# A Review of Cloud Seeding Experiments to Enhance Precipitation and Some New Prospects

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## ABSTRACT

Water is one of the most basic commodities on earth sustaining human life. In many regions of the world, traditional sources and supplies of ground water, rivers and reservoirs, are either inadequate or under threat from ever-increasing demands on water from changes in land use and growing populations. This has prompted scientists and engineers to explore the possibility of augmenting water supplies by means of cloud seeding.

This paper provides an overview of the current scientific status of weather modification activities to enhance precipitation for both glaciogenic and hygroscopic seeding experiments. It is important to emphasize that although funding for scientific studies has decreased substantially during the past decade, operational programs have actually increased.

During the last 10 years there has been a thorough scrutiny of past experiments involving experiments using glaciogenic seeding. Although there still exist indications that seeding can increase precipitation, a number of recent studies have questioned many of the positive results, weakening the scientific credibility. As a result, considerable skepticism exists as to whether these methods provides a cost-effective means for increasing precipitation for water resources.

Recent results from hygroscopic seeding experiments provided for some renewed optimism in the field of precipitation enhancement. Although promising results have been obtained to date, some fundamental questions remain that need to be answered in order to provide a sound scientific basis for this technology.

## 1. Introduction

Water is one of the most basic commodities on earth sustaining human life. In many regions of the world, however, traditional sources and supplies of ground water, rivers and reservoirs, are either inadequate or under threat from ever-increasing demands on water from changes in land use and growing populations. In many countries water supplies frequently come under stress from droughts and increased pollution in rivers, resulting in shortages and an increase in the cost of potable water. Ground water tables have been steadily decreasing in many areas around the world where ground water is one of the primary sources of freshwater. This is particularly evident in the southwest United States and Mexico. To help alleviate some of these stresses, cloud seeding for precipitation enhancement has been used as a tool to help mitigate dwindling water resources.

While many countries conducting weather modification activities are located in semiarid regions of the world, several countries in the Tropics such as Indonesia, Malaysia, India, and Thailand are also involved in weather modification activities. Although these countries receive a relatively large amount of rainfall, a 5% below normal rainfall year translates into a drought for them due to their infrastructure and agricultural practices that are more water intensive than in other parts of the world. Weather modification activities to enhance water supplies have been conducted for a wide variety of users including water resource managers, hydroelectric power companies, and agriculture.

Only a small part of the available moisture in clouds is transformed into precipitation that reaches

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the surface (National Academy of Sciences 1966a,b, 1973; Weather Modification Advisory Board 1978). This fact has prompted scientists and engineers to explore the possibility of augmenting water supplies by means of cloud seeding. If more water could be transformed into precipitation, the potential benefits appear very attractive. The ability to influence and modify cloud microstructure in certain simple cloud systems such as fog, thin layer clouds, simple orographic clouds, and small cumulus clouds, has been demonstrated and verified in laboratory, modeling, and observational studies (American Meteorological Society 1992). Although past experiments suggest that precipitation from single-cell and multicell convective clouds may be increased, decreased, and/or redistributed, the response variability is not fully understood. It appears to be linked to variations in targeting, cloud selection criteria, and assessment methods. The complexity of atmospheric processes and specifically cloud and precipitation development has prevented significant progress in developing a cloud seeding technology that can be tested and verified in a repeatable manner with the level of proof required by the scientific community.

In the annual register of National Weather Modification Projects, compiled and published by the World Meteorological Organization (WMO) since 1975, 27 countries provided information on 88 ongoing weather modification activities in 1994. It should be emphasized that these data only pertain to countries that report such data. Many countries do not report their activities, making the above estimate conservative. In the United States alone, the National Oceanic and Atmospheric Administration (NOAA) reported information about 36 ongoing weather modification activities in 12 states in 1994. The federal government sponsored only one of these projects. Twenty-nine projects were for precipitation enhancement. These activities are operational programs that operate on the basis of past scientific results.

The fact that many operational programs have been on going and have increased in number in the past 10 years indicates the ever-increasing need for additional water resources in many parts of the world, including the United States. It also suggests that the level of proof needed by users, water managers, engineers, and operators for the application of this technology is generally lower than what is expected in the scientific community. The decision of whether to implement or continue an operational program becomes a matter of cost/benefit risk management and raises the question of what constitutes a successful precipitation enhancement program. This question may be answered differently by scientists, water managers, or economists, and will depend on different factors depending on who answers the question. This difference is illustrated by the fact that although scientific cloud seeding experiments have shown mixed results based on the level of proof required by the scientific community, many operational cloud seeding programs are still ongoing. However, it also emphasizes the fact that the potential technology of precipitation enhancement is very closely linked to water resources management. It is thus important that the users of this potential technology are integrated into programs at a very early stage in order to establish the requirements and economic viability of any program (Ryan and King 1997). In addition, the continued need for additional water and the fact that most programs currently ongoing in the United States and the rest of the world are operational programs emphasizes the need for continued and more intensive scientific studies to further develop the scientific basis for this technology.

In the past, weather modification activities were often initiated in times of a drought when desperate water needs exist. In many cases, the programs were discontinued when the drought was over. Apart from the question of whether these programs are successful or not, the more relevant question is whether cloud seeding should be initiated during drought conditions at all due to the limited number of clouds available for seeding. A better approach that has been adopted by some operational programs is to view the technology as a longer-term water resources management tool. It may be better to continue seeding during non-drought years in order to build up water supplies for the future.

In the scientific community weather modification is still viewed as a somewhat controversial topic. Changnon and Lambright (1990) identified several problems and difficulties that have arisen during the conduct of weather modification experiments. According to Changnon and Lambright, based on their analyses of the National Hail Research Experiment and the Sierra Cooperative Pilot Program (SCPP), the major scientific controversies were a result of six factors. These factors were 1) proceeding with an inadequate scientific knowledge base, 2) a flawed project-planning process, 3) differing views between funding agencies and project scientists, 4) lack of continuing commitment by the principal agency conducting the experiment, 5) changes in project directors, and 6) poor performance by project scientists. Because of the complex nature of precipitation enhancement experiments, it is extremely important to funding agencies, water managers, and scientists that current experiments are critically reviewed in terms of these six factors in order to avoid repeating the mistakes listed above.

## 2. Precipitation processes

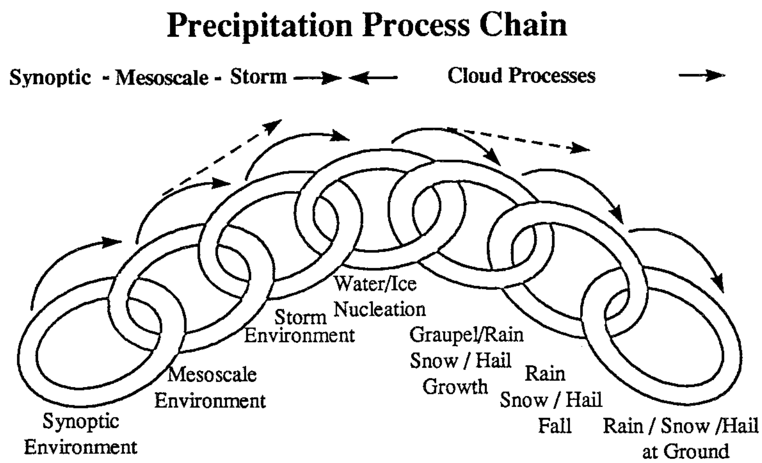


FIG. 1. The "precipitation process chain," illustrating the sequence of events, not necessarily independent, that lead to precipitation at the ground. Processes within each "link" or event often occur on different spatial and temporal scales.

Weather modification research requires the involvement of a large range of expertise due to both the multifaceted nature of the problem and the large range of scales that are addressed. The large- and mesoscale dynamics determining the characteristics of the cloud systems down to the small-scale microphysics determining the nucleation and growth characteristics of water droplets and ice particles all form part of the chain of events of precipitation development (Fig. 1). Although our knowledge of the individual aspects in the chain has significantly increased in the past 20 years, there still exist major gaps about certain physical processes.

Precipitation initiation and development can proceed via several physical paths (Fig. 2), involving various microphysical processes that proceed simultaneously but at different rates, with one path becoming dominant because of its greater efficiency under given atmospheric conditions. The efficiency with which clouds produce rain at the surface varies greatly. Precipitation efficiency, defined as the ratio of the rate of rain reaching the ground to the flux of water vapor passing through cloud base (Marwitz 1972), can range from zero in nonprecipitating clouds to greater than unity for short times, in very intense, time-dependent, convective systems (Cotton and Anthes 1989). Some of the earliest studies showed that ordinary thunderstorms transform less than 20% of the influx of water vapor into rain on the ground (Braham 1952). The principles of most, if not all, precipitation enhancement hypotheses are rooted in these efficiency factors that, in general, seek to improve the effectiveness of the precipitation evolution path. The seeding conceptual model (physical hypothesis) describes how this is accomplished by the seeding intervention and specifically how the initiation and development of precipitation in seeded clouds differ from that in unseeded clouds and may affect the dynamics of the cloud.

Precipitation formation mechanisms can differ dramatically from one location to another, and at one location, depending on the meteorological setting. Precipitation growth can either take place through coalescence or the ice process or a combination of the

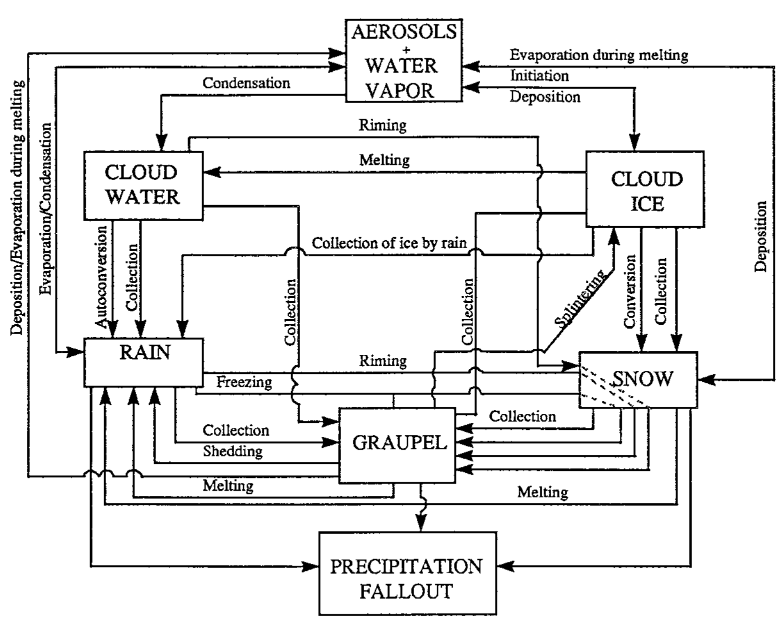


FIG. 2. Various pathways by which water vapor is transformed into various types of cloud particles and precipitation. Adapted from Houze (1993, 96).

two (Fig. 2). In clouds with tops warmer than 0°C, precipitation can develop by means of the coalescence process. Clouds are further categorized as either continental or maritime, which describes the degree of colloidal instability. However, when cloud tops reach temperatures colder than 0°C, ice develops and precipitation can develop through a different set of paths, as is displayed in Fig. 2.

The number concentration and size spectrum of cloud droplets can also vary dramatically, depending on the cloud condensation nucleus (CCN) size distribution. A maritime droplet spectra will consist of fewer particles but more large drops than in a continental spectrum (Pruppacher and Klett 1978).

Another distinction that is often made in continental summertime convective clouds (Braham 1986; Silverman 1986) is the temperature levels at which the ice crystals nucleate. In clouds with "cold bases" (< +10°C) and a narrow cloud droplet spectra, ice tends to develop between the −9° to −12°C levels (Krauss et al. 1987; Bruintjes et al. 1987). In clouds with "warm bases" (> +10°C), coalescence usually occurs together with an active multiplication process in the −5° to −8°C region (Hallet and Mossop 1974). The dominant ice crystal habit will differ in both cases, with hexagonal plates and dendrites being the dominant graupel embryos in the former case and large frozen drops and columns and capped columns in the latter. In the latter case precipitation development via the ice phase is initiated earlier and functions more efficiently than in the former case (Johnson 1987; Bruintjes et al. 1987). The concentrations of ice crystals in the latter case are usually higher than in the former case. It is clear that responses to seeding will differ, depending on the precipitation mechanism that is operating at the time.

The multitude of different paths by which precipitation initiation and development proceeds (Fig. 2), based on the meteorological variability in space and time and the inability of past experiments to always measure these differences, has been and still remains one of the primary reasons why many experiments did not provide conclusive results. It is therefore necessary to understand these differences and identify covariates that describe the different meteorological conditions in order to include these factors in the evaluation of cloud seeding experiments. Field experiments conducted in combination with theoretical and numerical modeling efforts based on the development of new instruments and advanced computer systems have shown (Klimowski et al. 1998), and continue to offer, the greatest opportunity for providing the understanding necessary to successfully assess precipitation enhancement potential and evaluate such experiments.

## 3. Evaluation of seeding technologies

### a. *Methods of evaluation*

The evidence that is required to establish that a cloud seeding methodology is "scientifically proven" can be divided into two aspects, namely, statistical and physical evidence. Statistical evidence is usually obtained by an experiment based on a seeding conceptual model that is conducted and evaluated in accordance with its original design using accepted statistical principles and procedures, and results in the rejection of the null hypothesis at an appropriate level of statistical significance and power of detection. The statistical evaluation enables the detection, in an as unbiased manner as possible, of a change (seeding signal) in a response variable, as specified by the seeding conceptual model, which is usually small compared to its natural variability.

Physical evidence constitutes the measurement of key links in the chain of events associated with the seeding conceptual model establishing the physical plausibility that the positive effects of seeding, suggested by the results of a statistical experiment, could have been caused by seeding intervention. The physical evidence enables the establishment of a cause-and-effect relationship between the seeding intervention and the changes in the response variables[1] as documented in the statistical evaluation. This is usually accomplished by means of case studies of the behavior of seeded and unseeded clouds that are conducted on a sample of clouds involved in the statistical experiment or separate from it, and/or as an integral part of the statistical experiment through the identification of a series of response variables associated with the seeding conceptual model. Such variables must be capable of being measured to the degree necessary to discern the anticipated changes due to the seeding intervention.

Physical evidence is essential in confirming the validity of the seeding conceptual model in order to provide the basis for transferring the cloud seeding

[1]Response variables are parameters that represent key links in the chain of physical events as described by the seeding conceptual model.

methodology to other areas. The seeding conceptual model determines the recognition of seeding opportunities, implementation of a seeding strategy, and the evaluation of the effects of seeding.

The earlier statistical experiments measured primarily precipitation and snowfall at the surface as the response variable, and physical studies did not form an integral part of these experiments [Australian experiments, Ryan and King (1997); Climax, Mielke et al. (1971)]. The physical chain of events was treated as a “black box,” making it difficult to explain the results in a physical manner (Cotton 1986). Both the Whitetop (Braham 1979) and the Israeli experiments (Gagin and Neumann 1974) could also be classified as black-box-type experiments. However, both had parallel observational studies that either supported or did not support the basic concept. While the physical studies were not an integral part of the statistical tests of the basic concept, they helped in the interpretation of the statistical results and placed the physical concept on a firmer scientific base (Cotton 1986). The problem with a pure black-box experiment is that if just one weak link exists in the hypothesized chain of physical responses, all is lost without our knowing which was the weak link (Cotton 1986). If measurements of the key links in the chain of physical events associated with the seeding conceptual model had been obtained, it might have been possible to detect the problem and alter the strategies and experimental design to overcome the weakness (Cotton 1986).

In physical experiments such as in the Cascades in Washington (Hobbs 1975a,b; Hobbs and Radke 1975), the High Plains Experiment (HIPLEX-1; Bureau of Reclamation 1979; Smith et al. 1984; Cooper and Lawson 1984), and SCPP (Bureau of Reclamation 1983; Reynolds and Dennis 1986), the aim was to test the cause and effect relationships of key links in the physical chain of events associated with the seeding conceptual model.

The key benefits of a physical evaluation are that it provides the information necessary to determine whether or not the seeding conceptual model is working as postulated and, if not, why and where it is different. It provides the information needed to determine if and how the seeding methodology can be improved (optimized), and finally it provides the information needed to determine the conditions under which the seeding methodology can be used in other geographical locations (transferability criteria), within the same country or other countries. However, the physical approach is not without pitfalls either. For example, Cotton (1986) mentions the fact that changes in seeding strategy to optimize detection of a response in the intermediate links in the chain of responses may have an adverse effect on the bottom line response, namely, rainfall on the ground.

It is very important to consider the possible pitfalls that have affected experiments in the past. They can range from errors in the statistical design, the conceptual model and associated anticipated responses; changes in seeding strategy and/or seeding material; inappropriate statistical and/or evaluation methods; and inadequate tools to conduct the experiment. In addition, the seeding conceptual model and seeding strategy established in one area may not be transferable to another (List et al. 1999).

With respect to statistical design and methods it is also important to consider the appropriate method and its power to detect the statistical significance of changes in response to seeding (Smith et al. 1984; Mielke et al. 1984; Fletcher and Steffens 1996; Gabriel 1999). In addition, it is important to consider the power of the statistical method in order to determine the length of an experiment to obtain statistical significance (Gabriel 1999). Ryan and King (1997) also mentioned these issues in their review of the Australian experiments.

### b. *Cold-cloud seeding*

The inception of the modern era of weather modification began with the discoveries of Schaefer (1946) and Vonnegut (1947) showing that supercooled liquid water could be converted to ice crystals using either dry ice or silver iodide. The motivation and conception of these projects were based on conceptual models developed from past experience defining conditions that are conducive to positive seeding effects. These conceptual models were based on (i) visual observations of clouds that did not precipitate, (ii) the presence of supercooled water, (iii) the similarity with clouds in other regions that responded positively to seeding, and (iv) data collected with aircraft and radars, among others (Vali et al. 1988).

Since the discovery of glaciogenic materials more than 40 years ago, both silver iodide and dry ice are still the most widely used cloud seeding materials in the world. Both materials enhance the ice crystal concentrations in clouds by either nucleating new crystals or freezing cloud droplets. Based on their ice-nucleating capabilities two seeding concepts have been proposed in the past, namely, the static and dynamic seeding concepts (Braham 1986).

1) Static seeding concept

*(i) Convective clouds*

Some of the initial steps in this chain of events have been demonstrated in field measurements and laboratory and modeling studies, including increased concentrations of ice crystals and the more rapid production of precipitation particles in cumulus clouds. In the HIPLEX-1 experiment a detailed seeding hypothesis (Smith et al. 1984), together with a well-designed field program that monitored each step in the physical hypothesis, was conducted. Although the experiment failed to demonstrate statistically all the hypothesized steps, the reasons for the failures could be traced to the physical dataset (Cooper and Lawson 1984). This in itself is a significant result that indicates the importance of the ability of physical measurements and studies to provide an understanding of the underlying physical processes in each experiment.

It is interesting to note that although the HIPLEX-1 seeding hypothesis called for the ice crystals produced by seeding to develop into graupel, measurements at –6°C in HIPLEX-1 clouds did indicate large numbers of aggregates (Cooper and Lawson 1984). This was due to the short-lived nature of HIPLEX-1 clouds and the rapid decrease in supercooled liquid water, which is the primary growth source for graupel. The aggregates, on the other hand, had much lower fall velocities than graupel particles and stayed aloft and evaporated, resulting in no increase in precipitation. This result indicates that not all clouds may be amenable to seeding and that there exists a certain window of opportunity. For the static seeding concept this opportunity appears to be limited to continental cold-based clouds with top temperatures approximately between –10° and –20°C, and limited to the time when significant amounts of supercooled liquid water is available for growth by riming of the seeded produced ice crystals (Cooper and Lawson 1984).

Experiments that used a combination of the statistical and physical approaches are the Canadian studies by Isaac et al. (1977, 1982) and English and Marwitz (1981), the WMO Precipitation Enhancement Project (WMO 1986; Vali et al. 1988), the Australian experiments (Ryan and King 1997), the South African studies by Krauss et al. (1987), and others (e.g., Dye et al. 1976; Holroyd et al. 1978; Sax et al. 1979; Hobbs and Politovich 1980; Orville 1996).

Most of these experiments were conducted on semi-isolated cumulus congestus clouds to provide a relatively simple cloud dynamics framework to confirm fundamental cause and effect relations of cloud microphysical processes. However, such clouds do not contribute significantly to rainfall at the ground. Convective complexes contribute significantly more than semi-isolated cumulus congestus clouds to the rainfall at the surface in most regions where a major part of the annual precipitation is the result of convective activity (Bureau of Reclamation 1979). However, convective complexes are much more complex dynamically than the smaller clouds because they are, to a large extent, manifestations of mesoscale and large-scale dynamical processes.

The increases in precipitation at the ground due to the static seeding concept in convective cumulus clouds have in general been inconclusive and the initial optimism has been replaced by a more cautious approach. Braham's (1986) list of factors that have limited research progress can be summarized in two points: the large natural variability and an incomplete understanding of the physical processes involved.

The Israeli experiments (Gagin and Neumann 1981) have provided the strongest evidence to date that static seeding of convective cold-based continental clouds can cause significant increases in precipitation on the ground. However, Rangno and Hobbs (1995) have questioned the validity of the conclusions of the Israeli experiments. From their reanalyses of the Israeli I and II experiments they claim that seeding-induced increases in Israeli I were contaminated by a type I statistical error (i.e., a lucky draw). In addition, they claimed that naturally higher precipitation in the north target area on seeded days during Israeli II could have been mistaken for a seeding-induced change in precipitation.

The apparent decrease in rainfall in the south target area in Israeli II was linked to the incursion of desert dust by Rosenfeld and Farbstein (1992). They suggest that desert dust contains more ice nuclei and also can provide coalescence embryos that can enhance the collision–coalescence process in clouds, providing for more efficient precipitation processes in the clouds.

The original thought that clouds in Israel were continental in nature and that ice particle concentrations in these clouds were generally small for cloud tops warmer than –12°C with neither coalescence nor an ice multiplication process operating has also been questioned. Rangno and Hobbs (1995) and Levin (1992) presented evidence for the existence of large supercooled droplets and high ice concentrations at relatively warm temperatures in these clouds. Although the measurements represented a limited number of cases, it somewhat erodes the earlier perception that clouds over Israel were highly susceptible to seeding (Gagin 1986; Gagin and Neumann 1974).

The criticisms of Rangno and Hobbs (1995) have generated a significant number of responses in the scientific literature (Rosenfeld 1997; Rangno and Hobbs 1997a; Woodley 1997; Rangno and Hobbs 1997b; Ben-Zvi 1997; Rangno and Hobbs 1997c; Dennis and Orville 1997; Rangno and Hobbs 1997d). Although many of the issues were clarified by these comments, the perception that the Israeli experiments were the most successful example of precipitation enhancement has been weakened.

Mather et al. (1996) reported results from randomized cloud seeding experiments using dry ice in South Africa. They hypothesize that their results do not totally fit the static seeding hypothesis but also include the freezing of large drops that grow much faster than graupel particles (Johnson 1987). The results from 127 storms analyzed using radar data indicate that radar-measured rain flux and storm area from seeded clouds were significantly larger than for the unseeded clouds. In their analyses a floating target defined by the storm track from the radar was used. Although these results indicate increases in rain from specific storms, they do not address the issue of rainfall increases over a target area on the ground. Results of this study also indicated that clouds in which the coalescence process was active seem to be more amenable to seeding (Mather et al. 1986).

*(ii) Winter orographic cloud seeding*

Since the first conceptual models (Bergeron 1949; Ludlum 1955), attempts began to increase winter snowpack on mountain ranges by seeding clouds with silver iodide or dry ice, and several operational and research winter orographic cloud seeding programs have been conducted worldwide. Many of the steps in the physical chain of events associated with the static seeding concept have also been documented in these experiments (Elliott 1986; Reynolds 1988; Reynolds and Dennis 1986; Super 1990; Reinking and Meitin 1989). These studies have shown that seeding does increase precipitation under certain favorable conditions (American Meteorological Society 1992) and can result in increases in snowpack. However, there are still many unanswered questions. In particular, the variability of clouds in complex terrain and associated temporal and spatial changes in wind flow and regions of supercooled liquid water lead to difficulties in the targeting and dispersion of seeding material and the identification of suitable seeding situations.

A review of the relevant literature immediately highlights the correlation between the temporal and spatial evolution of cloud liquid water (CLW) and the complexity of the terrain (Rauber et al. 1986; Rauber and Grant 1986; Marwitz 1986; Deshler et al. 1990; Huggins and Sassen 1990). Rangno (1986) notes that the cloud variability encountered in several mountainous areas in the United States poses severe challenges for forecasting seeding opportunities and determining a treatment strategy, especially when seeding opportunities are short lived. This conclusion was reiterated by Super and Holroyd (1989) based on studies in Arizona where they specifically noted that, although CLW was present in all storm systems, it was highly variable in time. However, in most of these studies, measurements of CLW with microwave radiometers indicated many hours of CLW that could potentially be seeded (Huggins 1995).

The temporal and spatial variability of CLW also poses a severe problem for targeting regions of CLW with seeding material. This was especially highlighted in seeding experiments over the Sierra Nevada (Deshler et al. 1990), where the complete chain of events from seeding to precipitation could be documented in only 2 of 36 experiments. The authors ascribed the failures to difficult technical and logistic limitations, and to the variability of even simple cloud systems, and not necessarily to the seeding conceptual model. This was particularly evident in the spatial and temporal distributions of CLW and in the natural fluctuations in ice crystal concentrations. Huggins and Sassen (1990) were also unable to document the physical chain of events from seeding to precipitation at the surface in seeding experiments in the Tushar Mountains in Utah. Once again, insufficient knowledge about the transport and dispersion of the seeding material was quoted as one of the primary reasons for failure. In the Utah experiment as well as in many other orographic seeding experiments, seeding generators were located in fixed positions upwind from the target while the measurement facilities were concentrated in a single location downwind from the seeding generators. These locations were chosen assuming a mean wind direction and assuming that no changes in wind direction occur between the seeding generator and the target position. One would expect that with fixed seeding and target locations, seeding effects would only be detected when the flow is parallel to a line connecting the seeding generator and the target. Thus, the opportunities to document the chain of physical events are limited. This approach also assumes that CLW regions will always be present in the same location and that sufficient amounts are present for seeding material to interact with and to produce precipitation in the target area.

Due to the problem of insufficient knowledge about the wind flow patterns and associated CLW regions, some investigators proposed conducting continuous seeding during the entire storm duration in the hope that seeding would have positive effects when CLW was present and no effects when CLW was not present (Super and Holroyd 1989; Super 1990). However, this approach may further mask seeding effects and may even have negative effects in certain instances. This may explain why some seeding experiments in winter orographic regions have produced either inconclusive or negative results.

The results from the CLIMAX I and CLIMAX II experiments (Grant and Mielke 1967; Mielke et al. 1981), which were the most compelling evidence in the United States for enhancing precipitation in wintertime orographic clouds, were also recently challenged by Rangno and Hobbs (1987, 1993). Although the Rangno and Hobbs reanalyses still indicate a possible increase in precipitation of about 10%, which still is significant, it is considerably less than originally reported.

Ryan and King (1997) recently presented a comprehensive overview of more than 40 years of cloud seeding experiments in Australia. They concluded that seeding was not effective in enhancing winter rainfall over the plains area of Australia. However, there was evidence to suggest that cloud seeding is effective for limited meteorological conditions in stratiform clouds undergoing orographic uplift. Especially in the Tasmanian program, strong statistical evidence for rainfall enhancement for cloud-top temperatures between −10° and −12°C in a southwesterly airstream was found. The reason for failures could in some instances be traced to insufficient knowledge, and flaws in the statistical design and conduct of the experiments. Ryan and King (1997) noted that extreme care needs to be taken in the statistical design and conduct of cloud seeding experiments.

The timely identification of regions of supercooled liquid water and the efficient targeting and dispersion of seeding material in mountainous terrain remains a difficult problem. This will have to be considered when developing guidelines and strategies for dispersing seeding material. An important aspect emphasized in nearly all past experiments was the need for more wind measurements in time and space between the seeding release site and the target area. Although this requires a dense network of sensors, recent studies (Bruintjes et al. 1994, 1995; Heimbach and Hall 1994, 1996) have shown the utility of using state-of-the-art models for guiding and understanding the flow patterns and associated CLW regions in complex terrain. Orville (1996) provided a review of the important advances in modeling efforts for weather modification. In addition, new observational tools provide the opportunity to address the above problems with renewed vigor.

*(iii) Summary*

During the last 10 years there has been a thorough scrutiny and evaluation of cloud seeding projects involving the static seeding concept. Although there still are indications that seeding can increase precipitation, a number of recent studies have questioned many of the positive results, weakening the scientific credibility of some of these experiments. As a result, considerable skepticism exists as to whether this method provides a cost-effective means for increasing precipitation for water resources.

2) Dynamic seeding concept

The second approach is the dynamic seeding concept. The thrust of this concept is to seed supercooled clouds with large enough quantities of ice nuclei or coolant to cause rapid glaciation of the cloud. Due to seeding, supercooled liquid water is converted into ice particles, releasing latent heat, increasing buoyancy, and thereby invigorating cloud updrafts. In favorable conditions, this will cause the cloud to grow larger, process more water vapor, and yield more precipitation. Furthermore, the formation of the precipitation might cause more intense downdrafts and interactions with the environment, promoting more active convection.

The dynamic seeding concept was first tested by Simpson et al. (1967). The hypothesized chain of events in these earlier experiments has been summarized by Woodley et al. (1982). Few of the hypothesized steps in the chain of events have been measured in past experiments or have been verified and validated by numerical models (Orville 1996).

Observations have shown the rapid glaciation of seeded clouds (Sax et al. 1979; Hallet 1981), and some evidence has been presented that clouds developed to greater heights as a result of dynamic seeding (Simpson et al. 1967). Due to the difficulty measuring and documenting the chain of hypothesized responses, the initial experiments including FACE (Florida Area Cumulus Experiment) -1 and FACE-2 (Woodley et al. 1982; Woodley et al. 1983) have mainly resorted to a black-box-type experiment with its resultant pitfalls (Cotton 1986).

After some initial encouraging results, this concept has been explored in a number of projects. The results from the Texas experiments (Rosenfeld and Woodley 1989, 1993) suggested that seeding with silver iodide increased the maximum heights by 7%, the areas by 43%, the duration by 36%, and the rain volumes of the cells by 130%. Although these results are encouraging, they also create new questions. The increase in cloud-top height is considerably less than originally hypothesized or found in the earlier experiments.

In response to these findings, Rosenfield and Woodley (1993) modified the initial hypothesis to explain the lack of increase in cloud-top heights from seeded clouds. While an unseeded cloud would go through five stages, including the cumulus growth stage, supercooled rain stage, cloud-top rainout stage, downdraft stage, and dissipation stage, the seeded cloud would go through several more stages. While the first two stages are the same, the third stage would show the first effects of seeding and is called the glaciation stage. This stage also includes the freezing of raindrops, which subsequently results in the unloading stage. The following stages include a downdraft and merger stage, mature cumulonimbus stage, and finally the convective complex stage. In cases where the buoyancy cannot sustain the water loading in the glaciation stage, dissipation may follow. It has to be emphasized that this is a proposed chain of events that has not been verified.

Rosenfield and Woodley (1993) suggested modifications to the conceptual model that included more attention to microphysical processes. The modified conceptual model involves the production and sustenance of greater precipitation mass at and above the seeded region, which allows more time for continued growth of the cloud. The subsequent unloading of this enhanced water mass increases the downdraft and precipitation while at the same time allowing for additional growth in the region that retains some of the previously released latent heat. This modified concept assumes the existence of large drops that facilitate the rapid conversion from supercooled water to ice in the cloud (Cotton 1982; Koenig and Murray 1976).

Although this conceptual model is plausible and provides for a logical chain of events to enhance precipitation, it is a very complex conceptual model for which many of the steps in the chain are very difficult to measure. Therefore, if one link in the process is incorrect, it would be very difficult to trace the effects of seeding, especially in convective clouds, which by nature exhibit a large natural variability. Focused experiments to collect measurements, as well as modeling studies, are needed to validate and support this hypothesis.

Although rainfall increases from individual clouds on a limited scale have been documented, evidence on what the effect on area rainfall would be has not been documented. This method therefore remains as yet an unproven technology for increasing rainfall for water resources.

### c. *Warm-cloud seeding*

Since its inception, the term "hygroscopic seeding" has taken on slightly different meanings depending on the experimental design, type of seeding material used, and the type of cloud that was the subject of experimentation. In all instances the ultimate goal has been to enhance rainfall by somehow promoting the coalescence process. The direct introduction of "appropriately" sized CCN that can act as artificial raindrop embryos using either water sprays, dilute saline solutions, or grinded salts are the most common hygroscopic seeding techniques used previously (Biswas and Dennis 1971; Murty 1989; Czys and Bruintjes 1994). The primary objective of introducing artificial raindrop embryos (salt particles larger than 10-$\mu$m diameter) is to short-circuit the action of the CCN population in determining the initial character of the cloud droplet population and, thus, jump-start the coalescence process. This concept has been previously used in programs in the United States and other countries (Biswas and Dennis 1971; Cotton 1982; Bowen 1952) and is still widely used in southeast Asian countries and India (Murty 1989).

Although this technique is widely used in countries in southeast Asia, the previous statistical experiments were generally inconclusive, although some suggested positive effects. Observations and modeling results have lent some support that under certain conditions with an optimal seed drop (artificial embryos) size spectrum, precipitation could be enhanced in some clouds.

Disadvantages of this approach are that large quantities of salt are needed and dispersion of the salt over areas comparable to a cloud inflow is difficult. In addition, the growth rates of the particles to raindrops must be matched well to the updraft profile or their growth will be inefficient (Klazura and Todd 1978; Young 1996). The optimal seed drop size is a function of the updraft velocity and the cloud depth, and depends on the mode of seeding [e.g., cloud base or near cloud top; Rokicki and Young (1978); Tzivion et al. (1994)]. In a modeling study, Farley and Chen (1975) found that salt seeding only produced a few large drops without significant effect on the precipitation process, unless drop breakup acted to induce a chain reaction that enhanced the effects of seeding. While some positive effects have been attributed to such seeding (Biswas and Dennis 1971), seeding with hygroscopic material has usually appeared less attractive than seeding with ice nuclei. While most hygroscopic seeding experiments using this approach seeded clouds with a wide range of seed drop diameters, Young (1996) pointed out that most seeding material might have been wasted, since only a small fraction of the mass is near the optimal seed drop size. This could explain why hygroscopic seeding with large particles have produced widely different results.

## 4. Recent progress

Recently a new approach to hygroscopic seeding has been explored in summertime convective clouds in South Africa as part of the National Precipitation Research Programme (Mather et al. 1997). This approach involves seeding summertime convective clouds below cloud base with pyrotechnic flares (Fig. 3) that produce small salt particles (about 0.5-$\mu$m diameter) in an attempt to broaden the cloud droplet spectrum and accelerate the coalescence process. The burning flares provide larger CCN (> 0.3-$\mu$m diameter) to the growing cloud, influencing the initial condensation process and allowing fewer CCN to activate to cloud droplets. The larger artificial CCN would inhibit the smaller natural CCN from nucleating, resulting in a broader droplet spectrum at cloud base. The fewer cloud droplets grow to larger sizes and are often able to start growing by collision and coalescence with other cloud droplets within 15 min (Cooper et al. 1997), initiating the rain process earlier within a typical cumulus cloud lifetime of 30 min.

The development of this approach was triggered by radar and microphysical observations of a convective storm growing in the vicinity of a large paper mill, which indicated an apparent enhancement of coalescence in these clouds as opposed to other clouds far away from the paper mill (Mather 1991). Earlier observations by Hindman et al. (1977) also suggested a similar connection between paper mills and enhanced precipitation.

There are significant operational advantages to this form of hygroscopic seeding. The amount of salt required is much less, the salt particles are readily produced by flares, and the target area for seeding is an easily identified region at cloud base where the initial droplet spectrum is determined (Cooper et al. 1997).

Mather et al. (1997) reported the results from a randomized cloud seeding experiment that was conducted from 1991 to 1996 in summertime convective clouds in the Highveld region of South Africa. The results of this experiment indicated that precipitation amounts from seeded storms were significantly larger than from control storms (Fig. 11 of Mather et al. 1997). The results were statistically significant at the 95% confidence level. Exploratory analyses indicated that seeded storms rained harder and longer than unseeded storms (Mather et al. 1997). Mather et al. (1997) also provided supporting microphysical evidence that supported the physical hypothesis. It is remarkable that statistical significance was reached on such a small sample set of 127 storms (62 seeded and 65 controls). Orville (1995) described the results from this experiment as perhaps the most significant scientific ad-

FIG. 3. Photograph of burning hygroscopic flares during a seeding experiment in Coahuila, Mexico.

vancement in the past 10 years in weather modification. A strong signal is readily detected, making statistical tests very reasonable (Orville 1995).

The calculations of Reisin et al. (1996) and Cooper et al. (1997) support the hypothesis that the formation of precipitation via coalescence might be accelerated by the salt particles produced by the flares. These studies also found that for clouds with a maritime cloud droplet spectra hygroscopic seeding with the flares will have no effect, since coalescence is already very efficient in such clouds. However, the results from the calculations should be interpreted with considerable caution because they oversimplify the real process of precipitation formation. Cooper et al. (1997) identified some of the shortcomings in the calculations related to mechanisms that broaden cloud droplet size distributions, sedimentation, and the possible effects on ice phase processes.

Bigg (1997) performed an independent analysis of the South African experiments and also found that the seeded storms lasted longer than the unseeded storms. Bigg (1997) also suggested some dynamic responses, which also were identified by Mather et al. (1997). Bigg suggested that the initiation of precipitation started at a lower height in the seeded clouds than in the unseeded clouds and that a more concentrated downdraft resulted closer to the updraft. The surface gust front was thereby intensified and its interaction with the storm inflow enhanced convection.

The promising new results of the South African experiment, as well as the model calculations, led to the start of a new program in Mexico in 1996 using the South African hygroscopic flares in a similar fashion as in the South African program. The program in Mexico is conducted under leadership of the National Center for Atmospheric Research in Boulder, Colorado. The program will take place over four to five years, including physical measurements and a randomized seeding experiment. Figure 4 shows a picture of typical convective clouds in Coahuila, and an overview of the experiment and some preliminary results are provided by Bruintjes et al. (1998).

Although this seeding method and the associated results have provided renewed optimism regarding the probability of enhancing precipitation using hygroscopic seeding, some critical problems remain. One of the fundamental impediments is the diffusion and transport of seeding material throughout the cloud. Weil et al. (1993) showed that only after more than 10 min can a plume released in a cloud spread over distances of several kilometers, as required to fill an updraft region of even one cell. A possible solution to this problem is to seed the strongest updrafts, which are expected to rise to near cloud top, where any drizzle size drops produced might spread and be carried downward in the descending flow near the cloud edge. According to Blyth et al. (1988), such material would spread throughout the cloud and might affect large regions of the original turret and, perhaps, other turrets. Such a circulation is supported by the observations of Stith et al. (1990). In addition, the suggested dynamic effects of Bigg (1997) need to be further explored. These concerns need to be addressed before this technique can be accepted as a proven technique to enhance precipitation on the ground in different cloud systems around the world. However, it is refreshing to see some new promising techniques in the field of weather modification.

Equally important for both hygroscopic and glaciogenic seeding experiments is the fact that our knowledge of cloud physics/dynamics and statistics and their application to weather modification has increased substantially since the first cloud was seeded in 1946. Technology development—such as aircraft platforms with a variety of measuring systems, mesoscale and rain gauge network stations, and remote sensing techniques from both space and the ground—has introduced a new dimension to describe the structure and evolution of cloud systems and has begun to

FIG. 4. Photograph of convective clouds near Monclova, Mexico.

address with renewed vigor some of the questions raised in the previous sections.

The last 10–15 years have seen significant progress in the development of new instruments to probe the atmosphere and cloud systems. Microwave radiometers, multiparameter radars, and lidars make it possible to quantify seeding responses that previously could not be measured. In addition, these new remote sensors are capable of obtaining measurements at higher resolution in both time and space than earlier instruments. With improved airborne instrumentation, it is now possible to document the physical processes in clouds in much more detail than a decade ago. These developments have introduced a new dimension to describe the structure and evolution of cloud systems.

With the advent of multiparameter radars having both Doppler and polarization measurement capabilities, it is now possible to study the flow patterns in individual cloud systems and identify particle types in the clouds. These measurements provide additional insight into the precipitation evolution in clouds. Such radars were used in a recent field program in Arizona and results obtained from measurements collected with these radars are described in Bruintjes et al. (1996) and Reinking et al. (1996). In addition, these measurements can be used to identify the effects of seeding on the evolution of precipitation (Klimowski et al. 1996).

Satellite-based microphysical retrievals can be combined with in situ cloud sampling to monitor the effects of natural and anthropogenic aerosol or hygroscopic seeding material on droplet size evolution, and the effects of ice-forming nuclei on ice-particle concentrations, both of which determine the efficiency of precipitation production (Wetzel et al. 1996; Rosenfeld and Gutman 1994). Wetzel (1995) has also studied the application of future possible satellite spectral channels (such as narrowband 0.85- and 1.6-$\mu$m channels) to improve microphysical analysis, such as identification of glaciated clouds, and the discrimination of clouds over high-albedo surfaces such as snow or sand. In the case of glaciogenic seeding, the near-infrared channels can be used to more effectively identify seeded clouds (Wetzel 1995), which have reduced scattering due to phase change and/or modified particle size, as well as to discriminate clouds from fresh snow cover.

Substantial work has also been conducted in the past 10 years regarding the dispersion and transport of seeding material in both convective and orographic clouds. The use of tracer material to tag a seeded region has been particularly helpful in this effort. The two tracer materials that are used most often are chaff and $SF_6$. Both materials could be released from either the air or the surface. The dispersion and transport of the chaff is monitored by radar, while the detection of the $SF_6$ is usually conducted with aircraft equipped to detect it at very low concentrations. (Stith et al. 1990; Klimowski et al. 1998).

Equally important are the advances in computer systems that are now able to handle very large amounts of data at high speeds, making it possible to use increasingly sophisticated and detailed numerical models. In the past, weather modification experiments incorporating modeling efforts were primarily dependent on simple one- and two-dimensional models to help understand atmospheric processes and to give guidance during field experiments. However, three-dimensional time-dependent models are now used in the analyses of data from some projects. Field tests to run these large models in an operational mode in the field as part of weather modification efforts were conducted during two recent field programs in Arizona. The preliminary tests were highly successful. The intent is to use these models in the future to guide seeding operations in real time and to help in the analyses of seeding responses. Orville (1996) provides a comprehensive overview of the use of numerical models in the field of weather modification.

## 5. Conclusions

The potential technology of precipitation enhancement is very closely linked to water resources management. It is important that the users of this potential technology are integrated into programs at a very early stage in order to establish the requirements and economic viability of any program.

The funding of weather modification research has seen some dramatic changes over the past 40 years. In the United States it peaked in the early 1970s at about \$19 million (U.S.) per annum. By the 1990s this level had decreased to less than \$5 million (U.S.) per year, with the largest part being funding by the NOAA Federal/State Atmospheric Modification Program. Although this program started to produce some exciting new insights into the field, it was canceled in 1995. The current budgeted amount of funding for research in this field is about \$0.5 million (U.S.) per year.

Operational programs have increased in the last few years but now without a sound scientific research program supporting them. Much of the research in precipitation enhancement is currently being conducted outside the United States. One of the leading causes for this demise in weather modification research has been the previous overselling of these programs with claims that only a few more years of research would lead to a scientifically proven technology. This approach indicated to some extent ignorance regarding the complexity of the problems that the field was faced with.

Future investigations thus should concentrate on establishing a physical hypothesis that incorporates all the major components of the precipitation formation processes in order to provide as sound a scientific basis as possible for estimating the magnitude of the expected effect. To attain this objective we will have to increase our understanding of the individual components of the precipitation formation process. Progress in understanding a single component of this process is intrinsically limited if an understanding of all the major components is not developed to comparable levels.

It is very important not to make the same mistake with the new hygroscopic seeding method. Although very exciting and promising results have been obtained to date, some fundamental questions remain that need to be answered in order to provide a sound scientific basis for this technique.

As mentioned in the introduction, water is becoming an ever more scarce and precious commodity around the world. The potential societal benefits of precipitation enhancement are therefore too important for us to ignore, and a coordinated strategy should be developed to provide a sound scientific basis for precipitation enhancement programs. With the new tools and techniques, the scientific community has an excellent opportunity to provide new insights, and to contribute substantially, to the benefit of water resources management around the globe.

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