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AIR WEATHER SERVICE

AN INTRODUCTION TO WEATHER MODIFICATION

By
Herbert S. Appleman

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PREFACE

The Air Weather Service mission includes the field testing and operational application of weather-modification techniques. It is increasingly probable that at some stage in their careers AWS personnel will be called upon to support one or more weather-modification projects. This report has been prepared to provide the basic knowledge in the fields of cloud physics and weather modification required to furnish such support.

HERBERT S. APPLEMAN
Chief Scientist, AWVPS
Hq Air Weather Service
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Chapter 1

INTRODUCTION

It is useful to start out by differentiating between climate modification and weather modification. The former concerns changes effective over large areas and long periods of time. Among the many suggested projects in this field are warming the Arctic by damming the Bering Strait, melting polar ice caps, and altering the amount or distribution of insolation received by the earth. However, even if such objectives could be achieved (a doubtful proposition in the foreseeable future), unpredictable by-products of the operation could well be catastrophic. Resulting calamities might include the flooding of heavily populated coastal plains, the turning of fertile areas into deserts, the destruction of fish, bird, and animal life, and the propagation of destructive insects and diseases into susceptible areas. Despite the realization that man is not yet ready for experiments in climate control, inadvertent climatic changes may possibly be taking place today. It has been suggested that the release of CO_2 from the combustion of coal and hydrocarbon fuels may significantly increase the greenhouse effect of the earth's atmosphere. Similarly, the effect of high-altitude aircraft and rocket-exhaust products in the very thin upper atmosphere, including the release of CO_2 and water vapor and the possible destruction of ozone, may in time lead to changes in our environment. Combustion products from factories and automobiles could add ice nuclei to the air (see chapter 2B) and perhaps affect precipitation.

Weather modification, the subject of this report, refers to the alteration of weather phenomena over a limited area for a limited period of time. Major goals include the increase of precipitation, the dissipation of fog and stratus, the modification of thunderstorms to eliminate or decrease hail, lightning, and strong winds, and the treatment of hurricanes to reduce their intensity, shorten their life, or alter their course. Other weather-modification operations that have been considered, but less urgently, include the prevention of precipitation and the creation of cloud decks in clear air. All the above have been attempted in the past.

Weather modification is frequently considered as synonymous with cloud seeding, because it usually involves attempts to alter in some way the life cycle of a cloud or cloud system through the addition of a foreign substance. Therefore, in order to develop effective weather-modification techniques, it is necessary to understand something of the natural cloud processes. However, the science of cloud physics is still relatively new, and some of the most fundamental processes involved are not fully understood. Consequently, the following discussion includes not only well-verified facts but also theories that, while reasonable in view of available observations, cannot yet be considered as completely proven.

Chapter 2

THE FORMATION OF CLOUDS

SECTION A — CONDENSATION NUCLEI

When a parcel of air is lifted — e.g., through frontal, orographic, or thermal effects — it encounters reduced pressure, expands, and cools. Since the amount of water vapor a parcel can hold varies directly with its temperature, the relative humidity of the parcel increases. When it reaches approximately 100% with respect to a plane water surface, the excess vapor condenses out and forms a cloud of minute droplets. Inasmuch as a curved water surface has a higher vapor pressure than a flat surface, the ability of the new droplets with their tremendously great curvature to exist at 100% humidity is something of a paradox. In fact, laboratory tests carried out on highly purified air samples show that a relative humidity of 800% is required for droplet formation. At this high concentration of water vapor, sufficient water molecules are able to cluster together as a result of random collisions to form a droplet large enough to have a vapor pressure less than that of the highly supersaturated air. Fortunately, the atmosphere is not so pure as to require such high relative humidities for droplets to form. In fact, air contains an abundance of particles (aerosols) upon which droplets can grow at relative humidities of 100%.

Atmospheric particles range from roughly 0.001 to 10 microns in radius. (One micron, denoted by the symbol μ, is equal to 10^{-4}cm.) The smallest aerosols are the so-called small ions of air, produced by cosmic rays and radioactivity emanating from the earth. These require saturations of around 400% before they can act as condensation nuclei, and hence play no role in cloud formation. Next come the very fine dust particles ranging from about 0.005 to 0.2 μ, called Aitken nuclei. Most of these, too, require supersaturations well above 100%. The only particles believed to be important to the condensation process are the very largest Aitken nuclei and the so-called large (0.2 to 1 μ) and giant (1 to 10 μ) condensation nuclei. Particles larger than 10 μ in radius are too heavy to remain airborne sufficiently long to be an important source of condensation nuclei.

Attempts have been made to analyze the composition of the various aerosols by use of electron microscopes and other techniques. The Aitken nuclei are too small for such analysis. The large and giant nuclei are believed to consist largely of hygroscopic particles, mainly sea salt or combustion products, frequently in combination with a small dust particle. These nuclei, with their relatively large surfaces, are able to serve as a basis for cloud-droplet growth at humidities of about 100%.

Over the oceans, where combustion products are scarce and only salt particles are present in important numbers, the air contains relatively few nuclei. As a parcel of air rises past the condensation level, the excess vapor condenses out on the available nuclei, producing relatively few, large drops — perhaps 30/cm^3. Over land, condensation nuclei are much more prevalent, so that clouds generally contain many small droplets — perhaps 300/cm^3. As seen later, this difference between maritime and continental clouds has a significant effect on the resulting precipitation processes.

SECTION B — FREEZING NUCLEI

Studies have shown that, regardless of temperature, nearly all cloud particles are initially formed as minute droplets on condensation nuclei. However, at sufficiently low temperatures the droplets freeze and continue growth as ice crystals. Although bulk water freezes near 0°C, water droplets remain liquid at much lower temperatures. This phenomenon is called supercooling. It arises from the fact that more energy is required to organize the water molecules into a crystalline (i.e., ice) structure than is available. A supercooled droplet is metastable, since it will remain liquid unless it can be pushed over the energy barrier into the still more stable ice phase. Thereafter, as long as the temperature remains below 0°C, the particle will remain in the ice phase.

The transformation from liquid to ice can be initiated by supplying the additional energy needed to overcome the energy barrier; this happens, for example, when supercooled droplets are struck by and freeze onto an aircraft wing, resulting in aircraft icing. Freezing can also be initiated by reducing the energy required for a crystalline structure to form. This can be done by cooling the droplet further, thus slowing the motion of the molecules, or by inserting an impurity into the droplet that has a structure upon which the water molecules can easily arrange themselves into ice-crystal form (a process known as epitaxy). Such impurities are generally crystalline in structure themselves, and are called freezing nuclei or ice nuclei.

Laboratory tests have shown that the freezing temperature of pure water droplets range from about -35°C for the larger droplets to -41°C for the smallest. In nature, however, some cloud droplets freeze at temperatures of

-15°C or even warmer. The freezing temperature varies with the composition, quantity, and size of the freezing nuclei present, also with the size and age of the droplet. (Among other reasons, larger and older droplets are more likely to contain an effective freezing nucleus.) It is still not certain what materials comprise the bulk of the natural freezing nuclei, but many authorities believe that clay particles are most important.

Unlike condensation nuclei, the concentration of freezing nuclei in the atmosphere is relatively sparse. A cloud often contains 100 or more droplets/cm^3, each formed on a separate condensation nucleus. The number of freezing nuclei, on the other hand, can be as low as 1 nucleus/m^3 effective at -10°C, 100 at -20°C, 1000 at -30°C, and 1,000,000 (i.e., 1/cm^3) at -35°C. (Higher concentrations have been measured in other air samples.) The reason for the great variability with temperature is that only the most efficient nuclei are able to overcome the energy barrier at -10°C, while at -35°C even the poorest nuclei are able to initiate the freezing process.

In general, long-lived stratiform clouds are predominantly ice crystal at temperatures of -15°C and below. Their long life allows time for the droplets to capture the relatively scarce freezing nuclei that are effective at such a high temperature. In addition, even inefficient nuclei may cause freezing if given sufficient time. Short-lived convective clouds, on the other hand, may remain predominantly liquid at temperatures of -25°C or below. True cirrostratus clouds differ from ice-crystal altostratus in that the former exist at temperatures where instantaneous freezing of the newly formed droplet occurs (e.g., -30 to -40°C or below), all growth being of a crystalline nature, whereas the warmer altostratus droplets undergo significant growth in the liquid state before freezing.

Chapter 3

THE FORMATION OF PRECIPITATION

SECTION A — THE CONDENSATION PROCESS

As described in chapter 2, section A, cloud droplets form by the condensation of water-vapor molecules onto suitable nuclei when a parcel of air rises, expands, and cools. Because of their minute size, the newly formed droplets have negligible fall speed and move with their immediate environment. As long as the parcel rises, condensation continues and the droplets grow. However, the effectiveness of condensation as a factor in droplet growth falls off rapidly with droplet size. It is readily shown that it takes nearly 50 times as many water-vapor molecules to increase the radius of a 10-μ droplet by 1 μ as that of a 1-μ droplet.

A further limitation to the importance of the condensation process as an important precipitation mechanism is the premature fallout of the larger droplets. The fall speed of a droplet with respect to its environment varies directly with its size. For example, a 50-μ radius drop has a terminal fall speed of 25 to 30 cm/sec, a 500-μ drop about 400 cm/sec, and a 3000-μ (3-mm) drop a little over 900 cm/sec. (This is a limiting value since larger drops break up due to the resistance of the air.) If the fall speed is greater than the updraft in the cloud, the droplet will have a net downward velocity. Widespread layer clouds are often created by vertical ascent speeds of the order of 10 cm/sec or less, which is roughly the fall speed of a 30-μ droplet. However, a falling drop of this size would fail to reach the ground, since it would evaporate within a short distance of the cloud base. It is generally considered that a radius somewhat greater than 100 μ is required for a drop falling from low stratus to reach the ground. Theoretically, those clouds sufficiently long-lived to permit droplet growth to this size by the condensation process, and with sufficiently strong ascent velocities to support such a droplet, could produce drizzle-sized drops by condensation alone.

Computations such as the above show that while the condensation process is responsible for the origin and initial growth of cloud droplets, and can produce drizzle in some cases, it is much too slow and weak a mechanism to be an important factor in the ultimate growth of droplets to precipitation size. Two other processes are generally accepted as the basis for nearly all important precipitation. One is the collision-coalescence mechanism, also called the coalescence or warm-cloud process. It is of particular importance in maritime and tropical air masses and probably initiates nearly all convective-cloud precipitation regardless of location or season. The second important mechanism is the ice-crystal, or Bergeron-Findeisen, process. It takes place only in supercooled clouds, and is most important in precipitation from altostratus and nimbostratus, especially in cold areas and seasons, and in the precipitation from the middle and late stages of cumulonimbus cells.

SECTION B — THE COALESCENCE PROCESS

With the exception of occasional cases of light drizzle, all precipitation from clouds not containing ice crystals is produced by the collision-coalescence mechanism. A cloud consists of various-sized droplets falling at differing speeds relative to one another. At first glance it appears as if a larger droplet should fall faster, overtake, collide with, and collect all the smaller droplets in its path. In reality, the coalescence process is extremely inefficient in the early stages of droplet growth. Although large droplets coalesce readily upon colliding, the ordinary cloud droplets usually bounce apart without merging. Furthermore, the volume swept out by a falling drop varies with the square of its radius, being nearly an order of magnitude less for a 10 μ drop than one of 30 μ. Experiments show that a droplet must have a minimum radius of about 20 μ in order to grow at all by coalescence, and efficient growth is not attained until it reaches 30 or 40 μ.

Since condensation is an effective growth mechanism only for very small droplets and coalescence only for rather large droplets, it appears that both processes are necessary to produce warm-cloud precipitation. However, since the bulk of the cloud droplets grow only to about 5 to 15 μ by condensation — much too small to initiate coalescence — a connecting link is required. Flight measurements have shown that every cloud contains a small number of exceptionally large droplets (radii of 20 to 30 μ), probably formed on giant condensation nuclei as described in chapter 2, section A. These large drops are able to start growing immediately by coalescing with the plentiful small droplets. In the case of widespread layer clouds with relatively weak updrafts, as these large drops attain fallout size they either evaporate or reach the ground as drizzle. In the case of thick convective clouds with moderate updrafts, on the other hand, the drops grow larger and rain showers often result. With sufficiently strong updrafts (greater than 9 m/sec), the large drops grow inside the cloud until they reach the maximum value of about 3 mm. At this point they break up into a multitude of tiny droplets plus a sizable number of droplets large enough to grow by coalescence [1]. (A single 3-mm drop could theoretically produce up to a million 30-μ droplets, each able to grow to precipitation size by coalescing with the smaller cloud droplets.) This increase in the number of potential precipitation particles has been likened to a chain reaction. If the convective cloud undergoes sufficient growth, the number of raindrops produced will reach a point where precipitation will occur, generally as a prolonged heavy rain shower.

Most tropical rainfall is produced by the coalescence process. The high moisture content and low concentration of condensation nuclei result in clouds composed of relatively large droplets suitable for coalescence. In general, tropical clouds produce showers well before the cloud top reaches the freezing level. Over the ocean near Puerto Rico [2] it was found that some clouds with tops of only 6000 feet (about 12°C) produced a radar echo (i.e., precipitation-sized droplets), and that all cumulus reaching 11,500 feet (5°C) showed echoes. (This does not necessarily mean that rainfall reached the earth in every case.)

In the temperate zone the greater part of convective-cloud precipitation occurs in the summer-half of the year. In these latitudes the lower moisture content of the air and the higher concentration of condensation nuclei result in clouds composed of many small droplets. Consequently, the coalescence process is less efficient than in the tropics and proceeds more slowly. In a study of convective clouds over New Mexico [3], no radar echo appeared until the cloud top reached at least 22,000 feet (about -12°C). Other less continental areas showed lower critical heights [4], including a number of echo tops warmer than 0°C. Because of the low freezing temperature of cloud droplets, it appears likely that the initial precipitation from most temperate-latitude convective clouds results from the coalescence process; however, the ice-crystal mechanism would be expected to play an important role with further cloud growth (see chapter 3, section D).

SECTION C — THE ICE-CRYSTAL PROCESS

As shown above, precipitation can be produced by coalescence in the case of convective clouds sufficiently long-lived and with sufficiently strong updrafts to permit growth of a large number of drops to precipitation size. In the middle and polar latitudes, however, much precipitation, particularly in the winter-half of the year, falls from widespread supercooled layer clouds (altostratus and nimbostratus) associated with deep lows and fronts. Here the cloud mass is long-lived, but the associated updrafts are generally too weak and the cloud depth too small for efficient coalescence.

In these conditions, the growth of the small cloud droplets to large precipitation particles takes place in quite another fashion [5]. As the air mass is lifted above the freezing level, the cloud droplets become supercooled. As time goes on, the droplets collect various impurities floating in the air. Some of these particles have the ability to act as freezing nuclei, transforming the affected droplet into an ice particle. Other ice-forming nuclei are hygroscopic and absorb and freeze a water film to form ice particles. Freezing nuclei vary in composition, size, and structure, and consequently have differing threshold temperatures at which they can initiate freezing. Generally, the most efficient first become effective at temperatures between -10° and -15°C, although the great majority have threshold temperatures below -25° or -30°C.

Due to structural differences, an ice crystal has a lower vapor pressure than a water droplet at the same temperature. For example, at -15°C the saturation vapor pressure over water is 1.91 mb, and over ice only 1.65 mb. Thus, an environment saturated with respect to water at this temperature has a relative humidity of 115% with respect to ice. As soon as a cloud droplet freezes, the surrounding excess water-vapor molecules start to sublime onto the ice particle. This, in turn, lowers the humidity of the cloud air below 100% with respect to water, so the cloud droplets start to evaporate. These new water-vapor molecules too are deposited on the ice crystal, resulting in its rapid growth. Eventually, if sufficient moisture is available, the crystal becomes large enough to fall through the updraft. During its fall the crystal intercepts and freezes supercooled droplets and grows by accretion. Generally, sublimation, also called deposition, is the more important growth mechanism until the ice particle reaches a radius of about 50 to 100 μ, and accretion, thereafter. If the cloud is deep enough, the falling particle will grow sufficiently large to reach the ground without evaporating. If the crystal remains in a below-freezing environment throughout its fall, it will reach the earth as a snowflake; otherwise, it may melt into a raindrop.

For significant precipitation to take place from a supercooled cloud by means of the ice-crystal process, it is necessary to have an ice-crystal concentration on the order of 1 to 10 per liter. For clouds extending to sufficiently low temperatures, ample droplets freeze to produce the necessary number of crystals. However, high crystal concentrations are frequently observed at warmer temperatures, even though the number of natural freezing nuclei is low. Various authors [6] [7] have proposed that the ice crystals initially formed by the available freezing nuclei break up into a number of pieces, each capable of growing a new crystal, and that this action continues throughout the life of the cloud. This process is analogous to the chain reaction of droplet break-up and growth involved in the production of precipitation by the coalescence process.

SECTION D — THE COMBINED COALESCENCE-ICE CRYSTAL PROCESS

Although only the coalescence process is important to the production of precipitation in warm convective clouds and only the ice-crystal process in supercooled layer clouds, both mechanisms are believed important in precipitation generated in those convective clouds that extend far above the freezing level. For example, the first part of the life cycle of a thunderstorm cell is called the cumulus stage. At this point most of the cloud droplets are small, no precipitation occurs, and no echo can be seen on standard 3-cm radar sets. If sufficient energy is available, the cell will grow into the cumulus congestus stage. Usually at this point the first radar echo is detected, indicating the existence of precipitation-size droplets. However, the cloud top is frequently warmer than freezing. Thus, the initial precipitation must often be a result of the coalescence process. Thereafter, the cell may grow to the -30° or -40°C level, or even higher, with glaciation of the cloud top, lightning, and heavy rain. Undoubtedly, the ice-crystal process as well as the coalescence process is producing precipitation during this period.

Chapter 4

WEATHER MODIFICATION

SECTION A — INCREASING PRECIPITATION

We have seen that the occurrence of natural precipitation is dependent upon several basic conditions. To begin with, there must be sufficient moisture and uplift to create a cloud. Next, a mechanism must be set in motion to enable the transformation of the small cloud droplets into precipitation-sized particles — mainly, the coalescence process in warm convective clouds (cumulus and cumulus congestus), the ice-crystal process in supercooled layer clouds (altostratus and nimbostratus), and both processes in convective clouds that extend well above the freezing level (large cumulus congestus and cumulonimbus). Finally, appreciable precipitation demands an environment conducive to protracted cloud growth.

If all the above criteria were completely satisfied, ample precipitation would occur naturally. The hope for useful precipitation augmentation lies in those cases where one of the conditions is not met adequately. However, the tremendous energies involved make it hopeless to attempt to change the existing environment over a large area. Humidity and stability conditions generally favorable for cloud growth must be present for either natural or artificial precipitation to occur.

The most obvious link in the precipitation chain that might reasonably be supplied by man is supplying suitable nuclei for transforming the small cloud droplets into precipitation particles. These would consist of large water droplets (or large condensation nuclei) to initiate the coalescence process in warm clouds, and ice nuclei to initiate the ice-crystal process in supercooled clouds. The addition of such nuclei is termed cloud seeding.

In addition to initiating the precipitation process, cloud seeding can sometimes release a small amount of latent energy in a cloud. For example, the addition of ice nuclei to a supercooled cloud releases the latent heat of fusion when the water droplets freeze. Similarly, the addition of certain hygroscopic particles may release heat of solution. In borderline stability conditions, where a cloud has grown significantly but cannot quite break through to initiate precipitation naturally, cloud seeding may result in such a break-through and continued cloud growth. Although such results have not yet been proven to take place, there is evidence that in some cases large supercooled convective clouds have been made to grow in this manner. The evidence with regard to warm-cloud growth is more questionable.

Warm-Cloud Seeding

Convective clouds that are large enough to play a significant role in the precipitation balance, but not extend to the freezing level, are most often found in the tropical and subtropical portions of the earth, as well as in parts of the temperate zone in summer. Efforts have been made to increase warm-cloud precipitation in Australia, Africa, the Caribbean, and other similar areas [8].

Warm-cloud seeding primarily provides the large droplets necessary to initiate the coalescence mechanisms. Consequently, its chief value is in those cases where sufficient large drops do not already exist. If a cloud is already precipitating or shows a precipitation echo on radar, the coalescence mechanism is underway and it would be pointless to add nuclei for this purpose. If coalescence has not already started but the cloud is still growing, coalescence would probably occur naturally in a few minutes. The premature release of precipitation by seeding could create a downdraft and dissipate a cloud that would have grown larger and yielded more rainfall if left untouched.

In a non-precipitating cloud that has ceased to grow, seeding could conceivably result in a release of the liquid water already present. In a cloud 4 km high with a liquid-water concentration of 1 gm/m^3, precipitation of all the water would result in about 0.2 inch of rain. Assuming half the sky to be covered with such clouds, the average rainfall over the seeded area would be only 0.1 inch. The effect of evaporation would decrease this quantity even more. Obviously, the cost of seeding would be far too expensive to justify such an operation.

It has been proposed that use of a hygroscopic seeding material might result in a release of the heat of solution, thus adding energy to a cloud and causing it to grow larger than it otherwise would. However, the agent most often suggested for this purpose, sodium chloride, actually absorbs heat as it dissolves (i.e., is endothermic) and hence would cool the cloud. The amount of heat released by even the most exothermic hygroscopic agent would be many orders of magnitude less than the heat of condensation already released by the cloud itself in growing to the point where it was large enough to justify seeding.

In practice, droplet seeding can be carried out in two ways. An aircraft can fly over the cloud top, spraying droplets large enough (e.g., 500 μ) to fall through the cloud updraft and grow by coalescence. A more economical procedure is for the aircraft to fly just above the cloud base and discharge droplets large enough to grow by coalescence (e.g., 50 μ) but small enough to be carried up into the cloud by the existing updraft. The latter procedure initially provides 1000 times as many potential precipitation particles from a given quantity of liquid water. Still another approach is to fly just below the cloud base disseminating large hygroscopic nuclei which will grow to precipitation particles inside the cloud. Finally, in some areas ground generators have been used to release hygroscopic nuclei beneath convective clouds. Warm-cloud seeding experiments have been carried out by all these techniques. However, in evaluating the success of a test, it is impossible to determine how the seeded cloud would have reacted if left unseeded. Furthermore, because of the great variability, it is extremely difficult to measure the precipitation from a convective cloud with any accuracy. Radar observations are often made, but radar is not a very precise indicator of precipitation. Consequently, evaluations must generally be based on statistical techniques (chapter 5). Unfortunately, statistical verifications of this type usually require many years of tests before the results can be accepted as meaningful.

In summary, if the environment is favorable for the growth of warm convective clouds, precipitation will occur naturally. If the environment permits only moderate cloud growth, the coalescence process can probably often be initiated by seeding with water droplets or large hygroscopic nuclei. However, it is unlikely that such seeding would release energy or cause the cloud to grow. Any precipitation produced would be light, frequently evaporating before reaching the surface. In some cases seeding might result in an overall decrease in rainfall by initiating a premature downdraft and dissipating the seeded cloud. It does not appear to be within the state of the art today to produce useful amounts of precipitation by seeding warm clouds.

Supercooled-Cloud Seeding

a. Convective Clouds. Convective-cloud precipitation occurs in the temperate zone as well as in the tropics, particularly in the summer-half of the year. However, whereas tropical clouds normally start to precipitate long before the cloud top reaches the freezing level, the mid-latitude clouds generally extend to much greater heights before precipitation occurs. If the cloud reaches well above the 0°C isotherm, the supercooled portion can be seeded with freezing nuclei to initiate the ice-crystal precipitation process. As described in chapter 2, section B, a few natural freezing nuclei become active between -10 and -15°C, or occasionally at even warmer temperatures, but the concentration may be too small to initiate precipitation by the ice-crystal process during the relatively short life-span of a convective cloud.

It is apparent, therefore, that seeding convective clouds with artificial freezing nuclei would be limited to clouds with tops well above the 0°C level but not expected to reach -25°C. The most obvious freezing nuclei are ice particles themselves, and cases have been reported of supercooled convective clouds being seeded by ice crystals falling from overhanging cirrus clouds [9]. One well-known artificial nucleating agent is dry ice (solid carbon dioxide). Dry ice pellets can readily be dropped from an aircraft into clouds. Since dry ice has a sublimation temperature of approximately -80°C, each falling pellet would instantly freeze myriads of tiny supercooled cloud droplets in and near its path [10]. It has been estimated that one gram of dry ice can produce from 10^{10} to 10^{13} ice crystals before evaporating, depending on the ambient temperature. Each crystal will then grow at the expense of the neighboring droplets and, hopefully, initiate precipitation.

In general, dry ice pellets must be dropped from an aircraft into each suitable convective cloud, an expensive procedure. Consequently, many laboratory experiments have been run to determine the effective freezing temperature of various chemicals that could be released either from aloft or from the ground. The most efficient chemical so far discovered is silver iodide [11]. A few silver iodide nuclei become active around -5°C, with the level of activity increasing by several orders of magnitude at temperatures near -10° to -15°C.

Silver iodide nuclei can be produced by burning a suitable solution (for example, a silver-iodide potassium-iodide acetone solution) in a network of ground-based generators or in an airborne generator. They can also be disseminated as a pyrotechnic in the form of flares, fusees, rockets, and artillery shells. The number of effective freezing nuclei produced per gram of silver iodide compound varies with the type of generator and the ambient temperature. A reasonable value is around 10^{13} at -10°C, with the number increasing rapidly at lower temperatures. One disadvantage of silver iodide is that it is inactivated by exposure to sunlight, the number of effective nuclei decreasing by as much as an order of magnitude in 15 minutes in strong sunlight.

One advantage of the ice-crystal process is that it results in a release of energy (the heat of fusion) when the supercooled liquid-water droplets are transformed into ice. Thus, whereas the coalescence process primarily precipitates out the liquid water naturally present in a cloud, the latent energy released by the ice-crystal process can conceivably result in an increase of the updraft, greater cloud growth, and the production of additional water available for precipitation.

Tests have been carried out in which supercooled convective clouds have been seeded with dry ice from aircraft and with silver iodide from surface and airborne generators and from rockets. Because of the natural variability of rainfall, randomized-seeding experiments must be continued over a period of several years (often five or more) before statistically significant results can be obtained (see chapter 5). For example, the University of Arizona carried out a series of tests on summertime cumulus extending well above the 0°C isotherm. Silver-iodide nuclei were disseminated from generators mounted on an aircraft operating near the freezing level. Half the test days were seeded, half unseeded, the selection being made by a random process. For the first two years of the project an apparently significant increase in precipitation was observed, but for the next two years an apparent decrease occurred. It was clear that this particular project would not yield meaningful results, so it was stopped. A more sensitive test was instituted with similar results.

A number of tests have been carried out in other geographical areas, some apparently successful, some not. Some have even shown decreases in rainfall (e.g., the University of Chicago Project White Top [12]). Experts differ as to the cause of these conflicting results. Many believe that seeding has no effect at all on precipitation and that the increases and decreases found were merely due to chance. Others believe that seeding increases the precipitation in some cases and decreases it in others, the cause for the differing results, as yet unknown. It has recently been theorized that supercooled convective clouds can be divided into three groups: (1) one group will grow and produce precipitation whether seeded or not, and hence seeding will show no effect; (2) one group will not grow, whether seeded or not, and hence once again seeding will show no effect; and (3) the third group will grow significantly only if seeded. The criteria for seeding include the cloud-base temperature, the diameter of the cloud tower, and the stability. Recent tests have shown marked cloud growth of the Group 3 clouds when seeded with silver-iodide flares dropped from an aircraft [13]. The seeding rate used was considerably greater than that in most past investigations. The extent to which the total precipitation of an area can be increased by this technique has not been determined, nor whether the increase would be sufficient to pay the cost.

In summary, it appears at least possible that heavy silver-iodide seeding will cause certain supercooled convective clouds to yield more precipitation than they otherwise would. Other clouds will not be affected, or may even be affected adversely. The amount of precipitation increase and determination of the seedability criteria are still under study.

b. Layer Clouds. Large-scale supercooled layer-cloud systems are generally found in the overrunning and convergence areas associated with extratropical low-pressure centers, fronts, and troughs, particularly during the cold seasons. The vertical ascent rate is usually too weak to permit significant precipitation growth by coalescence. However, as the cloud top approaches

-15°C, a few freezing nuclei become active and initiate the ice-crystal process. The number of effective nuclei is so small that the process progresses slowly, but cloud systems of this type are so long-lived that in most cases precipitation eventually occurs. If sufficient water vapor and vertical motion exist, more or less continuous precipitation results as the system moves across the country. The precipitation falls as snow, but melts into raindrops if the lower layers are sufficiently warm.

Inasmuch as a system of this type nearly always produces precipitation naturally in a favorable environment, it is rarely considered satisfactory for cloud seeding. The few experiments carried out in these situations support this belief. However, it is conceivable that rather light precipitation could be induced to fall somewhat sooner by seeding the supercooled layer before the natural ice-crystal process has become effective. In many cases it would be necessary to use aircraft seeding because the lapse-rate inversion associated with the overrunning would prevent surface-generated silver iodide nuclei from rising to the level of the supercooled clouds.

c. Orographic Clouds. Up to this point it has been shown that, while cloud seeding can initiate the precipitation process in some cases, it offers only limited hope for usefully increasing the amount of precipitation. This is mainly because the type of environment needed for significant artificial rainfall generally results in ample precipitation without seeding. However, this is not necessarily true in the case of wintertime orographic clouds. As storm systems approach mountain ranges, orographic uplift may result in cloud growth well above the freezing level, but not high enough to initiate the ice-crystal process. The air mass may then cross the ridge and the cloud droplets evaporate in the subsidence on the lee side. In this case, a row of silver-iodide generators located some distance upwind from the ridge line may initiate the ice-crystal process soon enough to permit precipitation to fall on the mountain slopes.

In general, seeding-produced snowfall from orographic clouds that would not precipitate naturally is of light intensity. However, relatively little will evaporate in the short fall to the mountain, and if surface temperatures are continuously below freezing, the snow might last until spring. Repeated seeding throughout the cold months could conceivably produce an appreciable increase in the snow pack, providing valuable water supplies in the ensuing spring thaws. Evidence from past experiments, while not conclusive, indicates that the seeding of supercooled orographic clouds with ground-based silver iodide generators may be an economically useful operation. It appears that the greatest effect is achieved when seeding operations are carried out during the passage of low-pressure systems, when the associated vertical lifting acts both to deepen the cloud and to carry the silver iodide nuclei up into the clouds.

SECTION B — FOG AND STRATUS DISSIPATION

A number of techniques have been tested to dissipate warm and supercooled fog and stratus [18] [19] [20]. A successful procedure would have many applications. It would enable aircraft takeoffs and landings (fog is the number one weather problem halting aircraft operations), aerial refueling, rocket launchings, astronomical observations, rescue and recovery missions, tactical support, reconnaissance, etc., which otherwise would be difficult or impossible. Two basically different approaches can be taken to rid the air of the tiny fog droplets. One is to evaporate them by adding heat, the other is to cause them to coalesce to fallout size.

Warm Fog and Stratus

The only operationally proven technique for dissipating warm fog is the application of heat. During World War II, a large number of burners placed at intervals along the airstrip were used to evaporate the fog from vital airbases in England. This original crude system (called FIDO) has since been greatly refined, using high-pressure burners to produce a clean-burning fuel-oil spray. Assuming an air temperature of 10°C (50°F) and a fog liquid-water content of 0.3 gm/m^3, it is necessary to warm the air only a half-degree Centigrade to enable it to hold the vaporized fog water. (More heating is required at cold temperatures, less at warmer temperatures.) The fuel cost to clear an area over the runway a half-mile long is not excessive. However, the installation of the high-pressure pump and burner system is very costly; an estimate at one air base was over $5,000,000. It clearly would be limited to permanent high-traffic bases.

The use of obsolete jet engines along the runway has been proposed as a replacement for the costly FIDO system. The engines not only produce tremendous heat, but provide sufficient mixing to mix the heat through a large volume of foggy air. In January 1968, AWS ran a test at Travis AFB using four C-141 Aircraft spaced one behind another at intervals of 750 feet along the runway. In three tests the visibility was raised from 1000 feet to over a half mile in less than five minutes (Figures 1a and 1b). Since new fog moves over the runway almost immediately after engine shut-down, an operational system would require continuous operation of the jet engines throughout aircraft takeoffs and landings. The French are considering installation of a jet-engine system at Paris, using underground engines alongside and vented toward the runway.

AFCRL and the Army (CRREL) are investigating the use of large helicopters to dissipate fog. This technique shows promise in those cases where a fog layer less than 300 feet thick lies beneath a layer of warm dry air. The helicopter slowly circles over the fog, mixing the dry air with the foggy air to evaporate the fog droplets. Under the proper circumstances, a sizable hole can be cut within 10 minutes. This technique is still undergoing development.

The other approach offering real promise of success, although currently undergoing research, is to seed the fog with a finely ground hygroscopic salt. As salt particles fall throughout the fog, they absorb surrounding water vapor, leading to evaporation of the fog droplets [14]. If the salt particles are too large, they will fall too rapidly to absorb much moisture; if too small, they will remain suspended even after absorbing their capacity of water vapor and make the visibility worse. The process of separating out the very fine particles is extremely costly, resulting in costs up to $3/lb for test batches of several thousand pounds. (The cost would no doubt fall considerably if the material were used operationally.) So far, results have shown some promise, but good clearings have been the exception rather than the rule. Generally, an aircraft skims the fog top and drops several hundred pounds of the salt over a period of some minutes in a racetrack pattern. Any improvement usually occurs within 10 or 20 minutes and lasts a similar length of time. In November and December 1968, AWS carried out a series of tests at Travis AFB using sized sodium nitrate disseminated by a powerful ground-based fan (Figures 1c and 1d). Some improvement was detected, but results were far from operational.

Many air-base operators consider sodium chloride (common table salt) too corrosive for airport seeding. Consequently, other chemicals are under test, such as the sodium nitrate used by AWS. The Naval Weapons Center is experimenting with an extremely concentrated hygroscopic solution which can be dispensed as a spray from an aircraft, thus avoiding the expensive sizing process. Other investigators are testing surfactants (surface active agents) designed to reduce the vapor pressure of some of the droplets, thus permitting them to grow at the expense of the untreated drops. Less promising approaches include the use of electrical charges and ultrasonic sound waves, both intended to induce droplet coalescence.

<u>Supercooled Fog and Stratus</u>

In general, the frequency of fog and low stratus decreases as the temperature falls below 0°C. This is partly because air masses with much-below-freezing temperatures are usually of continental rather than maritime origin and hence drier, and partly because cold air cannot hold as much water vapor for condensation as it cools further. However, in high latitudes during the cold season, a number of areas subject to the influx of maritime air undergo many hours of supercooled stratus and fog. These areas include the northeastern and northwestern parts of North America (e.g., Spokane has a relatively high frequency of such weather) and much of western and central Europe, particularly certain parts of Germany.

The dissipation of supercooled fog is the only truly operational weather-modification technique in use today. The Air Weather Service and a number of commercial airport authorities in the United States and Europe have engaged in this activity for the past several years. The most common procedure involves an aircraft flying a predetermined seeding pattern either in or just above the fog deck and dropping crushed dry ice at a specified rate. A boiling action may be noted as the dry ice transforms the seeded area from water to ice, releasing the latent heat of fusion. As the ice crystals grow, they are disseminated by eddy action to both sides of the track, widening the seeded area. After perhaps 10 to 20 minutes, crystals start reaching the ground. Fallout continues up to an hour or more after the start of seeding. Usable clearings form within 30 to 60 minutes, depending on fog thickness, temperature, wind speed, and other factors as yet unknown.

AWS has carried out operational seeding at Elmendorf AFB, Alaska, since November 1967 (Project Cold Cowl) and more recently in Germany (Cold Crystal). A dry ice crusher/dispenser, capable of automatically dispensing dry ice at a rate up to 60 lb/min, is mounted in a WC-130 aircraft (Figures 1a and 1b). Dry ice cakes are stored on board and loaded into the crusher as required during the seeding operation.

The usual AWS seeding pattern consists of five parallel lanes, three miles long and a half mile apart, flown just above the fog at a distance between 45 and 60 minutes upwind of the target area (Figure 2c). The normal seeding rate is 15 lb/mile. Since about half the crushed dry ice is in the form of powder and might sublime before reaching the fog deck, this ensures an effective seeding rate of 7 or 8 lb/mile.

The most difficult problem is the determination of the effective wind between the seeding and target areas. Frequently in a fog situation the air is stable and the pressure gradient weak. Air motions are primarily a result of locally produced gravity winds, perhaps 1 or 2 knots in intensity. Sensitive anemometers have been placed on the control tower at the test bases to give the best possible indication of the air flow. However, a small error in direction or speed can result in a serious displacement of the cleared zone from its desired location over the runway an hour later. Consequently, the seeded pattern is made as large as feasible to compensate for wind errors or wind shifts.

A high degree of success has been achieved in both Alaska and Europe.

Clearings have been obtained at temperatures as high as -1°C. In addition, a large number of tests were made using silver iodide fusees burned in a dispenser mounted on the side of the aircraft (Figure 2d). The silver iodide proved just as effective as dry ice when the temperature was below -5°C and the aircraft was either in or just above the fog deck. When seeding must be carried out at warmer temperatures or more than 200 feet above the fog top, dry ice is superior (Figures 3a-d). However, research is underway in an attempt to increase the effectiveness of silver iodide at temperatures between -1 and -5°C. Silver iodide has several inherent advantages over dry ice — light weight, push-button operation, and protracted storage life.

Ground-based seeding can be carried out using silver iodide flares or dispensers to spray liquid propane, carbon dioxide, or other refrigerants into the fog (Figures 4a-d). The liquified gases are too heavy and bulky for mobile use, but offer great promise when disseminated from a network of stationary dispensers. A fixed propane system is currently in operational use at Orly Airport, France, and a semipermanent installation is undergoing field testing by AWS at Fairchild AFB. The latter system consists of 20 dispensers, three near the touchdown area for calm-wind situations and the rest displaced at varying distances upwind along the most common wind directions. As with dry ice, clearing occurs 30 to 60 minutes after seeding. The close-in dispensers have fans to disseminate the ice crystals throughout the fog volume. The more distant dispensers rely on wind-produced turbulent eddies for this purpose.

Ground-based silver iodide flares also have unique advantages. They are small, light, highly mobile, and show promise of being able to clear tactical areas or air bases where the more expensive airborne or fixed ground-based systems cannot be justified because of infrequent occurrence of supercooled fog.

<u>Ice-Crystal Clouds and Fog</u>

Cirrus clouds and many altostratus and nimbostratus lying above the freezing level are composed primarily of ice crystals, with few or no supercooled droplets. Thus, it is not possible to initiate either the coalescence or ice-crystal process in attempts to dissipate the cloud deck. Similarly, ice fogs are not amenable to modification by seeding.

Ice fogs occur at very low temperatures — usually below -30°C — when the air is saturated by man-made sources of moisture [15]. Consequently, they are found primarily around air bases and other built-up areas in the interior of Alaska (e.g., Fairbanks), Canada, and Siberia. The water vapor produced by the combustion of hydrocarbon fuels (gasoline, kerosene, etc.) in generator, automobile, and aircraft engines (surface contrails) is one of the chief sources of ice fog at an air base. Other causes are the release of steam into the atmosphere from heating and power plants.

As noted above, ice fogs cannot be dissipated by seeding techniques. Also, inasmuch as the combustion of hydrocarbon fuels is a chief source of ice fog, it is obviously not possible to use the FIDO technique. Since the fogs cannot be dissipated, the problem can only be eliminated by prevention. At low temperatures care should be taken not to release steam into the atmosphere, and the operation of automobile and aircraft engines should be held to a minimum. Where possible, such activities should be limited to the downwind side of the airstrip. In general, the low temperatures required for ice-fog formation are limited to near-calm conditions where air movement is primarily a matter of downslope cold-air drainage.

SECTION C — MODIFICATION OF THUNDERSTORMS

Thunderstorms comprise one of the most important weather hazards because of the associated severe turbulence, strong and gusty surface winds, hail, and lightning. A number of experiments have been carried out to suppress hail and lightning by cloud-seeding techniques.

Studies indicate that not all thunderstorms contain hail. In fact, hail is rather infrequent in storms in the eastern and southeastern sections of the United States, whereas it is very common in thunderstorms in the Great Plains and Rocky Mountain regions [17]. A hailstone results from an ice particle (a hailstone embryo) falling through a deep cloud of supercooled water droplets and growing by accretion. A strong updraft is essential to the formation of large stones.

Two basic approaches have been taken toward hail suppression. Most common is heavy seeding of the potential cumulonimbus with silver iodide nuclei in an attempt to transform nearly all the supercooled water into ice crystals. Hopefully, these crystals would merely bounce off the falling ice particles, resulting in little or no growth. However, if only part of the supercooled water is transformed into ice, the problem could actually be worsened, since growth by accretion is especially rapid in an environment composed of a mixture of supercooled droplets and ice crystals. Consequently, this approach requires massive seeding well in advance of the first hailstone formation. Ground-based silver iodide generators, rockets, and other devices have been used to introduce the silver iodide into the storm cell. Since not all large cumulus grow into thunderstorms and not all thunderstorms produce hail, many clouds would be seeded needlessly. In view of the massive seeding required for this technique, the cost would be great. The Russians have claimed substantial success using artillery shells to place silver iodide in the zone of maximum liquid-water content in the cloud; they hope to create so many hailstone embryos that there will not be enough supercooled liquid water available to enable growth to damaging size. This would be much cheaper than attempting to convert the entire supercooled portion of the cloud to ice crystals. A plan is underway to test this technique in the United States using airborne silver iodide rockets and carrying out a more rigid evaluation of the results. An alternate approach is to seed the potential hailstorm with large hygroscopic nuclei which would produce a number of large droplets. Upon freezing, these would compete with the natural hailstone embryos for the available supercooled liquid water. Ideally, none could grow large enough to be damaging.

Large-scale hail-suppression efforts have been carried out for a number of years in Russia, France, Switzerland, and Italy, and smaller efforts in the United States and other countries. Results are contradictory. The Russian tests appear most promising, but it is generally agreed that further testing under scientifically controlled conditions is necessary before their conclusions can be accepted.

Lightning is another thunderstorm hazard that is under attack by weather-modificction scientists. Lightning kills many people each year, is a hazard to ground troops, a danger to aircraft refueling, missiles, and sensitive computers, and a leading cause of forest fires. A lightning discharge requires the buildup of tremendous potential differences between the negative and positive areas of the thunderstorm, or between the cloud and the ground. It has been proposed that if small dipoles could be placed in a thunderstorm, they would go into corona discharge at relatively low voltages, thus producing a current to neutralize the thunderstorm electric field and prevent it from building up to the level required for a lightning discharge. Some tests have been carried out by seeding thunderstorms with metallic chaff. Other tests have relied on ice-crystal dipoles produced by silver iodide seeding. However, some experts believe that silver iodide seeding could actually result in an increase in lightning activity. The use of seeding techniques to prevent lightning must be considered as still in the early stages of development.

SECTION D — MODIFICATION OF HURRICANES

A hurricane is such a large storm and releases such a tremendous quantity of energy every minute that attempts to alter its development by seeding techniques would appear hopeless. However, a hurricane does contain a huge quantity of supercooled water, so that seeding with freezing nuclei might result in some effect. Since it is not obvious exactly what the results would be, seeding has to be limited to those cases where no danger would result from a sudden change in storm intensity or direction of movement.

In 1947, 80 pounds of dry ice were dumped into a small hurricane, but facilities were not available to monitor the changes, if any. More recently, the combined U.S. Weather Bureau-Navy Project "Stormfury" seeded two hurricanes — ESTHER in 1961 and BEULAH in 1963 — with silver iodide [17]. A series of canister-type silver iodide generators (modified pyrotechnic flares) were dropped from a height of 35,000 feet along a radial path into the storm. Visual and radar observations were made both before and after seeding. Some relatively minor short-lived changes occurred in the wall-cloud radar echo and in the wind speed but, inasmuch as similar changes have frequently been observed in the past, it is not possible at this time to ascribe these effects to seeding. Many more experiments will be needed in order to learn whether it is possible to modify a hurricane by cloud seeding.

Chapter 5

EVALUATING THE SUCCESS OF WEATHER-MODIFICATION EXPERIMENTS

With the discovery of the cloud-seeding properties of dry ice and silver iodide at the end of World War II, many weather-modification operations were carried out with little understanding on the part of the operators as to the physical processes involved. Claims of success were made, particularly in regard to increasing precipitation, based on invalid verification studies. Unfortunately, it is not possible to determine the success of a weather-modification technique based on a single trial. In fact, weather is so variable that in most cases a well-planned program must be continued for 5 to 10 years or even longer in order to determine the effectiveness of a particular cloud-seeding procedure. Such studies and their verifications fall in the province of the research community rather than Air Weather Service. Consequently, only a brief description of accepted cloud-seeding verification techniques will be given here.

The simplest, but least sensitive, procedure is to determine the "normal" weather characteristics of the target area as shown by data over past years. For example, it may be found that the mean annual precipitation for the past 10 years was 30 inches, with an annual standard deviation of 5 inches. Assuming a normal distribution of the annual precipitation totals, the probability of exceeding 35 inches by chance (a departure from normal of one standard deviation) is 16%. The decision as to what constitutes an acceptable level of significance (i.e., the probability that an apparent effect is actually due to chance) is somewhat arbitrary, depending largely on the problem under study. Meteorologists generally require a value of 5% or less for cloud-physics experiments. In the above example, therefore, a rainfall of 35 inches in a seeded year could not be accepted as proof that the result was due to the seeding. A larger increase above normal, continued success over a period of years, or switching to a more sensitive type of test might result in a reduction of the level of significance to an acceptable value.

A more sensitive test is to use a target area, which is seeded, and a nearby control area with a similar meteorological regime, which is unseeded. A correlation study between the two areas is made using data from previous years. If seeding were effective, it would be expected to increase the precipitation over the target area but not over the control area.

More recently, randomization has been used. A forecast technique, objective if possible, is applied each day to determine whether an area is expected to have clouds suitable for seeding. If it is, the operator might select in turn a number from a series of random numbers. If the selected digit is odd, he would seed, and if even, not seed. Or, he could draw a slip of paper from a set, half of which are labeled "Seed" and half "Don't Seed." At the end of the project the precipitation of the seeded days is compared to that of the unseeded days.

In order to double the size of the data sample over the test period, the randomization technique can be combined with the use of two neighboring and similar target areas, A and B. Again, a determination is made as to whether or not the day is suitable for seeding. If it is suitable, the randomized technique is applied to determine whether to seed area A or area B. At the end of the season, the precipitation on the seeded days over the two areas is compared with that of the unseeded days.

More detailed descriptions of verification tests are available in the literature. The most important point for the Air Weather Service forecaster to keep in mind is that, due to the inherent variability of the weather, the apparent success or failure of a single or short-period seeding effort is meaningless. Even with a well-devised randomized technique, a test running 5 years or more may be required in order to provide significant information. If the effect of seeding is genuine but small, it may be all but impossible to distinguish it from the background clutter.

Weather-modification field tests are often supported by computer modeling and laboratory experiments. It is hoped that these approaches may optimize the field-test procedures, supplement the expensive and time-consuming field program, and take the place of field experiments in which the results could conceivably be both persistent and detrimental.

Chapter 6

SUMMARY

The ability to modify weather has such great potential value that tests are being carried out around the globe. Of primary interest are the ability to increase precipitation, to dissipate low stratus and fog, and to modify severe weather, particularly thunderstorms (hail and lightning) and hurricanes (intensity and direction of movement).

Studies of natural cloud and precipitation regimes indicate that the great majority of the original cloud droplets form as a result of condensation on the so-called large nuclei, consisting mainly of sea-salt and combustion particles. However, condensation growth is effective only while the droplets are very small and hence cannot lead to rainfall heavier than drizzle. The most important precipitation is produced by the coalescence process in warm convective clouds, by the ice-crystal process in supercooled layer clouds such as altostratus and nimbostratus, and probably by both processes in supercooled convective clouds such as cumulonimbus.

Cloud seeding for increasing rainfall is generally attempted when conditions appear suitable for important cloud growth but not quite to the point where precipitation will occur naturally. Salt-particle seeding is usually used in attempts to initiate precipitation in warm clouds, dry ice or silver iodide in supercooled clouds. At this time the success of cloud seeding in increasing precipitation has not been proven, perhaps largely because the conditions required to produce clouds large enough to yield significant rainfall when seeded usually result in natural precipitation. However, there is some evidence that under the right conditions, not as yet fully understood, seeding supercooled convective clouds with silver-iodide pyrotechnics may sometimes result in cloud growth and shower formation. In other cases it appears that seeding may actually suppress rainfall. There is somewhat better evidence that light snowfall can be produced by seeding wintertime supercooled orographic clouds. Over an entire winter season it may be that the snow pack in the mountains can be increased sufficiently to provide useful quantities of water during the subsequent spring thaws.

Unlike precipitation augmentation, the dissipation of supercooled fog and stratus is already a proven technique. The Air Weather Service, some commercial operators, and some foreign governments routinely employ fog dispersal to support airport operations in the northwestern United States, Alaska, and parts of Europe. The most common procedure uses an aircraft to dispense crushed dry ice into the fog deck. Silver iodide fusees have proved equally successful at temperatures below -5°C, and are undergoing development to make them effective at somewhat warmer temperatures. Ground-based systems using a network of fixed propane dispensers are under test by Air Weather Service, and one such network is in operational use at Orly Airport in France. A mobile system using silver iodide fusees is also under test for use at less frequently affected bases or for tactical use in temporary field locations.

Techniques for dissipating warm fog are also under investigation. The effectiveness of heat has already been proven, but high installation costs have deterred operational employment of the FIDO system. The use of surplus jet engines for this purpose appears promising. Another approach to warm fog dissipation is to seed the fog with hygroscopic nuclei dispensed from an aircraft or from ground-based fans. Although this technique merits further study, it is not yet operational. Helicopter mixing has proved successful in dissipating thin fogs overlaid by dry air. No technique is yet in sight for dissipating ice fog.

A great deal of effort has been spent on modifying thunderstorms to suppress hail and lightning. Results are controversial, and as yet no technique can be accepted as proven. However, this is an area where there is a definite possibility of eventual success. Experiments on hurricane modification are just beginning. Because of the tremendous storm size and energy involved and the few opportunities for testing, it will almost certainly be many years before a useful technique is achieved.

In conclusion, the forecaster should be cautious neither to make nor accept claims of successful weather modification unless supported by a valid verification program.

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EQUIPMENT AND RESULTS: GROUND-BASED DISSIPATION OF WARM FOG

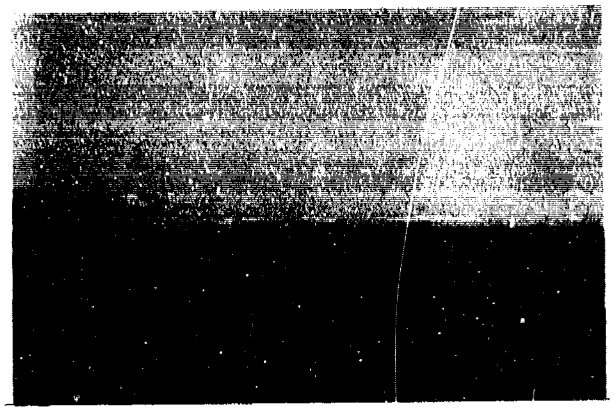

Figure 1a. Visibility Prior to Jet-Engine Turn-On.

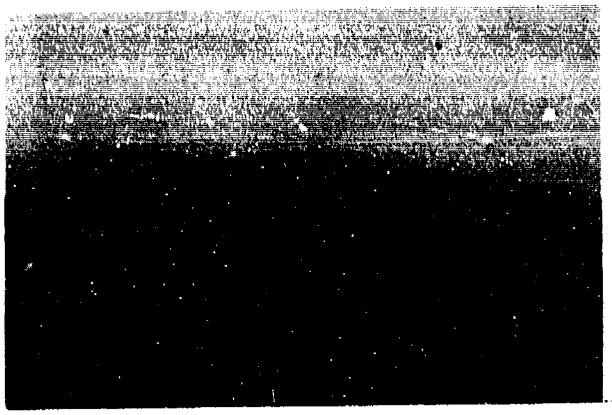

Figure 1b. Visibility Five Minutes After Jet-Engine Turn-On.

Figure 1c. Ground-Based Sodium Nitrate Dispenser.

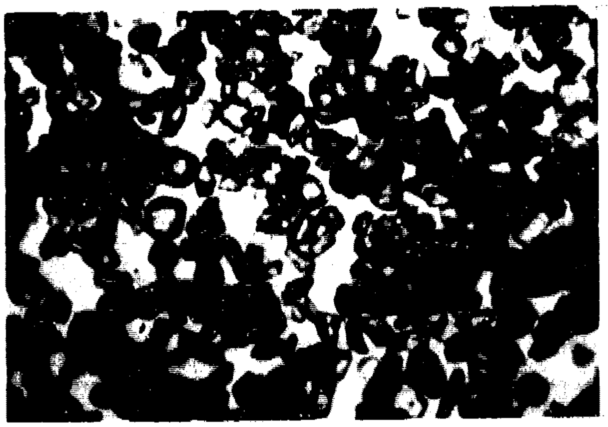

Figure 1d. Sodium Nitrate Sized to Between 20 and 40 Microns.

AWS EQUIPMENT FOR AIRBORNE DISSIPATION OF SUPERCOOLED FOG

Figure 2a. WC-130 Fog-Seeding Aircraft.

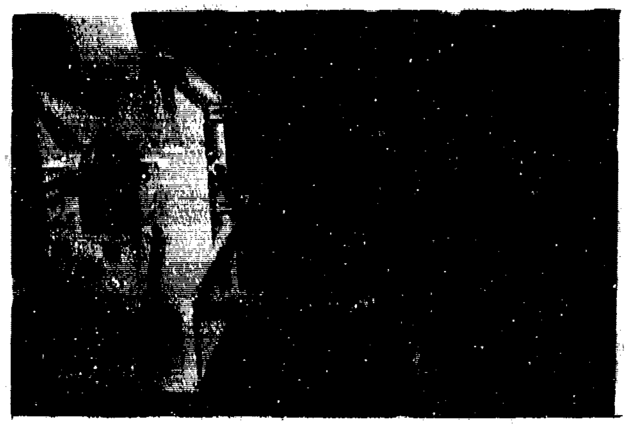

Figure 2b. Dry Ice Crusher/Dispenser Mounted in WC-130.

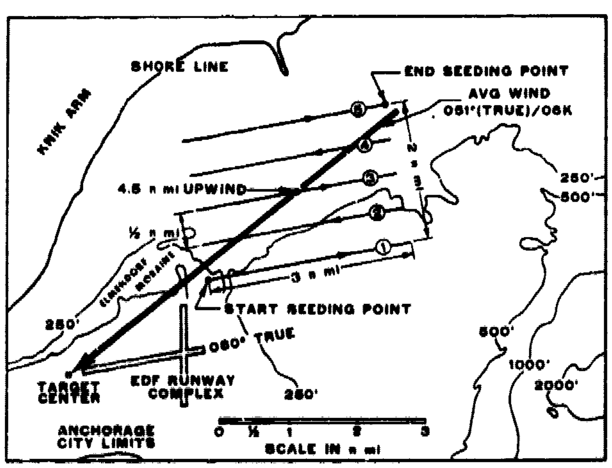

Figure 2c. WC-130 Seeding Pattern.

Figure 2d. Silver Iodide Fusees Mounted on WC-130.

RESULTS OF AIRBORNE DISSIPATION OF SUPERCOOLED FOG

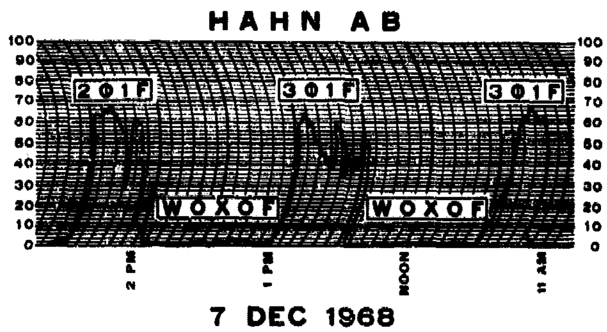

Figure 3a. Transmissometer Trace at Hahn AB During Passage of Three Airborne Dry Ice Seedings.

Figure 3b. Aircraft Photograph of Clearing Over Hahn AB.

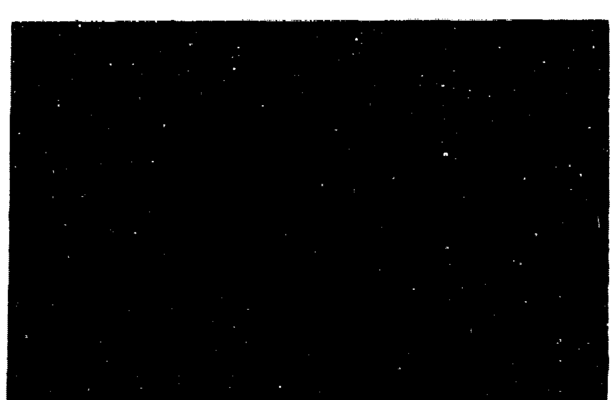

Figure 3c. Ground Photograph Prior to Seeding at Hahn AB.

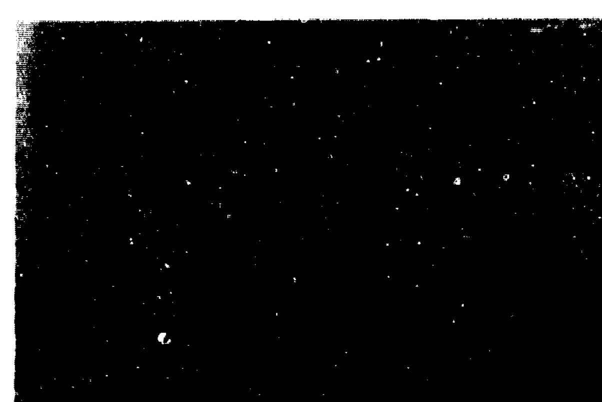

Figure 3d. Ground Photograph After Seeding at Hahn AB.

EQUIPMENT AND RESULTS: GROUND-BASED DISSIPATION OF SUPERCOOLED FOG

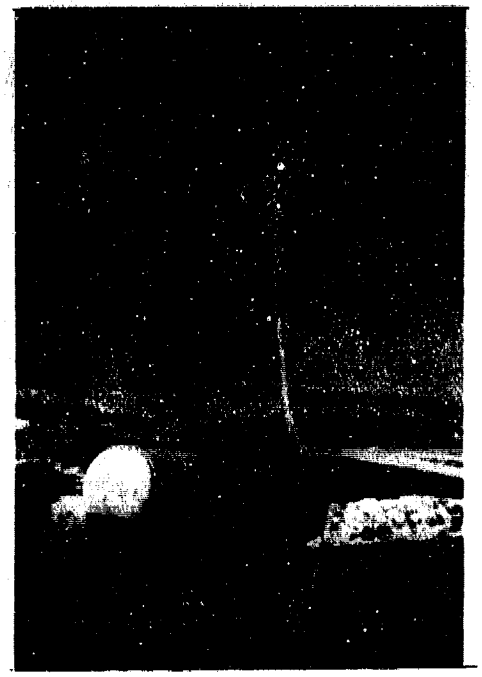

Figure 4a. Dispenser Emitting Liquid Propane Spray.

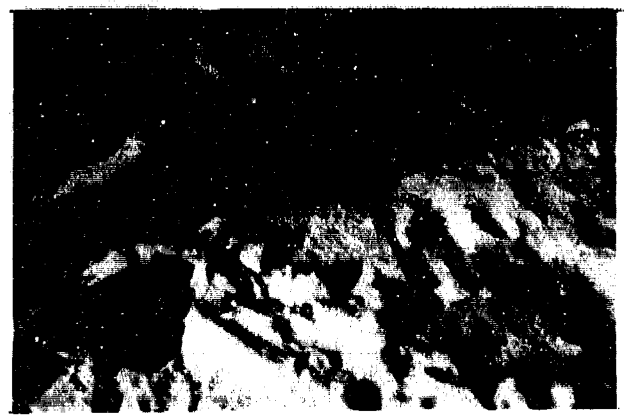

Figure 4b. Ground-Based Silver-Iodide Flare.

Figure 4c. Ground Photograph Prior to Seeding with Silver-Iodide Flares.

Figure 4d. Ground Photograph After Seeding with Silver-Iodide Flares.

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13. ABSTRACT

Weather modification techniques are explained and Air Weather Service activities in cloud-seeding and fog-dissipation experiments are discussed. Technical Report 177 issued 10 July 1964 is updated.

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