WINTER OROGRAPHIC CLOUD SEEDING STATUS IN THE INTERMOUNTAIN WEST[1]

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ABSTRACT

The current status of winter orographic cloud seeding technology was reviewed to assist in the consideration of a snowfall enhancement program for the Black Hills of South Dakota. However, this material is relevant to the intermountain west in general. The emphasis is on the physical evidence that key processes occur in the hypothesized chain of events from release of seeding agent to snow reaching the ground. The range of opinions concerning the technology is briefly noted. Some problems related to reliable production of silver iodide are discussed. Evidence is reviewed from a number of locations showing that excess supercooled liquid water often exists during portions of winter storms, though usually in limited amounts. Much of the liquid water is found near the windward slope and crest of the mountains. The main problem with seeding winter orographic clouds is the transport and associated dispersion of the silver iodide between its release and the supercooled water zone. An associated problem is ensuring that the seeding agent reaches a sufficiently cold region of liquid cloud in an appropriate concentration. While adequate transport and dispersion can be difficult with airborne seeding, it is a special problem with low-level ground generators. Evidence is cited showing that ground seeding projects have frequently failed to enhance the silver content of the target area snowfall. It is recommended that the silver content be monitored in all winter orographic projects which use silver iodide as a minimum first step in documenting whether or not the seeding agent was transported to the target. Where practical, additional testing of the physical hypothesis should be accomplished to improve validation of winter orographic cloud seeding.

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1. INTRODUCTION AND BASIC CONCEPTS

The purpose of this paper is to review the status of winter cloud seeding in mountainous terrain as a basis for considering the application of this emerging technology for snowfall enhancement in the Black Hills of South Dakota in particular, and the intermountain west in general. The current water shortage in the Black Hills motivated this review. The below normal snowpack in that region during recent winters has resulted in low reservoir storage, rapid lowering of well water levels and an increasing awareness by the residents that a serious water shortage has been developing. Even if the next few winters yield above average snowfalls, future water shortages are to be expected due to climatic variability and increases in population and consumption. Thus, it is prudent to consider the potential of winter cloud seeding for the Black Hills and surrounding region. The material presented also should be relevant to much of the intermountain west.

Discussion will focus on evidence from the intermountain west because it is more representative of the Black Hills than, for example, the mountain ranges of California. It is known that both ice multiplication and convection tend to be much more frequent in winter storms near the west coast than in the intermountain west. These and other differences dilute the transferability of results from west coast mountains to the Black Hills. A more general discussion of the current status of winter snowpack augmentation throughout the West is given by Reynolds (1988).

The results of statistical evaluations generally will not be considered, partially because of the difficulty of transferring results based on statistical evidence from one region to another without accompanying physical evidence. Each project's statistical evaluation must be carefully considered on its own, very preferably in light of a reasonable physical hypothesis and accompanying physical evidence that key processes in that hypothesis routinely took place. Unfortunately, due to lack of resources or adequate observing systems, most past statistical experiments lacked sufficient physical evidence. Braham (1981) stresses the need to improve understanding of basic cloud processes in future field experiments. Gabriel (1981) discusses some of the possible problems that can result from improperly applied statistical approaches. It is beyond the scope of this paper to attempt to evaluate the relevance of statistical results from various projects to the intermountain west in general, and the Black Hills in particular.

Orographic clouds are wholly or partially produced by the forced uplift of moist air which can occur when airflow is forced over mountains or hills. If the associated cooling of the lifted air results in the relative humidity exceeding 100 percent, tiny droplets will condense from the water vapor in the air. These droplets, much like those found in a fog, will result in a visible cloud. If the cloud is colder than 0°C, any existing droplets will be supercooled, that is, colder than the freezing point of bulk water but still liquid due to their small sizes. The terminal fall velocity of the tiny cloud droplets is very low so even slight upward motion in the atmosphere can keep them suspended. These supercooled water droplets will not freeze unless they get very cold (around -40°C), condense on or contact a small particle (an ice nucleus) that can cause them to become a ice crystal, or freeze onto a larger and faster falling ice particle that collides with them.

Cloud seeding involves the formation of ice crystals in clouds that are supercooled but have few natural ice nuclei. In general, these are clouds between 0°C and about -20°C, though the temperature at which significant natural ice crystals form can vary markedly, and factors besides temperature may be involved. In order for precipitation to occur, some of the droplets must be converted to ice which can grow rapidly into snowflakes inside a supercooled liquid cloud. The snowflakes can settle to the ground if they grow large enough and fall far enough before being carried downwind of the mountain barrier. Typically downward motion of the airstream to the lee of the barrier will evaporate the cloud droplets and sublimate the ice crystals so seeding involves a "race" to get snowflakes to the ground before the zone of downward motion is reached. Refer to Grant and Kahan (1974) or Dennis (1980) for a more detailed discussion of the physical processes involved.

2. VIEWPOINTS ABOUT WINTER OROGRAPHIC CLOUD SEEDING

Although winter orographic cloud seeding has been used operationally for four decades, a wide range of viewpoints exists about the effectiveness of the technology. The range among some laymen is especially pronounced, from the view that cloud seeding can always guarantee large precipitation increases, even in a drought, to an equally strongly held and incorrect view that seeding invariably leads to avalanches, severe flooding, decreased downwind precipitation, and other weather ills.

Fortunately, the range of viewpoints among scientists is considerably narrower. For example, the most recent statement of the 10,000 member American Meteorological Society (1985) on weather modification notes that "Precipitation amounts from certain cold orographic cloud systems <u>apparently</u> can be increased under favorable conditions with existing technology in the western United States." Yet the statement goes on to say, "In all cases where indications of precipitation increases have been <u>suggested</u>, confirmatory experiments are required before any of the technologies can be considered <u>scientifically proven.</u> The establishment of the <u>physical mechanisms</u> active in any demonstrated modification effect is also needed to achieve general scientific acceptance" (underlines added). The capability statement of the Weather Modification Association (1989) is more positive, stating, for continental clouds, "Evaluations of both research and operational winter orographic cloud seeding programs indicate that 5-20% seasonal increases in precipitation can be achieved." So some scientists believe that a viable technology presently exists capable of producing modest snowfall enhancement. Others see encouraging suggestions that certain clouds can be affected but lack of scientific proof that significant seasonal increases are achievable.

3. PHYSICAL CHAIN OF EVENTS FROM SEEDING TO SNOWFALL

The conceptual model of what should happen following seeding of a winter orographic cloud has not changed markedly since Ludlam (1955) wrote his classic article on the subject. Similar ideas were restated in different form by Super and Heimbach (1983) in discussing what general statements could be made about artificial seeding. They noted that, "In order for cloud seeding to increase snowfall from winter clouds over mountainous terrain, several links in a physical chain of events must exist. First, seeding material must be successfully and reliably produced. Second, this material must be transported into a region of cloud that has supercooled water or ice supersaturation in excess of that which can be converted to ice by naturally produced ice crystals. Third, the seeding material must have dispersed sufficiently upon reaching this region so that a significant volume is affected by the desired concentration range of ice nuclei or the resulting ice crystals. In the case of silver iodide (AgI) seeding this requires, fourth, that the temperature be low enough for substantial nucleation to occur. Once ice crystals form, they must remain in an environment suitable for growth long enough to enable fallout to occur, generally prior to their being carried beyond the mountain barrier where downslope motion, cloud evaporation and ice crystal sublimation typically exist."

We will next examine the status of knowledge for each of these essential links in the chain of physical events leading from release of the seeding agent to more snowfall on the ground. This will allow us to better evaluate the overall status of the technology of winter orographic cloud seeding and how it might benefit an area such as the Black Hills.

4. PRODUCTION OF SEEDING MATERIAL

We will discuss only AgI, the most common winter orographic seeding agent. It is beyond the scope of this paper to discuss in detail the several forms of AgI and their characteristics. It can be said that successful and reliable production of AgI is well documented in the laboratory, and it can also be reliably produced in the field. However, a note of caution is in order concerning reliable operation of AgI generators. Any mechanical device involving plumbing, pressure, flow of gas and corrosive fluid, and flame requires careful monitoring. Furthermore, AgI generators must function in a harsh outdoor environment. Monitoring is particularly necessary for the more complex radio-controlled systems used at remote locations. These sort of "housekeeping details" are not often discussed in the open scientific literature, but a number of technical reports show the need to carefully monitor the field production of AgI. For example, Hobbs et al. (1975) reported on the results of airborne tracking of AgI from radio-controlled generators in the San Juan Mountains of Colorado. They stated, "High ice nucleus concentrations (attributable to silver iodide particles) were sometimes measured immediately downwind of generators which were not supposed to be in operation, while on other occasions no ice nuclei were detected immediately downwind of generators which were supposed to be in operation." Even manual generators should be checked frequently for proper operation as they are also prone to flameout, clogged nozzles, and other problems. Moreover, ice nucleus output varies markedly with the type of generator used and the specific chemical formulation of the AgI. Therefore, while reliable AgI production is attainable, it should not be taken for granted.

It is noteworthy that the rate of production of ice nuclei varies substantially with the local windspeed. Garvey (1975) shows the output from several ground generators as measured in a cloud simulation laboratory for both light and strong winds in the vertical wind tunnel from which samples were drawn. Outputs can vary by over an order of magnitude as stronger ventilation affects flame temperature, quenching rate, coagulation losses, and other factors, resulting in higher ice nuclei production. The large majority of field programs make no provision for artificially controlling the airflow by ground generators, so the output varies with the natural wind. In practice, this variation often is minor compared with the temperature dependence of AgI discussed in section 7. Moreover, other important factors affect ice nuclei effectiveness. These include the nucleation mechanism, which is related to the specific chemical and physical nature of the particles, and cloud characteristics such as droplet sizes and concentrations.

5. AVAILABILITY AND LOCATION OF SUPERCOOLED LIQUID WATER

The second key link in the physical chain of processes is the routine transport of the AgI to a region of cloud with supercooled liquid water (SLW) present. We will first address when and where SLW exists before discussing attempts to target that region with AgI.

Aircraft observations of winter orographic clouds have been made for many years, but are usually limited to brief "snapshots" during the entire course of a storm. A more serious problem is that safety considerations constrain aircraft measurements to altitudes well above the surface. Upward motion and moisture content should be greater near the mountain slopes than at higher levels, resulting in more SLW production near the surface where aircraft sampling is often impractical. The tendency for greatest SLW content near the windward slope of a barrier is clearly shown by Hobbs (1975) from a composite of 22 aircraft missions over the Cascade Mountains, and by Hill (1986) based on 57 vibrating wire sondes over the Wasatch Mountains of Utah. Holroyd and Super (1984) examined data from many aircraft passes over the flat-topped Grand Mesa of Colorado and showed that SLW was concentrated over the windward slope and barrier top, with higher water contents nearer the surface. The empirical evidence that SLW is concentrated near windward barrier slopes and crests is supported by numerical modeling results such as presented by Young (1974) and Blumenstein et al. (1987).

Since deployment of the microwave radiometer (Hogg, et al., 1983), a wealth of continuous SLW observations have been made from several locations in the intermountain west including the Park Range of Colorado (Rauber, et al., 1986), the Grand Mesa of Colorado (Boe and Super, 1986; Thompson and Super, 1987), the Mogollon Rim of Arizona (Super and Boe, 1988; Super and Holroyd, 1989) and the Tushar Mountains of Utah (Sassen, 1985; Rauber and Grant, 1987). Microwave radiometer measurements provide only the integrated amount of SLW along the direction the reflector is pointed with no information about its spatial distribution. Fortunately, several of the cited studies were supported by aircraft and Sassen (1985) had lidar available so the approximate locations of SLW zones were often documented or inferred.

There is a remarkable similarity among the research results from the various mountain ranges. In general, SLW is available during at least portions of many storms. It is usually concentrated in the lower layers, and especially in shallow clouds with warm tops. Average integrated amounts are normally limited implying low cloud liquid water contents, in agreement with aircraft observations. This means that seeding cannot produce more than moderate snowfall rates except in rare cases. However, where estimates of the SLW flux have been made, it has been found that the seasonal amount of SLW passing over the barrier is a large fraction of the streamflow from the same area. This suggests that considerable SLW passes overhead during a winter, unused by nature. The challenge is to determine what fraction of the excess SLW can be brought to the surface by seeding. There is also some evidence that much of the seasonal SLW flux may be concentrated in a few large storms that already provide considerable snowfall during their efficient stages.

6. TRANSPORT AND DISPERSION OF AgI INTO THE SLW ZONE

It has been established that SLW often exists in winter orographic storms, tending to be at low levels over the windward barrier slope. We now will examine evidence for transport and associated dispersion of AgI into that zone, intended to result in an ice crystal concentration adequate to convert a large fraction of excess SLW into precipitation sized particles. The transport and dispersion (T&D) of AgI has been the weakest link in many, probably most, attempts to seed winter orographic clouds. Rangno (1986) and others have noted that achieving adequate T&D may the most difficult problem facing winter orographic cloud seeding. Yet the large majority of projects have assumed that the released AgI was transported and dispersed into the desired cloud region, resulting in an appropriate ice crystal concentration. It also has been assumed that a large volume of cloud was affected, even though the spacing between generators was large in several programs. We will see that these assumptions were often incorrect, at least in the limited number of projects where physical evidence permits evaluation. It should be noted that T&D effectiveness cannot be judged in the large majority of projects for lack of observations. However, the physical evidence that does exist gives cause for concern.

Many seeding programs have used ground-based rather than aircraft seeding, generally because of economy. A typical ground-based operation has AgI generators located at low levels in the valley or plain upwind of the barrier to be seeded. The airflow near mountain crest elevations during storms is used to determine what direction is upwind. Manual generator locations are often chosen for convenience of operation, near someone's home, or at least near all weather roads. Remote control generators have been used by some projects but they are more expensive than manual units, and reliability has often been less than desired.

One problem with low-level generators is that both windspeed and direction at easy-to-reach sites are usually quite different than experienced near mountain crests. Large mountain ranges tend to have "barrier jets" of the type discussed by Parish (1982) for the Sierra Nevada. Consequently, material released low on the barrier slope may be transported parallel to the barrier rather than up and over it into the cloud zone.

Another serious problem with low-level releases is that the seeding agent may simply be "pooled" in the blocked flow near valley floors just as smoke pollution is in many cities and towns near mountain slopes. The material will eventually be flushed out, but probably not when needed during storms, and likely its path will be other than up and over large barriers. Examples of this phenomenon are given by Walsh and Leverson (1979), Cooper and Marwitz (1980), and Benner and Long (1986).

Yet another concern is that generators may be spaced too far apart so that the plumes never merge, resulting in unseeded regions between plumes. It is known that instantaneous plume widths may be rather narrow in some situations. The meander of the plume with time may result in a relatively large area being affected over the course of a storm, but the area of effect at any moment may be small, seriously diluting seeding effectiveness.

Even where high elevation generators are used, the targeting problem can be difficult. The local airflow may be significantly different than the larger scale flow so that transport is not as expected. In all cases some verification should be sought that the seeding material is generally being transported where and when expected. A relatively simple "first step" is to examine whether any silver from the silver iodide ended up in the target area snowfall.

Analysis of the silver content of snow has been reported from some seeding projects. Finding enhanced silver contents does not prove that AgI seeding resulted in ice crystal nucleation, as scavenging by natural snow and accreted cloud water will transport silver to the surface. However, the lack of silver above background levels strongly suggests a targeting problem. The technique described by Warburton et al. (1989), in which an inert tracer with the same size distribution is released with the AgI, can indicate if the silver was brought to the surface partially by nucleation. This promising approach has not yet had widespread application so we will consider only the more common practice of sampling for silver.

Warburton et al. (1979) showed silver analysis results from the central Sierra Nevada, where five generators on the windward barrier slope were intended to affect the Lake Tahoe-Truckee River catchment area on the lee slope. Frequent samples were collected in the target area during eight seeded storms. Above background silver levels were present only 18 percent of the time. In addition, vertical profiles were sampled at 10 sites after the winter seeding program ended. Analysis of over 700 samples showed that "seeding silver" was present in only 10 to 20 percent of the seeded periods' samples. Moreover, the "excess" silver often appeared in narrow time and spatial zones, suggesting seeding plumes of limited width which were over particular sites for periods of 0.5 to 4 hours.

Long (1984) reported the results of silver analysis of snow from the Tushar Mountains of Utah. Silver iodide generators were operated at low elevations in the upwind valleys. Only 11 of the 145 samples had silver contents significantly greater than background.

Reynolds et al. (1989) discussed the results of silver analysis for 1,681 snow samples taken downwind from 24 ground-based generators, most of which were used by 3 operational projects. Even though most sites used remote control generators at relatively high elevations, "Silver sampling indicated a fairly low percentage of silver in snow over most sampling areas." The percentage of samples with enhanced silver levels was shown for each of the 13 sampling sites. Only two sites had above background silver levels more than 13 percent of the time. It was speculated that much of the AgI may have been transported below crest levels without passing over the barrier. Other reasons for the poor results may be too wide spacing between generators and failure of some generators to operate properly.

It has been documented that generators located well up the windward slope of mountain ranges can provide AgI plumes with 0.5 to 1.0 kilometer vertical extent in both stable and neutral atmospheres. Cloud layers with embedded convection should experience greater vertical mixing. The horizontal extent of the plumes varies with the mechanical turbulence present, distance downwind of the source and other factors, but often exceeds 3 to 5 kilometers in crosswind extent by the time the barrier crest is reached. Examples of T&D investigations supporting these claims include Super (1974), Super and Heimbach (1988), Holroyd et al. (1988) and Super et al. (1989). These studies used aircraft tracking and high altitude releases of AgI, except for the latter which tracked sulfur hexafluoride tracer gas.

Additional evidence for successful targeting with high level generators is given by silver-in-snow analyses as reported by Super and Heimbach (1983) and Heimbach and Super (1988), both for the Bridger Range of Montana, and by Stone and Warburton (1989) for the Lake Almanor project of California with westerly flow. However, the latter study indicated poor targeting with southerly flow, even with high altitude releases. It is interesting that the statistical analysis of Mooney and Lunn (1969) suggested significant precipitation increases with cold westerly storms but not with the cold southerly category.

There is an open question as to how high up the windward slope a generator should be located. If too low, the AgI may not be transported up the windward slope and dispersed into the cloud. If too high, insufficient time may exist for adequate vertical and horizontal dispersion of the AgI as well as for ice particle formation, growth and fallout to the intended target, especially if that target is the windward slope. The "best" location is as far down the slope as possible while still achieving T&D over the barrier. The exact "best" location will vary from storm to storm and even during a storm. Airflow modeling in complex terrain is still inadequate to predict where the "best" location is in any given situation so the decision must be based on empirical evidence, either from other T&D investigations or, preferably, from those conducted over the mountain range in question.

Aircraft seeding, though significantly more expensive than ground seeding, has the advantage that the material often can be released within the altitude zone one is attempting to affect. The targeting should, therefore, be much more certain. However, the question of volume filling remains. While a ground-based seeding agent may be widely dispersed by the mechanical turbulence induced by airflow over rugged terrain, dispersion from higher altitude aircraft releases may be quite limited in stratiform clouds as shown by Karacostas (1981) upwind of the Sierra Nevada of California and by Hill (1980) upwind of the Wasatch Mountains of Utah. Hence, the affected vertical zone may be shallow and lines of AgI released across the wind may not merge with one another before reaching the SLW zone unless the seeding lines are released close to one another. But that means a single seeding aircraft can treat only a limited crosswind distance. Hence, additional aircraft would be needed to seed a large mountain range, markedly increasing the cost. On a more positive note, the observations over the Grand Mesa reported by Super and Boe (1988) showed more rapid along-the-wind plume spreading, apparently caused by terrain-induced acceleration in the horizontal airflow when crossing the barrier. A single aircraft could likely seed a 50-kilometer portion of that particular mountain range with typical windspeeds.

The effectiveness of aircraft seeding (as well as ground-based seeding) can be expected to vary substantially among mountain barriers, depending upon atmospheric stability and winds during storms, the geometry of the mountains and other factors. It should not be taken for granted that aircraft seeding will always work well just because the material can be released at the desired level in the atmosphere. As with ground seeding, physical verification of targeting success is highly recommended.

Once it is established that the seeding agent is transported into a sufficiently cold SLW region for ice nucleation to occur, and is dispersed through a significant volume of the cloud, the question of achieving an appropriate concentration of active ice nuclei remains. Horizontal and vertical dispersion rates and transport speeds influence the resulting ice nucleus concentration for a given source strength (generator output). Estimating the "best" ice nucleus concentration to convert SLW to precipitation for particular conditions is a complex problem involving the specific modes and rates of ice nucleation, the production rate of SLW condensate, ice particle growth and fallout processes, and other factors. Rauber and Grant (1986) have calculated that even limited vertical velocities can produce sufficient condensate for diffusional growth of over 50 per liter small ice crystals. As crystals become larger and accretional growth commences, fewer ice particles (and, hence, ice nuclei) may effectively convert the condensate to precipitation. However, model results by Young (1974) suggested little difference in precipitation production for 50 or 100 ice nuclei per liter for the same assumed conditions. A detailed microphysical model such as Young's should be used to estimate the appropriate ice nucleus concentration for particular conditions.

A reduction of SLW should be associated with effective seeding which is intended to convert much of the SLW into precipitation particles. It is interesting to consider evidence for any SLW decrease from physical seeding experiments. Super and Heimbach (1988) reported on two experiments on January 15, 1985, with SLW observed crosswind of, and within, an AgI plume. No differences were obvious in liquid water content although mean ice particle concentrations clearly increased from near 1 per liter in the crosswind control zones to about 10 per liter in the seeded zones. Super and Boe (1988) described four seeding experiments on March 18, 1986, which compared SLW in a 5-kilometer zone immediately upwind of the target from periods with AgI seedlines present with natural periods shortly before and after. Liquid water amounts appeared to be reduced by approximately half in two cases, and not at all in the other two. The apparent reductions were not related to ice particle concentration which averaged about 10 to 20 per liter in the seeded zones and less than 1 per liter in the controls. Deshler et al. (1990) show some evidence of decreases in the water content of their December 18, 1986, seedlines after about 20 minutes, although natural variability is high. The vertically integrated SLW from a surface microwave radiometer decreased markedly as the seeded volume passed overhead. However, SLW amounts did not rapidly recover after passage so the authors state that, "It can only be speculated if seeding contributed to this decrease in liquid."

These examples suggest that seeding rates and subsequent concentrations of ice nuclei may have been too low to convert most of the liquid water to ice particles. Thus, while seeding in these experiments clearly enhanced ice particle concentrations within the clouds, and may have increased surface snowfall in some cases, the effectiveness of the water-to-ice conversion may have been limited by too few ice nuclei. The important question of appropriate ice nuclei concentrations certainly deserves further investigation, by both modeling and field experiments.

We have discussed some of the problems involved in the T&D of AgI intended for seeding mountain clouds. Successful T&D can be achieved in many situations. However, this key process requires careful planning which should be followed by observations to insure that the T&D is usually proceeding as planned. It is not practical to monitor all seeding attempts, but it is highly advisable to monitor a number of them at the onset of a program to document that the clouds are, in fact, being seeded. Clearly, the goal of enhanced precipitation cannot be realized unless the seeding agent reaches SLW cloud with reasonable frequency and in appropriate concentrations. Yet few projects have managed to demonstrate that this critical process routinely occurred. Improving upon this situation in the future is a worthwhile goal for the field of weather modification.

7. TEMPERATURE IN THE SEEDED ZONE

The temperature of the SLW zone is a very important factor to consider in deciding which method of AgI release to employ for a given mountain range. The effectiveness of AgI as an ice producing agent is very temperature dependent as shown by Garvey (1975) and others. Only a fraction of all the AgI particles produced by a generator have the ability to create ice crystals, but that fraction increases by about a factor of ten for every 4°C decrease in temperature over the range of interest in cloud seeding. What that means is that it is very difficult to produce enough active AgI particles to effectively seed a cloud at temperatures warmer than about -6°C, but easy to produce enough (perhaps too many) at temperatures colder than -15°C. Therefore, it may be impractical to seed warm clouds from the ground with AgI because the material will not disperse vertically to cold enough levels to create the necessary concentration of ice crystals. Super et al. (1989) discuss this problem for Arizona winter clouds where most storms may be too warm for AgI to be effective in the lowest kilometer above ground, the zone where surface released tracer gas was normally found. The statistical evaluation of the Bridger Range Experiment by Super and Heimbach (1983), supported by physical observations of successful T&D (and further by the measurements of Super and Heimbach, 1988), suggested that even as far north as Montana about half the winter storms were too warm for ground seeding.

The warmer storms tend to hold the most moisture so it is very important to improve our ability to create ice particles in warm supercooled cloud zones. Even aircraft seeding with AgI may not be effective if all the SLW is warmer than about -6 to -8°C. Work such as reported by DeMott et al. (1983) is improving the warm temperature nucleation with AgI. Agents that work at even warmer temperatures may be required in some situations. Dry ice will create ice at even slight supercooling but has to be dropped directly into the SLW cloud. That can result in other potential problems, such as the inability to disperse the material through a large volume before it reaches the cloud. Widespread dispersion is possible with AgI which can be released upwind of the clouds. Ground seeding with propane, described by Reynolds (1989), may hold promise in some locations. New bacterial nucleation agents may also help in warm conditions (Levin et al., 1987; Ward and DeMott, 1989). But both these approaches have yet to undergo thorough field testing.

It is beyond the scope of this paper to discuss the AgI nucleation process in detail. However, the specific process is very important to the final outcome following release of a seeding agent. It is noted that a number of different nucleation modes are possible depending upon the specific type (solution, combustion chemistry) of AgI used, and cloud characteristics. Some types are fast acting, such that all the nuclei potentially active at one temperature produce ice crystals in a few minutes (Finnegan, et al, 1984). Other types are much slower, continuing to form ice particles an hour or more after encountering SLW even at one temperature. Fukuta (1986) argues for use of the slower acting (contact freezing) types in some situations as this "automatically avoids over-generation of ice crystals." On the other hand, rapid nucleation may be highly desired where time is limited before the cloudy air evaporates to the lee of the barrier. The specific type of AgI to be used in a given project deserves careful consideration.

8. ICE PARTICLE GROWTH AND FALLOUT

The processes involved in the growth of ice crystals into snowflakes following nucleation, and subsequent fallout, are reasonably well understood. Many of the factors involved have been demonstrated in the laboratory, at least for short periods (e.g., Ryan et al., 1976) and for longer times in actual clouds (e.g., Holroyd, 1986). Computerized numerical models exist that handle the physical processes in considerable detail; for example, Young (1974) and Cotton et al. (1986). Some aspects of the modeling still rely on inadequate theoretical understanding, such as aggregational growth of many ice crystals into individual large snowflakes. But even a relatively simple model can be used to predict where seeding material should be placed in order for snowfall to reach a target (Rauber et al., 1988). The weakest point in use of models may be in supplying adequate input measurements rather than in the models themselves. There is no means to routinely monitor the three-dimensional SLW distribution, for example. Moreover, SLW usually varies considerably even at the same level with frequent dry regions encountered by sampling aircraft flying through orographic clouds. Similar comments could be made about the airflow over mountain barriers. Nevertheless, numerical calculations can give a good estimate as to whether or not a particular barrier is seedable for given conditions. Times from ice nucleation to snowflake fallout to the surface often vary from about 15 to 60 minutes. With typical windspeeds a region as large as the Black Hills should be seedable much of the time when the necessary SLW exists at cold enough temperatures and the T&D of the AgI is sufficient to affect a large fraction of the SLW zone.

9. CONCLUSIONS AND RECOMMENDATIONS

This review of the status of winter cloud seeding has attempted to show where physical evidence is reasonably solid and where it is weak in our attempts to enhance snowfall on orographic barriers in the intermountain west. The physical hypothesis for such projects should consider reliable production of seeding material, its transport and dispersion into SLW cloud, subsequent nucleation of an appropriate concentration of ice particles, and their growth and fallout to the surface before reaching the lee subsidence zone downwind of the barrier. Seeding material, generally some form of AgI, can be routinely produced by several types of generators if care is taken in maintenance. It was shown that most SLW is normally found in the lowest kilometer above the windward barrier slope in the absence of convection. A number of studies have shown that AgI released well up the windward slope will be transported over the barrier while mixing through 0.5- to 1.0-kilometer depth due to mechanical turbulence. Plume widths of 3 to 5 kilometers or more can be achieved by the time the seeding material reaches the crestline. Hence, much of the SLW region can be seeded with ground generators. However, the temperature in this zone is frequently too warm for significant ice formation with conventional types of generators and AgI. This indicates a continuing need to develop agents that are effective in slightly supercooled clouds (between 0 and about -6°C), and which can be released well upwind of the SLW zone to insure adequate dispersion.

The most serious problem for successful snowfall enhancement in the intermountain west continues to be the transport and dispersion of appropriate concentrations of the seeding agent. While successful targeting might be accomplished from the ground in some instances, and from aircraft in others, the success of several past applications is questionable. Projects employing valley or foothill releases of AgI generally have not offered supporting physical evidence that the agent reached the SLW zone, so their targeting is an open question. However, in those limited projects that used low-level releases and measured silver (or other tracers) in the target area snowfall, there is evidence suggesting that desired targeting often was not achieved. Several but not all projects that used high-level generators and silver or AgI monitoring were able to demonstrate the seeding agent was transported to the target zone.

Projects using aircraft seeding should ensure that parallel seedlines are released close enough to each other to merge before reaching the SLW. Some programs have attempted to affect long barriers with a single aircraft in spite of physical evidence that free air dispersion is limited. Only a fraction of the targeted cloud volume is likely to be filled with AgI which must seriously reduce seeding effectiveness.

It is strongly recommended that all winter orographic seeding programs using AgI take at least the minimum step of measuring the silver content of the target area snowfall. This relatively inexpensive "first look" does not prove seeding increased the snowfall if enhanced silver is found because scavenging could account for the elevated silver levels. However, failure to achieve above background silver levels is clear evidence that the targeting approach should be reconsidered. The addition of this simple test could add significantly to the credibility of the field, as claims of success would at least require demonstration of enhanced silver levels in the target area snowpack.

Whenever resources permit, winter orographic seeding projects should monitor as many key physical processes as practical during at least a subset of storms. Instrumentation now exists to monitor the transport and dispersion of AgI, or a tracer gas co-released with a seeding agent. Resulting ice particles can be monitored and tracked by aircraft where sufficiently low flight is practical. Physical seeding experiments such as described by Super and Boe (1988) sometimes can provide strong evidence that seeding resulted in snowfall on the ground. Application of very sophisticated numerical models, especially where supported by comprehensive field measurements, can substantially increase understanding of the complex interactions involved in winter clouds over mountains. Any and all of these approaches can help test at least portions of the seeding hypothesis and thereby improve the emerging technology of winter orographic cloud seeding. With the ever increasing demands on available water resources it is important to validate this potentially very beneficial technology.

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