

Guidelines for Operational Hail Suppression Programs

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American Society of Civil Engineers

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CHAPTER 1

SCOPE

This document describes a process through which hail suppression operations should be designed, organized, and conducted. The information contained herein is intended to be helpful to those persons wishing to implement operational hail suppression activities (described interchangeably in this document as programs and/or projects). The book provides information on the design, conduct, and evaluation of such efforts. Operational activities addressed by this standard include airborne, ground-based, and rocket and artillery delivery systems. Hail cannons, though used for hail mitigation in some areas, are not included in this document because there is currently no scientific evidence that they may affect hail development.

The International System of Units (SI units) is used throughout, with English equivalents also provided. Exceptions are the use of the Celsius (°C) temperature scale and, where appropriate, centimeters (cm) in lieu of meters (m). Chapter 9 provides all conversion factors used herein. Italics denote special emphasis.

1.1 APPLICABLE DOCUMENTS

Applicable documents (ASCE standards) can be found at ASCE, 1801 Alexander Bell Drive, Reston, VA 20191 (www.pubs.asce.org).

ASCE/EWRI 39-03, *Standard Practice for the Design and Operation of Hail Suppression Projects*, American Society of Civil Engineers, Reston, VA (2003a).

EWRI/ASCE 40-03, *Regulated Riparian Model Water Code*, American Society of Civil Engineers, Reston, VA (2003b).

EWRI/ASCE 42-04, *Standard Practice for the Design and Operation of Precipitation Enhancement Projects*, American Society of Civil Engineers, Reston, VA (2004).

ASCE 44-13, *Standard Practice for the Design and Operation of Supercooled Fog Dispersal Projects*, American Society of Civil Engineers, Reston, VA (2013).

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CHAPTER 2

THE HAIL PROBLEM

Unlike some other forms of precipitation, hail comes in bursts of short duration, falls over isolated and unpredictable locations, and usually occupies only a small percentage of the total area covered by precipitation during any given storm. Nonetheless, the sudden, instantly visible destruction caused by hail can have devastating financial and emotional impacts. It is not surprising, therefore, that people in many places have attempted to avert hail damage to their crops and other property.

Hailstorms can cause enormous losses, especially in developed (urban) areas where high-value property is concentrated in relatively small areas. Damages from individual hailstorms often total hundreds of millions of dollars, and in some cases have exceeded a billion dollars. Table 2-1 summarizes some of the more damaging hailstorms since 1990.

2.1 HISTORICAL PERSPECTIVE

People in ancient times used magic, including incantations, shouted and shook their fists, hurled lances, and shot arrows skyward in attempts to rout oncoming hailstorms. In Europe in the Middle Ages, Christians resorted to prayer and the ringing of church bells. It is not clear whether the ringing of the bells was expected to produce a physical effect or was viewed simply as an invocation of God's protection against impending disaster.

Small rockets containing explosive charges were developed in Italy. As early as 1937, these devices were being fired at storms from the ground. France, Switzerland, Kenya, and South Africa followed with similar trials, some of which lasted until 1960 or later. Some users of the devices argued that the shock waves they produced could soften or even shatter hailstones, especially if the hailstones contained pockets of liquid water.

Modern hail suppression technology is based on discoveries at the General Electric Research Laboratories in the late 1940s (Schaefer 1946; Vonnegut 1947) regarding the ice-nucleating properties of dry ice and silver iodide. Because it was well known that hailstone growth depends upon a supply of supercooled water in the hail-producing clouds, it was reasoned that early artificial freezing of that supercooled water would suppress the formation and growth of hail. Commercial hail suppression operations involving the release of silver iodide from ground-based generators and from aircraft became quite common in the United States during the 1950s.

Experimental programs were also undertaken in the United States and elsewhere, with operational programs in many other countries as well. A few such programs are mentioned below. The most extensive projects were undertaken by scientists and engineers in the Soviet Union, who pioneered new techniques for delivery of silver iodide or other seeding agents to target clouds. By the 1960s, their arsenal of anti-hail weapons included artillery shells and sophisticated rockets. On the basis of comparisons of

Table 2-1 Significant Hailstorms and Monetary Losses Since 1990

Date	Location	Losses
July 11, 1990	Denver, CO	\$625 million
September 7, 1991	Calgary, Alberta, Canada	\$400 million (CAD)
May 5, 1995	Dallas–Fort Worth, TX	\$1.1 billion
April 14, 1999	Sydney, Australia	\$1.5 billion (AUS)
May 18, 2000	McHenry, Lake, Kane, and Cook Counties, IL	\$572 million
April 10, 2001	St. Louis, MO	\$2.0 billion
June 9, 2001	Bismarck–Mandan, ND	\$230 million
April 20–21, 2006	San Marcos, TX	\$160 million
June 28–29, 2006	Villinger–Schwenningen, Baden–Württemberg, Germany	€150 million
March 25, 2009	Austin, TX	\$160 million
July 12, 2010	Calgary, Alberta, Canada	\$400 million (CAD)

crop damage in protected areas and in neighboring unprotected areas, substantial hail suppression effects were claimed (Atlas 1965; Battan 1965).

An extensive network of ground-based silver iodide generators has been used to suppress hail in southwestern France since 1951. Although targeting is less certain than with rockets or aircraft delivery systems, the program's operators consider it successful. For the period from 1965 through 1982, they reported a decrease in hail damage on the order of 40% (Dessens 1986), and more recently, for the years 1988–1995, a decrease of 42% (Dessens 1998).

One of the most extensive hail suppression research projects began in Alberta, Canada, in 1956. In one of the regions of greatest hail frequency in the world, the hail insurance premiums approached one quarter of the crop value. Airborne seeding served as the major method of dispensing the silver iodide nuclei. Although the research project was conducted for more than 30 years, with 14 years of cloud seeding, the participating scientists were unable to reach a conclusion about the effectiveness of hail suppression. The Alberta research effort is currently inactive, but an operational hail suppression project was launched in 1996, funded entirely by the property and casualty insurance companies (Krauss and Renick 1997).

A Swiss hail suppression experiment called Grossversuch III was conducted from 1957 to 1963. A network of 24 ground-based

silver iodide generators comprised the nucleus delivery system. A statistical analysis of the days with hail indicated that “seeding appeared to be effective in increasing the number of hail days.” Grossversuch IV (1977–1981) followed, in which Russian rockets were used in an attempt to replicate the striking successes claimed from various republics of the Soviet Union. The statistical and physical evaluation of Grossversuch IV did not confirm the Russian results. Some Russian scientists stated that the operational seeding in Grossversuch IV failed to follow the actual Russian procedures (Federer et al. 1986).

Hailswath was a field research program conducted during the summer of 1966, representing about two dozen entities, and was headquartered in Rapid City, South Dakota. There were interesting indications of seeding effects, but the scientists involved agreed that firm conclusions were not possible from such a short-term project.

In Kenya, Africa, a seven-year operational hail suppression program was conducted over tea estates where the hail frequency averages almost 200 days per year (Henderson 1969; Henderson et al. 1970; Rinehart and Henderson 1973). Pyrotechnics containing silver iodide were burned on aircraft flying through updrafts near cloud bases. Tea is harvested roughly every 15 days, and program evaluations included comparisons of crop production from areas under protection with areas not targeted by the seeding program. These simple evaluations suggested reductions in hail damage of 64%, but the program design did not allow for more sophisticated statistical tests.

The establishment of the National Hail Research Experiment (NHRE) in northeast Colorado, under the guidance of the National Center for Atmospheric Research (NCAR), was a step toward an improved design for a hail suppression research program. The NHRE included both a randomized seeding experiment, which was in the field from 1972 to 1974, and a broad program of physical research (Foote and Knight 1977, 1979). Small, spin-stabilized rockets fired upward from airplanes were the primary source of silver iodide ice nuclei. The primary statistical evaluation declared that “no change [statistically] significant at the 10% level in the distribution ascribable to seeding could be detected.” However, a later analysis of the distribution of seeding material in precipitation at the ground showed that much of the precipitation from seeded storms contained no silver iodide (Linkletter and Warburton 1977; Warburton et al. 1982). This finding suggested that the seeding agents had not been released in the proper locations in and around many of the “seeded” storms. The evaluation of the NHRE efforts was also made more difficult by changes in the target area. At the time, instrumentation capable of measuring much of the physical evidence (e.g., polarimetric radar) did not exist. A good general review of the status of hail suppression as of the late 1970s can be found in Dennis (1977).

The North Dakota Cloud Modification Project, an operational hail suppression program, was evaluated using crop-hail insurance loss-ratio data for the period 1976–1988. The study by Smith et al. (1997) indicated a 45% decrease in crop hail losses in the seeded area versus an upwind control area. These results were similar to those reported for other operational programs by Dennis et al. (1981), Dessens (1986), and Simeonov (1992).

2.2 THE STATUS OF HAIL SUPPRESSION TECHNOLOGY

A general discussion of the status of hail suppression technology as of the mid-1990s is provided in a summary document produced by the World Meteorological Organization (WMO 1996). Because our knowledge about hail formation is incomplete, there is still an experimental nature to any present hail suppression

operations. This situation should not be discouraging. There is, to some degree, a continuing experimental aspect to any complex activity conducted on a daily basis (compare, for example, medical practices). In the case of hail suppression, the fact that we have difficulty in fully explaining many of the atmospheric phenomena that interact to produce hail on the ground accounts in large part for the lack of precision in estimates of the effectiveness of hail suppression technology. Nevertheless, operational hail suppression programs continue. At present, there are approximately 17 countries where serious operational hail suppression projects are in progress.

The experts at WMO concluded that the tools now exist to provide answers to many of the long-standing questions about hail formation and urged that research programs and ongoing operational programs use as many of these tools as possible to elucidate hail formation processes and quantify the effects of seeding.

The following policy and/or capability statements summarize present opinions of the scientific establishment on the subject of operational hail suppression programs.

2.2.1 American Society of Civil Engineers The American Society of Civil Engineers (ASCE) Policy Statement No. 275 (ASCE 2012) addresses cloud seeding and can be found at the following link: <http://www.asce.org/issues-and-advocacy/public-policy/policy-statement-275---atmospheric-water-resources-management/>. It reads as follows:

The American Society of Civil Engineers (ASCE) supports and encourages the protection and prudent development of atmospheric water (also known as “weather modification” or “cloud seeding”) for beneficial uses. Sustained support for atmospheric water data collection, research and operational programs, and the careful evaluations of such efforts, including the assessment of extra-area and long-term environmental effects, is essential for prudent development. ASCE recommends that the results and findings of all atmospheric water-management programs and projects be freely disseminated to the professional community, appropriate water managers and to the public.

Atmospheric water management capabilities are still developing and represent an evolving technology. Longer term commitments to all atmospheric water resource management research and operational programs are necessary to realize the full potential of this technology.

Water resources worldwide are being stressed by the increasing demands placed upon them by competing demands generated by population growth and environmental concerns. As a result, nations have become more sensitive to year-to-year variations in natural precipitation. The careful and well-designed management of atmospheric water offers the potential to significantly augment naturally occurring water resources while minimizing capital expenditures or construction of new facilities. New tools, such as radar and satellite tracking capabilities and other imaging devices, atmospheric tracer techniques, and advanced numerical cloud modeling, offer means through which many critical questions might now be answered. Continued development of atmospheric water management technology is essential. ASCE has developed materials providing guidance in the use of atmospheric water management technology with weather modification organizations for dissemination to local communities and governments as well as state, regional, and international interest groups.

One of the ASCE developments dealing with weather modification technology has been in the area of defining atmospheric water management or weather modification per ASCE 40-03 (2003b), *Regulated Riparian Model Water Code*, ASCE 42-04

(2004), *Standard Practice for the Design and Operation of Precipitation Enhancement Projects*, and ASCE 44-13 (2013), *Standard Practice for the Design and Operation of Supercooled Fog Dispersal Projects*.

2.2.2 Weather Modification Association The most recent hail suppression capability statement adopted by the Weather Modification Association (WMA 2011) reads as follows (for the entire capability statement, visit the WMA website at www.weathermodification.org/capabilities.php):

The capability to suppress damaging hail continues to improve. Attracted by potentially large benefit/cost ratios, many countries are conducting projects where hailstorms are seeded to reduce the damage caused by hail. While there are a number of conceptual models regarding the formation and mitigation of hail, the most common treatment method for hail suppression involves the addition of high concentrations of ice nuclei (usually silver iodide smoke particles) into the new growth regions of storms from aircraft or ground-based sources to manipulate the hail embryo formation process and thus limit the growth of hailstones.

Evaluations of carefully conducted hail suppression research and operational projects have shown statistically significant reduction in damage caused by hail to agricultural crops and property. Studies of long-standing hail suppression operations in a number of locations around the world indicate a range of effects from 25% to 75% reduction in damage. Advances in radar data processing and evaluation techniques are helping to provide additional insights into the effects of cloud seeding. Microphysical measurements from single-cloud studies and radar analyses are also providing encouraging evidence consistent with the conceptual models of hail suppression. These technological advances and research efforts continue to develop improved understanding of hail growth and hail suppression.

2.2.3 American Meteorological Society The most recent capability statement adopted by the American Meteorological Society (AMS 2010) can be found at the following link: www.ametsoc.org/policy/2010plannedweathermod_cloudseeding_amsstatement.html. Here is an excerpt from the statement:

Planned weather modification programs benefit from a comprehensive understanding of the physical processes responsible for desired modification effects. Recent improvements in the composition and techniques for dispersion of seeding agents, observational technology, numerical cloud models, and in physical understanding of

cloud processes permit ever more detailed design and targeting of planned weather modification effects, and more accurate specification of the range of anticipated responses. While effects are often immediately evident in simple situations, such as when cloud seeding is used to clear supercooled fog and low stratus cloud decks, in more complex cloud systems it is often difficult to determine a seeding effect on a cloud-by-cloud basis. In these more complex situations large numbers of events must be analyzed to separate the response to cloud seeding from natural variability in cloud behavior. Rigorous attention to evaluation of both operational and research programs is needed to help develop more effective procedures and to improve understanding of the effects of cloud seeding. Research and operational programs should be designed in a way that will allow their physical and statistical evaluation. Any statistical assessment must be accompanied by physical evaluation to confirm that the statistical results can be attributed to the seeding through a well-understood chain of physical events. It should be noted, though, that in practice large potential benefits can warrant relatively small investments to conduct operational cloud seeding despite some uncertainty in the outcome.

2.2.4 The National Research Council and Weather Modification Association Viewpoints In October 2003, the National Research Council (NRC) issued a report to the National Oceanic and Atmospheric Administration (NOAA), which stated that understanding of the physics of precipitation processes and human effects on those processes was insufficient to warrant NOAA funding operational weather modification activities (NRC 2003).

The Weather Modification Association (WMA) then wrote a response to the NRC report (Orville et al. 2004), which noted that in spite of the NRC recommendation, numerous operational programs throughout much of the world were already ongoing at that time, many of which were funded by various governmental entities. The WMA response thus asserted that even in the absence of scientific “proof,” sufficient evidence exists for such programs and that the long-term existence of them itself constituted positive evidence of the efficacy of such programs.

A few months after the WMA response was published, the need to reconcile the two viewpoints was recognized, and a committee composed of some of the authors of the NRC report and the WMA response coauthored a paper that addressed both viewpoints and clarified some misunderstandings (Garstang et al. 2005). All three of these papers are recommended reading for those who wish to better grasp the differences between research and operational viewpoints about the technology.

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CHAPTER 3

HAIL CONCEPTS

Hail, the product of vigorous deep convection, requires those same conditions that are conducive to the development of thunderstorms (Fig. 3-1). These conditions include water vapor, especially in the low levels, instability (warm air in the low levels with cold air aloft), and a trigger mechanism: meteorological conditions that initiate storm development.

Recent advances in science and technology have provided and continue to provide an increasing convective storm knowledge base. The physical concepts upon which hail suppression operations are based are subject to further refinement and modification as well, but are summarized in the following sections.

3.1 REQUIREMENTS FOR HAIL DEVELOPMENT

A hailstone is formed when a frozen particle in a cloud encounters supercooled water in an updraft structure that keeps the nascent hailstone aloft within the cloud during its growth stage. A frozen particle that has the potential to grow into a hailstone is called a “hail embryo.” Hail embryos are generally either small rimed ice particles or frozen raindrops. Such embryos grow to become hailstones by continued accretion and freezing of supercooled cloud water or raindrops (and sometimes smaller ice particles as well). Many smaller hailstones melt into rain during their fall to Earth; therefore, hail at the ground is more prevalent in places where cloud bases are cool and subcloud air is relatively dry, as in mountains or high plains, than it is at places near sea level. However, hailstones larger than about 2 cm (0.8 in.) diameter will reach the ground without completely melting under almost any conditions in cloud and below cloud base.

The combination of updrafts and supercooled water concentrations required for hailstone development is found only in vigorous convective clouds. The severity of hailstorms is affected by many interacting factors, including the static stability of the atmosphere (which tends to be reduced as air near the ground warms during the day), terrain, the supply of water vapor near the ground, and the winds at all levels of the troposphere. The proximity of strong jet-stream winds appears to favor intense convective developments, and hence the probability of large hail.

Hail mostly ravages those regions of the world that are located in middle latitudes downwind of mountain ranges and have ground elevations of 500 to 3,000 m (1,600 to 9,800 ft) above sea level. They include the regions in the lee of the Rocky Mountains from Alberta, Canada, to northern Mexico, in the lee of the Andes in western Argentina, near the Pyrenees, the Alps, and the Caucasus Mountains in Europe, and near the Tibetan plateau in western China.

The smallest hailstorms may consist of a single convective cell with a lifetime of 20 or 30 minutes. However, most hailstorms are multicellular and may last for several hours, while individual cells form and dissipate within them. Hailstorms arranged in



FIGURE 3-1 A hailstorm as seen from a distance in the Great Plains of North America. Numerous new daughter/feeder cells are developing between the two mature cells on the left and right
Source: Photograph by Bruce Boe; reproduced with permission.

squall lines may last even longer, especially if the squall line is associated with an active cold front. Some storms evolve into “supercells,” which may last several hours in relative isolation. In the context of hail development, the term *supercell* is generally taken “to denote a long-lived, intense cell with a relatively steady, usually bounded, weak echo region” (Knight and Knight 2001). These supercell storms are characterized by quasi-steady-state updrafts, which appear to ingest adjacent developing cloud turrets, in contrast to multicell storms, in which the individual flanking line turrets—each in turn—grow, mature, and then rain out as they dissipate. Because supercell storms are among the most intense storms, successful modification of them is problematic.

Severe hailstorms usually extend to the upper limit of the troposphere, called the tropopause, and sometimes penetrate a kilometer or more into the stratosphere. Because the height of the tropopause decreases toward the poles, the height of a typical hailstorm varies with latitude. Hailstorms in Texas often tower to 15 to 18 km (49,000–59,000 ft) above sea level, whereas a hailstorm in Alberta might reach only to 8 or 10 km (26,000–33,000 ft). In either case, updrafts of 10–15 m s⁻¹ (22–34 mi h⁻¹) are common, and updrafts in stronger storms easily exceed 30 m s⁻¹ (70 mi h⁻¹); the strongest updrafts, those that produce giant hailstones, approach 50 m s⁻¹ (110 mi h⁻¹) (Musil et al. 1986). Although most hailstones are relatively small (a centimeter [0.4 in.] or so in diameter), larger hail is common and especially damaging to property. Two extremely large hailstones are shown in Fig. 3-2.



FIGURE 3-2 The largest hailstones officially recorded in the United States are the Aurora, Nebraska, stone of June 22, 2003 (left), and the Vivian, South Dakota, stone of July 23, 2010 (right). The Aurora stone is the largest in circumference, at 47.63 cm (18.75 in.), but the Vivian stone holds the records for both diameter (20.3 cm [8.0 in.]) and weight (0.88 kg [1.94 lb])

Source: Photographs provided by the National Weather Service, Hastings, Nebraska (Aurora stone) and National Weather Service, Aberdeen, South Dakota (Vivian stone).

The formation and growth mechanisms of hailstones are complex. The supercooled water that is the raw material for hailstone growth may exist as supercooled cloud droplets or supercooled rain and drizzle drops. The release of latent heat as the supercooled water freezes onto the growing hailstone warms the hailstone surface, often to 0°C. Hailstone growth in this situation is called “wet growth,” and excess water is shed from the surface of the wet hailstone, slowing its growth. When the hailstones are small and there is less supercooled liquid water or the growth environment is very cold, the latent heat release is insufficient to warm the hailstone to 0°C and the supercooled water freezes very quickly on contact, a condition referred to as “dry growth.” In clouds containing large amounts of supercooled water, the transition from dry to wet growth occurs at surprisingly low ambient temperatures, sometimes down to –30°C. It is in clouds with strong updrafts at temperatures of –20 to –40°C that hailstones can grow most rapidly, a fact that explains the association of hail with tall, vigorous convective clouds.

3.2 THE SCIENTIFIC BASIS FOR HAIL SUPPRESSION

The precise conditions that make some thunderstorms produce hail while others do not remain a matter of some conjecture. Every vigorous thunderstorm contains millions of hydrometeors that could function as hail embryos, yet many thunderstorms produce negligible hail, or no hail, at the ground.

Embryos that grow into large hailstones must encounter, in addition to the supply of supercooled water, strong updrafts that support them inside the cloud as they grow. These updrafts may be provided by the intensification of the host convective cell, or they may be realized for particular embryos by a fortuitous trajectory that places them in the more intense parts of a storm as they grow. Hail suppression, to be successful, must disrupt this complex process because there is no scientifically credible method to break up a hailstone in midair once it has formed.

The effects of seeding clouds for hail suppression on the storm’s rainfall production are not fully understood. Some evaluations from nonrandomized, operational hail suppression

programs suggest net increases in rainfall, whereas others indicate no discernible effect. Statistically significant changes in rainfall have not been reported in the literature. Nevertheless, possible effects on rainfall are a natural concern for those near and within project target areas, so means to collect and analyze meaningful precipitation data should be considered. Numerical cloud modeling may also be useful in this regard (Farley et al. 1996).

A number of hail suppression concepts have been formulated. The five concepts most commonly used in the context of operational hail suppression projects involve seeding the storm with nucleating agents and are summarized in the following sections.

3.2.1 Beneficial Competition Adding to the supply of hail embryos naturally available by seeding with ice-nucleating agents that would freeze some of the supercooled water drops in theory could lead to the formation of more numerous but smaller hailstones. For complete suppression of hail, the concentration of hail embryos would have to be increased to the point that the more numerous embryos “compete” for the remaining available supercooled liquid water to produce sufficiently small hailstones, which melt entirely during their descent through the warm subcloud layer. Delivery of sufficient amounts of the agent to the right parts of the storm to accomplish this goal presents a challenge. Failing that, the resulting hailstones might still be more numerous and somewhat smaller, though large enough to survive transit through the warm subcloud melting layer. In many cases, increased numbers of smaller hailstones might effectively reduce property damage, but a diminution of crop-hail damage is less certain. A risk associated with the beneficial competition concept is that one might add too few additional ice particles and simply produce more hail.

3.2.2 Early Rainout This concept calls for ice-nucleating treatment(s) that speed the development of precipitation within treated cumulus congestus (towering cumulus clouds with well-defined outlines) cells, often on the periphery of the main thunderstorm itself. Ice-phase precipitation in the form of

snow and graupel (ice pellets 5 mm or less in diameter) thus develops faster as a result of treatment, falling from the clouds and melting before experiencing the stronger updrafts that would sustain hail growth. This early rainout of precipitation results in the precipitation of smaller hydrometeors from less mature, less vigorous clouds.

3.2.3 Trajectory Lowering If developing hydrometeors do not fall from the cloud complex (as in early rainout), they may still grow sufficiently large to follow a lower trajectory (involving shorter growth and residence times). Thus they do not get carried aloft into the region of the storm with the strongest updrafts and greatest amounts of supercooled water during their lifetime. As a result, their size is limited and they may still be able to melt substantially before reaching the ground. Trajectory lowering may result from attempts to achieve early rainout; the two concepts are closely related.

3.2.4 Promotion of Coalescence The promotion of coalescence of cloud droplets near cloud base with hygroscopic seeding agents can affect the microphysics of an incipient hailstorm in a number of ways. It may lead to early rainout, with associated trajectory lowering, and reduce the flux of water to the upper supercooled cloud. It also may lead to frozen raindrops as an enhanced hail embryo source for beneficial competition. Appleman (1958) and Ludlam (1958) described the concepts involved in seeding with salt particles to prevent hail formation, building on the view of coalescence as a natural hail suppression mechanism (which might explain the lower probability of hail precipitation in storms that are warm-based). Salt was used experimentally in the North Dakota Pilot Project, a combination rainfall enhancement and hail suppression project, in 1972 (Miller et al. 1975). Hygroscopic seeding for hail suppression was used on at least one project in the Soviet Union during the 1960s (Lominadze et al. 1973).

3.2.5 Dynamic Effects The release of convective instability by ice-nucleant seeding in numerous small cloud towers over a larger area, rather than allowing its release within a single intense, hail-producing updraft, could conceivably reduce the damaging hail from a large storm. Some have also hypothesized that downdrafts induced by seeding might disrupt the organization of the strongest updraft or might generate outflow boundaries that trigger new but smaller convection (WMO 1996, Smith et al. 2001).

3.2.6 Other Concepts A sixth concept, glaciation of supercooled cloud water in the main updraft, has fallen from favor, largely because of the large amounts of seeding agent required to achieve complete glaciation. If the seeding agent used relies primarily upon contact nucleation (the chance encounter of ice nuclei (IN) with supercooled liquid water droplets), timing is also a factor. When nucleation of cloud droplets is to occur primarily through collisions between the droplets and nuclei, 10 or 20 minutes might be required, unless tremendous numbers of nuclei are introduced. In that time period, most nuclei introduced into a strong updraft at cloud base would be ejected from cloud top without ever encountering a cloud droplet. A number of modern seeding agent formulations produce ice nuclei that have hygroscopic tendencies and function in the much faster condensation-freezing nucleation mode. However, even if nucleation could be achieved in the mature updraft as soon as the seeding agent reaches supercooled altitudes, the time required for the resulting ice crystals to grow by diffusional growth (about $1 \mu\text{m s}^{-1}$) to precipitable sizes would result most often in increased ice particle concentrations only within the cloud

anvil (anvil-shaped cloud that comprises the upper portion of a thunderstorm). The greatest difficulty may reside in attempted glaciation of an updraft many kilometers in diameter; adequate dispersion of sufficient nucleating agent within such a large volume would be a daunting task and far from practical.

3.3 CONCEPT VISUALIZATION

Fig. 3-3 depicts a multicell thunderstorm, consisting of developing cloud turrets organized in a “flanking line” (left), a mature cell possessing a strong updraft and large (and still growing) hydrometeors, and dissipating cells producing precipitation (right). In multicellular storms, the developing cells of the flanking line each in turn mature, becoming the dominant cell, as the older cells weaken and rain out. In contrast, the principal defining characteristic of the archetypal supercell is a quasi-steady-state mature updraft, which ingests the growing clouds of the flanking line as they mature. No differentiation between the two storm types is made in Fig. 3-3; the concepts presented below may apply to both. Fig. 3-3 illustrates hail suppression concepts based primarily on microphysical effects from seeding, as described in Sections 3.2.1 through 3.2.4.

The hail suppression concepts (except for dynamic effects) (Knight and Knight 2001; Smith et al. 2001) share the following:

1. Developing cloud turrets, probably cumulus congestus, are treated rather than the main cumulonimbus storms. This method means treating the young clouds with modest updrafts, rather than mature cells with strong updrafts.
2. Precipitation development is accelerated. Promotion of coalescence is initially directed at liquid-phase processes, though enhanced drop freezing may ensue; the other concepts are based largely on glaciogenic effects. Dynamic effects may also result from the redistributed release of latent heat (primarily from freezing), and from redistribution of condensate within the targeted cloud turrets.

The dominant path of hail development in unseeded (natural) storms is illustrated in Fig. 3-3 by the open triangles (Δ) indicated in the key of the figure. The path originates in the central portion of the natural hail embryo source region, at temperatures somewhat lower than -15°C . The embryos are carried aloft as they become hailstones within, or on the periphery of, the strong, mature updraft. As they migrate toward the edge of the updraft or gain terminal velocities exceeding those of the updrafts, descent begins; a hail cascade develops near and beneath the sloped updraft.

Timely seeding of growing, supercooled but largely ice-free, turrets on the storm flank is illustrated in four ways, all somewhat interrelated.

The early rainout concept is illustrated by the paths shown by the solid dots ($\bullet$) as shown in the key of Fig. 3-3. Two of the many possible trajectories are shown, but the objective is clear: Get a significant fraction of the developing hydrometeors to precipitate before encountering the main updraft, where hail development might occur. The “early” precipitation ideally would carry a fraction of the supercooled cloud water with it as well, reducing the supply remaining to support hail growth.

The trajectory-lowering concept ($\circ$), which is shown in the key to Fig. 3-3, is illustrated as an extension of the early rainout concept. In this case, early rainout is not achieved but the hydrometeor development has been sufficiently advanced that the natural hail embryo source region is largely avoided; the resulting graupel and/or small hail tends to melt before reaching the surface. The hydrometeors must become large enough to fall

HAIL SUPPRESSION CONCEPTS Largely Microphysical Effects

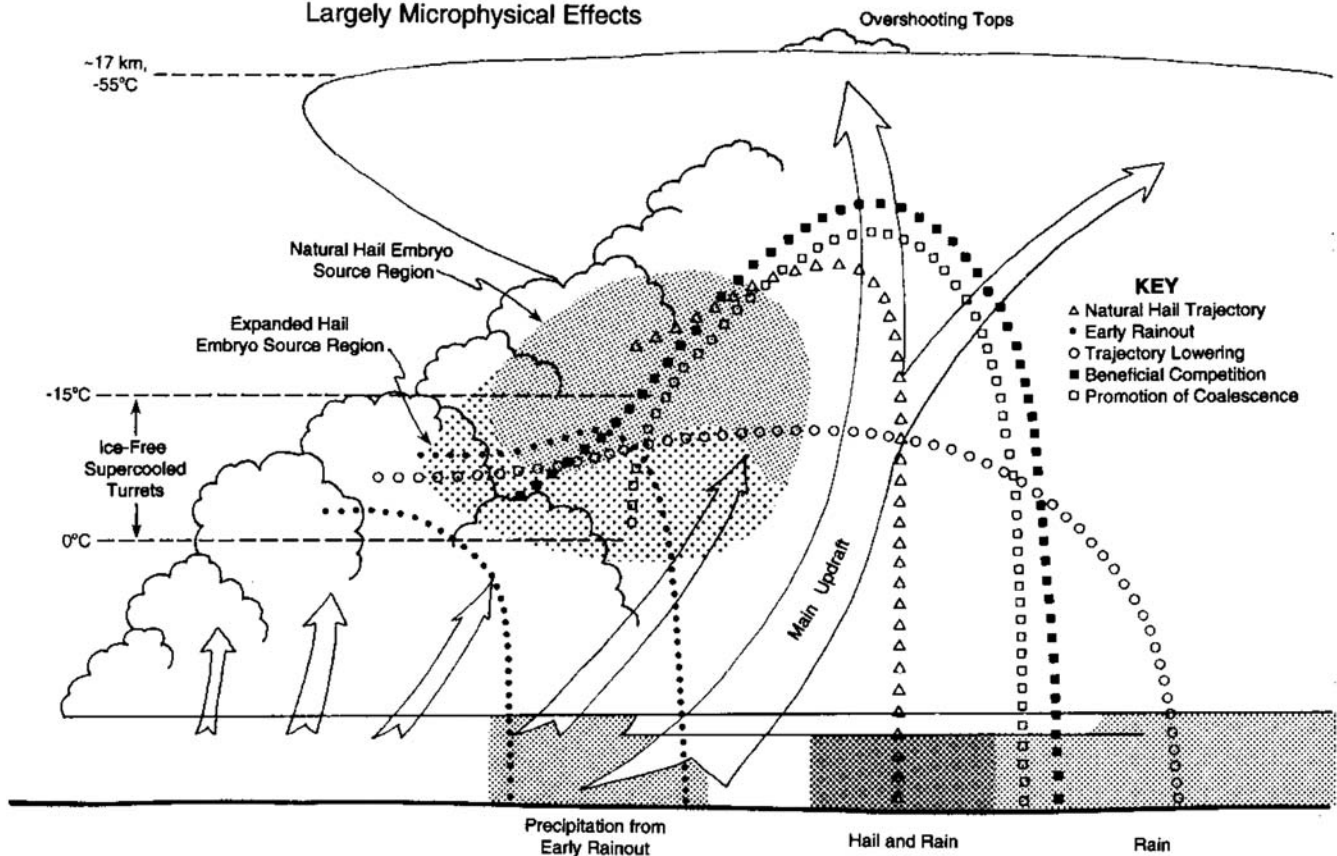


FIGURE 3-3 Four of the five basic concepts for hail suppression through cloud seeding are schematically illustrated. Possible dynamic effects are not depicted

Source: WMO 1996; reproduced with permission.

from the cloud before a mature updraft lifts them into a supercooled hail growth environment.

The accelerated hydrometeor development resulting from seeding may produce large numbers of potential hail embryos, many or most at altitudes below the natural hail embryo source region. The expanded hail embryo source region provides the initiation of beneficial competition, as shown by the solid squares (■) in the key to Fig. 3-3. With this concept, the idea is to redistribute the ice mass spectrum from low concentrations of large hailstones to higher concentrations of small hailstones. The small hailstones have a much greater probability of melting before reaching the ground.

The promotion of coalescence is an alternate means of inducing beneficial competition; hence the trajectory (□), which is shown in the key of Fig. 3-3, is shown approximating that of beneficial competition. Hygroscopic (rather than glaciogenic) seeding acts to modify the cloud droplet spectrum, resulting in greater numbers of large droplets, which accelerate the coalescence process. Since the ice-phase processes are not initially involved, and because greater cloud water contents aid this process, the source region may be closer to the stronger updrafts and perhaps lower in the cloud. Ideally, the supercooled raindrops freeze, creating an enhanced supply of embryos for beneficial competition. Ice multiplication through the splintering of freezing raindrops also may contribute to further glaciation.

Dynamic effects are not specifically illustrated in Fig. 3-3. The most common of these would be additional growth of the

seeded turrets (from redistributed latent heat release caused by early glaciation), increased updraft speeds within them, and the development of incident downdrafts and outflows associated with the accelerated development of precipitation. One might also plausibly argue that greater release of convective instability within the flanking line would effectively redistribute it over a larger area, thus perhaps weakening future updrafts as they mature.

3.4 CLOUD MODELING

Considerable success has been achieved using numerical cloud models to simulate hailstorms and hail development (e.g., Farley et al. 1996, Orville 1996). Cloud modeling has contributed significantly to the development of the contemporary conceptual models for hail suppression. Contemporary numerical models now contain explicit and spectral-bin microphysical parameterizations, though they have not yet been used to model hailstorms (Carrio and Cotton 2011, Khain et al. 2011).

If a cloud model, after “programming” with actual atmospheric conditions, can successfully reproduce a cloud or storm like that actually observed in those same atmospheric conditions, the model has reinforced the physical concepts used therein. Put another way, cloud models are tools that can be used to test concepts. If the model using a certain concept gets it right, this strengthens the faith in the concept. (For more information on numerical cloud models and their application, see Section 4.4.5.)

CHAPTER 4

THE DESIGN OF HAIL SUPPRESSION OPERATIONS

When hail suppression operations are being considered, it is already understood that hail damage is a significant problem in an area in which the political subdivision, organization, or other sponsoring entity has interest and/or responsibility. The next step is to determine the scope of the hail problem, the geographic area requiring protection, and the seeding agents and methods to be used. Consideration must also be given to how the project is to be evaluated. Once these tasks are done, the framework of the program can be established and the appropriate daily project designs can be produced. These basics are discussed in this chapter.

Planners are urged to consult legal counsel to carefully weigh all aspects of their proposed programs in the context of applicable local law. The sponsors also are encouraged to engage a scientific team knowledgeable about severe storms and cloud seeding to either develop or review the design and intent of the proposed operational program and to render opinions as to the likely efficacy and safety of the proposed program.

4.1 DEFINITION OF PROJECT SCOPE

The project target area generally is the geographical area or portion thereof in which the sponsoring entity has an interest. If the objective of the project is to reduce property damage, the focus is on areas in which property is concentrated, i.e., cities and towns. If reduction of crop-hail damage is the primary function, the target usually is significantly larger.

The definition of the target area, the seeding agent(s), and the method(s) for delivering the seeding material are among the most important decisions to be made in the design phase. When designing a new project, all information available about the local area and the proposed seeding methods should be analyzed in depth. This information includes the climatology, meteorology, and geography of the target area; the seeding agents, techniques, and equipment to be used; and likely operational procedures. In addition, data collection efforts that allow project evaluation should be integrated into the overall design; this method often requires designation of a “control area” near (and with hail characteristics well correlated to) the target area. Evaluation considerations are discussed in Chapter 6.

Local legal requirements must also be considered. Most areas require at minimum the licensing and permitting of operations. Others may have minimum qualifications for those individuals actually conducting the operations. Environmental regulations also may require some additional study before operations begin. Legal and environmental requirements are discussed further in Sections 4.6 and 4.7.

4.1.1 Historical Hail Losses The aim of hail suppression projects is to reduce the losses caused by hail. Finding a

reliable source of historical data concerning the losses in the project target and control areas over a long period is helpful for establishing economic objectives and for evaluating the resulting economic effect of the hail suppression efforts.

Hail damage affects a range of economic activities, although most hail suppression projects are operated in areas where agricultural interests dominate the local economy. Hailfall in most areas tends to occur mainly during the growing seasons. Because many factors are involved in the assessment of crop damage, obtaining a reliable database on the losses caused by hailfall is not an easy task. For example, the magnitude of the crop damage is related not only to hailfall intensity but also to crop type and the growth stage and health of the plant. Even so, some kind of database of past losses should be developed, if possible, to allow economic objectives to be more realistically established. Storm data published by the National Climatic Data Center contains damage estimates from reported hail events (<http://www.ncdc.noaa.gov/stormevents/>).

Some hail suppression projects are now focusing on urban areas to reduce property losses (Krauss and Renick 1997). These projects are not limited only to the growing seasons but extend to all times when hailstorms might develop. In Alberta, Canada, this fact translates into an earlier start date; potentially damaging hail occurs there in early summer before crops have begun to develop but property (e.g., homes and automobiles) is exposed and subject to damages.

4.1.2 Historical Radar Data In many locations, historical weather radar data may be obtainable. These data often reveal preferred areas for storm genesis, common storm motions and paths, and often, detail about the cellular character of the storms themselves. Treatment strategy for storms may vary depending upon whether the storms are multicellular or are characterized by a single, persistent, long-lived mature updraft (supercells). In the United States, the best source for such radar data is the National Climatic Data Center (in Asheville, North Carolina), which has archived the National Weather Service WSR-88D (NEXRAD) Doppler weather radar data for all U.S. sites since 1996.

4.1.3 Basic Project Area Concepts Concepts relating to the target area, operations, and evaluations are outlined below. These terms, which are fundamental to the design of any hail suppression project, are illustrated in Fig. 4-1.

1. **Target Area.** The area in which the objective is to reduce the losses and damages caused by hail. Seeding is conducted with the intent of affecting hailfalls over the target area.
2. **Control Area.** An area over which unseeded cloud systems and their effects are observed for comparison with those over the target area. It should be located near the

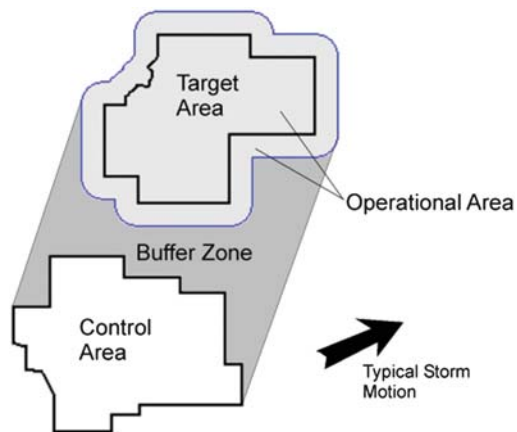


FIGURE 4-1 Terms related to the project area and operations
Source: ASCE (2003a).

target area (but not downwind) and be of similar size and with a well-correlated hail climatology.

3. **Operational Area.** The area over or adjacent to the target area within which seeding operations are actually conducted. The operational area ideally should extend upwind of the target area because the effects of seeding are not instantaneous. Clouds that develop upwind of the target area must be treated before they move over it, as well as while they are above it.
4. **Buffer Zone.** An area separating the target area from the control area; it buffers the control area from the possible effects of seeding within the operational area.

4.1.4 Initial Design Considerations After the project area has been defined, the other basic parameters can be established. This is done by answering the following questions:

1. During what seasons or months is the project scheduled to operate?
2. Will the character of the seeding agents be glaciogenic, hygroscopic, or both, and by what mechanism are the agents expected to function?
3. What seeding method(s) is (are) best suited for the project? Will seeding agents be dispensed from the ground, from aircraft, by projectiles, or by some combination? If by aircraft, will the agents be released subcloud in updrafts, during passes through the clouds, by direct injection of the seeding agent(s) at cloud top, or by some combination of these methods?
4. Will operations be conducted 24 hours each day, or only during daylight hours?
5. How will operations be directed?
6. What will be the role of forecasting, both short-term and long-term?
7. What types of meteorological data will be available, and how will they be used?
8. How will the project effectiveness be evaluated?

Before final decisions are made, it is recommended that all seeding options be appraised and that both economic and scientific perspectives be carefully weighed. Once the design has been determined and the project established, the basic design should not be altered unless unresolvable difficulties are discovered. Doing so will complicate evaluation efforts, which, because of natural variability in the weather, cannot be based on just one or

two seasons. This stipulation reemphasizes the importance of a sound initial design.

4.1.5 Climatology The most complete climatological information available should be collected about the target and control areas. The World Meteorological Organization (WMO 1992) recommends the acquisition of climatological data during the design phase. This knowledge of storm and hail climatology should be incorporated in the design of a project. Many references provide useful information about hailfalls and hailstorms through climatological analysis of different parts of the world. See, for example, Carte et al. 1963; Hitschfeld 1971; Morgan 1973; Prodi 1974; Dye et al. 1976; Changnon 1977; Federer 1977; Foote and Knight 1977, 1979; Morgan et al. 1980; Morgan 1982a, 1982b; Dessens 1986; Boe 1992; Sánchez et al. 1994; Smith et al. 1997; Dessens 1998; and Tsagalidis et al. 2006).

Project designers must consider the following climatological variables:

1. Surface area affected by typical hailfalls;
2. Distribution and locations of known high-risk areas, those that tend to suffer from hailfall most frequently;
3. Range of hailstone sizes observed;
4. Diurnal distribution of hail;
5. Monthly or seasonal distribution of hailfalls;
6. Spatial and temporal distribution of the appearance of radar echoes from convective clouds;
7. Relationships between radar-derived storm characteristics and hailfall at ground level; and
8. Concentration of natural ice nuclei.

Design of the project can be further enhanced if, in addition to these variables, information is available about the general behavior of convective cells in the project area, the expected range of hailfall intensities, and the relative quantities of water and hail that are typically precipitated.

Possible local sources of real-time meteorological data should be located to support project forecasting and nowcasting (very-short-term forecasting in the 0- to 60-min time frame). The Internet is one possibility; local colleges, universities, and governmental weather offices are others. Networks of surface meteorological stations are operated by many agencies (e.g., highway departments) and can provide valuable data.

Climatological analyses should identify areas prone to storm development, including forcing by local terrain, which should be considered in the placement of seeding facilities and should also aid operational decision making.

4.2 SEEDING AGENT SELECTION

Hail suppression involves intervening in the microphysical and/or dynamic development of convective cells to restrain, deactivate, or disrupt those processes in the interior of the cells that result in the formation of hailstones.

The method most widely used consists of introducing glaciogenic agents, materials that have the capacity to generate additional ice particles in the clouds. When added to the natural population of ice particles (if any) within the embryo source region, the collective ice particle population should alter the cloud sufficiently to result in the reduction of damaging hail (according to one or more of the hail suppression concepts presented in Section 3.2).

There are many natural glaciogenic agents. Not all, however, form ice crystals with the same facility, given that their efficiency in this respect is a function of their composition, size, and cloud temperatures. In fact, each substance has a threshold

temperature at which it begins to cause the formation of ice crystals.

Although glaciogenic agents intended to increase ice particle formation are the most common, another method involving a quite different approach called “hygroscopic seeding” (Dennis and Koscielski 1972; Mather 1991; Cooper et al. 1997) is being used with increasing frequency. The principal hail reduction mechanisms which hygroscopic seeding sets in motion are called “early rainout” or “beneficial competition” (see Section 3.2). This technique aims to speed the development of large cloud droplets and formation of raindrops through coalescence in the warmer (lower altitude) parts of the cloud. The full effects of this class of seeding agents continue to be explored.

4.2.1 Silver Iodide Silver iodide (AgI), in combination with various other chemicals, most often alkali iodide salts, has been used as a glaciogenic agent for half a century. In spite of its relatively high cost, it remains a favorite, especially in formulations that result in ice nuclei (IN) with hygroscopic tendencies.

Silver iodide has utility as an ice nucleant because it has the three properties required for field application:

1. It is an ice nucleant, regardless of the specific mechanism;
2. It is relatively insoluble at 10^{-9} g of AgI per gram (or 10^{-9} oz of AgI per ounce) of water, so that the particles can nucleate ice before they dissolve; and
3. It is stable enough at high temperatures to permit vaporization and recondensation to form large numbers of functional nuclei per unit mass of AgI burned (Finnegan 1998).

Also, the ice crystallization temperature threshold for AgI is higher than the threshold for most naturally occurring IN, which commonly have thresholds closer to -15°C (5°F) or lower. The chemical formulations of AgI seeding agents may be modified further, so that the resulting IN function at even higher temperatures (Garvey 1975; DeMott 1991).

In many cases, the AgI aerosol is formed by a generator that burns it to produce particles from 0.1 to $0.01\text{ }\mu\text{m}$ (4×10^{-5} to 4×10^{-6} in.) diameter (Figs. 4-2 and 4-3). The process can be carried out using generators that burn a solution of acetone with an AgI concentration on the order of 1–2%.

Solutions may be obtained premixed or can be mixed in the field. Though AgI is insoluble in acetone, commonly used solubilizing agents including ammonium iodide (NH_4I), and any of the alkali iodides cause it to go into an acetone solution. The AgI must be thoroughly dissolved because undissolved reagent can block flow in the generator, resulting in failures. Additional oxidizers and additives commonly include ammonium perchlorate (NH_4ClO_4), sodium perchlorate (monohydrate) ($\text{NaClO}_4\text{H}_2\text{O}$), and paradichlorobenzene ($\text{C}_6\text{H}_4\text{Cl}_2$). The relative amounts of such additives and oxidizers modulate the yield, nucleation mechanism, and ice crystal production rates. Some of the substances used in AgI mixtures are oxidants and may corrode the metal parts of some IN-generating equipment. Care should be taken in the mixing and storage of any AgI seeding solution; consult the material safety data sheets (MSDSs) for specific information on each substance.

The generation of AgI aerosols also can be accomplished by burning specialized pyrotechnics (Figs. 4-2 and 4-3). In many cases, a mixture containing silver iodate (AgIO_3) has been used. Powdered aluminum and magnesium, and some kind of organic agglutinant, also are often added to the mixture (Dennis 1980).

Once produced, some AgI aerosols, particularly those containing ammonium iodide, may lose some of their glaciogenic



FIGURE 4-2 Glaciogenic cloud seeding pyrotechnics called “burn-in-place” flares are commonly burned in flight, attached to racks affixed to the trailing edges of the aircraft wings

Source: Courtesy of James Gunkelman, Ice Crystal Engineering.



FIGURE 4-3 Racks for ejectable glaciogenic pyrotechnics are commonly mounted on the aircraft belly (top). These flares are 20 mm (0.79 in.) in diameter, and each typically contains 20 g (0.04 lb) of nucleant and binder. When fired, only the flare candle leaves the aircraft (bottom); the aluminum casing remains in the rack

Source: (top) Courtesy of Weather Modification, Inc.; (bottom) ASCE (2003a), photograph by Christopher Woodley.

capacity within an hour or so of generation if exposed to direct sunlight (and ultraviolet (UV) light in particular). Other aerosols have shown limited degradation with exposure to sunlight. The degree of photodeactivation, if any, depends upon the formulation and the amount of incident UV solar radiation. In any

instance, solutions should be protected from UV light during storage to avoid possible loss of effectiveness.

In recent years, advances in nucleation physics have resulted in a number of more effective pyrotechnic formulations, which produce nuclei that, in addition to having ice nucleation thresholds near -5°C , also are somewhat hygroscopic. The resulting nuclei are not only effective as IN, but also attract water molecules. This attraction results in particles that in relative humidities near water saturation quickly form droplets of their own, which then freeze shortly after becoming supercooled. This condensation-freezing nucleation process generally functions faster than simple AgI, which laboratory testing has shown functions primarily by the contact nucleation process. That process is more dependent upon cloud droplet concentration, and consequently much slower (DeMott 1991). Speed in nucleation is very desirable in applications such as hail suppression, where quick glaciation in modestly supercooled cloud turrets is required (Pham Van Dihn 1973, Rilling et al. 1984, Finnegan et al. 1994, DeMott et al. 1995).

4.2.2 Dry Ice Another glaciogenic seeding technique creates cloud ice particles by dispensing dry ice (CO_2) pellets (Fig. 4-4) into the supercooled cloud. Dry ice modifies the natural ice formation process by rapidly transforming nearby vapor into ice crystals, which grow by vapor deposition from evaporating supercooled cloud droplets. The direct freezing of cloud droplets by dry ice is a secondary effect (Schaefer 1946, Holroyd et al. 1978, Vonnegut 1981). A hail suppression project using this seeding agent was carried out during the 1970s in South Africa, and dry ice is currently used on the North Dakota Cloud Modification Project (Langerud et al. 2010).

Compared with silver iodide complexes, this approach has an advantage in that it makes use of a natural substance (frozen carbon dioxide, CO_2 , which sublimates at -78.5°C (-109.3°F) at 1,000 hectopascals), and it is more effective than silver iodide at temperatures higher than -4°C . Another major advantage is its low cost relative to silver iodide. However, effective delivery of the CO_2 requires direct injection by aircraft at altitudes above the 0°C level. The CO_2 is also difficult to store because sublimation (and therefore loss) is continuous. It is not common for dry ice to be the only seeding agent used in a hail suppression project, although it is sometimes used in conjunction with AgI complexes, as is currently the case in North Dakota and Kansas.



FIGURE 4-4 Dry ice, in extruded pellet form. The pellets shown, of varying lengths, are about 0.6 cm (0.25 in.) in diameter
Source: Courtesy of Brook Mueller.

4.2.3 Other Ice Nucleants Certain proteins derived from a naturally occurring bacterium, *Pseudomonas syringae*, fall within the description of nucleating proteins because of their ability to induce the formation of ice crystals in seeding applications. This bacterium is but one example of many other substances that have this property. Among these are metaldehyde and 1,5-dihydroxynaphthalene, which have contact freezing temperatures of -3°C (27°F) and -6°C (21°F), respectively. Their efficiency in generating ice crystals is similar to that of dry ice (Kahan et al. 1995; Keyes et al. 2006). At present, however, no hail suppression projects exist that make operational use of these materials.

4.2.4 Hygroscopic Agents The intent with hygroscopic seeding, still exploratory for hail suppression seeding operations, is to activate and/or increase the warm-cloud collision-coalescence precipitation process, thus creating additional drops that might be frozen either naturally or by supplementary glaciogenic seeding. Such frozen drops would then function as additional embryos, which compete for available supercooled cloud water, as espoused in Section 3.2.1.

Research experiments carried out in South Africa in the early 1990s showed that other concepts also are involved; these experiments have underlined the potential importance of seeding with hygroscopic agents. Mather strongly recommended the use of hygroscopic agents to combine hail suppression with rain enhancement activities (Mather 1991; Mather and Terblanche 1994).

Hygroscopic agents *deliquesce* (that is, become liquid solutions by absorbing moisture from the air) at relative humidities significantly less than 100%. Although there are many naturally occurring hygroscopic substances, potassium chloride (KCl) particles have the advantage of only requiring relative humidities on the order of 70–80% for deliquescence and readily act efficiently as cloud condensation nuclei (CCN) (Keyes et al. 2006). Mather (1991) made use of flares containing primarily potassium perchlorate, which when burned produce KCl particles of about 1 μm (0.0004 in.) diameter. Another formulation, tested at the National Center for Atmospheric Research, uses calcium chloride (CaCl_2) as the primary salt, which produces a highly hygroscopic aerosol when burned (Fig. 4-5).

4.2.5 Quality Control There are few manufacturers of seeding agents in the world, but some organizations do offer to prepare seeding chemicals or solutions for weather modification purposes. From the outset, project planners have two options: to prepare their own seeding agents or to buy them commercially. Whichever option is chosen, the following should be considered:

1. Manufacturers of pyrotechnics should be required to present evidence of their product's nucleating ability, if possible, as tested in a cloud chamber. The output of other seeding agents, including those prepared by project personnel, should be similarly tested when burned with the equipment to be used in the operations.
2. Both active and inactive ingredients of all seeding agents, including flares, should be specified.
3. Material safety data sheets (MSDSs) should accompany all materials, whether in raw form or ready for use.
4. The quality of all materials should be specified and assured.
5. Any acetone-based AgI solution should be transparent, i.e., colorless to faintly yellow.
6. If flares or rockets are to be used, their warehousing should be carefully planned because explosive materials are involved.



FIGURE 4-5 Hygroscopic calcium chloride pyrotechnics are shown in action. Ignition on an aircraft flare rack is shown in (A), the burn in (B), and for comparison, a ground burn without wind in (C). Each of the flares shown contained 1.00 kg (2.21 lb) of reagent
 Source: (A) and (B) courtesy of Christopher L. Grilliot; (C) courtesy of James Gunkelman.

7. Dry ice pellets should be of consistent sizes and should be transported and stored in containers that minimize sublimation and limit the development of water ice within the dry ice.

4.3 DELIVERY METHODS

The consistent, proper placement of the seeding agent(s) in both time and location (targeting) is absolutely essential in any program of applied cloud seeding and cannot be overemphasized. Many programs have failed to produce the desired results, only to find later in the course of postanalyses that the seeding agent was not properly targeted.

It is therefore extremely important that a delivery method be selected that functions reliably in the meteorological conditions and storm environment typical of the project. This section provides an overview of various equipment and techniques required for the generation of the seeding aerosols and delivery of the seeding agents, along with illustrations of each type.

There are two basic philosophies currently applied in operational hail suppression programs: *broadcast seeding* and *direct targeting*. Broadcast seeding is the continuous emission of seeding agent (usually silver iodide (AgI) aerosols), most often from ground-based generators. This method significantly increases the concentration of ice nuclei in the atmosphere when forecasts suggest that there is a risk of hail in some part of the target area. The AgI aerosol generators are positioned with the intention of boosting the ice nuclei concentration in and below the hail growth zone, so that when the hailstorms are forming, the inflow to the storms includes a portion of the low-level air containing the aerosol.

Direct targeting involves the application of seeding material directly to the cloud, at the place and time when the mechanisms that govern the formation and growth of hail may be successfully modified or restrained. Means of detecting developing storms early and of predicting the risk of hail are, therefore,

required for both broadcast seeding and direct targeting to be effective.

Delivery options are as follows:

1. Aircraft carrying seeding devices. These may be nuclei generators that burn an AgI-complex-acetone solution, pyrotechnic flares, or mechanisms that dispense dry ice. This delivery technique is currently in widespread application and is favored for its relatively certain targeting and modest response time.
2. Ground-based ice nuclei generators, usually deployed in networks, which emit continuous plumes of AgI aerosols. This technique relies upon local air currents to transport the seeding agents to the growing convective clouds. This is the type of system used in southern France since 1951, across wide areas of Spain since 1975, and in various other countries around the Mediterranean Sea. This delivery technique involves a longer response time and often uses more seeding agent.
3. Rockets or artillery shells containing nucleating material. These systems have been widely used in Eastern Europe and Asia. Rocket and artillery systems can involve short response times, but the expense of the expendables themselves and restrictions upon their use imposed in many locales limit the applicability of these techniques.

Because there may be no single “best” delivery technique, the possibility of using a mixed system should not be ruled out. One system might be more suitable than another, for instance, during day or night situations or over a particular type of terrain.

4.3.1 Airborne Application Ice nucleus generators (Fig. 4-6) located under the wings or on the wing tips, racks of ejectable flares mounted on the bottom of the aircraft fuselage, burn-in-place flares held in wing racks, and dry ice dispensed from a hopper internal to the aircraft all can be used to seed effectively in airborne applications. In the case of the generators, the aerosol



FIGURE 4-6 An airborne ice nucleus generator is shown affixed to an aircraft wing. Such generators consist of three sections: a compressed air tank to provide flow to the liquid seeding solution (front), the solution reservoir (middle), and the combustion chamber (aft). Capacity is typically about 30 L (8 gal.)
Source: Courtesy of Jesse Bader.

emission is typically 100 to 200 g (0.22 to 0.44 lb) of AgI per hour, whereas the burn-in-place flares, which burn from one to several minutes, typically contain from 20 to 150 g (0.044 to 0.33 lb) of the agent. Some of the characteristics of these systems are described in ASCE Manual No. 81 (1995; 2006).

When dispensed at convective cloud base (from wing-tip generators or burn-in-place flares), the seeding material must be introduced into the ascending currents (updrafts) of the newly developing convective clouds on the flanks of the mature storms. This also is true of clouds that are developing independent of mature storms but are likely to develop into thunderstorms themselves. The aircraft typically has to be able to sustain flight in the subcloud updraft region, feeding the nucleant directly into the updraft. Although the targeting of this technique is relatively certain, some time (perhaps 10 to 20 min) is still required for the seeding aerosol to be transported aloft to the supercooled portions of the cloud. When cloud bases are found at lower altitudes (higher temperatures), the transport to supercooled cloud regions requires more time, so it is imperative that seeding be initiated sufficiently early. This requirement means initiation of treatment before the subject cloud tower becomes supercooled in most cases.

Seeding in mature updrafts should be avoided as unproductive, since these updrafts often exceed 20 m s^{-1} (45 mi h^{-1}), and any ice particles that might result have no chance of growing to precipitable size before being transported to cloud top (see Section 3.2.6). In addition, storms with such strong updrafts can and frequently do produce large hail, which is a risk to both aircraft and occupants.

When ejectable flares or dry ice are used, the seeding agent(s) can be released during cloud penetration or dropped into the cloud top from above, and a significant quantity of seeding material can be discharged in only a few seconds. The effects of this kind of delivery are almost immediate if the targeted cloud is supercooled. During direct injection of seeding agents from aircraft inside growing supercooled turrets, vertical wind speeds (both rising and descending) of 10 m s^{-1} (22 mi h^{-1}) or more may be encountered. Strong turbulence is not unusual, especially in the shear zone between the descending air at the turret boundaries and the interior updrafts.

The dry ice pellets must be small enough to sublimate as much as possible during their fall through supercooled cloud. American

projects typically use pellets of 11-mm (0.43-in.) diameter. If released at the cloud top in turrets growing upward at 10 m s^{-1} (2,000 ft per min) through the -10°C (14°F) level, a portion of each such pellet remains still unsublimated by the time it falls into warm (0°C , 32°F) cloud, and thus is wasted. Smaller diameter pellets may be used if available, as long as they are not so small as to clog the dispensing mechanism. Initial dry ice seeding rates during flight through supercooled updraft should be near 0.5 kg (1.1 lb) km^{-1} (Holroyd et al. 1978), but trials in local cloud conditions are recommended.

Ejectable flares that burn 20 g (0.044 lb) of nucleant in about 30 seconds are most often used for on-top seeding. Formulations producing nuclei that act predominantly in the condensation-freezing mode are preferred since, in hail suppression operations, quick nucleation and freezing of the supercooled liquid water is necessary. Smaller turrets have limited updraft and supercooled liquid water, and only a single flare is needed. An additional flare is usually fired every several hundred meters of flight in broader or faster growing turrets, or every 4 to 5 seconds if flying at $67\text{--}100 \text{ m s}^{-1}$ ($150\text{--}225 \text{ mi h}^{-1}$). This seeding rate is based on turbulent mixing observations in actively growing cumulus, which showed overlapping seeding plumes within 250 seconds with this rate (Grandia et al. 1979), providing enough ice nuclei to deplete the cloud liquid water within a 10 m s^{-1} (22 mi h^{-1}) updraft.

The purpose of glaciogenic seeding is to start ice formation before it would naturally occur and to generate significantly increased ice concentrations as the targeted turret matures. Therefore, in-cloud or on-top treatment should be conducted on developing cloud turrets that are both supercooled and ice-free. The time window between a turret reaching supercooled conditions and the appearance of natural ice particles can be quite narrow. Once ice particles begin to develop, they quickly multiply within the cloud turret, so treatment of turrets that already contain significant (natural) ice is unnecessary and a waste of precious time and resources. A bigger turret is usually closer to developing ice naturally, and the objective is to give each turret as much head start as possible.

Modern global positioning systems (GPSs) are a relatively inexpensive means of confidently determining the position of the aircraft (and also any ground vehicles in the field). With a suitable radio link, the aircraft position can be transmitted to the ground weather radar site and automatically plotted on the radar screen. This method offers another important source of documentation of aircraft cloud treatment operations. It is possible to automatically record exactly when and where treatment was carried out and show this in relation to the radar or other types of images. The recording of aircraft position with GPS is not linked to the radar antenna rotation, as it is with the older identification, friend or foe (IFF) transponder-type positioning system. The information also contributes to operational safety. In operations with more than one aircraft airborne at any time, the positional information can be exchanged between aircraft and aid in maintaining separation or coordinating movements. From the aircraft flight tracks and the verbal reports via radio from the pilots, the targeting can be accorded considerable confidence, especially when the seeding agent is released directly in the cloud turret.

The airplanes used for direct injection seeding must be equipped with the instrumentation required for flight under instrument flight rules (IFR) conditions. In the United States, the Federal Aviation Administration (FAA) is required to certify all cloud-seeding aircraft, including the modifications made to accommodate equipment, and this certification brings with it certain restrictions and limitations. Generally, the private

companies equipping hail suppression projects use twin-engine, turbo-charged aircraft. Speed and rate of climb should be considered because the aircraft should be capable of quickly getting to rapidly evolving clouds. Twin-engine aircraft are desired for these performance reasons and also for the ability to safely return to an airport should one of the engines malfunction.

4.3.2 Ground-Based Ice Nucleus Generator Networks The production of AgI aerosols may be carried out by a generator burning a solution of acetone, AgI, and other ingredients. This process is discussed in greater detail in Section 4.2.1. The most common method is to use generators in fixed surface positions, forming a network. The number and position of these generators should be calculated considering at a minimum the following factors:

1. Characteristics of the aerosol emission from the type of generators and seeding solution;
2. Background concentration of naturally occurring ice nuclei in the target area;
3. Most likely wind trajectories prevailing in conditions conducive to the formation and/or propagation of convective storms; and
4. Information about local atmospheric stability, including inversions that might trap the seeding agent within the boundary layer, thereby inhibiting dispersion of seeding material into areas where storm inflow is likely to tap it.

One approach is to space the ground-based ice nuclei generators at a distance comparable to the diameter of the smaller convective cells, on the order of 8 km (5 mi), as was done in some Great Plains hail suppression programs in the 1950s. This method would ensure that any developing storm would have a chance of ingesting aerosol from at least one ground-based generator. If the primary storm formation areas are known (through meteorological radar data, for example), the IN aerosol concentration can be boosted by the deployment of additional generators in these areas (Castro et al. 1998). Modeling of seeding agent dispersion (dispersion modeling) also should be conducted (Admirat 1972; Pasquill 1974; Bruintjes et al. 1995) to aid the determination of the number and placement of generators required to deliver sufficient ice nuclei to cumulus cloud altitudes.

The aerosol emission level for ground generators typically varies from 8 to 40 g (0.018 to 0.088 lb) of AgI per hour. Fig. 4-7 shows a generator used on the French Anelfa program. It uses a propane flame to burn an AgI acetone solution at the rate of 1.1 L/h (0.29 gal/h), releasing 8.6 g (0.019 lb) of AgI per hour (Dessens et al. 2009). Ground-based generators can be switched on and off manually, each one by a designated responsible individual, or automatically from a central control station. In both cases, maintenance service is essential to replace supplies when necessary and maintain each generator in operating condition. The generators are generally kept burning throughout the time the suitable clouds are within the target area.

When possible, ground-based generators should be situated in mountainous or hilly regions upwind of the target area, so that the wind and natural turbulence can loft the seeding material and assist dispersion. However, damaging hailstorms are not limited to hilly or mountainous terrain; the plains of North America regularly experience vigorous hailstorms. Therefore, it also may be desirable to deploy ground-based generators in relatively flat terrain, relying on convective heating to mix the seeding agent throughout the moist boundary layer upon which the developing storms feed (McPartland and Super 1978; Heimbach and Stone 1984; Griffith et al. 1990). The network used in southern France



FIGURE 4-7 A ground-based ice nucleus generator used for hail suppression efforts in the French Anelfa program
Source: Courtesy of Claude Berthet, Anelfa.

is shown in Fig. 4-8 (C. Berthet, personal communication, 2011). To ensure targeting in as many meteorological situations as possible, the network is made up of 700 generators deployed over about 60,000 km² (23,166 mi²). Thus, it is apparent that development of a ground-based generator network is not simply a matter of deploying a dozen or so generators.

At least some fraction of the generator network needs to release seeding material whenever there is a risk of storms, so it is essential for the project to be able to count on accurate forecasting. This accuracy is particularly important when the generator network is not automatic because of the inevitable delay involved in switching on the generators. The individuals responsible for each machine have to be alerted and get to their posts before each generator can be activated. With an automatic network, however, the generators can be activated or deactivated within a few minutes.

Whereas airborne targeting by aircraft flying in updrafts below convective cloud bases in visual meteorological conditions (VMCs) has often been used in North America, there are sometimes circumstances when excessively low cloud bases, darkness, or instrument meteorological conditions (IMCs) make it unsafe to dispense seeding agent from below base. In such cases, an ancillary ground-based generator network might prove helpful.

4.3.3 Rockets and Artillery For many years, rockets and/or artillery have been used to deliver seeding material into storm cells in China and the countries of the former Soviet Union (the Russian Federation, Moldavia, Ukraine, and the Transcaucasian republics). Rockets also have been used in Argentina, Bulgaria, Croatia, Hungary, Serbia, Slovenia, and various other states. Neither rockets nor artillery have been used in Western countries because of the greater costs and the potential risks to aircraft and population.

Scientists of the former Soviet Union pioneered this hail suppression technique, which made use of rockets carrying substantial quantities of seeding material (several hundred grams of AgI each). Recently, the Russian Federation and others have developed the Antigrad Automatic Control System, which uses rockets to target developing supercooled turrets of the flanking line. When a convective storm meeting the radar criteria for seeding is detected, rockets are launched. One such rocket, the Alazan-5, can deliver 630 g (1.39 lb) of AgI and has a range of

HAIL PREVENTION NETWORK

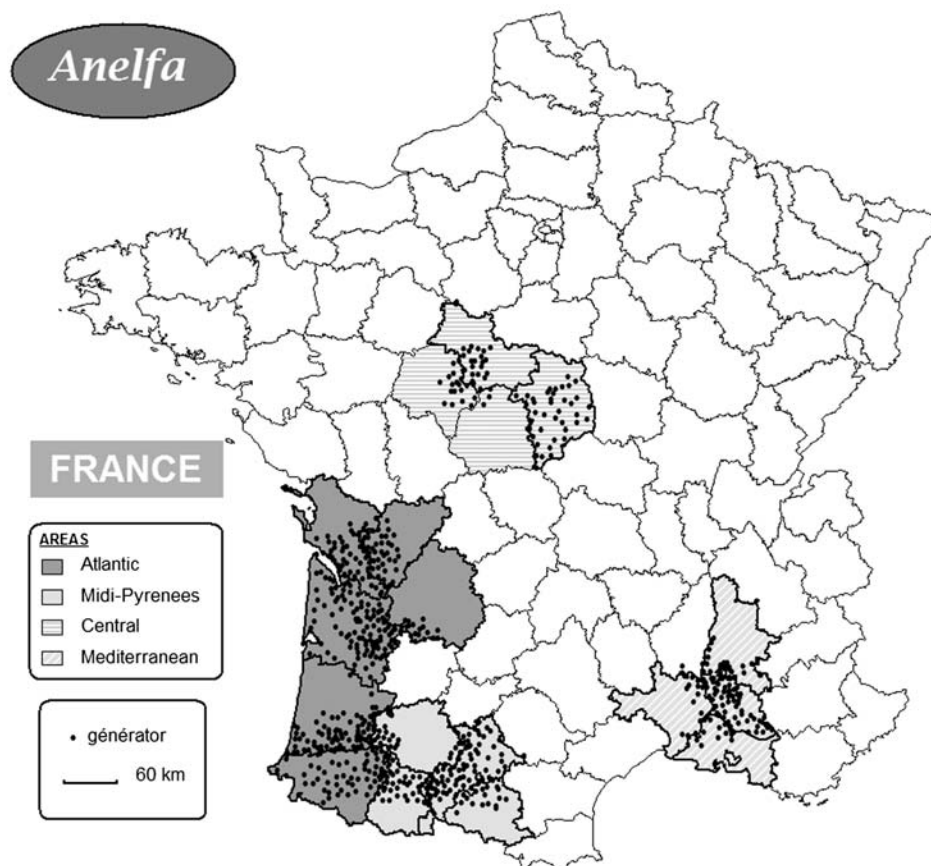


FIGURE 4-8 Ground generator locations in the Anelfa hail suppression program in southern France

Source: Courtesy of Claude Berthet, Anelfa.

9.5 km (5.9 mi). Another, the Krystal, can deliver 173.6 g (0.38 lb) of AgI, in the form of 28 individual 6.2-g (0.014-lb) flares, to a maximum range of 12 km (7.5 mi). Both of these rockets are equipped with self-destruct charges to fragment the rocket after dispersion of the seeding agent. The newest rocket, the Alan, can deliver 42 g (0.093 lb) of AgI, also to a maximum range of 12 km (7.5 mi). The Alan is parachute equipped; no self-destruct charge is needed.

The rockets are designed to release a plume of nucleating material once a certain height has been reached. Launch crews may receive details about the necessary elevation and azimuth angles and the AgI ignition altitude for the launch from the radar, or the targeting may be automated by telemetry of aiming and firing instructions to the launcher. The greatest advantage of the system is its potential to reach any region of convective cells in a very short time; all of these rockets attain their targets within one minute.

Disadvantages are firing restrictions because of air traffic and, in some cases, the presence of populated areas. It is doubtful that such a system could be used in the United States because the requisite federal approval almost certainly would not be obtained. In addition, the self-destruct mechanism occasionally may misfire, so care must be taken to launch the rocket in a direction that will not result in damage to the public or to property. With the Antigrad system, such sectors can be programmed into the launchers, so that firing within them does not occur. A more serious shortcoming may be that the targeting instructions are

derived from the radar returns, yet the desired ice-free, super-cooled cloud turrets rarely generate a discernible radar echo with radar systems typically used in operational hail suppression programs. Rockets and artillery are unacceptable as a means of seeding in urban areas.

The verification of the targeting for such rockets has never been accomplished. Though visual and radar indications suggest that the rockets can reach the intended cloud complexes, the release and dispersion of the seeding agent within the intended turrets has not been verified by in situ microphysical measurements.

Finally, there must be a sufficient number of launching sites to cover the seeding area. For an area of 1,000 km² (386 mi²), from 20 to 25 sites are required, each of which needs at least one launch pad and an arsenal for storing the rockets. In each of these rocket-based projects, personnel requirements are significant because there must be trained staff at the radar and launch sites whenever storms are forecast, sometimes 24 hours a day. All of these requirements make it a costly system to operate. When coupled with the expense of the seeding rockets, the potential for rocket debris to reach the ground after self-destruct or if self-destruct fails, and airspace limitations because of general and commercial aviation, most contemporary hail suppression projects have sought alternate treatment techniques. Anyone considering the use of rockets should first determine what local, state, and federal flight restrictions apply and how such restrictions might affect operations.

4.4 METEOROLOGICAL DATA COLLECTION AND FORECASTING

Meteorological data collection is necessary in the short term for forecasting and cloud treatment purposes and in the long term for project evaluation. Both are essential for program success. Short-term “opportunity recognition” is the identification of those cloud systems and cloud regions capable of producing damaging hail in the target area, and it is immediately followed by the application of the hail suppression seeding. If a storm threatens the target area, the proper time and place for the application of the treatment must be determined. This method requires knowledge of the storm location and motion, as well as the local mesoscale and synoptic meteorological conditions. Accurate short-term forecasting is thus needed to stay abreast of developing weather because as new storms develop, existing storms can persist, intensify, decay, or change direction and speed.

4.4.1 Forecasting and Nowcasting “Response time” is the time required to recognize a potential hail threat, notify appropriate responders (e.g., pilots, airspace use coordinators, and ground-based generator operators), and initiate seeding treatment. Because thunderstorms can develop rapidly in unstable atmospheres and because cost almost always precludes having responders always at the ready, day and night, forecasting and nowcasting (very-short-term forecasting in the 0- to 60-min time frame) play a vital role in any hail suppression project. Better forecasts translate to more on-time treatments of potential hail clouds.

4.4.1.1 Government Forecast Information The U.S. National Weather Service (NWS), the Meteorological Service of Canada, and analogous organizations in other countries provide forecasts about expected storm conditions, and these conditions should be available to the operators of hail suppression programs in these locales. In particular, where official government forecasts of severe weather (large hail, severe winds, tornadoes) or flooding are issued, it is important to be aware of any warnings that apply to the operational area. Policies must be developed for reacting to the issuance of a severe weather advisory or warning in the area. For instance, it may be decided that it is best to suspend cloud treatment operations when certain classes of severe weather have developed, e.g., tornadoes (see also Section 4.6).

4.4.1.2 On-Site Operational Forecasts Some forecasting should be carried out by the project itself. Only the presence of a skilled forecaster, knowledgeable in the forecasting of thunderstorms and in the local effects influencing them, can ensure the timely direction of operations. Such a forecaster needs meteorological information to be integrated with the radar and other information available at the operations center, as well as information from personnel in the field, to update forecasts on a very short timescale (nowcasting). Some weather modification operations have found it necessary to operate their own rawinsonde (balloon-borne weather instrument packages that measure temperature, moisture, and winds) equipment to obtain the atmospheric temperature and moisture profile and winds aloft, close to the target area, and on time schedules critical to their operations. In the United States, rawinsonde observations are made by the NWS only in the early morning and early evening, and thunderstorm activity usually begins in the early afternoon. The meteorological information used by the forecaster might include surface and upper air observations and also forecast maps produced by the large national or regional numerical forecast centers.



FIGURE 4-9 Weather radar installation. Shown is a 5-cm (2-in.) wavelength facility located in Stanley, North Dakota. The antenna and pedestal are housed within a fiberglass radome that allows operation to continue even in strong winds. The building is air-conditioned to provide comfort to the electronics and project staff. An auxiliary power unit provides power when commercial service fails

Source: Courtesy of Darin Langerud.

4.4.2 Remote Sensing It is now possible to obtain useful information about storm development and the near-storm environment in real time, without having to enter the cloud itself or its immediate vicinity. These techniques, termed “remote sensing,” include meteorological radar, satellite imagery, wind profilers, and lightning detection networks. The following sections describe some of these techniques.

4.4.2.1 Meteorological Radar Aside from the treatment equipment itself, the most important tool for operating a hail suppression operation is the meteorological radar (Fig. 4-9). A high-quality, properly sited radar (location that avoids excessive ground clutter and beam blockage) enables storm monitoring over a large area, in spite of the presence of intervening clouds. The monitoring can provide measurements of vertical development (height of storm tops), intensity (radar reflectivity), location, motion (direction and speed), and, with an experienced operator, the probability of hail development or even the presence of hail. Choices of wavelength and other characteristics of the radar are important. Wavelengths of 3 cm (1.2 in., X-band) or less are not satisfactory for observing mature convective storms because of the great likelihood of significant attenuation (absorption and scattering) of the radar beam by rain and hail. However, attenuation is negligible at wavelengths of 10 cm (3.9 in., S-band) or greater. This makes 10-cm wavelength the best choice for convective storm applications, but many projects opt for a 5-cm (2 in., C-band) wavelength, mainly for reasons of cost. The antenna size required to achieve a given beam width (typically between one and two degrees) at 10-cm (3.9-in.) wavelength is twice that at 5 cm (2 in.). For example, a 5.4-cm (2.1-in.) wavelength (C-band) circular-parabolic antenna must have a 2.4-m (7.9-ft) diameter to produce a nominal 1.6-degree beam width, whereas the same beam width at S-band wavelengths requires an antenna of 4.9-m (16-ft) diameter.

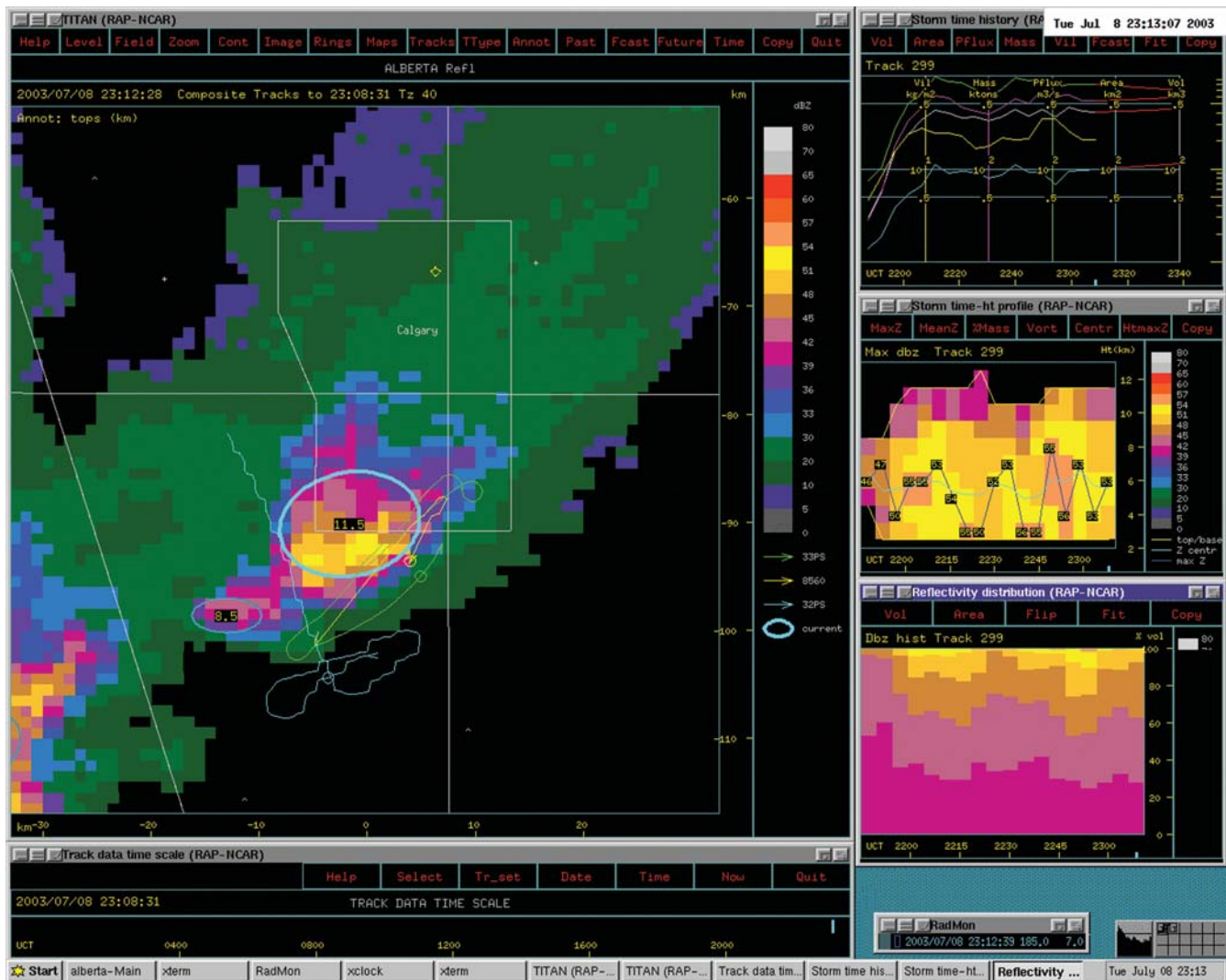


FIGURE 4-10 Composite radar reflectivity as shown in plan view by the TITAN processing software for a potential hailstorm in Alberta, Canada, on July 8, 2003, at 23:12 UTC (Coordinated Universal Time), left. The storm centroid being tracked is outlined within the larger drawn oval, which is annotated with the number "11.5," indicating cloud top height in kilometers. The tracks of two seeding aircraft are plotted as lines below (south of) the cell. To the right are three time profiles. The upper right trace shows the cell-specific histories of evolution of cell height and reflectivity, and the lower right window contains the reflectivity distribution as a function of time

Source: Courtesy of Weather Modification, Inc.

The radar cost is increased by an even greater multiple. To ensure adequate coverage of the target and adjacent areas and to minimize the "ground clutter" detected by the radar, the selection of radar hardware and the siting of it should be made with the advice of an expert in radar meteorology.

It would be possible to carry out a hail suppression operation in many locations using only the publicly available radar information such as might be obtained from the NWS (part of the National Oceanic and Atmospheric Administration [NOAA]). However, it is preferred, especially in projects using faster delivery systems such as aircraft or rockets, for each project to have independent radar with full control to ensure that the latest information is available and can be updated on a timescale of a few minutes.

Project radar can be operated manually to obtain the information needed to guide cloud treatment actions, but manual operation does not lend itself well to the fullest documentation

of storm development and morphology. Modern digitized radar allows systematic recording of storm data on tapes, disk, and CD-ROM so that operations can be documented, reviewed, and, if desired, analyzed. Data obtained with well-calibrated digital weather radar are also an important resource for storm research and for program evaluation. Digitized radar can be operated under computer software control, and there exist various software techniques for performing sophisticated analyses of the data, either in real time or from the recorded data.

An example of useful automated radar analysis is the family of programs for the automatic identification and tracking of individual storms in systematically recorded volumetric radar data (Fig. 4-10). One such program is TITAN (thunderstorm identification, tracking, analysis, and nowcasting), developed in South Africa and refined at the Research Applications Program of the National Center for Atmospheric Research (NCAR) in Boulder,

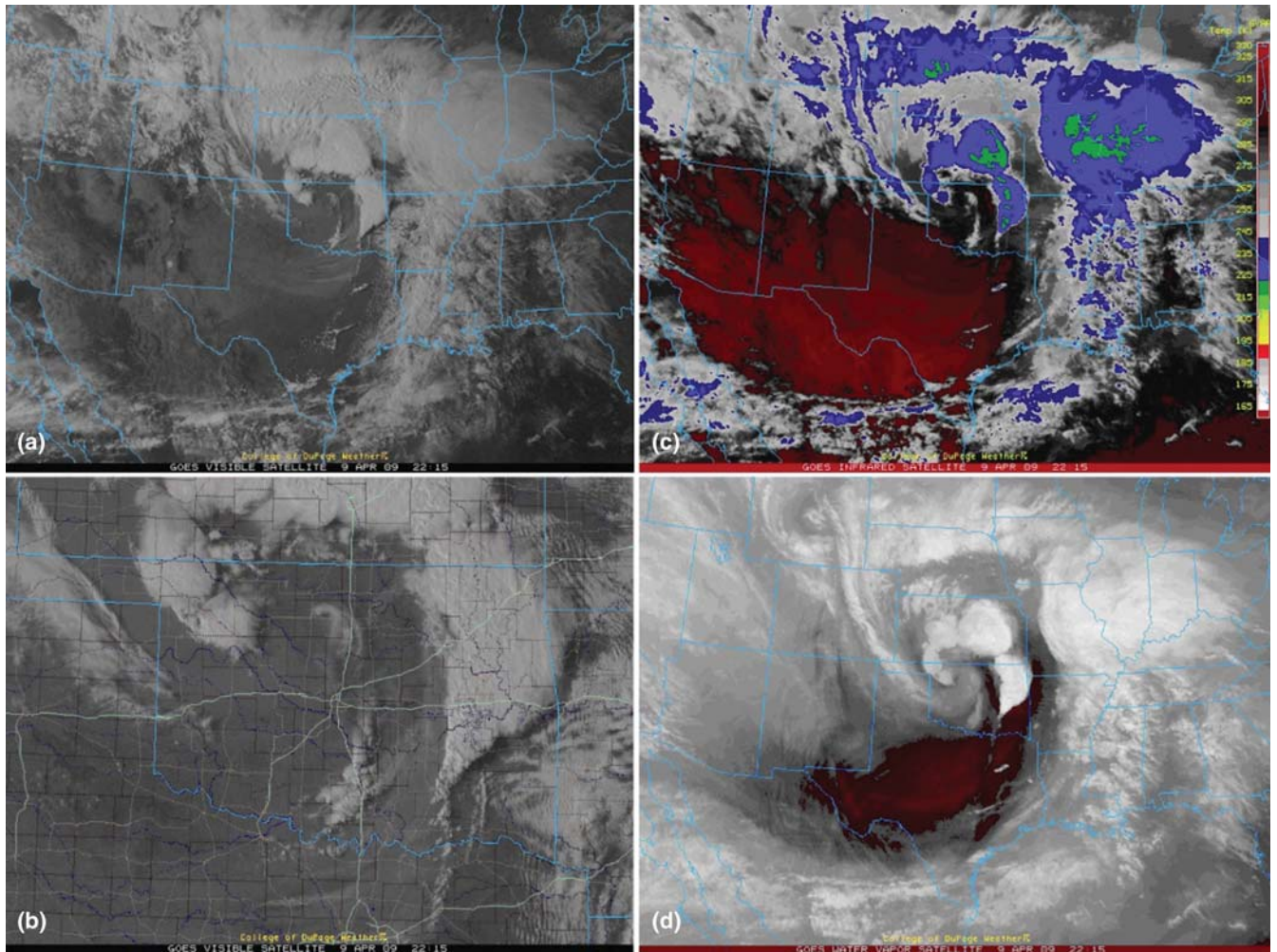


FIGURE 4-11 Satellite imagery is commonly available in a variety of forms and resolutions. Visible imagery at 2-km (1.24-mi) resolution is shown in the upper left. The same storm is also pictured at visible wavelengths, but at 1-km (0.62-mi) resolution at the lower left, with major roadways and local political boundaries overlaid. Infrared imagery (upper right) at 4-km (2.49-mi) resolution provides less detail than visible imagery but is available day and night and offers additional information—cloud-top temperature—which cannot be determined from visible wavelengths. Images recorded at wavelengths strongly affected by water vapor (lower right) give insight regarding the positioning of moisture and moisture boundaries, critical factors in the initiation and propagation of deep, moist, convection, and thus hail. Source: Courtesy of the College of DuPage Weather Lab, <http://weather.cod.edu/satrad/>.

Colorado (Dixon and Wiener 1993, <http://www.ral.ucar.edu/projects/titan/home/>). Storms are identified on each volume scan as volumes enclosed by an envelope composed of a surface of threshold reflectivity, and a complex algorithm associates a storm cell on one scan with its position on the next.

For each scan, a large number of variables (e.g., height, volume, and mass) are calculated for each storm cell, and the time history of these cells affords information about the storm life cycle. At the discretion of the operator, the storm outlines for each volume scan can be overlaid on the radar display. Storm positions in past scans are shown in one color, the present in another color, and extrapolated future storm positions in yet another.

4.4.2.2 Satellite Data Satellite information can be of considerable use in conducting hail suppression operations, especially for forecasting thunderstorm activity. The best sources for this information are geostationary satellites, whose orbits are just high enough that their speed matches that of the rotating Earth below. Thus, these geostationary satellites always remain

above the same spot and are able to continuously provide imagery in visible, infrared, and “water vapor” wavelengths (Fig. 4-11). The NOAA Geostationary Operational Environmental Satellites (GOES) provide excellent coverage of the Americas. Analogous coverage is provided of Europe, Africa, and Asia by Meteosat satellites, operated by the European Community.

Visual-wavelength imagery is generally available at resolutions as small as 1 km (0.62 mi), although only during daylight hours (Fig. 4-11a and 4-11b). The newest GOES satellites now routinely provide visual-wavelength imagery of sufficient quality that cloud structure can be resolved on the flanks of mature thunderstorms, in some cases even the larger individual cloud turrets. Infrared imagery resolution is somewhat coarser, generally 4–8 km (2.5–5 mi) per pixel (picture element) (Fig. 4-11c). This resolution means that less detail can be resolved in the infrared, but, unlike the visual-wavelength imagery, it is available throughout the night as well. Infrared satellite imagery provides a measure of the temperature of the cloud top, which

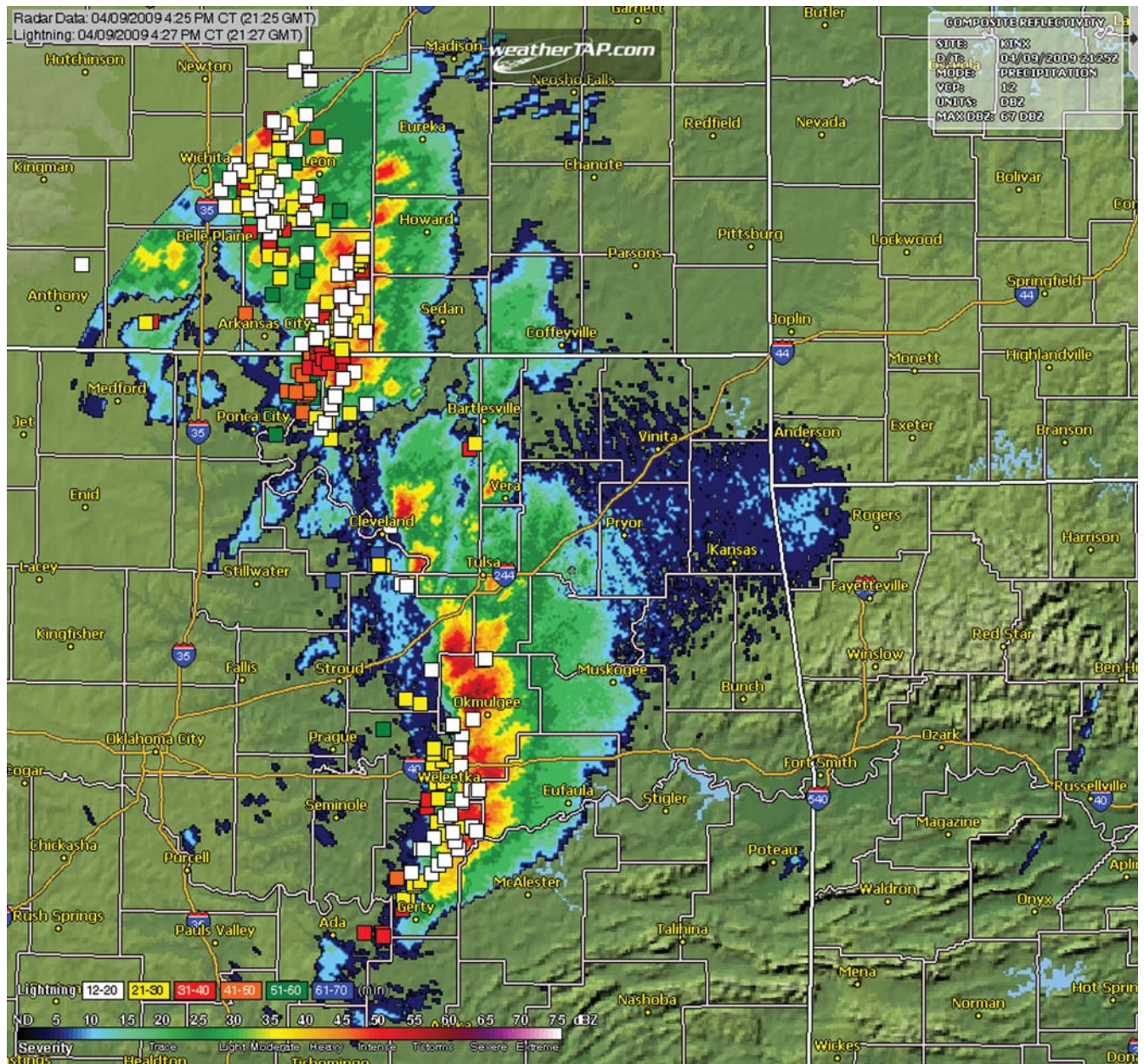


FIGURE 4-12 Cloud-to-ground lightning data recorded by the National Lightning Detection Network (NLDN) is available through subscription with the network operator or available on a time-delayed basis through a number of resellers. Shown here is a radar image produced from National Weather Service data, with NLDN lightning strikes superimposed (colored boxes). The key is shown at the lower left in the image

Source: Courtesy of WeatherTAP, <http://www.weathertap.com/lightning>.

can be combined with appropriate sounding data to derive cloud-top height. Water vapor imagery is derived from an infrared band that senses the amount of water vapor of the top third of the troposphere (Fig. 4-11d). This imagery can also be useful in detecting higher clouds, such as those associated with jet stream motions, and consequently is helpful with forecasting. Video loops of imagery clearly show the rate of change in cloud structure, thus indicating areas of rapid growth where intensifying convective storms are forming. Areas of explosive growth are indicative of severe weather and hail potential.

Data from these satellites are available at many government and university sites on the Internet. In addition, imagery can be received directly by means of on-site receiving equipment. Use

of satellite images in conjunction with radar and lightning data presents a powerful technique for following developments in convective systems organized on a large scale.

4.4.2.3 Lightning Location Automated systems for display of the locations and polarities of cloud-to-ground lightning now cover the entire United States (Orville 1994), as well as the United Kingdom (Lee 1986). These systems can be of great value because they identify, in almost real time, active convective storm systems that are generating cloud-to-ground lightning. In addition, the character of the observed lightning flashes themselves can provide indications regarding storm life cycle or intensity (MacGorman and Rust 1998) or severity

(MacGorman and Burgess 1994). The lightning information supplements radar and satellite data, positively identifying electrically active clouds, even those at great ranges from project radar systems.

These data are available in real time by subscription from the network operator, and usually from a number of other websites in near real time (with payment of a minimal fee), with display delays ranging from 12 to 30 min, as shown in Fig. 4-12.

4.4.3 Visual Cloud Appearance Visual cloud appearance is often the primary criterion upon which aircraft treatment decisions are based. It allows treatment decision makers to assess the growth stage of the cells of interest and allows pilots to gauge the potential risks associated with treating them. Whereas radar echoes provide a measure of the strength of mature cells, it is the nonechoing developing cells that should be targeted. During passage of a storm, cloud features and motions can be misleading to untrained people, as can be appreciated by interviewing eyewitnesses after a hailstorm. Even the direction of storm movement can be erroneously perceived.

Experienced weather modification pilots and well-positioned ground-based observers can provide helpful real-time visual storm reports that describe what a storm is doing at that moment. Project radar systems typically detect only clouds that have begun to produce precipitation embryos. This means that an observer can see and report new cloud development before it produces radar echoes, sometimes minutes before the radar operator has any chance of seeing it on the radar. These minutes can be critically important, for it is these growing, supercooled, ice-free cloud turrets that should be targeted. It is, therefore, important not to rely solely on radar.

4.4.4 Updraft Growing turrets, particularly those about to become or just becoming supercooled, are those most suitable for glaciogenic treatment. The strength of the turret updraft is a good indicator of growth rate and hence cloud vigor. Aircraft penetrations should always be flown with the aircraft in level flight; therefore, updrafts and downdrafts register as altitude changes. Because one of the criteria for treatment should be the existence of an updraft (perhaps of some threshold speed), it is desirable to have real-time knowledge about the updraft character. Thus, instrumentation that reliably provides near-instantaneous data is desirable. These instruments range, in order of simplicity, from the vertical velocity indicator and the instantaneous vertical velocity indicator, to GPS, to flight management systems, and even to inertial navigation systems. An experienced radar meteorologist can deduce approximate updraft strengths from Doppler radar velocity data by identifying areas of low-level convergence, but this technique works only with echoing (mature) storm cells, not the young cumulus congestus clouds desired for treatment. Thus, meteorologists must resist the temptation to ascribe such updraft observations to suitability for seeding.

4.4.5 Numerical Cloud Modeling The ever-increasing speed and computational power of computers allow the physical processes within the atmosphere to be modeled with equations, beginning with prescribed conditions matching some (known) initial atmospheric state. These iterative cloud models can be in one, two, or three dimensions, and may be time-dependent or steady-state models. The complexity of a model is determined by the trade-offs between time and space resolution and degree of detail used in representing the dynamical and microphysical processes of formation and development of cloud, rain, and hail (Orville 1996).

In many operational applications, one-dimensional models serve as a refinement of the classical techniques for analyzing the atmospheric soundings (obtained by weather balloon instruments) to predict things such as vertical storm development and maximum probable hailstone size. Multidimensional cloud models are more complex and have been used only in research projects. However, with today's computer technology, their use in operational programs is becoming practical.

4.4.5.1 Predictive Modeling Some existing cloud models can be initialized with local conditions (a sounding) and run quickly enough that the output can be useful in field programs. In two North Dakota field programs (Boe et al. 1992; Boe 1994), a two-dimensional, time-dependent (2D-TD) cloud model was initialized daily with the atmospheric data collected by the balloon-borne sounding made locally by the NWS at 7:00 a.m. local time. The model was then "run" on a Cray supercomputer at the NCAR in Boulder, Colorado, and the resulting predictions for the day's weather were downloaded in time for the daily 11:00 a.m. local time project weather briefing (Kopp and Orville 1994). The scale of cloud development (if any) and the timing of the onset of convection were both predicted and presented to the researchers gathered for the morning weather briefing as part of the routine forecast. Fig. 4-13 shows one aspect of model performance in a predictive mode. Computers also are being used to model airflow in complex terrain (e.g., Stone 1998). Such models can be helpful in planning the placement of ground-based aerosol generators.

4.4.5.2 Diagnostic Modeling Cloud-scale computer models also can be used post hoc to examine the evolution of observed cloud systems. Such models use knowledge of various cloud processes, both dynamic and microphysical, to simulate cloud development. A good indicator of the validity (accuracy) of such cloud models is how well they replicate the actual cloud systems observed, given the best knowledge of initial environmental conditions. Cloud models are helpful in evaluating observed cloud behaviors, including the effects of treatment,

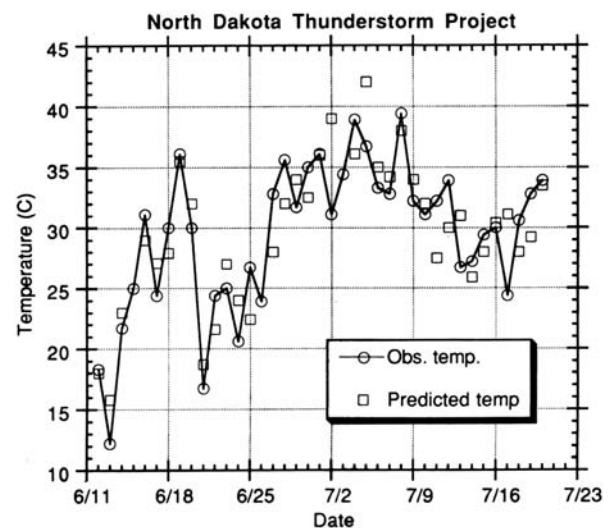


FIGURE 4-13 The observed maximum temperature for each day of the North Dakota Thunderstorm Project and the corresponding model-predicted temperature

Source: Kopp and Orville (1994); reproduced with permission of American Meteorological Society.

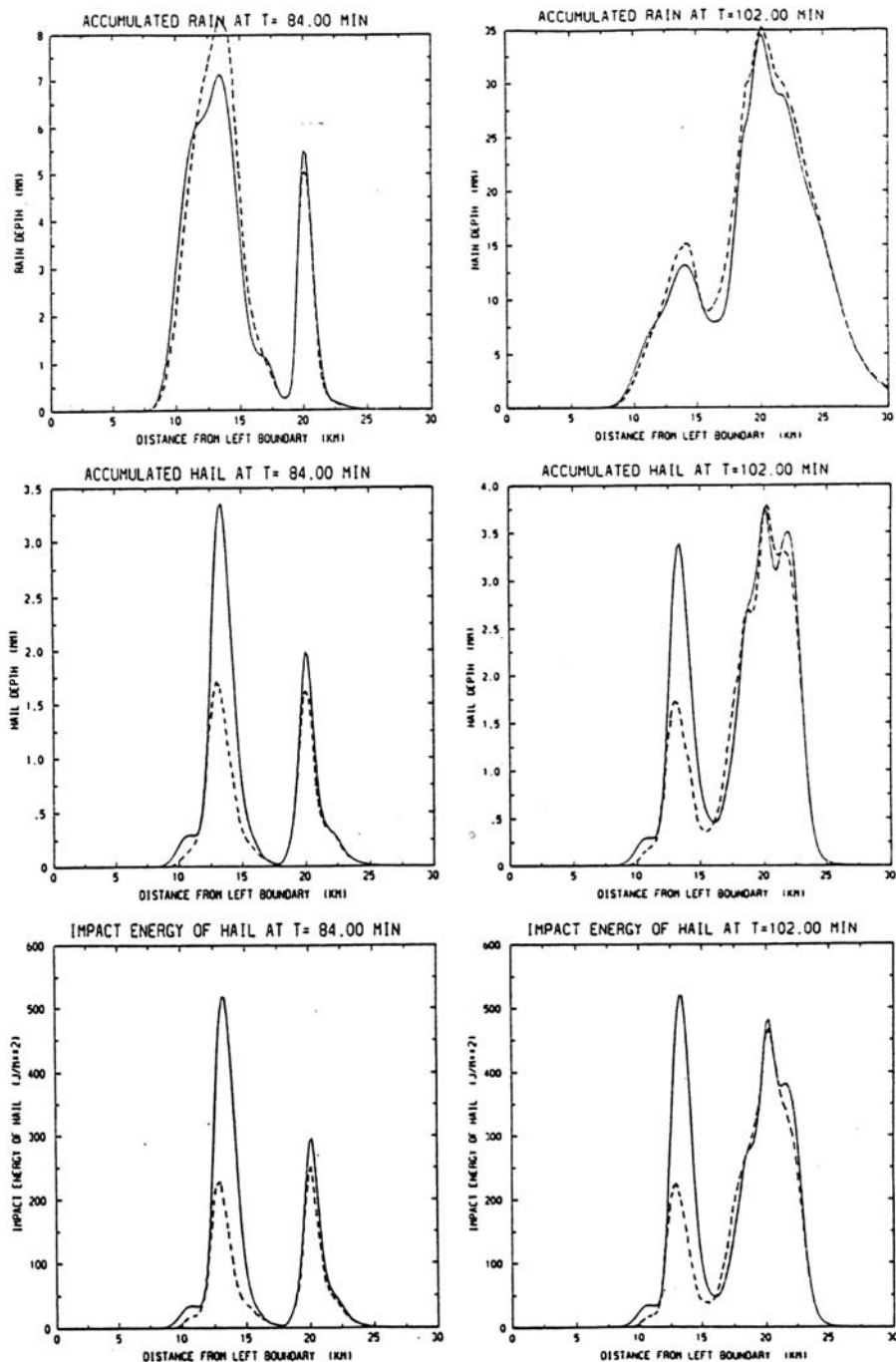


FIGURE 4-14 Hail impact energy for the same storm, seeded (dashed) and unseeded (solid) as predicted by an analytical cloud model
Source: Farley et al. (1996); reproduced with permission from R. D. Farley.

and often yield insight into processes not previously understood (e.g., Farley and Orville 1999). As computational capabilities increase, numerical models have evolved incorporating greater complexity and higher temporal and spatial resolution. Much of the recent modeling, with respect to hail and hailstorms, has focused on improvements in cloud microphysical schemes (Milbrandt and Yau 2005a, 2005b, 2006a, 2006b; Khain and Lynn 2009; Noppel et al. 2010; Khain et al. 2011).

Because no two clouds are exactly the same, it is impossible to find two identical clouds, seed one, and leave the other untreated

as a control. However, the effects of seeding can be examined by modeling two clouds that begin with identical initial conditions and simulating seeding in one but not the other. Any differences in behavior can then be attributed to the seeding. In fact, this option is attractive because the timing (relative to the life cycle of the subject cloud), locations, and amounts of seeding can be varied in a succession of model runs to better understand the importance and effects of targeting. Of course, caution must be used in drawing conclusions based on the modeling of only single cases. Output from such a diagnostic model run is shown in Fig. 4-14.

4.5 SELECTION AND SITING OF EQUIPMENT

The optimum siting of equipment is critically important to the success of any program. Whether aircraft, ground-based generators, rockets, or artillery, the deployment of these facilities relative to the target area must be carefully planned. Response time and expense should be minimized. Safety, ease of access, and convenience should be maximized for project personnel.

Once the seeding methodology has been determined (see Sections 4.2 and 4.3), the local storm climatology, based on radar data if records are available, and the available funding usually determine what equipment is deployed. For example, if three seeding aircraft can effectively treat as many thunderstorms as usually develop at one time, and funds are available to deploy three aircraft, the project should plan to deploy three aircraft. It is likely that an unusual number of storms will occasionally develop. When this occurs, three aircraft might not be enough. Nevertheless, four aircraft would not be deployed (in this example) because the additional cost does not warrant deployment of facilities that would be largely unused. This consideration drives the deployment of all facilities, whether they are aircraft, ground generators, or rocket launchers.

Section 4.5.1.1 covers in situ cloud measurements.

4.5.1 Aircraft Considerations Aircraft used in cloud treatment operations in or around thunderstorms should possess certain minimum performance characteristics to satisfy operational and flight safety requirements. Light, single-engine aircraft are used on some projects primarily because of their modest operating costs. However, many projects operate twin-engine aircraft in the belief that if one engine malfunctions, the aircraft can still return under power to a nearby airport. Unpowered, forced landings (especially in the dark) in the vicinity of thunderstorms, are dangerous.

For direct injection at the tops of growing supercooled clouds, some operations use turboprop or small twin-engine jet aircraft. Piston-driven aircraft can perform satisfactorily at cloud top, but they are slower and have lower rates of climb, requiring a greater initial response time. Although pressurization of the aircraft cabin is not required if oxygen is available to the top-seeding flight crews, it is desirable. Oxygen masks are not needed, and the greater comfort reduces crew stress.

Aircraft types proposed for cloud base and/or penetration seeding of cumulus turrets should be examined carefully, and their relative performance specifications should be weighed in consideration of the operational design. Program or project sponsors may choose to require demonstrations of aircraft performance as a condition of the contract award to ensure that the aircraft are capable of performing as offered. Sponsors also may wish to review the aircraft maintenance history.

When aircraft are to be used for hail suppression seeding operations, close coordination is necessary between those directing operations and the flight crews. Since flight crews benefit from being able to view the project radar and visit with project forecasters before undertaking operations, it is desirable to base at least a portion of the project aircraft fleet at an airport near the project radar. However, advancements in communications technology and the ready access to weather information via the Internet may make it possible for some project personnel to monitor the project radar imagery from off site. If pilots can see the radar depiction of the developing storm complex before they are dispatched to intercept it, they have a better grasp of the situation and are more certain in their actions. When target areas are large, aircraft should be based at several airports within or near the target. Pilots who do not have access to real-time radar

information should be provided quality preflight weather briefings by the project meteorologist. Of course, all airports must have ready supplies of fuel, adequate runways, and navigation aids. Maintenance services are not strictly required but are desirable.

4.5.1.1 In Situ Cloud Measurements In situ cloud measurements are those obtained by entering the place to be measured; they are helpful in quantifying real-time cloud conditions, including updraft, ice content, liquid water content, and temperature. In hail suppression programs using aircraft for delivery of the seeding agents within the cloud top, in situ measurement can be accomplished by instrumenting the seeding aircraft. The flight crew then knows as they penetrate the potential target turrets how suitable for treatment such turrets are. The additional expense is not excessive, and the information gained is most helpful. In addition, the data are available for postanalysis if efforts are made to refine and improve treatment procedures, which is strongly encouraged.

All instruments must be calibrated against laboratory primary standards before and after each field use. During field use, calibration can be achieved either by flight past calibrated instruments on a tower or by flight close to other aircraft that have well-calibrated instrumentation. Some instruments, such as those for measuring cloud water content, can be accurately calibrated only by operation of the instrument in a carefully controlled environment, such as a wind tunnel, in which varying concentrations of liquid water are established.

4.5.1.2 Cloud Ice Content It is important to know, at least in a relative sense, how much ice is present within the cloud under consideration for treatment. Without instrumentation designed for this specific task, the flight crew is reduced to visual observation while in clouds, perhaps augmented by the audible “click” of graupel or hail as it hits the windshield. Instrumentation tailored to this purpose ranges from simple ice particle counters to more sophisticated optical array instruments, such as those manufactured by the Colorado-based Droplet Measurement Technologies (DMT), or older instruments such as the one- and two-dimensional cloud and precipitation probes from the Colorado-based Particle Measuring Systems (Knollenberg 1970, 1976, 1981; Fig. 4-15), which can provide hydrometeor spectra data (numbers and sizes of hydrometeors). The latter cannot be used without implementation of on-board computers to process, display, and archive the data. Cloud particle imaging equipment is now available that offers remarkably clear images of hydrometeors (e.g., Korolev et al. 1999). Another relatively new instrument, the high-volume precipitation spectrometer, has greatly improved the statistics of precipitation particle sampling (Lawson et al. 2001).

4.5.1.3 Cloud Water Content For glaciogenic seeding to be effective, the subject cloud must contain supercooled liquid water (see Section 4.5.1.4). For quantification of the cloud water content, several options are available. Without instrumentation, the flight crew usually can gain a reasonable qualitative feel for cloud water content just by observing the rate of ice accretion on the leading edges of the airframe and windshield. If more quantitative measurements are desired, for example, instrumentation ranging from simple hot-wire sensors, such as the DMT hot-wire cloud water sensor, the CSIRO-King probe, the forward-scattering spectrometer probe (FSSP), or the cloud, aerosol, and precipitation spectrometer (CAPS), could be used. The FSSP and the CAPS record the cloud droplet spectrum itself, which is useful information when hygroscopic seeding is being conducted or considered.

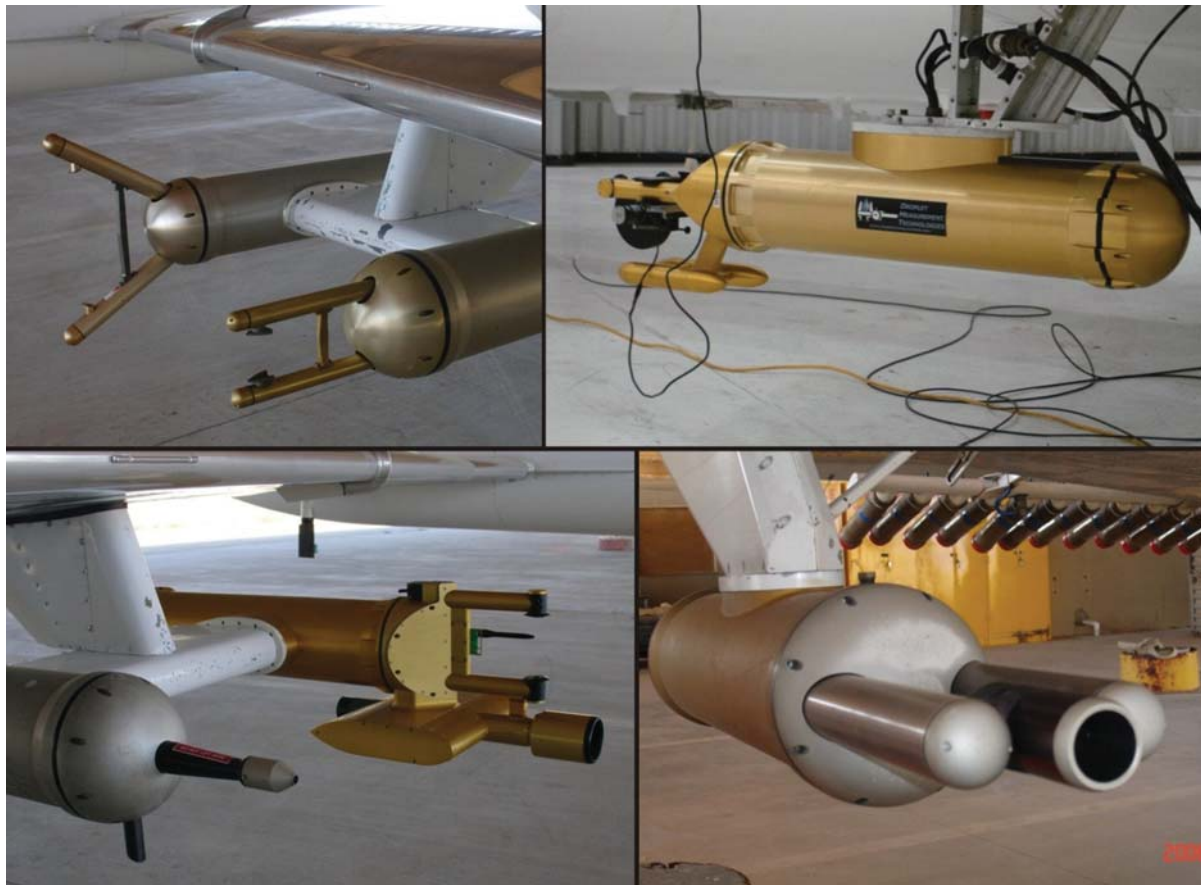


FIGURE 4-15 External airborne instrumentation. Some of the many available cloud and aerosol instruments are shown. Two-dimensional imaging of cloud- and precipitation-sized hydrometeors is possible with the 2D-P and 2D-C probes (upper left), as well as the CAPS (lower left, on right), and the cloud combination probe (CCP) (upper right). Cloud droplets are measured by the FSSP (lower right), and also the CCP (upper right). Undifferentiated aerosols can be measured with a passive cavity aerosol spectrometer probe (PCASP) (lower left, on left)

Source: Courtesy of Todd M. Schulz and Bruce A. Boe.

4.5.1.4 Temperature Temperature must be known to determine the degree of supercooling. Simple outside air sensors are effective when the aircraft is flying in clear air. Accurate sensing of temperature during flight within cloud becomes more difficult. This is because cloud droplets first wet, then evaporate from the sensing surface, resulting in evaporative cooling. Temperature sensors that use an aerodynamically induced reverse flow effectively avoid this problem by sampling air taken in from an aperture located on the instrument's downwind side. The "reversing" of the flow is possible only for the air itself; the cloud droplets are too massive and cannot change direction fast enough to make the turn into the sensor, and they therefore pass on beyond the instrument. Such instruments provide for improved in-cloud temperature measurement, without the effects of evaporative cooling. The locations of these instruments on the airframe are also extremely important. Care needs to be taken to avoid placement in locations where changes in aircraft attitude can result in erroneous measurements.

4.5.2 Placement of Ground Generators The number of ground-based ice nuclei generators required for hail suppression operations varies depending upon target size, topography, and the nature of the prevailing wind regimes. The nuclei produced by the generators can reach the growing cloud systems in two ways:

1. By convective currents (thermals) produced by surface heating, or
2. By lift provided by flow over the topography in cases where mountains are present and local winds are favorable.

Project planners should study the project area climatology to ascertain which of these, if either, is likely to be the primary vertical transport mechanism. The time required for transport from the surface to cloud base altitude varies considerably depending upon the vigor of the convection, from as little as 15 min to as much as several hours. Therefore, generators must be activated before anticipated storm development. This requirement underscores the importance of accurate forecasting. Targeting a fixed area with ground-based generators requires a portion of the generator network to be deployed upwind of the target, which means placement of generators outside the target area on several sides, to account for all common upwind flow regimes. Surface winds tend to converge into areas where new convective development is occurring, so operating generators 15 to 25 km (9.3–15.5 mi) upwind of vigorous storms can be useful (Dessens 1998; Fig. 4-8).

Although it has been shown that transport of surface-based seeding agent releases to convective cloud base can be accomplished (Heimbach and Stone 1984; Dessens et al. 2006), this should not be taken for granted. Seeding should be done over

large areas and extended time intervals because releases drift with the environmental winds. Individual clouds are generally not targeted.

4.5.3 Placement of Rocket Launchers or Artillery The greatest advantage of treatment via rocket or artillery is the potential for extremely small response time if they are positioned within range of the target cloud(s). Sites are normally fixed (nonmobile), so given the relatively short ranges of most rockets and artillery (up to 12 km, or 7.5 mi), many sites are required to ensure coverage of most target areas. Launch sites can be determined by drawing circles of the same scale as the maximum range of the rockets or artillery and moving the circles around on a map of the proposed target area until the desired coverage is achieved.

4.6 LEGAL ISSUES

The legal aspects of cloud seeding relate to regulation by law and to the possibility of litigation by people who feel that they have been or would be harmed by such activities. Environmental concerns are discussed in Section 4.7. The legal considerations for hail suppression are essentially the same as those set forth for precipitation augmentation operations (AU: Based on reference deletion, Text citation of "Davis 1995" RemovedBomar 2006).

4.6.1 Potential for Litigation Project sponsors should address the potential for lawsuits, even if no unusual weather occurs during the project period. Sponsors should require contractors who provide weather modification services to obtain liability insurance covering the effects of operations. This special insurance is termed "consequential loss insurance" and is not normally a part of ordinary liability insurance. If insurance is infeasible or prohibitively expensive, sponsors should consider the level to which contractors may be self-insured. Since severe storms are being dealt with in hail suppression operations, concerns relating to public safety and well-being may be heightened. Perhaps the greatest concern is that, for whatever reason, seeding might be perceived to produce more or larger hail or excessive rains. This scenario is the primary reason that project sponsors and operators should carry consequential loss liability insurance covering the effects of weather modification. Since the burden of proof rests with the plaintiff, proving any such claim is unlikely.

Another concern relates to the treatment of tornadic or funnel-bearing clouds. A suspension policy should be in place governing seeding practice in case of such an event. Decisions not to seed tornadic or funnel-bearing clouds arise from concern about project personnel safety, public perception, and possibly even litigation. With the wide variety of laws, rules, and regulations among various states and countries, it is impossible to make a blanket recommendation on a specific course of action. It is recommended, however, that the responsible entities create a suspension policy that addresses these concerns and draws on information and expertise from other pertinent agencies. For example, the regulatory entity in the state of North Dakota has taken the position that such storms are not to be seeded, even though they may pose a significant risk of hail (Langerud et al. 2010).

4.6.2 Regulation Most locales have some regulatory agency responsible for the enforcement of laws or ordinances relating to the conduct of cloud seeding operations. In the United States, Public Law 92-205 requires that all cloud seeding operations be reported to NOAA. Under this law, initial reports must be submitted that describe the geographic location of operations, the proposed dates of operations, and the seeding agent(s) to be used. A file number is assigned to each project in the United

States. Upon conclusion of the project, a final report must be submitted that summarizes the dates of operations, as well as the quantities of seeding agent(s) dispensed. Interim reports may be required. Failure to file these reports within 45 days of the conclusion of the project is punishable by a fine up to \$10,000.

Many states have promulgated laws, rules, and regulations that establish the process through which proposed projects must be approved. Usually these processes require that the people who conduct the operations become licensed in that state. Licensure considers the credentials, character, and experience of the project manager(s) but not specific projects. Typically, a permit also must be obtained for each specific project area. Thus, both a license and a permit are usually required before operations can be conducted. It is essential that projects comply with local, state/provincial, and federal laws, so project designers must identify all relevant laws and regulations early in the process.

ASCE (2003b) has the Regulated Riparian Model Water Code (ASCE 40-03), which includes atmospheric water management, and the EWRI Committee Report on Appropriate Rights Model Water Code (Dellapenna 2007) deals with similar articles. Also AU: Based on reference deletion, Text citation of "Davis (1995)" RemovedBomar (2006) recommend the same type of regulations.

4.7 ENVIRONMENTAL CONCERNS

It is incumbent upon the project designers to fully address the potential effects of seeding operations upon the environment. Many research programs have included investigation of the potential for environmental impacts from seeding agents. These studies began in the 1970s and mostly concluded in the 1980s. The results from these studies concluded that "the major environmental concerns about nucleating agents (effects on plant growth, game animals, fish, etc.) appear to represent negligible environmental hazards" (Klein 1978).

In the past several decades, numerous projects have conducted environmental assessments or prepared environmental impact statements without any adverse findings. In some locations, however, such assessment may be required by local, state, or federal law; in others, none may be formally required. Even when the latter is the case, the types of seeding agent to be used, and estimates of the quantities to be used, have served as the basis for a simple environmental assessment. The amounts of seeding agent used are not large, and the agent is dispersed over a wide area over a period of many days. Thus concentrations of the material introduced into the environment are quite low. Even the most active programs disperse seeding agents at rates too low to be readily detected by conventional analytical chemistry equipment, but this exercise is worthwhile because it is reassuring to area residents.

The two most frequent environmental quality issues are the potential for undesired effects to result from seeding and the possible toxicity of the seeding agent(s). The first of these relates to concerns about excessive or insufficient precipitation. The latter arises because silver iodide complexes, the most common of the glaciogenic agents, are sometimes dispensed over large areas for many seasons and consequently raise questions about potential environmental impact (Reinking 1995; Keyes 2006) of the accumulating material. Neither issue has ever been found to pose a substantive problem, however.

Still, each project may find it helpful to assess the possible short-term and long-term (cumulative) effects of additional silver and/or iodine in the air, water, and soil. In addition, other materials are now being used with increasing frequency in pyrotechnic compositions and seeding solution formulations. Also, trace metal impurities are associated with major

components of the aerosols produced by individual combusted pyrotechnic compositions or solution formulations. Thus, their compositions should be reviewed on the basis of environmental impact, with respect to the threshold toxicity limit and any local “hazardous materials” restrictions or the like.

4.7.1 Redistribution of Precipitation Most current evidence indicates slight net increases in precipitation both within and downwind of hail suppression project areas. Nevertheless, plans should be made to collect data sufficient to evaluate this aspect of the program. Chapter 6, which presents some evaluation concepts, offers further guidance in this regard.

4.7.2 Seeding Agent Safety Material safety data sheets (MSDSs), which are required by law, provide the user with specific information about the proper handling and use of these materials. Most cloud seeding agents are not considered hazardous. Exceptions include those that are readily combustible, such as pyrotechnic devices and acetone solutions (see Section 5.5). The proper procedures for the handling and storage of hazardous materials of all kinds are thoroughly prescribed by local, state, and federal laws and are the responsibility of the contractor or agencies actually in charge of the operations.

Acetone is also regulated in the United States under the Chemical Diversion and Trafficking Act of 1988, which mandates requirements for sales of precursor chemicals that may be

used in the production of illicit drugs. Customers who wish to purchase acetone for cloud seeding purposes must work with their vendors to comply with these regulations.

Only specialized facilities that use the most sensitive analytical chemistry techniques are readily capable of detecting seeding material on a regular basis. Analytical techniques exist for the detection of silver and other trace metals from air filters, precipitation, and soil sediment samples at parts per billion concentration levels (1.0×10^{-12} g [0.4×10^{-14} oz] of AgI mL⁻¹) or lower (Warburton et al. 1982). If the possibility for residual effects of seeding agents becomes an issue, well-established procedures are available for addressing it.

Hail suppression programs are generally designed to be carried out over a period of many years, and the accumulating quantity of seeding agent dispersed can become significant. To give an example, in southern France an ongoing hail suppression project covers a target area of 40,000 km² (15,400 mi²) and uses thousands of kilograms of AgI annually (Dessens 1998). This makes it recommendable, especially for long-term projects, to introduce some means of environmental evaluation. This provision is primarily for social and client reassurance; Klein (1978) has shown that the quantities of AgI released in projects such as this scarcely increase or contribute significantly to the concentrations of atmospheric Ag caused by other human activity.

CHAPTER 5

CONDUCT OF OPERATIONAL HAIL SUPPRESSION PROJECTS

Those conducting hail suppression operations should be vigilant and always prepared to react when potential hailstorms begin to develop. In this chapter, some guidance is provided for project infrastructure and operational decision making. In addition, guidance is offered regarding the operations manual; personnel requirements; operational decision making; communications; safety considerations; and public relations, information, and involvement.

5.1 THE OPERATIONS MANUAL

An operations manual should be prepared to guide the conduct of the hail suppression operations (Schock et al. 1976; Langerud et al. 2010). The operations manual should furnish clear definitions of all terms used in conducting operations, describe the types and functions of all information-gathering systems used and all actions to be undertaken, define all phases of operations, and state criteria for initiation and termination of each phase. Procedures for recording and reporting operational information should be given, particularly to comply with any relevant weather modification laws or regulations. The circumstances under which seeding is to be suspended also should be clearly defined so that prompt decisions can be made when circumstances warrant. Sections 5.2 through 5.6 describe other issues that should be addressed in the operations manual.

New program directors are advised to obtain copies of manuals used on other established projects and use them as guidance for form and content. Although they are not specific to the new project, the manuals can provide an idea about the necessary organizational infrastructure. Commercial cloud seeding firms can usually provide samples of manuals used on their other projects; this is a great first step in creating a new, project-specific manual.

5.2 PERSONNEL REQUIREMENTS

National, state, and local laws should be consulted to determine whether personnel in control of operations are required to be certified. Many of the duties required of operational hail suppression personnel require special knowledge and skills. The state in which operations are planned should be contacted. Some of the specific skills required of various project personnel are discussed in this section. The Weather Modification Association (WMA) has established processes for the certification of weather modification operators and managers (www.weathermodification.org/certifications.php).

5.2.1 Meteorological Staff At least one meteorologist with experience in forecasting of convective weather should be part of every operation. This requirement would ensure an adequate understanding and prompt interpretation of all meteorological

information flowing into the radar-equipped operations center from which operations are directed. An experienced project meteorologist can produce forecasts tailored to the local situation and needs and might also function as a radar operator and/or operations director. Larger projects, particularly those that are meant to conduct operations 24 hours a day, 7 days a week, must retain sufficient meteorological staff to support around-the-clock operations. Meteorological duties may include forecasting and nowcasting, radar operation, data acquisition, and, often, the direction of seeding operations. How these tasks are assigned depends on the project. If project staffing provides for more than one meteorologist and treatment is done by aircraft, it is strongly recommended that any project meteorologist not directing operations occasionally fly aboard seeding aircraft. This experience provides the meteorologist with firsthand knowledge of flight conditions aloft and an understanding of the pilot's perspective of storm development.

Operations that involve some form of direct targeting are usually directed from the project radar by a person experienced with hail suppression and radar operations. This individual, the operations director, may or may not have responsibility for operation of the radar itself. At the project radar equipment, which may be operated by another field meteorologist, any information important to decision making should be available to the field operations director. Such decisions typically concern such things as the launching of aircraft or rockets, ignition of ground-based silver iodide generators, and the termination of operations.

Communications are of paramount importance when running hail suppression operations. Radio contact must be maintained between aircraft and the radar center. Cellular telephones and/or pagers can be useful in maintaining contact with personnel in the field. Communications among the operations center, the ground-based generator, and/or the rocket-launching sites usually can be accomplished by similar means.

The operations director is usually the individual accorded the responsibility for the assignment of daily operational status to project personnel and for initiation and suspension of seeding. Typical status categories include "weather watch," when no workable clouds are forecast in the short term; "standby," when suitable clouds are forecast to develop some time in the next few hours; and "alert," when development is either occurring or thought to be imminent.

5.2.2 Cloud Treatment Pilots Hail suppression projects that use aircraft for cloud treatment should be concerned that licensed, instrument flight rules (IFR)-rated pilots be well trained and have experience flying close to thunderstorms. This flying can be done safely only if the pilot has the knowledge and experience to avoid dangerous situations.

Projects that deliver seeding agents by aircraft ensure the most certain, direct, and economical use of seeding agents. However, because the pilots are such a critical link in the delivery, every effort should be made to ensure that they are well trained for the task. The pilots hired should either have experience seeding thunderstorms or should receive adequate preproject training, preferably the former. Arrangements can sometimes be made for new pilots to fly with experienced pilots on other projects, or they could be sent to the University of North Dakota for formal instruction in weather modification flight.

5.2.3 Support Personnel All types of hail suppression operations require personnel to maintain and operate equipment or make observations. Technical requirements are high for people maintaining radar or other electronic and computing equipment; an engineer or skilled technician may be required. Less skilled persons can be used for many other tasks, such as maintaining ground-based silver iodide generators and passive hail sensors (hail pads). Other workers are needed to deliver seeding agents to field sites, activate and deactivate ground-based generators, and complete and track project paperwork.

Training needs vary for workers employed to load and ready rocket launchers, depending upon the type of rocket-based seeding system used. Those preparing launchers controlled from the operations center require less skill than those who receive launching instructions verbally because the latter must load, aim, and fire the rockets; the former is targeted and fired by computer control.

5.3 OPERATIONAL DECISION MAKING

Close coordination is required between the operations director, who determines when to start and stop seeding, and the seeders, who actually dispense the seeding agent. Whereas the field

meteorologists, led by the operations director, normally work from the operations center, which may include the project radar, the seeders may be waiting at airports or within their aircraft, or at remote generator or rocket-launching sites. The relationships among the various project personnel are illustrated in Fig. 5-1.

5.3.1 Chronology Most projects begin each operational period, usually defined as a calendar day, with a weather briefing, wherein project staff are informed by the forecaster of the likelihood of clouds that meet the criteria for seeding as set forth in the operations manual. If such conditions already exist at the time of the scheduled briefing, operations are already underway. However, the forecast is still given so that the personnel have some idea as to what weather situation to expect and how long they may be expected to continue operations. After the weather briefing (if operations are not under way), duty assignments for the day are made by the operations director.

The balance of the operational period is then spent waiting for clouds presenting a hail threat to the target area to develop or for operations to be called “down” for the day. Because forecasting is an imprecise science, most operational programs, especially those that conduct operations around the clock, never formally excuse operational personnel from their assigned duties for fear of missing unforecast hail threats. Projects anticipating frequent long periods (say, 12 h) of continuous operations should consider retaining sufficient staff for multiple shifts to ensure that all on duty are adequately rested.

Once operations begin, staff are engaged accordingly. If no threatening clouds develop, the operations director, after consulting with the forecaster, can at some point downgrade the operational status so that personnel are less restricted. For example, if cloud development is initially thought likely, project personnel should be placed on “alert” and thus be compelled to

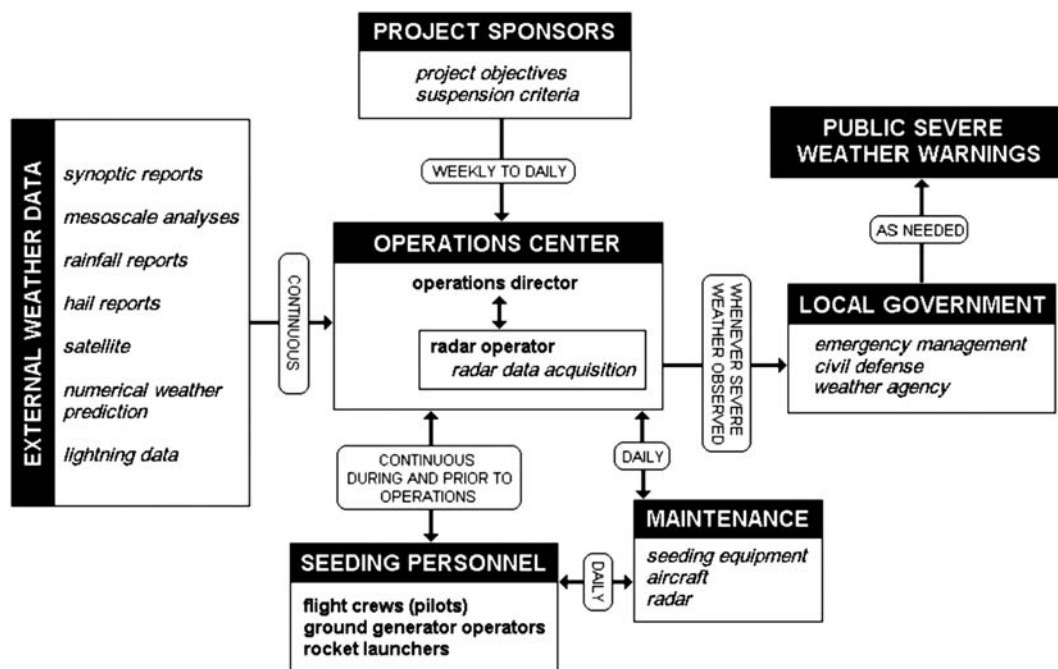


FIGURE 5-1 The interrelationships of project personnel on a typical hail suppression program. The decisions to begin and end operations are made by the operations director (often located at the project radar), in accordance with project objectives and suspension criteria

Source: ASCE (2003a).

remain at or near their operations stations. If at a later time, the forecaster determines that cloud development is no longer likely, personnel should be given a status of “standby” or less. The lower status allows them the flexibility to do other things, such as paperwork or simple maintenance chores. The whole cycle repeats the following day.

Invariably, some project days clearly lack the degree of atmospheric instability necessary for the development of strong thunderstorms. When such days are identified, complex maintenance and other tasks that require personnel to be away from their duty stations can be accomplished.

5.3.2 Opportunity Recognition Simply releasing seeding agents when thunderstorms are present does not ensure that the seeding agent will reach the targeted cloud turrets and produce the desired result. This statement applies to all treatment methods, unless the seeding agent is released directly in the location of interest. Otherwise, some assumptions must be made about the likely trajectories of the seeding material. In any case, it is useful for those directing operations to know, with as much certainty as possible, which clouds have been seeded. The degree of uncertainty varies considerably, depending upon the treatment method.

The best tools for recognizing hail suppression opportunities are human eyes, well-calibrated radar, real-time satellite imagery, and lightning detection systems, in that order. A skilled forecaster can help a great deal by alerting project personnel when storms are most likely to develop.

5.3.2.1 Aircraft Flight Crews When using aircraft for hail suppression seeding operations, close coordination is necessary between the radar operator/operations director and the flight crews. Flight crews and meteorologists alike should remember that the seedable cloud candidate is not the mature storm but rather the developing cloud turrets on the flank of the mature storm. If no mature storm has yet developed, the candidate is the most vigorous of the developing towering cumulus in the cloud field. The preferred candidates are largely ice-free but supercooled, so cloud-top temperatures between -5°C and -10°C (23°F and 14°F) are most desirable when seeding is done by direct injection at or near cloud-top altitude. If treatment is done from cloud base, release of ice-nucleating aerosols can begin in the updrafts beneath even smaller (younger) clouds because several minutes are required for the aerosol to be transported aloft to supercooled cloud.

The exact positioning of the treatment is usually based on the judgment of the pilots, based on visual clues and experience. The operations director should keep the crews aware of any severe weather signatures, warnings, and the synoptic and mesoscale weather situation. Conversely, the pilots will see developing clouds before they become detectable by the radar. In general, cloud turrets that produce radar echoes have already produced significant ice and are no longer seedable. Therefore, radar rarely reveals the locations of treatable cells themselves, only the parent storm complexes.

5.3.2.2 Treatment by Ground-Based Generators When ground-based generators are activated, the aerosol is produced at the surface and has to be transported to the target clouds. Convective air currents (thermals), perhaps coupled with orographic uplift (from mountains), are relied upon to carry the aerosol aloft, where it can be ingested by the growing clouds. Since the thermal that generates the cloud itself is often surface-based, it is logical that seeding agent would also reach the cloud, if the agent is present when the thermal develops.

However, the aerosol must be generated and then dispersed in the boundary layer before the cloud first develops, so seeding should begin well in advance of storm development. The key to operating a ground-based ice nucleus generator network is then the successful prediction of storm development in and near the target area. Because forecasting the time of initial cloud development is difficult, most projects elect to activate ground-based generators up to several hours before cloud development is thought likely. Because forecasts are fallible, there are times when the generator network is activated but storms do not develop.

Seeding with ground-based generators becomes less certain when mature storms move into target areas. Stronger storm updrafts may account for most of the vertical transport of the seeding agent, and seeding the main updraft is not thought to be effective (see Chapter 2). In addition, nocturnal storms often draw water vapor from a layer aloft, and not directly from the surface. In such cases, ground-generated aerosols can simply “pool” near the surface and never reach the developing cloud turrets.

It also should be recognized that, under some circumstances, seeding by aircraft is not possible because low cloud bases and/or low visibilities render aircraft operations unsafe. In such cases, seeding with ground-based generators affords the best avenue for getting seeding agent to the desired clouds.

5.3.2.3 Treatment by Rocket or Artillery Rockets and artillery clearly provide the fastest means of getting seeding agent to target clouds. Delivery is “point and shoot,” with the rocket or shell reaching its destination within moments. Opportunity recognition for programs that use these seeding systems is similar to that in aircraft-based projects, except that all observers are on the ground, so none have the advantage of the view from aloft. As mentioned previously, rockets and artillery have limited ranges, most no more than 12 km (7.5 mi), so many launch sites are needed. The operational infrastructure must provide for the identification of the site in best position and establish the means by which the targeting information is to be transmitted. Some rocket-based seeding systems are computer-controlled, eliminating the need for an operator to position the launcher and fire the rockets.

The difficulty with seeding by rocket is that the target clouds are not detectable by radar systems of the type typically used by operational programs and, therefore, are not depicted by radar. Adjacent mature thunderstorm cells usually are detected, but their locations provide only general guidance as to where the developing turrets are located. If cloud turrets are developing 10 km (6.2 mi) from a launching site and intervening cloudiness prevents visual targeting, the correct targeting of any rockets or artillery shells fired from that site is really only by chance.

Thus, there is some uncertainty as to precisely where the ordnance should be aimed, even when suitable storms have been identified. Targeting is perhaps more certain than with ground-based generators, but still less certain than with aircraft.

5.4 COMMUNICATIONS

Communications channels among project personnel, project sponsors, and local weather officials should be open and available at all times. The most common avenues for communications are conventional telephone, cellular telephone, and two-way radio. Project personnel might also consider carrying pagers that tell them to “phone in” for further information.

However, it is just as important that project personnel know whom to contact in any given situation, as well as how to reach

them. In addition to routine operational communications (e.g., which aircraft is to launch), there are also matters of a more urgent nature, such as the need to suspend operations because of a perceived public hazard or the observation of tornadic circulations. In such cases, those who need to know should be notified immediately, without delay. Where operationally possible, sharing of real-time information with local government weather offices (e.g., NWS weather forecast offices) is encouraged. It also is important that provisions be made to document all operational decisions so that, if the need ever arises, the timeliness of actions taken in the course of operations can be established.

Many programs have found that the additional severe-weather-spotting capability afforded by their radar systems and project personnel is well received by the local population and appreciated by the weather offices as well. In the event that a project is based some distance from official government weather radar systems or observing sites, the project sponsor could notify the appropriate local civil defense entity (e.g., sheriff's department, emergency management agency, or police department) of the project and invite them to visit and/or contact the operations center whenever they see fit.

5.5 SAFETY CONSIDERATIONS

Policies and procedures that ensure public safety and environmental integrity should be implemented. Persons of many different skills and abilities are required to accomplish this level of safety. Many times, expertise can be drawn from beyond the project by consulting local experts. For example, knowledge of local topography and climatology is often available through the National Weather Service. In all phases, safety should be highest on the list of priorities.

5.5.1 Safety of Field Personnel There are many potential hazards associated with hail suppression operations. These include microwave (radar) radiation; flammable and/or explosive chemicals, oxidizers, and solutions; lightning and other severe weather; and aircraft propellers. In addition, operations often continue for extended periods, tiring personnel and increasing the risk of accident.

5.5.1.1 Radar Safety Radar systems transmit microwave radiation and so can pose a significant health risk if left radiating in a fixed position at a low-elevation angle for an extended period. Radar systems should be equipped with safety switches so that technicians can effectively disable the set when working on or near the antenna or on the transmitter or receiver. Such "lock-out, tag-out" procedures safeguard the technicians and ensure that the radar is not accidentally damaged by power being applied when it should not be.

5.5.1.2 Use, Handling, and Storage of Seeding Agents All personnel who work with or near seeding agents should be provided with material safety data sheets (MSDSs) regarding each of the seeding agents so that they are fully aware of all proper and safe handling and storage requirements, as well as the potential hazards. Some chemicals used in seeding formulations, such as AgI, are not combustible in raw form and pose no fire or explosive threat. On the other hand, oxidizers such as sodium perchlorate burn vigorously at very high temperatures if ignited and may explode in confined containers. These must be stored only in approved, appropriately labeled containers, in suitable locations. Pyrotechnic devices used for cloud seeding, such as burn-in-place and ejectable flares, are officially classified as Class 1.4S explosives (the same as most fireworks), and they

must be labeled, handled, and shipped accordingly. It is illegal to ship any amount of Class 1.4S explosive on any passenger aircraft.

Liquid seeding solutions are primarily acetone-based. This highly volatile chemical poses a significant fire risk, is of low viscosity (splashes easily), and produces potentially toxic vapors. Acetone solutions must be prepared and dispensed only by trained personnel equipped with rubber gloves and protective eyewear. Eyewash stations should be provided to field sites where the solution is handled. When handled outdoors or in a large space (an aircraft hangar, for example), the vapors do not become concentrated to hazardous levels.

Dry ice is solid carbon dioxide and has an unventilated surface temperature of -78°C (-109°F). If allowed to come in contact with bare skin, freezing or severe frostbite can result in an extremely short time. Dry ice, therefore, should be handled, sifted, and loaded into seeding equipment only by persons wearing insulated gloves. Personnel also should be made aware that dry ice sublimates continuously at normal atmospheric pressures and temperatures and therefore displaces the oxygen needed to sustain life. This phenomenon can cause hyperventilation in people and animals. Personnel should never transport dry ice within the passenger compartment of any vehicle, and all dry ice dispensing equipment on board an aircraft must be vented to the outside only.

5.5.1.3 Severe Weather Hazards Hailstorms are thunderstorms. This means that each of them is capable of producing deadly lightning. Lightning is a potential hazard primarily to those on the ground, especially those working outdoors. In general, if you can hear thunder, there is some risk of cloud-to-ground lightning at your location. The nature of hail suppression operations that use aircraft is that, on occasion, there are circumstances when personnel are refueling or rearming seeding aircraft as a thunderstorm is bearing down on an airport or as a storm is departing the vicinity. Both are high-risk situations in which the flight crew (and any others assisting on the ground) must place safety first and delay until the storm has moved safely away. It may not take a lightning discharge to cause a tragedy, for even a static discharge at the wrong place during refueling could cause loss of aircraft and life. Since many lightning-strike victims are not killed outright, it is a good idea to provide personnel with cardiopulmonary resuscitation (CPR) training, which could prove invaluable in many other circumstances as well. The other significant weather hazard to which personnel are often subjected is strong thunderstorm winds, which are especially dangerous to flight crews during takeoff and landing. Flight crews must resist the temptation to "beat a storm" by taking off immediately in advance of gust fronts, and operations directors should further discourage such practices.

5.5.1.4 Aircraft Safety The specifics of aircraft safety during flight operations are not addressed herein because pilots trained in seeding operations are already cognizant of how to do so safely. However, personnel other than flight crews benefit from instruction on safety when around aircraft on the ground. The best safety tip is to never approach propellers (turning or still) if anyone is in the aircraft. If ground personnel are to assist flight crews at any time, the flight crews should fully brief the ground personnel on rules to observe around the aircraft.

5.5.2 Seeding Suspension Criteria Public safety may become an issue whenever attempts are made to alter natural processes of any kind in any significant way. It is important to address scientifically based concerns and also any public perceptions (or misconceptions). One means of mitigating common concerns related to

excessive precipitation events has been through the use of seeding suspension criteria, wherein the presence or development of certain clouds or atmospheric conditions meeting specific criteria automatically triggers an immediate cessation of treatment.

There are many reasons why seeding might be suspended. Some hail suppression projects suspend operations if a storm becomes tornadic (see Section 4.6) or when certain weather warnings are issued by the responsible public agency. All projects should have plans to implement immediate suspension of operations whenever flash flooding is possible, regardless of whether “official” entities have issued statements.

Seeding also may be suspended for longer periods. For example, if the target area has become excessively wet, the local sponsors may elect to stop operations, even though hail is still possible. The reasoning behind this is that seeding to suppress hail also accelerates initial precipitation development, which often results in increased rainfall. In projects sponsored by agricultural interests, hail suppression operations also may be suspended if a harvest is to be completed.

The criteria by which operations are to be suspended should be delineated in the project operations manual. This method should include any graphical methods that might use radar or precipitation observations. Special weather statements, watches, and warnings issued by the responsible governmental entities (e.g., the National Weather Service) also can be incorporated in the suspension criteria.

5.6 PUBLIC RELATIONS, INFORMATION, AND INVOLVEMENT

The public should be provided with factual information about the project goals, objectives, and methodologies of hail suppression operations. If not, the result could be inaccurate speculation or

deliberately misleading statements from members of the public opposed to the program. It is therefore important that adequate information be provided as often as possible. In general, open and accessible project managers find that most local people are reasonable and objective.

Many locales require hearings before a project can be undertaken or before a license or permit for the project can be granted. Concerned individuals generally present themselves at such meetings. Their concerns should be carefully examined, and those that can be immediately and honestly addressed should be. Others may require some additional information gathering; this should be done, and the concerned parties should be informed of the findings. Some objections, such as conflict with religious beliefs, sometimes cannot be addressed in ways that the objector finds acceptable. Concerns about adverse environmental effects from the seeding agents, excess (or insufficient) rainfall, or cost are more readily dealt with.

It can be advantageous for the program to establish a local public involvement committee, composed of responsible and open-minded citizens, if such persons can be identified and are willing to participate. Persons with extreme or inflexible views should be avoided. The local committee can serve as an avenue for concerns to be presented to the program sponsor and, hopefully, for information exchange. If the local people can be made to understand that they have a stake in the program and can comprehend how the program is to be evaluated, they are much more likely to support it.

Informational brochures about weather modification operations, most common questions, and results can be obtained from most longer term projects and also from the WMA. These brochures can be helpful and may provide ideas for locally produced information that is specifically tailored to the project at hand.

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CHAPTER 6

EVALUATION OF HAIL SUPPRESSION EFFORTS

The rationale for conducting project evaluations is to find out how successful the operations are in achieving the desired results. This assessment is more easily said than done. It is impossible to unequivocally determine the effects of seeding on the hailfall from a single convective cell. However, hail suppression projects can be justified if seeding produces a tendency toward reduced damage. Statistical evaluations are intended to identify and quantify such tendencies, but physical measurements of the clouds and precipitation also are desirable. The statistical evaluation of any program can be strengthened by such physical measurements, so that a physical basis (explanation) of the observed effects can be established. In some projects, the sponsors have funded the deployment of a seeding aircraft equipped with microphysical instrumentation to make measurements before and after treatment. These measurements provide physical evidence of how seeding alters the cloud microstructure (Sánchez et al. 1998; Krauss 1999). Although these measurements are not made of every treated cloud, sponsors gain confidence in the seeding system, and scientists evaluating the program get some direct physical measurements of cloud characteristics and responses to treatment.

In this chapter, some of the available means for evaluation are presented. All project sponsors are strongly urged to include some evaluation procedures in their program design.

6.1 PROJECT AREA EVALUATION APPROACHES

Most current hail suppression programs are sponsored by entities that desire the maximum immediate beneficial effect. Thus, it is rare that project sponsors are willing to leave a fraction of the potential hailstorms unseeded. Nevertheless, this is what must be done to achieve the best scientific evaluation. However, other options also may provide good evidence of program efficacy.

6.1.1 Randomized Versus Nonrandomized Programs There are three basic approaches that may be considered for program assessment, each with advantages and disadvantages.

1. With *randomization*, storms in the target area are seeded or not seeded on a randomized basis to develop two unbiased classes of storms for comparison.
2. With *target vs. control* design, all storms in the target area are seeded, and measurements are compared with non-seeded storms in a nearby control area.
3. Projects evaluated on *historical data* compare storm measurements from within and beyond the project area both before and during the project to elucidate any changes observed because of seeding.

In the mathematical sense, the best way to evaluate the efficacy of a cloud seeding program is to randomly select some storms for

seeding and leave others untreated. Ideally, such randomization should be blind to those conducting the seeding and also to those involved in the subsequent analysis. To ensure against bias in the selection of candidate clouds, the initial selector, usually a program director, makes a random choice (seed or don't seed) and relays the decision to the individual who is actually doing the seeding (the seeder), who makes a second randomized decision to either heed or ignore the first directive. Ideally, the seeder treats the cloud with either live nucleant or placebos, not knowing where each is loaded. This approach is termed a "double-blind" experiment; the seeder does not know if the cloud was really treated, nor does the program director. Only after the postanalysis of the hailfall and rain, when all of the randomization decisions are combined with the known location of the seeding agent and placebo, does it become known which cases were treated and which were not. The end result of such a randomized program is more credible because the possibility of bias, conscious or unconscious, is eliminated. The drawback is that a portion of all storms is not treated, which reduces both the overall apparent effect and the benefit-to-cost ratio.

The alternative to randomized seeding is to treat every storm meeting the seeding criteria within the intended target area while monitoring the treated storms in the target and the nontreated storms over the nearby control area. To properly evaluate such a program, it is necessary that the long-term climatologies of the storms in both areas be well-correlated.

6.1.2 Selection of Target and Control Areas The selection of the target area is made based upon the interests of the program sponsors (see Section 4.1). Once the target is determined, project evaluators should identify a nearby area that has storm climatology as similar as possible to that of the target and that is preferably upwind to avoid inadvertent contamination by seeding agents. Thus, differences in hail damage and precipitation between the two areas are more readily demonstrated to result from seeding operations rather than from natural variability.

6.1.2.1 Precipitation Patterns The historical rain and hail patterns in the target and control areas should be as similar as possible. Analyses are based upon perceived deviations during seeding from this historical relationship, so the more these two areas are climatologically alike, the easier this comparison is.

6.1.2.2 Storm Frequency Because the target and control areas should have equal probability of hail (at least in the absence of hail suppression seeding operations), a control area should be selected that has nearly the same long-term probability of damaging hail as the target area. Usually this means that the two areas are close to each other and of similar character in land use, topography, and vegetation.

6.1.2.3 Contamination The control area should be located so that treated storms do not move from the target into the control area. Yet, to obtain optimum climatological similarity, the target and control should be as close together as possible. The control area frequently ends up being adjacent to but upwind of the target area, though an intervening buffer area is desirable. For evaluation purposes (except in randomized projects), any cases that may have been contaminated by seeding effects (the entrance of either seeding agent or treated storms) in the control area should be excluded from the evaluation. In a randomized project, all cases have to be included, though a stratification eliminating contaminated cases can also be examined.

6.2 EVALUATION MEASURES

There are a number of ways to approach the evaluation of hail suppression programs. The most direct way is to measure and analyze the physical properties of the precipitation intended to be affected by the operations, e.g., the hail and rain reaching the surface. Another means is to study secondary data sets, such as crop-hail or property insurance loss claims. The economic side of operations can be evaluated by modeling the effects of observed or predicted changes in hail losses. An example of this type of model would be changes in crop-hail insurance claims. Yet another indication of program effects might result from careful examination of crop yield data. If the program is successful, the average production should increase. Finally, some indications of the efficacy of operations also can be gained through the use of numerical (computer) cloud models that simulate the effects of seeding. Historically, simulations have generally been reserved for programs that have significant research components. However, simulations would likely prove beneficial to any program, especially if both seeded and nonseeded storms were included in the model component.

Whether or not physical measurements are made, the natural variability of hail is such that a sound evaluation requires the project to run for a number of years, preferably 10 or more. Project sponsors must be aware of this requirement from the beginning. An understanding should therefore be established as to how “preliminary” evaluations might be used in the earlier years to get a sense of program efficacy.

6.2.1 Evaluations Using Direct Evidence Direct measurement of hail and rain affords the best basis for project evaluation. Though obtaining these measurements in sufficient quantity and quality is difficult and costly, serious consideration should be given to this aspect.

6.2.1.1 Hail Pad Networks The best method currently available to quantify surface hailfall is to use a hail pad network. A hail pad is a flat piece of material placed horizontally in an exposed area (Schleusener and Jennings 1960). The pad is generally composed of firm foam of some type that deforms permanently when struck by hail (Fig. 6-1). To protect from degradation of the foam by UV sunlight, the pad should either be covered with a thin layer of aluminum foil or painted with a thin layer of UV-blocking latex paint. Hail pads should be routinely checked for evidence of hail impacts. When such impacts are recorded, the foam piece is labeled and removed for analysis and replaced with a new one.

Because hail is a highly variable phenomenon with respect to both space and time, the best results for evaluation are obtained when hail pads are deployed in regular grid spacings over large areas. For example, a hail pad network consisting of 150 pads deployed in a 10 by 15 array, with each pad 1 km (0.6 mi) from its neighbors, would have a reasonable chance of detecting

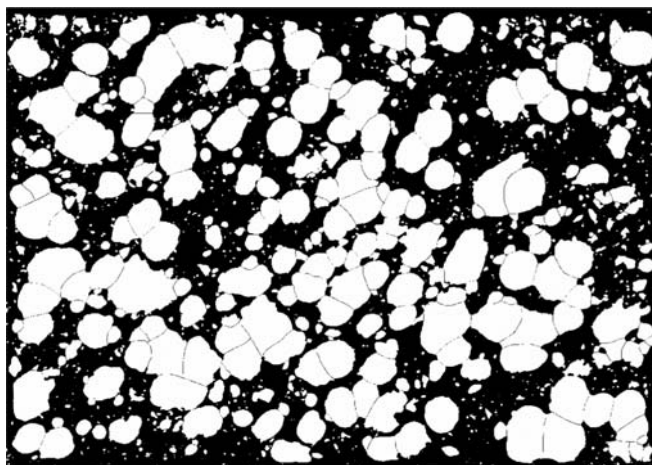


FIGURE 6-1 An image of a hail pad showing hail impacts
Source: Dessens et al. (2014); reproduced with permission from Elsevier B.V.

modest-to-large hail streaks through the area covered by the network. Similar networks would be required in both target and control areas. Hail pad networks are extremely labor-intensive. They require regular inspection after each storm and also during periods of nonconvective weather to ensure that all pads are properly positioned and undamaged. Pads that receive hail damage must be numbered, removed, replaced, and then analyzed for the number and sizes of impact marks. Before 1985, hail pads had to be laboriously and subjectively analyzed by hand; but there now exist automatic means for objective analysis that use various digital imaging techniques. Generally, a hail pad network requires a full-time crew during the hail season, and a like amount of time for postanalysis. In spite of this, hail pad networks are possibly one of the least expensive sources of direct evidence of hail size and impact energy. In Europe, hail pad networks have been used successfully in Spain (Fraile et al. 1991, 1992), France (Dessens 1998), Italy, and Greece. In some cases, the networks have been used to evaluate nonrandomized programs (Dessens et al. 1998, 2006). The data provided are also useful in hail research.

6.2.1.2 Rainfall Data The best measurements of rainfall are obtained through surface rain gauges. The quality of each individual measurement depends upon the size of the orifice of the gauge, gauge shielding (if any), gauge siting, and whether the precipitation data are time-resolved. Standard recording rain gauges with 8-in. (20.32-cm) orifices are well suited to this task but are expensive and require attention on the same order as hail pads. Few high-quality reporting sites are generally found in the desired areas. Thus, a project interested in using direct rainfall measurements for evaluations must significantly augment existing reporting sites. This augmentation must be done in both the target and control areas. This technique is really only applicable to programs that adopt randomization, since without it any observed difference between target and control could just be a reflection of the regional climatology. Thus the target vs. control approach requires a historical, nonseeded data set similar to that available for the project period.

6.2.1.3 Radar Data Today's radar hardware and software provide a means by which larger scale cloud behaviors can be documented with relatively little effort. Data recording systems such as TITAN record reflectivity in a volume-scan mode, estimate storm-integrated precipitation, and perform a wide

variety of real-time tasks helpful in directing operations as well as providing data useful for evaluation purposes. These operations include such things as user-selectable vertical cross sections, vertically integrated liquid (VIL) cloud water, and projected storm tracks. A radar positioned to provide comparable areal and range coverage for both target and control can be helpful in evaluations by documenting storm characteristics, such as radar-estimated rain volumes, for both seeded and unseeded storms.

Most portions of the United States are now adequately covered by the National Weather Service (NWS) WSR-88D NEXRAD Doppler radar network. Real-time data and products from these radar systems are available through both public and private sources. Data are also archived and available through the National Climatic Data Center. The future holds considerable hope for project analysis and evaluation through the NWS radar network now that dual-polarization capability has been added. This capability has been shown to provide the ability to differentiate between ice-phase and liquid water-phase hydrometeors (Reinking et al. 1998) and to improve the radar detection of hail (e.g., Heinselman and Ryzhkov 2006). Thus, dual-polarization capability should become an excellent tool for the future assessment of hail suppression operations.

Although radar is helpful for documenting storm behavior, its use for quantitative evaluation of hail suppression efforts would be complex. Storms are viewed by radar differently, depending upon distance from the radar (range), viewing aspect, and the possible presence of other intervening clouds and precipitation. Thus, quantifying differences among storms, some seeded and some unseeded, that are at different ranges and viewed from different aspects becomes complex.

6.2.2 Evaluation through Secondary Evidence Secondary evidence, that is, data that reflect program efficacy but that are not direct measures of it, may be useful. Insurance loss-cost ratios and crop yield statistics are two examples of secondary evidence (Table 2-1). Both can provide evidence of program efficacy.

6.2.2.1 Crop-Hail Insurance Data Many hail suppression programs are sponsored for the express purpose of reducing crop-hail damage. Thus, examination of crop-hail data for evidence of seeding effects (e.g., Peterson 1975; Hsu et al. 1981; and Smith et al. 1997) seems obligatory. Data for much of the United States are collected by the National Crop Insurance Services, though access to the data can be a problem. Considerable care would have to be taken to ensure that the policy forms used were the same in both target and control areas through the period of interest and that a representative amount of liability was sold in each. This latter is important because any uninsured crop loss caused by hail would never show up in the insurance crop-loss data if the loss was not covered by insurance.

The vulnerability of crops to hail varies not only with hail size and amount and wind, but also with the crop type, its health, and its stage of development. In some cases, hailfall occurs where total crop loss has previously occurred, in which case the latter hailfall would go unrecorded in crop-hail insurance data. Thus, the use of crop-hail data must be undertaken with considerable care, and results of such evaluations must be presented with the appropriate caveats.

6.2.2.2 Insurance Property Loss Data Hail damage to property has become a major problem, with the first \$1.1 billion

hailstorm now on record that occurred in Dallas–Ft. Worth, Texas, in 1995 (Institute for Business and Home Safety [IBHS] 1998). Storms that cause \$100 million or more in damages are not uncommon. For example, storms that cause more than \$300 million of damage occurred during the 1990s in Orlando, Florida; Wichita, Kansas; Dallas, and Oklahoma City (Changnon 1997). However, property and casualty losses are recorded and reported differently among organizations, and, unlike crop-hail insurance, quality statistics are not available for the industry. Statistics that are available from individual companies are seldom reported by area and date, and many include all storm damage, not just that caused by hail. Thus, getting meaningful data of this type is currently problematic. The insurance industry is becoming increasingly aware of the need for better reporting, but most companies consider their data proprietary, fearing that the competition might gain an advantage if data are divulged. The IBHS has considered serving as an anonymous clearinghouse for hail-loss information, but this would require further standardization of reporting, which would be an expensive conversion for many companies. Therefore, property hail-loss statistics are not currently available for project evaluation purposes. Even though hail-loss reduction in a large urban area would be extremely beneficial, meaningful statistics on total current property losses are not available.

6.2.2.3 Crop Yield Data The National Agricultural Statistics Service (NASS) publishes crop yield statistics for most of the nation. These numbers, if carefully examined, can be used to approximate project benefits. Observed changes in crop yields can be used as an indicator of program efficacy but not as a precise measure of it. A positive change in yield should be encouraging, and a negative change would be cause for concern. The advantage of using crop-yield statistics is that they are readily available, relatively inexpensive, and regularly compiled. Obtaining historical data also is generally not problematic.

In general, their meaningful use would require a long-term hail suppression project of at least 10 growing seasons. Target and control areas are required that have well-established, long-term historical cropping practices and similar yields (or at least well-correlated yields) in nonseeded periods. Other factors that might explain observed differences must be carefully screened. Among these are changes in farming practices in either the target or control area. These possible changes include irrigation, use of agrichemicals, and seed varieties.

6.3 DISSEMINATION OF RESULTS

Comparisons of secondary data of the types listed in Section 6.2 in the target and control areas could be a start. In the early years of a new program, after the conclusion of each season, it is a good idea to release statements (based on such comparison) to the media concerning perceived program efficacy. Appropriate caveats must be included. Such preliminary results often can be helpful from the standpoint of encouraging the sponsor; however, they are seldom statistically significant.

As data accrue over several years, the results gain enhanced certainty, and confidence increases accordingly. Publication of these findings should follow, preferably in refereed scientific journals. If there is interest at any nearby universities, researchers there should become involved, particularly if objectivity can be maintained.

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CHAPTER 7

GLOSSARY OF TERMS AND ACRONYMS

Definitions are from the *Glossary of Meteorology* (AMS 2000), where applicable.

accumulation zone—Hypothetical, relatively small regions within mature updrafts of hailstorms where supercooled liquid water drops have accumulated, creating a region well suited to the rapid development of large hail. Although such zones have been encountered by research aircraft on rare occasions, their true role, if any, in hail development is uncertain.

AgI—*See silver iodide.*

AMS—American Meteorological Society, 45 Beacon Street, Boston, MA 02108-3693. <http://www.ametsoc.org/>

ASCE—American Society of Civil Engineers, 1801 Alexander Bell Drive, Reston, VA 20191-4400. <http://www.asce.org/>

attenuation—In physics, any process in which the flux density (or power, amplitude, intensity, illuminance, etc.) of a “parallel beam” of energy decreases with increasing distance from the energy source; for example, attenuation in the atmosphere, often caused mostly by precipitation, reduces the intensity of the electromagnetic wave (radar signal) along its path from and back to the radar. Attenuation thus lessens the ability of radar to sense all clouds and precipitation, such that the depicted information becomes inaccurate or incomplete.

AZ—*See accumulation zone.* Also used to indicate azimuth, especially in radar manuals.

broadcast seeding—The release of seeding agent, either from aircraft or from the ground, in conditions thought favorable for the development of treatable convective storms but either before such storms have developed or at some distance from the storms (i.e., not within the storm or in its immediate proximity). *Compare direct targeting.* Broadcast seeding is also a routine practice to increase precipitation within winter clouds in mountainous areas.

buffer zone—The area between the target area and control area that buffers the control from the possible effects of seeding within the operational area.

burn-in-place flare—A pyrotechnic device burned in a fixed position, such as the trailing edge of an aircraft wing. *Compare ejectable flares.*

C-band radar—A radar system operating at a wavelength of approximately 5 cm.

CaCl—*See calcium chloride.*

calcium chloride—The salt commonly used in hygroscopic cloud seeding pyrotechnics.

CCN—Cloud condensation nuclei. The tiny particles, either liquid or solid, upon which condensation of water vapor first begins in the atmosphere; necessary for the formation of cloud droplets.

CD-ROM—Compact disk, read-only memory. Much of the project data today is archived to CD-ROM because most modern computers can read them.

cell—A convective element (cloud) that, in its life cycle, develops, matures, and dissipates, usually in about 30 min.

certified manager—Person with certification of weather modification project managerial experience and skills granted by the Weather Modification Association.

certified operator—Person with certification of weather modification project operational experience and skills granted by the Weather Modification Association.

cloud droplet—A particle of liquid water from a few micrometers to tens of micrometers in diameter, formed by condensation of atmospheric water vapor and suspended in the atmosphere with other droplets to form a cloud. These liquid water droplets are too small to precipitate.

cloud model—Physical description of cloud processes programmed into a computer to simulate cloud development and evolution. Useful in understanding the relative importance of the many factors that influence cloud development, and the only way in which *exactly the same cloud* can be both seeded and unseeded.

CO₂—*See dry ice.*

coalescence—In cloud physics, the merging of two water drops into a single larger drop. This merging occurs through the collision of two drops, which then unite.

conceptual model—A theoretical model, for example, of storm and hail development, based upon current knowledge and scientific concepts. *See also cloud model.*

contamination—The inadvertent distribution of seeding agent into areas that, according to project design, were not to have been seeded. Contamination becomes a problem only when such areas are intended to serve as control areas but contain storms, which then can no longer be considered unseeded.

control area—An area where cloud seeding operations do not take place, preferably similar in character and near the project target area. The behavior of storms over the control area is compared to treated storms over the target area to assess differences and thus measure project effectiveness. *See also buffer zone, operational area, and target area.*

crossover design—A project that uses areas that alternate between target and control designations, usually according to some randomization scheme. Crossover project design reduces the possibility of geographically induced bias in the evaluation.

direct targeting—The placement of seeding agents directly into the target cloud mass, either by release during penetration by aircraft, rocket, or artillery projectile, or from aircraft flying directly below cloud base in updraft. *Compare broadcast seeding.*

droplet spectrum—The number, concentrations, and sizes of the droplets within the cloud volume of interest.

dry growth—Growth of a hailstone or hail embryo in supercooled cloud that has a relatively low liquid water content, so that

supercooled cloud droplets or raindrops freeze upon impact, resulting in accretion that is opaque and porous.

dry ice—Frozen carbon dioxide (CO₂). Dry ice pellets have an unventilated surface temperature of -78.5°C (-109.3°F) and have been used considerably for glaciogenic cloud seeding. Ventilated surface temperatures, such as might be realized during free fall within a cloud, are near -105°C (-157°F).

dynamic seeding—The treatment of clouds with the intent of using the latent heat produced by additional, or accelerated, freezing and perhaps in some cases by condensation or deposition to invigorate cloud development.

ejectable flares—Pyrotechnic devices that are ignited and released (ejected) from aircraft. *Compare* **burn-in-place flare**.

embryo—*See* **hail embryo**.

FAA—Federal Aviation Administration. The government entity that regulates aircraft operations, safety, and use of airways in the United States. Analogous entities also exist in most other nations. <http://www.faa.gov/>

flanking line—Developing convective cells on the flank (side) of a mature thunderstorm.

glaciogenic—Causing the formation of ice.

glaciogenic seeding—Treatment of clouds with materials intended to increase and/or initiate the formation of ice crystals.

GOES—Geostationary Operational Environmental Satellite. These are the latest NOAA weather satellites, currently operational over the continental United States.

GPS—Global positioning system. A global, multiple-satellite-based navigation positioning system that provides consistently accurate positions.

graupel—White, opaque, approximately round (sometimes conical) ice particles that have a snowlike structure and are typically about 2–5 mm (0.08–0.20 in.) in diameter. Also known as snow pellets, they form in convective clouds when supercooled water droplets freeze to an ice particle upon impact.

Grossversuch IV—A Swiss hail suppression research program conducted from 1977 to 1981, which attempted to replicate the reported successes of the former Soviet Union's hail suppression program. *See also* **NHRE**.

hail—Precipitation in the form of balls or irregular lumps of ice, always produced by convective clouds, nearly always by cumulonimbus. By convention, hail has a diameter of 5 mm (0.20 in.) or more.

hail cannon—A vertically pointing device that uses explosions to attempt to prevent hail development. Though no scientific basis for the functionality of hail cannons has been published in refereed literature, their use continues in a few places, usually in high-value, limited-area agricultural endeavors, such as orchards.

hail embryo—Small ice particles, often graupel or frozen raindrops, that, when resident in an updraft of sufficient supercooled liquid water content, grow into hailstones.

hail pad—A device made of a relatively soft but nonresilient material, such as Styrofoam, that deforms when impacted by hailstones. The size and depth of the deformations are used to estimate the kinetic energy and size of the hailstones. *See also* **UV**.

hail streak—A deposit of hail on the ground. Sometimes used interchangeably with *hail swath*, a hail streak also may be a region of greater damage within a hail swath, presumably because of greater sizes or numbers of hailstones.

hail swath—The surface path of hail at the surface. *See also* **hail streak**.

hailstone—An individual unit of hail.

hydrometeor—Any product of condensation, deposition, or condensation and freezing in the atmosphere. This definition

includes cloud water or ice of any size, either suspended in the air or precipitating.

hygroscopic—Pertaining to a marked ability to accelerate the condensation of water vapor; in general usage, the ability of a crystalline solid (e.g., salt) to absorb vapor but at such a low rate under most conditions that it does not dissolve completely.

hygroscopic seeding—Treatment of clouds with hygroscopic materials that encourage the formation of larger droplets, changing the cloud droplet spectrum to enhance development of precipitation through coalescence.

IBHS—Institute for Business and Home Safety (formerly the Insurance Institute for Property Loss Reduction), 1408 North Westshore Boulevard, Suite 208, Tampa, FL 33607. <http://www.disastersafety.org/>

ice nucleus (IN)—Any particle that serves as a nucleus for the formation of ice crystals in the atmosphere.

IFF—Identification, friend or foe. A secondary radar aircraft tracking system that interrogates aircraft-carried L-band transponders. The IFF systems have largely been replaced with GPS-based systems, which are considerably more precise and also more reliable.

IFR—Instrument flight rules. The FAA regulations pertaining to flight at altitudes of 18,000 ft (5.5 km) above mean sea level or higher over U.S. airspace, or in any meteorological conditions necessitating the use of aircraft instrumentation for safe navigation.

IMC—Instrument meteorological conditions. *See* **IFR**.

IN—*See* **ice nucleus**.

in situ measurement—Measurements made in place, as within the cloud of interest. *Compare* **remote sensing**.

inertial navigation system—A self-contained navigation technique using accelerometers and gyroscopes to track the position, orientation, and velocity of a moving object.

instantaneous vertical velocity indicator—An instrument that informs the pilot of an airplane's ascent or descent.

KCl—*See* **potassium chloride**.

latent heat—The heat released or absorbed per unit mass by a system in a reversible, isobaric–isothermal change of phase. More simply, the heat released when water vapor condenses (latent heat of condensation), or when liquid water drops freeze (latent heat of fusion). In the case of water droplets freezing upon contact with hail, the latent heat elevates the surface temperature of the growing hailstone.

loss–cost ratio—In insurance, the ratio of loss to the liability, multiplied by 100. For example, a \$20 loss on a policy that has an insured liability of \$40 would be a loss–cost ratio of 50%.

Meteosat—The current European weather satellites. *See also* **GOES**, Meteosat's counterpart in the United States.

mitigation—As it relates to hail suppression, the act of reducing the severity or seriousness of damage from hail, either by suppressing its formation or by reducing its size distribution.

NaCl—*See* **sodium chloride**.

NASS—National Agricultural Statistics Service, 5285 Port Royal Road, Springfield, VA 22161. <http://www.nass.usda.gov/>

NCAR—National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO, 80307-3000. <http://ncar.ucar.edu/>

NEXRAD—*See* **WSR-88D**.

NHRE—National Hail Research Experiment. Conducted in the early 1970s in northeast Colorado, it attempted to replicate the reported successes of the former Soviet Union's hail suppression program. *See also* **Grossversuch IV**.

NOAA—National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The parent organization of the U.S. National Weather Service and the federal agency to which

all U.S. weather modification activities must be reported. <http://www.noaa.gov/>

nowcasting—Very short-term forecasting, from the present to about two hours.

NWS—National Weather Service, the U.S. public weather forecasting agency. The NWS is a division of NOAA. <http://www.nws.noaa.gov/>

operational area—The area over or within which seeding operations are actually conducted, including the target area and usually adjacent areas beyond the boundaries of the target area, where seeding is conducted with the intent of affecting clouds over the target.

overseeding—A condition resulting from the application of too much glaciogenic seeding agent in which too many small ice crystals may form, none of which is large enough to precipitate or aggregate.

placebo—Treatment with an inert substance, usually without the knowledge of those applying the treatment. In a randomized cloud seeding program, clouds are treated with real seeding agents or a placebo, which might be only an audible event such as a recorded “bang” that sounds like a flare firing or a flare containing sand.

potassium chloride—KCl, a simple salt sometimes used as a primary ingredient in hygroscopic cloud seeding pyrotechnics. *See also* **calcium chloride**.

program—Cloud seeding within the total area of a county, state, country, or geographic region. May consist of both airborne and ground-based seeding. Used interchangeably with “project” in this document.

project—Cloud seeding within the total area of a county, state, country, or geographic region. May consist of both airborne and ground-based seeding. Used interchangeably with “program” in this document.

quasi-steady-state—A situation that is changing slowly enough that it can be considered to be constant.

raindrop—A drop of water of diameter greater than 0.5 mm (0.20 in.) falling through the atmosphere. In careful usage, falling drops with diameters lying in the interval 0.2 to 0.5 mm (0.08 to 0.20 in.) are called “drizzle drops” rather than raindrops, although this notion is frequently overlooked.

rawinsonde (or radiosonde)—An instrument package that senses and transmits weather information such as pressure, temperature, and humidity (and designated rawinsonde if tracked electronically to derive wind data). Rawinsondes are carried aloft by weather balloons twice daily from numerous sites all over the world; they can also be used by projects to bolster local forecasting efforts.

remote sensing—The remote measurement of properties of interest, as with radar and satellite. *Compare* **in situ measurement**.

response time—The time that elapses from identification of a seeding opportunity until the release of seeding agent actually begins.

S-band radar—A radar system operating at a wavelength of approximately 10 cm.

seeding agents—Agents dispensed by any means in or near a cloud volume that are intended to modify (seed) the cloud characteristics.

silver iodide—AgI, a common glaciogenic seeding agent.

sodium chloride—NaCl, the chemical composition of common table salt. Because of its hygroscopic properties, historically it has been used occasionally for hygroscopic seeding. Hygroscopic seeding programs have more recently used potassium chloride (KCl).

supercell—Thunderstorms characterized by an intense, quasi-steady-state mature updraft. Such storms account for a large fraction of all tornadoes and much of the large hail.

supercooled water—Water, still in liquid state, at temperatures lower than 0°C (32°F). Under ideal conditions in the free atmosphere, water may exist in a supercooled state to temperatures as low as –40°C (–40°F).

suppression—Act of reducing the occurrence or size of hail from storms that produce hail.

target area—The area for which cloud seeding operations are targeted; often, they are near a control area that is similar in character and climatology. The behavior of treated storms over the target area is compared to untreated storms over the control area to assess differences and thus measure project effectiveness. *See also* **buffer zone**, **control area**, and **operational area**.

terminal velocity—The particular falling speed, for any given object moving through a fluid of specified physical properties, at which the drag forces and buoyant forces exerted by the fluid on the object just equal the gravitational force acting on the object. For hydrometeors, it is the greatest fall speed relative to the surrounding air that a hydrometeor will attain, as determined by the mass of the particle and frictional drag of the air through which it is falling.

thermal—A relatively small-scale, rising current of air produced when the atmosphere is heated enough locally by the Earth’s surface to produce absolute instability in the lowest layers.

TITAN—Thunderstorm Identification, Tracking, Analysis, and Nowcasting. Software for the display and analysis of weather radar data, widely used in operational convective cloud seeding programs.

tropopause—The boundary between the troposphere and the stratosphere, usually characterized by an abrupt change in lapse rate. Because of the change in lapse rate, the tropopause height limits the maximum vertical growth of deep moist convection (thunderstorms).

UV—Ultraviolet electromagnetic radiation, of shorter wavelength than visible radiation, but longer than X-rays. Ultraviolet radiation (light) is a component of normal solar radiation. Foam hail pads degrade with prolonged exposure to UV radiation and so are either covered with foil or painted.

vertical velocity indicator—An instrument that informs the pilot of an airplane’s rate of ascent or descent.

VIL—Vertically integrated liquid. A radar estimate of the cloud liquid water, from the lowest angle sampled through cloud top. VIL is used as an indicator of storm intensity or the presence of hail.

VMC—Visual meteorological conditions.

wet growth—Growth of a hailstone or hail embryo in supercooled cloud that has a liquid water content such that the release of latent heat of freezing by accreted liquid warms the surface to near 0°C (32°F), so that not all of the accreted supercooled liquid immediately freezes upon impact. This phenomenon results in ice growth that is often transparent and almost solid.

wing-tip generator—Ice nucleus generator mounted at the tips of aircraft wings, or sometimes below the wings, also usually near the ends.

WMA—Weather Modification Association, P.O. Box 845, Riverton, UT 84065. <http://www.weathermodification.org/>

WMO—World Meteorological Organization, 7 bis, Avenue de la Paix, CH 1211 Geneva 2, Switzerland. <http://www.wmo.int/>

WSR-88D (NEXRAD)—The 1988 vintage Doppler weather radar network deployed in the United States by the National Weather Service during the 1990s.

X-band radar—A radar system operating at a wavelength of approximately 3 cm.

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CHAPTER 8

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CHAPTER 9

CONVERSION OF UNITS

This manual of standard practice specifies units in accordance with the International System of Units, or SI (from the French, *Le Système International d'Unités*). In the SI, the base unit of length is the meter (m); of mass, the kilogram (kg); of time, the second (s); and of temperature, the Kelvin (K). Derived SI units include those for area, the square meter (m²); for volume, the cubic meter (m³); and for speed, a meter per second (m s⁻¹). Other derived SI units relevant to this standard practice include force, the newton (N, or mkg s⁻²); pressure, the pascal (Pa, or Nm⁻²); and energy, the joule (J, or N m). Also included in the derived SI units is Celsius temperature (°C), which is equivalent to K-273.16.

In addition, a number of prefixes are approved for use with SI units, so that very small or very large quantities need not be rendered in unwieldy formats. Several such prefixes are listed in Table 9-1.

These prefixes are approved for use with SI units, so that 1,000 m also can be expressed as 1 km. Likewise, one millionth of a meter can be expressed as 1 μm. In this document, these approved SI prefixes are used wherever applicable to reflect

Table 9-1 Approved SI Prefixes

Factor	Name	Symbol
10 ⁶	mega	M
10 ³	kilo	k
10 ²	hecto	h
10 ⁻²	centi	c
10 ⁻³	milli	m
10 ⁻⁶	micro	μ

the common usage. Examples are listed in Table 9-2. Alternate common English equivalents, other common units, and the conversion factors also are shown. A limited number of other units outside the SI are approved for use with the SI. Among these are minutes (min), hours (h), days (d), and liters (L).

Table 9-2 Conversion Factors

Quantity	SI Units	Equivalent cgs Units	Other Common Units	Equivalent English Units
Length	1 meter (m) 1,000 m 1,000 m 0.001 m	100 centimeters (cm)	3.28 feet (ft) 1.0 kilometer (km) 1.0 km 1.0 millimeter (mm)	1.09 yards (yd) 0.54 nautical mile (mi) 0.62 statute mi 0.039 inches (in.)
Area	1 square meter (m ²) 1,000,000 m ²	10,000 cm ²	10.8 ft ² 1.0 km ²	1.2 yd ² 0.39 mi ²
Volume	1 cubic meter (m ³) 1,000,000,000 m ³ 10 ⁶ m ³	1,000,000 cm ³ 1 cm ³	35.3 ft ³ 1.0 km ³ 1 cc	1.31 yd ³ 0.24 mi ³ 0.034 fluid ounces (fl oz)
Mass	1 kilogram (kg)	1,000 grams (g)	35.36 ounces (oz)	2.21 pounds (lb)
Pressure	1 pascal (Pa)	10 dynes cm ²	0.098 millibar (mb)	0.0003 in. of Hg
Speed	1 meter per second (m s ⁻¹)	100 cm s ⁻¹	3.6 km h ⁻¹	2.24 mi h ⁻¹
Temperature	273.16 Kelvin (K)		0.0 degrees Celsius (°C) °C = K - 273.16 K = °C + 273.16	32.0 degrees Fahrenheit (°F) °F = (1.8°C) + 32 °C = 5/9(°F - 32)
Time	1 second (s) 60 s 3,600 s 86,400 s	1 s	1 minute (min) 1 hour (h) 1 day (d)	1 s 1 minute (min) 1 hour (h) 1 day (d)

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