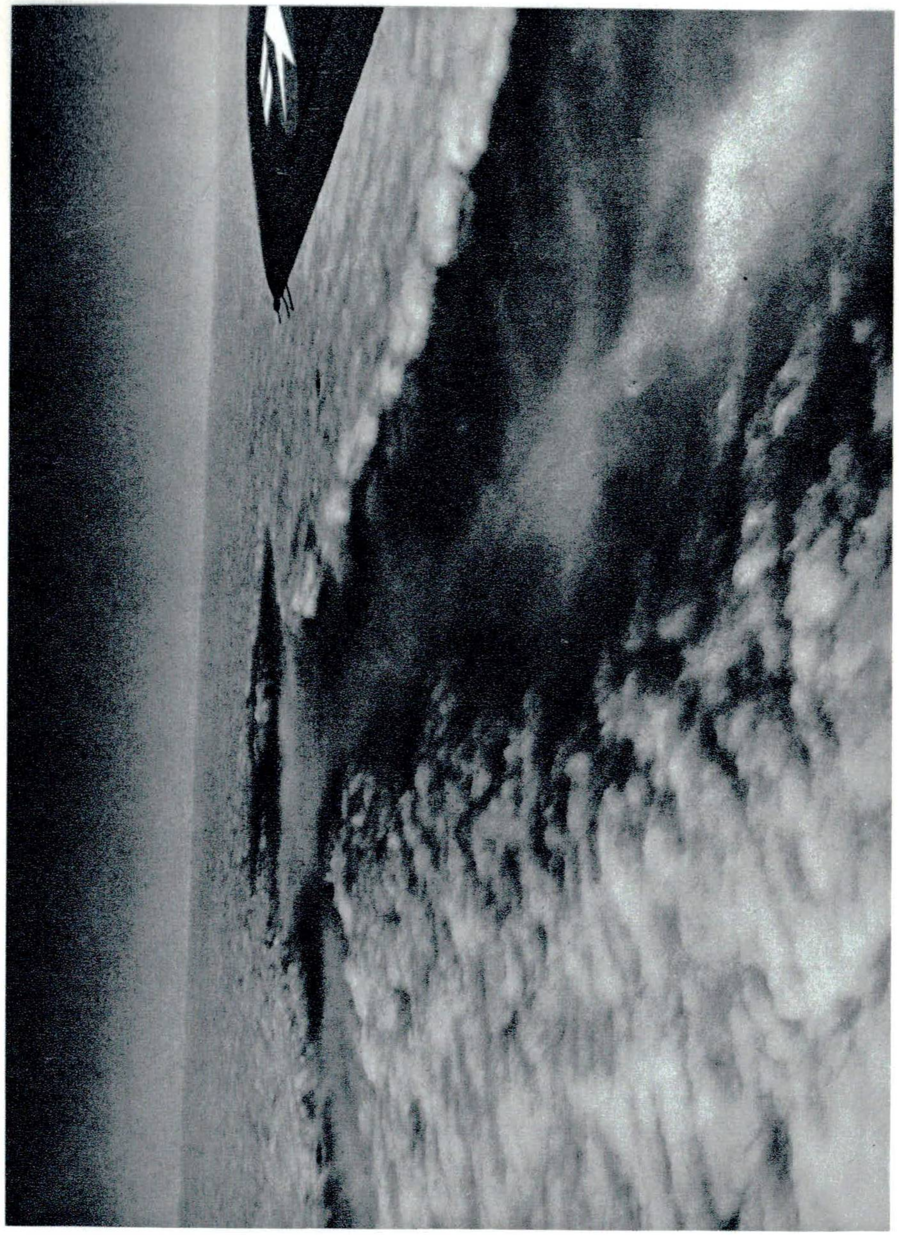

Fig. 17. A view of the "Gamma" pattern after 21 minutes produced by seeding with dry ice pellets at the rate of 1·3 pound per mile. Each leg (not all shown) about 30 miles long. Flight 52, November 24, 1948, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

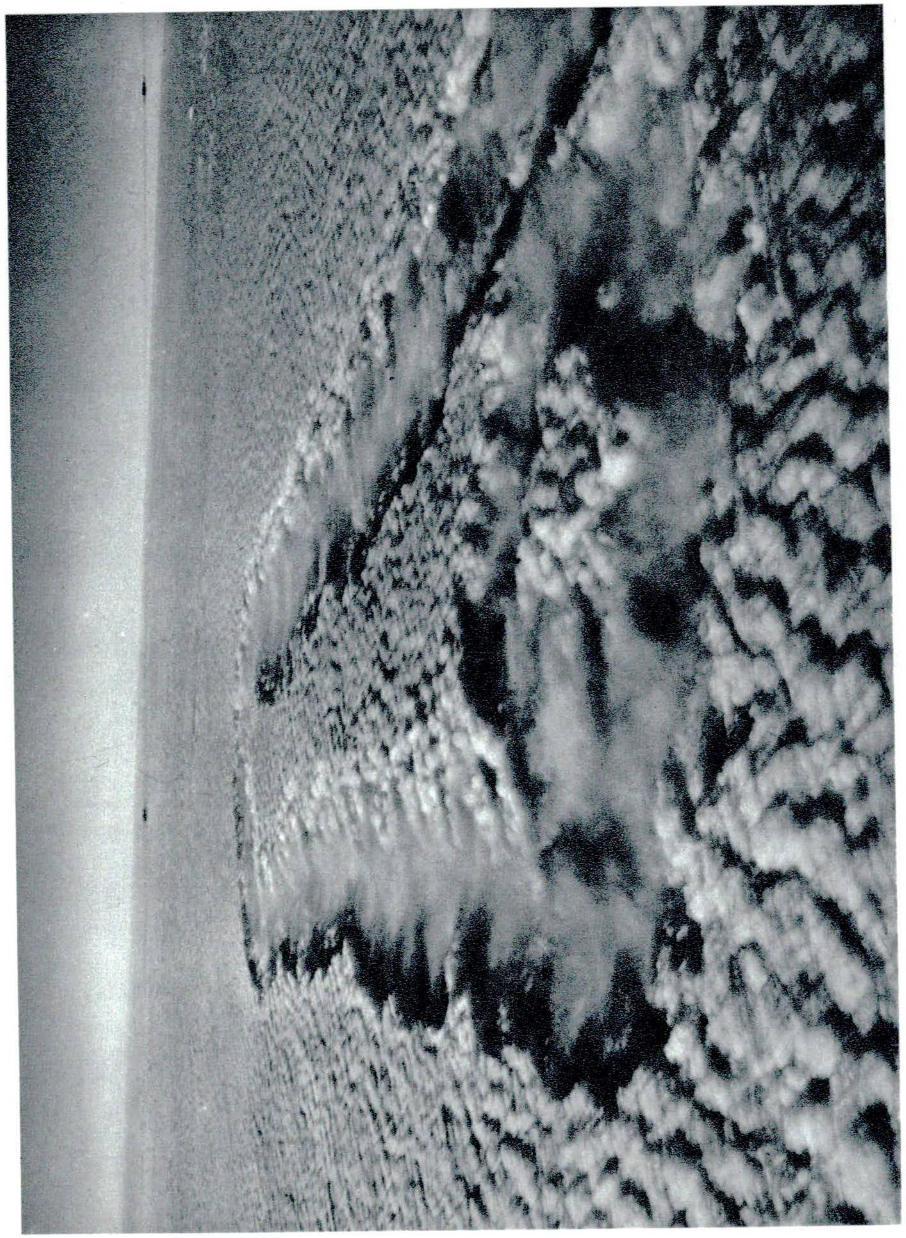

Fig. 18. View of "Racetrack" pattern produced with dry ice seeding using less than one pound of dry ice per mile of flight. Straight legs are 18 miles long. Flight 53, November 24, 1948. Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

Fig. 19. View of "Figure Four" pattern produced by dry ice seeding. Legs 10 miles long. Flight 73, March 10, 1949, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

Fig. 20. View of two "L" type patterns produced by dry ice seeding of supercooled stratus cloud. Flight 80, March 31, 1949, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

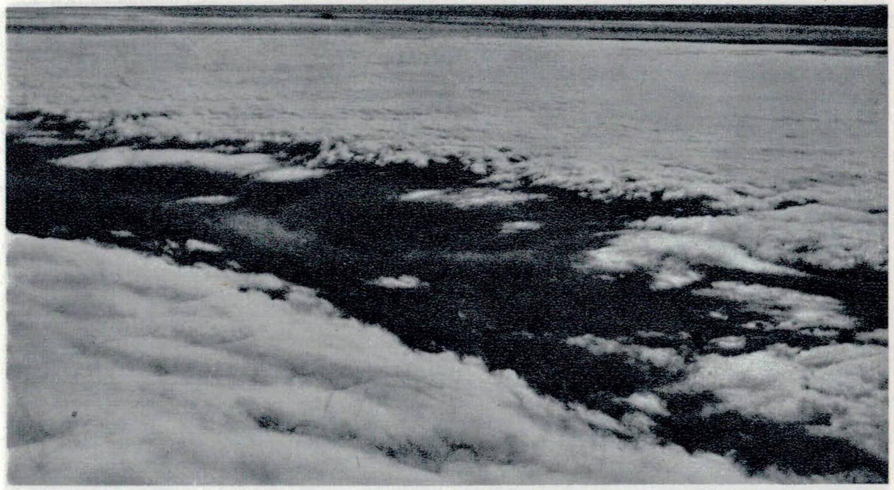

Fig. 21. View of a large gap in an overcast produced by dry ice seeding with new clouds beginning to fill in the empty spaces. Flight 52, November 24, 1948, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

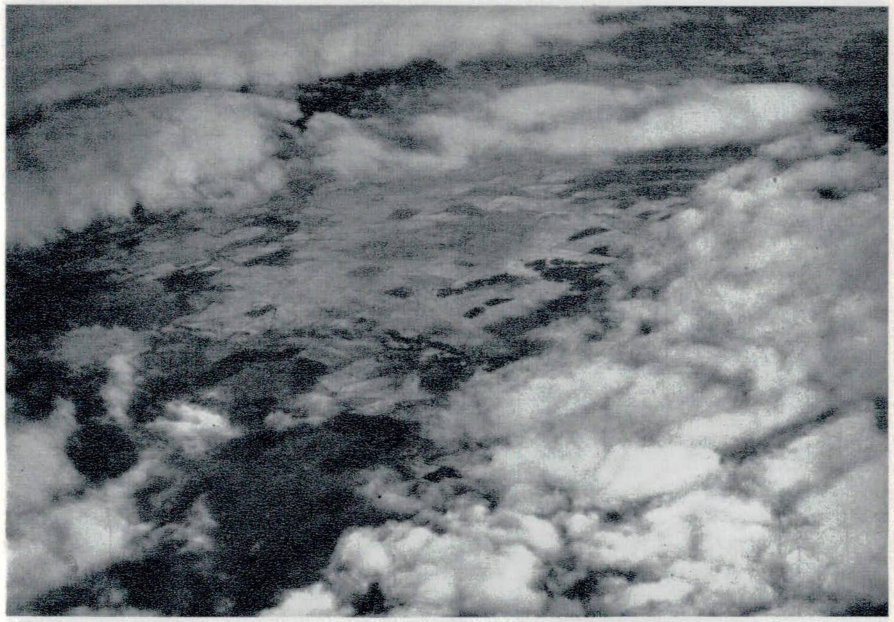

Fig. 22. Portion of nearly 250 square miles of stratus cloud removed by seeding at rate of 1·3 pounds per mile. Flight 52, November 24, 1948, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

Fig. 23. Hole having an area of 70 square miles cut into a stratus cloud by a dry ice seeding in an "L" pattern. Flight 23, April 29, 1948, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

Fig. 24. Large area of supercooled stratus cloud modified with dry ice. Flight 83, Project *Cirrus*. (Official Photo, Signal Corps Engineering Laboratory.)

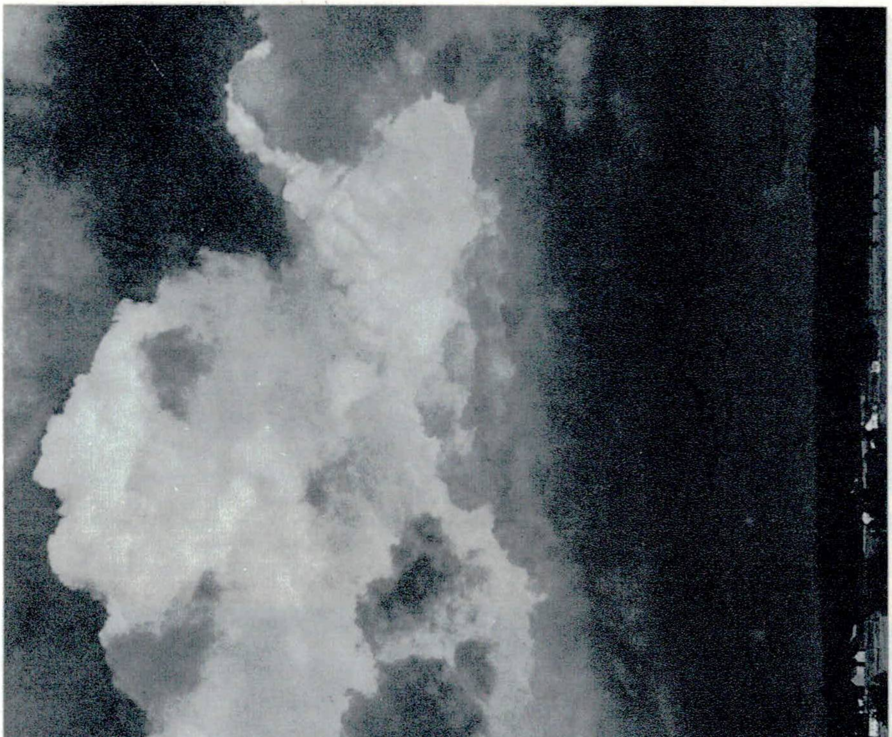

Fig. 25. Appearance of cumulo-nimbus cloud system which produced the first local showers on the fourteenth day of a drought in Eastern New York.

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SUBJECT

LOCATION

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+
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(Research Laboratory)

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Miss Alice Neil, Research librarian, called my attention to the accompanying proofs of an article by Vincent Schaefer which embodies the material that he gave last summer before the United Nations conference on the "Conservation and Utilization of Resources, at Lake Success. It is to be published in the ZÜtschieft für Angewandte Mathematik und Physik, Zürich by Dr. R. Sänger, Editor.

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Dr. Schaefer has returned another proof to the editor with his corrections, so it would be very difficult to make any changes at this time, however, I believe that this is more restrained than the other article which we were discussing and so there should not be any difficulties. I believe that Vince is anxious to get this copy back so please return it to him either directly or through me, as soon as possible.

Very truly yours,

Jim

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No objections from Public Relations standpoint.
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