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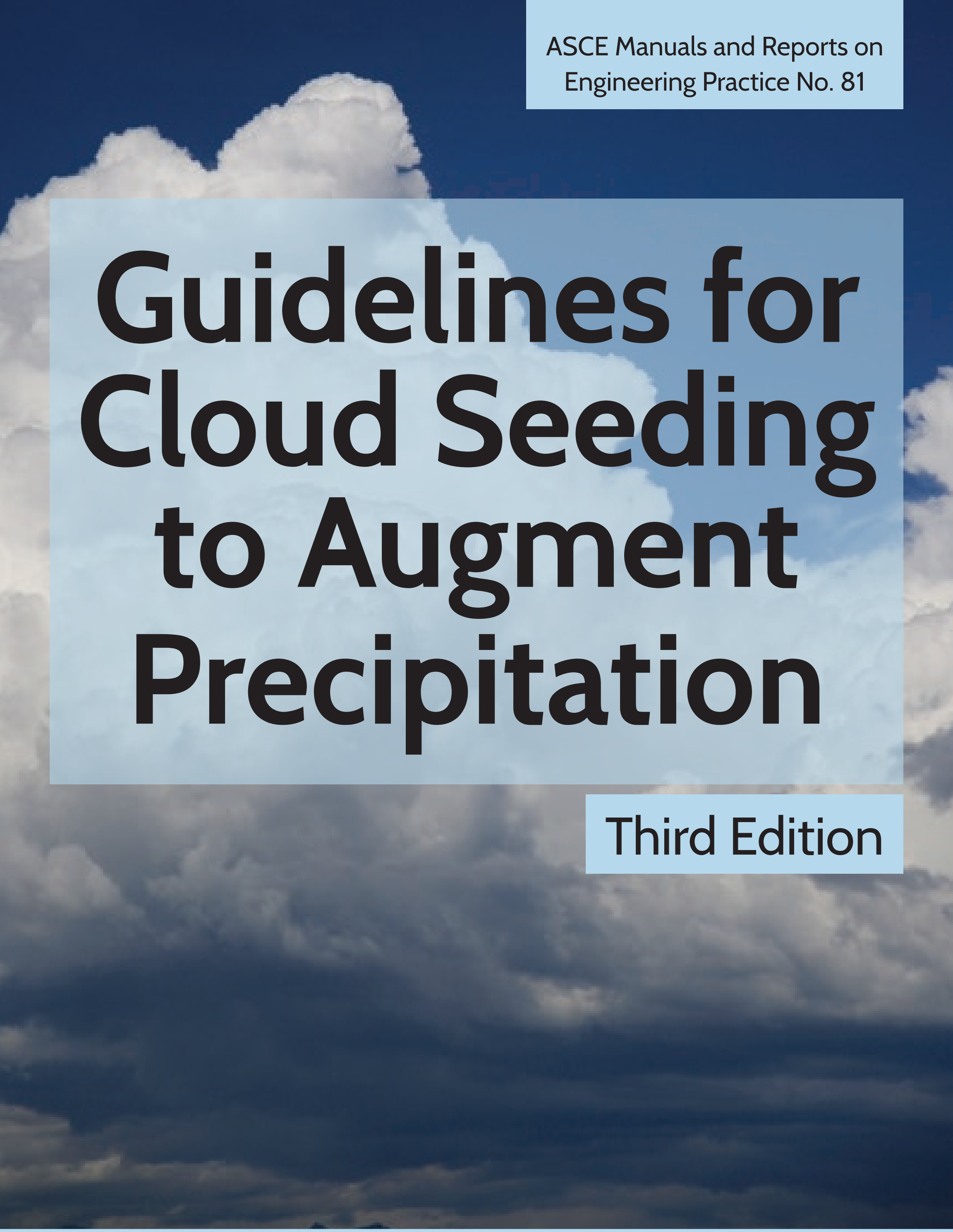

Guidelines for Cloud Seeding to Augment Precipitation

Third Edition

EDITED BY
Conrad G. Keyes Jr., George W. Bomar, Thomas P. DeFelice, Don A. Griffith, and Darin W. Langerud

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Sponsored by the
Atmospheric Water Management Standards Committee of
the Standards Development Council of the
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MANUALS AND REPORTS ON ENGINEERING PRACTICE

(As developed by the ASCE Technical Procedures Committee, July 1930, and revised March 1935, February 1962, and April 1982)

A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to the average engineer in his or her everyday work, rather than findings that may be useful only occasionally or rarely. It is not in any sense a "standard," however; nor is it so elementary or so conclusive as to provide a "rule of thumb" for nonengineers.

Furthermore, material in this series, in distinction from a paper (which expresses only one person's observations or opinions), is the work of a committee or group selected to assemble and express information on a specific topic. As often as practicable the committee is under the direction of one or more of the Technical Divisions and Councils, and the product evolved has been subjected to review by the Executive Committee of the Division or Council. As a step in the process of this review, proposed manuscripts are often brought before the members of the Technical Divisions and Councils for comment, which may serve as the basis for improvement. When published, each work shows the names of the committees by which it was compiled and indicates clearly the several processes through which it has passed in review, so that its merit may be definitely understood.

In February 1962 (and revised in April 1982), the Board of Direction voted to establish a series titled "Manuals and Reports on Engineering Practice," to include the Manuals published and authorized to date, future Manuals of Professional Practice, and Reports on Engineering Practice. All such Manual or Report material of the Society would have been refereed in a manner approved by the Board Committee on Publications and would be bound, with applicable discussion, in books similar to past Manuals. Numbering would be consecutive and would be a continuation of present Manual numbers. In some cases of joint committee reports, bypassing of Journal publications may be authorized.

A list of available Manuals of Practice can be found at http://www.asce.org/bookstore.

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PREFACE

Traditional water resources management pertains to making reasonable use of available water and desalinization and to minimizing loss because of floods. Atmospheric water management provides a cost-effective means for augmenting available water and reducing damage during meteorological events.

In many areas of the United States and the world, a need existes for new water supplies. These updated guidelines are intended to provide water resources managers and others with information and references that they will need for decision making regarding the use of cloud seeding to augment available water supplies.

This manual incorporates pertinent background on the science and practice of weather modification by cloud seeding to augment precipitation. Legal, social, environmental, and economic factors motivating and limiting operational cloud seeding are reviewed. The technologies, instrumentation, and procedures needed to implement a cloud seeding program are described. This is all intended to give water resources managers the broad spectrum and practical details of what is involved in utilizing cloud seeding (atmospheric water management) technology.

The American Society of Civil Engineers (ASCE) Weather Modification Committee (1960–1985) and the Climate and Weather Change Committee (1985–1996) were fortunate enough to bring together experts in the weather modification field and have them devote a great amount of uncompensated volunteer time to write the first versions of this valuable document. The 1982 Weather Modification Committee, the 1993 Climate and Weather Change Committee, and the 1982 and 1994 Executive Committees of the Irrigation and Drainage Division are to be commended for their thorough and helpful review of the first document that was published in the ASCE Journal of Irrigation and Drainage Engineering in March 1983, pp. 111–182 (parts written by Paul C. Summers: Foreword; Robert D. Elliott: Summary; Olin H. Foehner, Jr.: SEE Issues; Ray Jay Davis: Legal Aspects; Lewis O. Grant:

Scientific Basis; Don A. Griffith: Modes and Instrumentation; and Conrad G. Keyes Jr.: How to Implement).

The original task committee appreciated the extensive technical editing of each section of the manual by the personnel of OPHIR Corporation. The Consortium of Atmospheric Resources Development provided funds for the review of the first version of this manual, and the North American Interstate Weather Modification Council provided funds for travel to a meeting of the 1992–1993 Task Committee involved in the revision of the 1983 guidelines published by ASCE.

The 1995 manual was authored by the following individuals (by section): (1) Robert D. Elliott, Conrad G. Keyes Jr., and Roger F. Reinking; (2) Roger F. Reinking, Neil H. Berg, Barbara C. Farhar, and Olin H. Foehner, Jr.; (3) Ray Jay Davis; (4) Lewis O. Grant, Harold D. Orville, Marcia Politovich, Roger F. Reinking, David Rogers, and Joseph Warburton; (5) Don A. Griffith, Marcia Politovich, James H. Renick, David W. Reynolds, and David Rogers; and (6) Conrad G. Keyes Jr., Joseph A. Warburton, and James H. Renick. Most of these individuals were involved with the Climate and Weather Change Committee of the Irrigation and Drainage Division of Management Group D of ASCE.

The 2006 manual was authored by the following individuals (by section): (1) Thomas P. DeFelice and Conrad G. Keyes Jr.; (2) Conrad G Keyes, Jr.; (3) George W. Bomar; (4) Robert Czys, Thomas DeFelice, and Don A. Griffith; (5) Don A. Griffith; and (6) Bruce A. Boe and Conrad G. Keyes Jr. Most of these individuals have been long-standing members and/or officers of the Weather Modification Association. The final reviewers from the Blue Ribbon Review Panel for the EWRI Standards Development Council included Darin W. Langerud, Paul L. Smith, Mark E. Solak, and William L. Woodley.

This current edition or revision of the manual was produced by those listed within each chapter and approved for publication by a majority of the Atmospheric Water Management (AWM) Standards Committee (SC). The editors from the EWRI Revision of Manual 81 Subcommittee are Chief Editor Conrad G. Keyes Jr. and Coeditors George W. Bomar, Thomas P. DeFelice, Don A. Griffith, and Darin W. Langerud. Other authors on chapters include Robert Czys and Bruce A. Boe (both were lead authors in 2006). The other subcommittee reviewers from the AWM SC and/or the Weather Modification Association include Joseph H. Golden, Maurice D. Roos, and Paul Smith. The final reviewers of all chapters from the Blue Ribbon Review Panel for the EWRI Standards Development Council (SDC) include Duncan Axisa of NCAR, Mark Schneider of NDARB, and Mark E. Solak of NAWC. Some members of the AWM SC had additional final input on the draft chapters before all work was provided to the Chair (Ben Willardson) of the EWRI SDC for approval for publication by ASCE.

Conrad G. Keyes Jr., ScD, P.E., P.S., D.WRE, WMA CM, Dist.M.ASCE, F.NSPE

Emeritus Professor and Department Head, New Mexico State University

DEDICATION

This manual is dedicated to many of the original coauthors of the 1983 and/or 1995 versions of the guidelines. These individuals made significant contributions to the "cloud seeding to augment precipitation" community during the many years of their professional lives and served ASCE as dedicated volunteers during many years of the development and publication of this subject.

RAY JAY DAVIS passed away August 10, 2000, at his home in Provo, UT. Ray received a B.A. from Idaho State University in 1948, a J.D. from Harvard Law School in 1953, and an L.L.M. from Columbia Law School in 1956.

An academician throughout his 45-year legal career, Ray Jay was a Professor of Law at Brigham Young University from 1979 until his retirement in April 2000. He also taught law at the University of Arizona (17 years), Temple University, and the University of Arkansas.

His research career was primarily devoted to studying and writing about the legal rules that govern, or should govern, the appropriation and use of water, particularly water contained in the earth's atmosphere. He served as chair for a monumental project undertaken by ASCE to produce a model state water code to be transmitted to all 50 state legislatures with a recommendation for adoption and to be published abroad as a law reform source in foreign countries. He was also the author of the legal section of first edition of ASCE Manual 81 and the initial version of the guidelines in 1983.

Ray served as the chair, a member, a principal investigator, or an advisor to countless committees to governmental agencies of different states and to agencies of the federal government. He represented the United States at the United Nations Conference on International Legal Principles for Weather Modification. He made presentations at conferences in foreign countries and served as an advisor on the legal ramifications of cloud seeding to nine western and midwestern states. Some of his writings have been translated into French, Russian, and Spanish. A prominent legal treatise states, "Professor Ray Davis is the leading figure on weather modification law" (Robert Beck, *Water and Water Rights*, Vol. 2 Section 3.04[a]). His resume lists a total of 193 published items, including nine books and 20 chapters in books and treatises.

He was especially proud of authoring the *Arizona Workers Compensation Handbook*, the draft *Model State Water Allocation Code* and the textbook *Law in Action: American Government*. Ray Jay was an active member of the Weather Modification Association, and he served as its "legal eagle." He received the WMA's Thunderbird Award in 1978 at the association's annual meeting held in Tucson, Arizona.

ROBERT (BOB) D. ELLIOTT, a true pioneer in purposeful weather modification, died of a stroke at his home in Santa Barbara, CA, on April 5, 2002. Bob was 87 years old. He graduated from the California Institute of Technology in 1937 with an M.S. in meteorology. During World War II, Bob was a naval aerological officer based in Washington, D.C. The aerological group was responsible for the preparation of all weather forecasts for U.S. Navy operations, including the preparation of forecasts for the D-Day invasion. During this period he developed a storm typing system that is still in use by some meteorologists. The first *Journal of Weather Modification* published in 1969 contains the following discussion on the background of the Weather Modification Association: "On April 4, 1951, Messrs. Stuart Cundiff, William Lang, Eugene Bollay, Robert Elliott, John Battle, and E. C. Hartman met during a luncheon at the Mission Inn in Riverside, California. The object of this meeting was to discuss possible methods of organizing and controlling cloud seeding operations and evaluations in California for purposes of raising the standards with respect to those engaged in the business of weather modification." Bob was appointed treasurer of the organization with the suggested name of Artificial Precipitation Operators Association. At a subsequent meeting on April 17, 1951, the name of the organization was changed to Weather Control Research Association (now the Weather Modification Association). Bob served as president in 1951 and 1952 and vice president from 1957 to 1959. Bob was honored by the WMA in 1973 as the recipient of the first Thunderbird Award, and in 1978 he was selected as the third recipient of the Schaefer Award.

Bob participated in several landmark weather modification research programs throughout his professional career. Among these were the early Santa Barbara experiments conducted in Santa Barbara County, the Bureau of Reclamation's Colorado River Basin Pilot Project, and the Sierra Cooperative Pilot Project. One of Bob's interests through his involvement with these research programs was the development of computerized targeting models that could be used to calculate the transport of cloud seeding materials, their interaction with the cloud microphysics, and the resultant fallout of seeded precipitation. Bob was heavily involved in the development of a model that could be used in real time to help meteorologists predict this sequence of events.

The American Meteorological Society (AMS) in 1961 honored Bob with the presentation of the Award for Outstanding Contributions to the Advance of Applied Meteorology. He was elected a Fellow of the AMS and was a member of the original Board for Certified Consulting Meteorologists. He served on several committees, including ones organized by the American Society of Civil Engineers that, among other activities, developed the guidelines on cloud seeding in 1983. Bob was also a member of the American Association for Advancement of Science, the American Geophysical Union, and Sigma Xi.

OLIN H. FOEHNER JR., who served as the first director of the Sierra Cooperative Pilot Project (SCPP) of the Bureau of Reclamation of the U.S. Department of the Interior (USDI), and who was the original ASCE author of Section 2 of these guidelines, was lost at sea while scuba diving near St. Martin in the West Indies, May 27, 1983. During his active and productive career, Olin was a strong proponent of weather modification research and operational programs at the international level. Olin exercised a leading role in the planning and design of SCPP from its early stages until spring 1981 when he was reassigned as director of the Colorado River Enhanced Snowpack Test (CREST). During his time as SCPP director, the project moved from the initial planning to the design phase, the project's Auburn field office was established, the Skywater X Conference on the SCPP Design was held, the Sierra Ecology Project was initiated in cooperation with the Forest Service Pacific Southwest Forest and Range Experiment Station, and numerous other cooperative activities were initiated with the states of California and Nevada, various universities, and the private sector. A public involvement program with active participation of members of the Citizens Council was also created.

Olin's energy, his dedication to the long-term Bureau's Skywater objectives, and his appreciation for new ideas contributed immeasurably to the progress and success of SCPP, the Division of Atmospheric Water Resources Management, and the Bureau. Many colleagues miss both his expertise and his good humor.

LEWIS (LEW) O. GRANT was born on March 29, 1923, in Washington, PA. He passed away on July 29, 2013 at the age of 90. Lew grew up in Henryetta, Oklahoma, and served as a weather officer in both the Air Force and in the Field Artillery during World War II. In 1947 he completed requirements for a B.S. in physics from University of Tulsa and then in 1948 earned his master's degree in atmospheric science from the California Institute of Technology, Pasadena, California.

After serving in World War II, he was part of a team that was instrumental in helping the new State of Israel to develop its water resources, particularly in the Negev desert. The men on his team became his lifelong friends. Prior to moving to Ft. Collins, CO, Lew worked for the American Institute of Aerological Research in the areas of water resources, agriculture, cloud physics, and weather modification. In 1959, he joined the Engineering Department at Colorado State University to establish the Atmospheric Science Department. He was a CSU emeritus professor from 1993 to 1998.

Lew was a fellow of the American Meteorological Society and the Weather Modification Association and a past member of the American Geophysical Union. He was a past member of the Cloud Physics, Water Resources, and Weather Modification Committees of the American Meteorological Society. He served as a member of the National Science Foundation Advisory Committee for Atmospheric Science, the trustee from the university sector for the Weather Modification Association, and the university representative and president of the Consortium for Atmospheric Resource Development. He is the author or coauthor of more than 100 publications and/or scientific conference papers.

Several of the many awards Lew received as an atmospheric weather scientist include the Colorado State University Andrew Clark Award for excellence in research, the Vincent Schaefer Award of the Weather Modification Association, the 1993 Colorado State University Dean's Council Award, the 1976 Colorado State University Co-Interdisciplinary Environmental Research Award, and the Farm Bureau "Cloud Squeezer" Award in 1977.

HAROLD (HARRY) D. ORVILLE died Monday, June 6, 2011, in Rapid City, IA, at a local nursing home. He was 79. He was born January 23, 1932, in Baltimore, MD, to Howard and Lillian (Duvall) Orville. He grew up in Arlington, VA, graduating from high school in 1950. Harry graduated from the University of Virginia in 1954 and married Laura Milster that same year. Harry served with the Army Signal Corps and was honorably discharged in 1956 as a 1st lieutenant. He received his master's degree from Florida State University, Tallahassee, in 1956, and his Ph.D. from the University of Arizona, Tucson. Harry came to the Black Hills and the South Dakota School of Mines and Technology in February 1965. Harry helped set up the Department of Meteorology—the academic arm of Institute of Atmospheric Sciences—and became department head in 1974, serving for 20 years in that position. He took sabbaticals with the National Oceanic and Atmospheric Administration and the World Meteorological Organization, traveling extensively around the world. He served as interim vice president at SDSM&T in 1987 and 1993 and as acting director of IAS. After retiring from full-time teaching in 1996, Harry was named a distinguished professor emeritus in the Department of Atmospheric Sciences. Harry was a fellow of the American Meteorological Society and in 1993, was awarded the Charles Franklin

Brooks Award, the highest award for service. In 1965 Harry became the manager of Harney Little League teams, was active in the Boy Scouts of America, and served as PTA president. Harry was an avid golfer, becoming a member of the Hole in One Club in 1998, and initiated the annual South Dakota School of Mines and Community Golf Tournament, which has raised tens of thousands of dollars for scholarships. The seventh annual event took place the day that Harry passed away.

DONALD (DON) ROTTNER cofounded the OPHIR Corporation, a research and instrumentation company that focused on the atmospheric sciences. Don was president of OPHIR at the time of his death in Lakewood, CO, on May 23, 1995, about four months after the final editing of the ASCE Manual 81 of which he was one of the coeditors. In January 1980 Don started the OPHIR Corporation and was granted patents by the U.S. Patent and Trademark Office bearing his name as a coinventor.

In June 1963, the Air Force transferred Don to the University of Wyoming as a student and officer trainee. He received his B.S. in civil engineering in 1965, was commissioned in December 1965, and began service as a bioenvironmental engineer in the Biomedical Sciences Corps of the Air Force. He left the military to enroll in the Department of Atmospheric Sciences at the University of Wyoming in September 1969. After receiving an M.S. in 1971, Don joined the staff of New Mexico State University, where he worked as an assistant project engineer on a cloud seeding project conducted by the NMSU Department of Civil Engineering. He joined the Division of Atmospheric Water Resources Management of the Bureau of Reclamation in June 1972, and he became a professional member of the AMS that same year.

Working on Project Skywater, Don made significant scientific contributions. He was responsible for assembly, quality control, and archival of the data collected by a five-year, multimillion-dollar weather modification program in southwestern Colorado. The data management program maintained a huge database that included digital radar, satellite imagery, cloud physics measurements, rawinsondes, pibals, acoustic sounders, ground-based radiometers, precipitation networks, and ice crystal habits and concentrations. He used his expertise with OPHIR Corporation and his past experience in weather modification to become one of the coeditors of the ASCE Manual 81 in 1995, and he influenced at least two other employees of the OPHIR Corporation to be heavily involved with the same publication.

JOSEPH (JOE) A. WARBURTON suddenly and peacefully passed away at home on April 30, 2005, in Reno, NV, at the age of 81. He was born May 16, 1923, to Agatha and Joseph Leslie Warburton and was a born-again Christian who served the Lord his entire life. His contributions to the scientific community, Masonic fraternity, and humanity were larger than life. He loved laughing; farming in Yerington, NV; playing golf and piano; telling funny stories and jokes; and spending time with his family and special friends.

Joe served in the Australian Imperial Forces during World War II. Following graduation from Goulburn High School in Goulburn, NSW, Australia, he attended the University of Sydney in 1946, graduating with honors in physics and mathematics. Advanced studies in radio astronomy and the physics of the lower atmosphere led to a master's degree and Ph.D at the University of Queensland. He was employed at C.S.I.R.O. in Sydney. Joe established the Warburton Family Science Award at Goulburn High School to provide scholarships to outstanding science students.

In mid-1965, he along with his wife, Winifred, and their seven children emigrated to Reno, NV, where he was appointed to a senior scientist position at the Desert Research Institute. In 1969–1970 he served the university system as the president of DRI and later as the executive director of the Atmospheric Sciences Division from which he retired in 1993, the University Board of Regents awarding him emeritus status. Joe was currently working on a weather modification program he developed for the Snowy Mountains Hydroelectric Authority in Australia, in addition to writing a book titled *The Science of Weather Modification*.

Joe's scientific work is described in more than 120 papers published in scientific journals in the United States and other countries. He conducted research projects in Antarctica, France, Greenland, Switzerland, Canada, China, Australia, Morocco, Saudi Arabia, Iran, and Spain. Joe was appointed a fellow of the Australian Institute of Physics and was a member of the American Meteorological Society, secretary/treasurer of the North American Interstate Weather Modification Council, a member of the Antarctican Society, and an alumnus of the University of Queensland. His scientific awards include the Antarctic Service Medal and the Vincent L. Schaefer Scientific Award for outstanding original contributions in the field of weather modification. He was appointed as a visiting fellow at the Australian National University in Canberra, Australia, in 1996. He was recently honored for his work in the Antarctic by having a landmark named after him, Warburton Ledge, located four miles east of Mount McClintock in the Britannia Range, Antarctica.

CHAPTER 1
INTRODUCTION AND BRIEF SUMMARY

Thomas P. DeFelice, Ph.D., M.ASCE[1]*; and*
Conrad G. Keyes Jr., Sc.D., P.E., D.WRE, Dist.M.ASCE[2]

Modern cloud seeding technologies may be successfully applied to help resolve community water resource demand-related issues and have been for more than 60 years. Recent technological and scientific advances have strengthened the impetus for seeking applications of modern cloud seeding technologies that could benefit our society, primarily in regions where additional precipitation is viewed as an economic asset. The augmentation possible is fractional, and where successful, may be in the range of 5 to 20% (Elliott et al. 1995). However, this much additional rainwater over the farm belt could benefit agriculture; over mountainous terrain this could benefit the hydroelectric power industry, municipal water supply, and irrigation interests. The technology is not without limitations, which must be recognized and incorporated into decisions regarding its use. The technologies have changed slightly since DeFelice and Keyes (2006). The most significant changes in technology that are beginning to transfer into operations in the past 20 years include a polarimetric radar system (e.g., Thompson et al. 2014) and improved analysis tools that handle variable target/control area selection or individual radar cell selection (e.g., Woodley et al. 2003a, b; Woodley and Rosenfeld 2004).

It remains necessary to develop public consensus within an intended target area, because the smallest possible scale of treatment covers several hundred hectares or several million square meters. Many farmers might benefit from enhanced precipitation, while others might not in a farm area having mixed crops. In a mountainous region where hydroelectric power

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generation would be greatly benefited, traffic over mountain passes might be impaired, whereas ski resorts might be aided (Elliott et al. 1995). Rational assessments of each implication require scientific studies, which, to date, all suggest that developing the operational application of cloud seeding technologies can help mitigate the aforementioned impacts, provide sustainable water supplies, help reduce airborne hazards, and even improve evaluation methods for operational activities (DeFelice and Keyes 2006). Silverman (2001a, b) suggests that it might not be prudent to wait until drought conditions have developed to employ cloud seeding technology and that cloud seeding technology should be implemented as an integral part of an overall management strategy for a watershed or region.

1.1 WHY SEED CLOUDS?

Clouds form as part of the hydrologic cycle, which describes the processes of evaporation of water into (and within) the atmosphere, condensation, and precipitation that runs along and within the lithosphere into water bodies, only to repeat the cycle again. The efficiency of the precipitation process may be enhanced via application of cloud seeding technology. Precipitation efficiency is defined as the fraction of condensed water vapor that ultimately reaches the ground. The precipitation efficiency of a thunderstorm, for example, has been approximated as 19% (e.g., Houghton 1968).

Cloud seeding technology can help facilitate some components of the water cycle, which are important in dealing with many present and potential future scientific, environmental, and socioeconomic issues. A common misconception is that cloud seeding robs "Peter's" rain to water "Paul's" land. Properly conducted cloud seeding operations increase precipitation efficiency, resulting in more total rainfall, which falls over a broader area, compared with the unseeded case. Hence, cloud seeding benefits both "Peter" and "Paul." Obviously, this could be beneficial for farmers (e.g., DeFelice et al. 2014). Given the advances in our understanding of the hydrologic cycle and of precipitation processes, we have a better picture of when and where the atmosphere or cloud can most likely be modified to benefit humankind.

There are determinable benefits from cloud seeding to enhance precipitation efficiency within a cloud. These benefits manifest themselves in terms of increased hydroelectric power and agricultural production, salinity reduction, and strengthened ski industries; futhermore, water supplies are improved for fish and wildlife, recreation, municipalities, and industry. Thus, although the primary motivation for cloud seeding may be economic, there are clearly other potential benefits to public and private enterprise. Elliot et al. (1995) reported that rainfall increases of 10 to 40% (compared with normal rainfall) would increase corn and soybean yields by 4 to 20% if natural rainfall were near normal. The direct beneficiaries in winter mountain snowpack augmentation projects include those using the resultant enhanced streamflow for hydroelectric power generation and irrigation water and enhanced snow-base for ski resorts. It has been estimated that a 1 to 2% increase in rainfall (compared with normal rainfall) would, in many cases, pay for such cloud seeding projects.

1.2 APPROACHES AND RESTRICTIONS TO SEEDING CLOUDS

Chapter 3 of this manual covers the recent developments pertaining to legal implications of the use of cloud seeding technology. Awareness of public concerns, a responsive and well-guided public involvement program, a corresponding decision process, and ongoing evaluation of both the direct and indirect effects will provide many appropriate checks and balances as cloud seeding programs are conducted. If stakeholder groups and public concerns, perceived or otherwise, are not addressed prior to a project, a community might not accept a cloud seeding project within the watersheds surrounding the community in which it lives. Social, environmental, and economic factors also will affect whether a cloud seeding program is accepted by a community. Risk–benefit assessments in each of these categories, relative to alternatives for providing more water, are appropriate. The experiences from more than 60 years of seeding clouds, relevant lessons-learned exercises, conferences, discussions, and general public forums have generated, among other things, environmental issues (risks or impacts) including potential effects on cultural resources, erosion rates, duration of snowmelt, and contributions to the greenhouse effect. Legal guidance and restraints concerning cloud seeding ensure fair balance between opportunities to advance individual and group desires and concerns and the need to consider the rights of the remainder of society. The development of environmental impact statements (EISs) and reports has been necessary in some cases. Some early environmental concerns focused on the seeding agent, i.e., the ice-forming nucleant, AgI (silver iodide). Heavy metals occur in nature, and residual silver from seeding is normally produced in concentrations far below toxic levels (e.g., WMA 2009). This is only one of many environmental aspects of cloud seeding. It should be recognized that effects of added water on the environment could be negative and positive. Organizations that undertake operational cloud seeding should be prepared to invest the considerable time and costs of preparing EISs, especially if federal funds are used, and to consider the subsequent costs of environmental monitoring during operations (e.g., Elliott et al. 1995). Some states require the sponsorship of a weather modification operation to be responsible for conducting preliminary studies to assess, and quantify, various impacts the proposed seeding operations may have on the environment.

The chapter on legal considerations applied to atmospheric water management or cloud seeding has been adapted from Davis (1995) with adjustments to reflect recent developments pertaining to legal implications of the use of cloud seeding technology. Legal considerations apply to atmospheric water development implementation decisions in the same way that they apply to development of any other part of the hydrologic cycle. The ability of the federal government to affect weather modification policy resides within various appropriation acts that make government funding available for research in and development of cloud seeding technologies. The only federal statute governing weather modification pertains to reporting activities; practically all of American law specifically targeting weather control activities rests with the states.

As a means of avoiding misapplication of the technology by poorly qualified individuals; by groups focusing narrowly on special interests' benefits; or in uncontrolled, unmonitored, or conflicting projects, a legal system has gradually been developed for controlling the application of the cloud seeding technology. Many states in the United States have regulatory laws in place. Licensing, permitting, and reporting may be required. A U.S. law requires that the people who are carrying out weather modification activities report them (Elliott et al. 1995). Davis (1995) provided a list of current state statutory and regulatory references on weather modification.

1.3 SCIENTIFIC BASIS FOR CLOUD SEEDING

Cloud seeding technology is based on sound scientific principles. Chapter 4 of this manual describes the scientific basis necessary to provide an adequate understanding of how and why precipitation enhancement might be achieved. The basic principles of precipitation enhancement are well understood, but there is still much to learn about how clouds naturally produce precipitation, despite the significant advances made in recent years with regard to the amount and quality of empirical data, theoretical development, and instrumentation dedicated to this natural phenomenon. The fundamental scientific premise has been that a cloud's precipitation efficiency can be increased or that a cloud's vertical development could be enhanced (i.e., taller clouds typically produce more precipitation). The result is a more productive cloud. Initial experiments in the middle 1940s under the direction of Nobel Laureate Irving Langmuir at the General Electric (G.E.) Laboratories in Schenectady, NY, and the 1946 seeding field test by Vincent Schaefer in which dry ice was dropped into a stratiform cloud deck, were the first examples to support this premise. The dry ice acted very quickly after entering the supercooled water droplet cloud to transform the cloud hydrometeors into millions of fine ice crystals that grew and fell from its base, thereby increasing the efficiency of the precipitation process and leaving behind a distinct clearing in the cloud deck. This stratocumulus cloud evidently did not have many available naturally occurring ice forming nuclei to initiate the precipitation process.

Later, Vincent Schaefer and Bernard Vonnegut of the G.E. Laboratories discovered how to produce ice embryos by introducing a swarm of minute silver iodide (AgI) smoke particles into a supercooled cloud. Their structure is similar to that of ice, and water vapor deposits on them to form ice. Subsequently, other investigators discovered other nucleating agents. Presently, AgI produced in complexes with other chemicals remains the chief agent in use for glaciogenic seeding, although dry ice and some organics are occasionally used.

Scientific studies of ice crystal nucleation also yielded questions about the details of how nature produces precipitation. It is now recognized that clouds suitable for seeding are supercooled, relatively free of ice at critical times in their evolutions, and have appreciable natural dynamic forcing (Elliott et al. 1995). Clouds not meeting these criteria have little chance of producing precipitation and cannot be usefully seeded for this purpose. These studies have also led to the need for technologically advanced tools designed to measure, numerically model, and verify cloud processes, the dispersion of seeding material, and the effect of the seeding material on the cloud precipitation processes. These technologies would also be useful for evaluating cloud seeding potentials and effects. All tools have their limitations, and these should be included in any risk–benefit analysis, but the tools for cloud seeding have improved dramatically in recent years.

1.4 THE CONDUCT OF CLOUD SEEDING OPERATIONS

Seeding operations are conducted for several reasons besides the fact that cloud systems are inefficient at producing precipitation that reaches the ground. The principal elements of cloud seeding operations are the cloud with a potential to have its precipitation efficiency augmented; seeding material selection and its delivery and dispersion within the cloud volume; the resulting cloud physical, dynamic, and microphysical transitions to stimulate additional precipitation; the meteorology associated with the cloud system; and the fallout of precipitation. Chapter 5 of this manual focuses on the seeding material selection, its delivery and dispersion within the cloud, and the resulting dynamic cloud effects, that is, the how-to-do-it section.

The most commonly used method for producing artificial ice-forming nuclei is a seeding device or generator that, via combustion, vaporizes silver iodide (AgI) in solution with acetone and other chemicals, emitting numerous tiny (0.01 to 1.0 μm) AgI-containing nuclei. Flares impregnated with AgI offer another fairly common nucleant release option. Different AgI-complexes nucleate clouds at different rates and by different microphysical mechanisms, so appropriate selection is important. Cloud temperature is a governing parameter. The AgI–containing nuclei generally become active ice nucleants at air temperatures near and colder than −4 °C. Laboratory tests of the Weather Modification Inc. (WMI) wingtip generators with North Dakota AgI-acetone formulation yielded approximately 10^{14} ice particles per gram of AgI produced at −10 °C (DeMott 1997). A second popular material/method is to drop dry ice pellets into a cloud that contains supercooled water droplets. The dry ice method generally yields 10^{12} or more ice crystals per gram of dry ice and is effective at air temperatures as warm as about −1 to −2 °C.

Effective delivery and dispersal of the seeding agent from the source through the recipient cloud requires meticulous planning for optimal implementation during operations. The type of generating system employed and its mode of operation depend on the type of cloud systems requiring treatment. It also depends on making full use of available historic meteorological data and ancillary data where appropriate; time of operations (winter, summer); target area size, topography, and accessibility; funding available; and other project-specific aspects. Ground-based systems are most useful in wintertime projects in mountainous areas. They have limited utility in summertime projects. Aerial dispensing systems are ideally suited to summertime cumulus seeding either at cloud base, in cloud, or at cloud top. Both silver iodide and dry ice can be dispensed aerially; silver iodide and liquid propane can be dispensed from the ground, but dry ice cannot.

All projects require monitoring of seeding agent delivery and dispersal and evaluations to quantify their success. The evaluations often rely on statistical techniques, because the cost of direct monitoring technologies can be high. Evaluations should also include, whenever feasible, physically or chemically based approaches to verify and help quantify success. Seasonal streamflow or snow course, precipitation gauge, wind sensor, upwind rawinsonde, and modernized weather radar data (e.g., ASCE 2004; Elliott et al. 1995; DeFelice 1998) might all be useful in evaluation efforts. Instrumentation systems provide needed input data for real-time decisions, such as forecasting probable seeding opportunities, determinating “seedable” situations, conducting seeding operations, and exercising project suspension criteria. Instrumentation can also provide data for post-project assessment of the probable effects of cloud seeding based on critical parameters, such as precipitation or streamflow (DeFelice and Keyes 2006).

Project planners should bear in mind that the hygroscopic flare method is still considered somewhat new and is not yet used as widely as the AgI complexes, although it has shown considerable promise (Segal et al. 2004;

Cooper et al. 1997; Mather et al. 1996, 1997). Additional experimentation using this technique has been conducted in Mexico for rain enhancement (Bruintjes 1999). Future experimentation is needed to demonstrate that this technique can increase precipitation over a fixed target area for a significant period of time (e.g., a summer convective season).

The ongoing advances in technologies used to enhance precipitation or to monitor its success have allowed research project investigators to move away from purely statistical evaluations toward physical evaluation derived from direct observations of the seeding material delivery to clouds, the resulting physical response, the precipitation fallout, and the chemistry of seeded and unseeded precipitation that has reached the ground. The vastly improved numerical models that simulate cloud processes complement many new remote and in-situ atmospheric and cloud sensing technologies (e.g., sensor for continuously profiling the wind and temperature and radiometers and ground-based ice detector systems to determine the presence of supercooled liquid water, especially in orographic clouds). Measuring devices once considered for use in purely research projects are gradually moving into operations and should be reviewed by the would-be cloud seeder and used where affordable for both real-time guidance and postproject evaluation.

1.5 HOW TO INITIATE A CLOUD SEEDING PROJECT

Chapter 6 on how to implement a cloud seeding project has been adapted from Keyes et al. (1995) with major adjustments to reflect recent developments pertaining to the initiation or implementation of a cloud seeding project. The implementation of a weather modification program shall include protocols for ensuring that environmentalists, meteorologists, and water planners work together to safely and effectively yield and manage additional water resources in a target area. This final section provides readers with a blueprint for arguably the most difficult component of a cloud seeding project, i.e., its implementation. It suggests what some of the basic questions should be and then proceeds to methods for obtaining the answers.

Each scientist, engineer, and planner associated with a cloud seeding project must

1. Consider the overall need for a precipitation augmentation project;
2. Know the feasibility of the operation before implementation is initiated;
3. Know the approaches to augmenting precipitation;
4. Monitor program performance, evaluate program success; and
5. Document a lessons-learned exercise at program completion.

Criteria that administrative agencies consider for permit granting include project personnel and their field experience, seeding agents and modes, equipment, target area, operational plan, safeguard criteria, information gathering and evaluation plan for projected impact of seeding, and contract and cost information. Advisory boards or committees of experts often aid in the permit decision.

Chapter 6 covers such topics as initial program assessment and the factors governing implementation; needs and goals including the origin of need and program justification, political, and/or institutional justification; the feasibility study including program expectations and its objectives; program definition, which defines seeding modes and agents; an evaluation plan and quantification of findings; program control as in seeding decisions, data collection and access, and seeding suspension criteria; and program management including a lessons-learned exercise.

1.6 CONCLUSIONS

Cloud seeding technologies have been used to increase agricultural production. They have been applied to improve water supplies for various applications (e.g., recreation, fishing, municipalities industry) and to enhance ski industry activity.

The startup, continuation, and/or revision of a cloud seeding program to augment precipitation will most likely depend on the viability of the technology; the perceptions of the benefits and liabilities as derived from the whole environmental, social, economic, and legal process; the diligence with which effects are monitored; and how well public involvement is maintained. It is foreseen that a new era of technology will facilitate the acquisition of continuous, comprehensive, real-time, high-resolution (in time and space) observations for predicting and recognizing seeding opportunities, conducting seeding operations, and monitoring and determining cloud seeding effects.

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CHAPTER 2

SOCIETAL, ENVIRONMENTAL, AND ECONOMIC ASPECTS

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2.1 INTRODUCTION

Sociologists, ecologists, economists, geographers, political scientists, and as atmospheric scientists have addressed the complex issues that arise with the development and application of cloud seeding technology. Selected information exemplifying these aspects of cloud seeding is summarized in this chapter. This material is intended to stimulate appropriate consideration for the interdisciplinary factors that affect a successful cloud seeding program and/or projects according to Keyes (2006).

2.2 SOCIETAL ASPECTS

The decision to adopt cloud seeding historically has focused on the question, "Can we do it?" However, as technical capabilities improve, a value question arises, "Should we do it?" (Sewell 1969). Attempting to modify precipitation by seeding clouds is a product of people's continual search for means to manage their environment. Even in situations where cloud seeding offers potential economic benefits or environmental advantages, the weather can be purposefully managed only if those affected agree that it should be done (Borland 1977; Farhar 1977). Much of what actually can be done is governed by societal and/or political choice. The human dimensions of cloud seeding programs and/or projects must be considered if the technology is to be effectively used (Davis et al. 1980).

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Historically, interest in cloud seeding has risen during dry periods and waned when rain and snow are plentiful. Most communities where cloud seeding has been carried out have accepted scientific experimentation, and some communities have actively sought operational projects. In a few U.S. states, grassroots groups organized political opposition against cloud seeding, such as in California, Colorado, Delaware, South Dakota, and Texas. For proponents and opponents alike, once issues and attitudes toward cloud seeding are established, they tend to persist for a very long time (Farhar and Fitzpatrick 1990). Therefore, the would-be cloud seeder or water manager may be served best by gaining insights from social science about public response to cloud seeding and introduction of new technology in general (Reinking et al. 1995).

2.2.1 Studies

Research on social aspects has focused on public response to field studies where they have been proposed and introduced and on decision processes regarding the adoption of cloud seeding. Four kinds of studies have been conducted:

1. Surveys of citizen attitudes, opinions, beliefs, knowledge, and favorability toward cloud seeding (e.g., Farhar and Rinkle 1977; Krane 1976; Farhar and Mewes 1975; Larson 1973; Haas et al. 1972);
2. Monitoring of project areas to determine the factors associated with acceptance and rejection of cloud seeding (e.g., Farhar and Fitzpatrick 1990; Farhar and Mewes 1975; Farhar 1975a, 1976, 1977, 1978; Haas 1974);
3. Technology assessments of hail suppression conducted by an interdisciplinary team (Changnon et al. 1977); and
4. Nationwide surveys of weather modification experts (Farhar and Clark 1978).

Also, the 1988–1990 study by Farhar and Fitzpatrick (1990) revisited four cloud seeding projects studied a decade or more earlier, and Walkinshaw (1985) reported on the economic and social impacts of long-term weather modification projects in the United States.

2.2.2 The Diffusion of Innovations and Cloud Seeding

The diffusion of any technology into a population follows a well-understood pattern (Rogers 1983; Rogers and Shoemaker 1971). The rate of adoption is more rapid for technologies adopted by individuals (such as hybrid seed corn or the original birth-control pill) than for technologies adopted by communities (such as kindergarten or cloud seeding). In the former case, the innovation can reach saturation in as little as five years, whereas it took 50 years for kindergarten to be adopted by essentially all U.S. communities, according to Reinking et al. (1995).

The population usually can be represented as a "normal" curve based on the length of time individuals take to make the adoption decision. At the leading edge of the normalized population curve, representing about 2.5% of the population, are the innovators. They adopt quite early in the process and reap the benefits of doing so ahead of others, i.e., the innovative farmers who were the first to adopt hybrid seed corn reaped the financial benefit of having higher corn yields well before their neighbors.

Early adopters, the next 13.5% of the population, accept the innovation soon enough to benefit from early acceptance; opinion leaders are usually found within this group. The innovators and early adopters are highly receptive to change relative to the specific idea or technology that they favor, but they do not necessarily support all new ideas or technologies. The same innovators would not necessarily favor cloud seeding, hybrid seed corn, and birth-control pills. Following these groups are the early majority (those still adopting the innovation on the early side of the mean time required by the population) and the late majority (those adopting somewhat more slowly than the mean). This intermediate, great majority, representing two-thirds of the population, neither actively promotes nor opposes the introduction of new technology (Dennis 1980; Rogers and Shoemaker 1971). The opinion leaders (part of early adopters) shape the attitudes and actions of the early majority toward any innovation, including cloud seeding. This is why the opinion of community leaders is so important in the social acceptance of cloud seeding projects. The "laggards," comprising some 16% of the population, would prefer no change and are the slowest group to adopt. If a new technology does not work but is applied anyway, the laggards are most likely to avoid any associated disbenefits (Reinking et al. 1995).

2.2.3 Assessing Public Attitudes

The perceived value of cloud seeding, derived by weighing both potential opportunities and adverse effects, incorporates considerations beyond simple economics and the efficacy of the technology. The issues surrounding cloud seeding may reach deeply into social relationships and even into aesthetic and spiritual values, including concern about the risk of human intervention in weather processes (Reinking et al. 1995). Fear of disasters that might be perceived as potential effects of cloud seeding, such as flooding, avalanches, or ecological calamities that might carry property and social losses, also shapes attitudes (Dennis 1980; Farhar 1977; Larson 1973; Sewell 1966). There are, and most likely always will be, those who are convinced that it is possible to modify the weather and those who believe it is a fraud (Sewell 1966), irrespective of the scientific basis.

Scientifically conducted surveys can measure the distribution of opinion in factors that affect the social acceptability of projects. Examining the range of social factors that can come into play provides some perspective on this. Attitudes toward weather modification in Colorado, Florida, and South Dakota were measured using survey items that measured (i) favorability to the technology, (ii) beliefs that cloud seeding was effective in increasing precipitation and suppressing hail, (iii) concern about risk, (iv) credibility of sources of information about the cloud seeding program, (v) knowledge about the program, (vi) evaluation of the cloud seeding program, and (vii) preferred decision making and funding sources (Farhar 1975a, b).

Belief in the effectiveness of the technology, favorable attitudes toward it and toward science, and low concern about risk were statistically most highly correlated with positive public assessment of operational seeding programs. Belief in efficacy emerged in this and other research as the most powerful predictor of societal program evaluation outcomes. Information on the efficacy and secondary effects of cloud seeding is commonly and appropriately sought from the technical experts. Scientists themselves have divergent views on its efficacy (Farhar and Clark 1978). Although this is the nature of scientific probing, public disillusionment can be fueled by scientists who disagree in public about the facts and the attendant uncertainties (Lambright 1972; Changnon and Lambright 1990). Conversely, problems may occur if operators do not openly state the uncertainties. More recent AMS, ASCE, WMA, and WMO statements on atmospheric water management have been presented in the standard practice documents on precipitation enhancement (ASCE 2004), fog dispersal (ASCE 2013), and hail suppression (ASCE 2015). Some of the details of these statements are provided in Chapter 5, section 5.4, and other reports by the National Research Council of the National Academy of Science on weather modification were under review at the time of the second edition of this manual (Keyes 2006).

The South Dakota experience with cloud seeding is significant because the first state-sponsored weather modification program began there in 1972. At its height, the program included about 60% of the land area of the state at a cost of approximately $1 million each growing season. Surveys of the South Dakota public from 1972 to 1975 found the majority were favorable toward the program (Farhar 1973, 1975b). South Dakotans favored cloud seeding because they believed it would help farmers in a state where agriculture is the mainstay of the economy. Only after an opposition group organized and the legislature failed to appropriate funds did majorities fail to favor the program (Reinking et al. 1995). In contrast, river basin projects in California, Nevada, North Dakota, and Utah have maintained research and/or operational programs with public support for more than 50 years.

When a weather modification project has local sponsorship and strong local support over several years, even a large-scale negative weather event (such as a flash flood disaster) in the presence of cloud seeding may not produce organized protest. For example, findings from South Dakota show that the majority of respondents did not attribute the Rapid City flood to cloud seeding that had been carried out in the area. Even those who thought cloud seeding was to some extent responsible for the flood did not organize against it. A committee of scientists released an official report 18 days after the flood stating that cloud seeding was not its cause; this may have alleviated some citizen concern (Dennis 1980; Farhar 1974).

2.2.4 Assessing Community Dynamics

When federally funded undertakings have a significant effect on the quality of the human environment they must comply with the National Environmental Policy Act (NEPA). NEPA was designed to assure a concerned public that societal values will be considered in connection with such federal activities (Davis et al. 1980; Anderson 1973). Societal considerations are also now part of the permit issuance process for seeding projects in some states (Davis et al. 1980; Davis 1975). Moreover, both the final report of the Weather Modification Advisory Board (1978) and the report of the USDA required by Public Law 95-490 (1979) called for increased societal awareness by weather modifiers (Davis et al. 1980).

The decision to adopt cloud seeding most often is made by organizations and communities, not by individuals. Therefore, public opinion is but one factor in a community where this decision is being made. Furthermore, although several communities adopted cloud seeding during the 1950s and again during the 1970s, most of these projects have been discontinued since that time. This probably can be attributed to early overselling and consequent unrealistic expectations of a technology still in its infancy. Cloud seeding adoption by communities has not followed the "bell-shaped" distribution, according to Reinking et al. (1995).

Public acceptability is not identical to unanimous agreement. Public acceptance means that sufficient majority support exists to move a project forward without serious social polarization. Systemic (community-level) variables relevant to acceptance of cloud seeding (Mewes 1977; Weisbecker 1974; Haas et al. 1972) include the following:

1. Environment and conditions: Climate, water supplies, economic activities, topography, and population;
2. Structure and process: Institutions, organizations, power elites, stakeholder interests, and relationships among groups;
3. Interaction between the project community and communities downwind and downstream; and
4. The stream of events: Contingency events and planned action.

Stakeholder groups—the range of associations; state, local, and tribal governments; and individuals with economic or domain interests—may be affected by the proposed action. Difficulties in the application of a cloud seeding technology can arise if certain groups can be identified as economic losers (Haas 1974). The direct benefits of augmenting snowpack are in some cases realized downstream rather than in the affected target area; in one such case, some project area residents were opposed to cloud seeding because of "a resentment of outside politicians who make their winters longer and their weather-related problems worse, ... and the perception that the controlling authority will not be influenced by the wishes of the project area residents" (Weisbecker 1974). In some agricultural areas, where direct impacts and benefits of cloud seeding are collocated, the greater the affiliation of the cloud seeding program with some farm organizations, the more favorable the attitude toward the program will be (Larson 1973). Thus arises the issue of trust. Closely related is the issue of control. The desire is always strong to participate in—or have trusted representatives participate in—decisions that affect stakeholder interests.

The Sierra Cooperative Pilot Project (SCPP) offers another relevant case study. Agriculture, utilities, water districts, lumbering, cattle ranchers, and recreational interests use the Sierra Nevada's most valuable asset, water. SCPP's primary purpose was to develop and refine an effective snowpack augmentation technology that was socially and environmentally acceptable. In preparation for SCPP, the sponsoring U.S. Bureau of Reclamation and the State of California conducted 21 meetings in California and Nevada communities during 1974 to inform the public and to involve them in the project's planning process. The U.S. Bureau of Reclamation then sponsored a societal assessment of citizen and organizational response to the proposed project (Farhar and Rinkle 1977). The assessment concluded that the proposed project appeared to be acceptable; however, diversity of weather modification needs and some fear of local disbenefits characterized opinions. "The potential for opposition [was] definitely present, both at the systemic and individual levels" (Farhar and Rinkle 1977). With a recommendation from the researchers, SCPP managers established a citizen advisory committee in January 1978. The managers attended numerous public meetings and distributed a monthly newsletter to interested organizations and individuals throughout the area.

After seeding began, some opposition was expressed over concerns about increased snow-removal costs, greater flood and avalanche hazards, reduced ski business resulting from excessive snow and difficult driving conditions, increased road wear from tire chains, and general property damage. Project managers met with county supervisors and other interested organizations in the area, discussed their concerns with them, and successfully abated further opposition. SCPP also used project suspension criteria in cases of heavy snowfall and avalanche danger to mitigate these objections.

Over a period of years, these actions of involvement and responsiveness on the part of SCPP project managers decreased stakeholder and public concerns. Despite the presence in the area of several factors that could have contributed to the organization of opposition, the project enjoyed 10 years of experimental cloud seeding data collection in an atmosphere of public acceptance.

2.2.5 Decision Processes

Knowledge derived from the social science research in precipitation modification has helped and can help the involved parties communicate effectively and design strategies and policies that address public concerns fairly, allowing decisions to be made intelligently and responsively. So, sociologically, what are the most important factors affecting decisions to start, continue, or discontinue use of cloud seeding technologies (Reinking et al. 1995)? One social study, hereafter known as the Colorado State University (CSU) study, analyzed community responses and changes in response to the application of cloud seeding technology in four areas over a 15-year period (Farhar and Fitzpatrick 1990). Much of the following is based on the findings of the CSU study. These findings should not be regarded as universal, but they do offer considerable insight. According to the study's analysis, predominant (albeit nonexclusive) factors that should be considered when deciding about cloud seeding are

1. Built-in safeguards,
2. Local economic benefit,
3. Scientific evidence of effects,
4. Cost effectiveness,
5. Drought conditions, and
6. Compensation for disbenefits.

Clearly, a responsive approach toward stakeholders and public concerns can lead to a positive attitude toward project management (Farhar and Fitzpatrick 1990; Keyes 2002). Local control consistently has been found to be the preferred form of decision making on cloud seeding (Farhar 1977). Satisfaction regarding the aforementioned factors when taken into account leads to community satisfaction with the decision, whether the project is accepted or not. Public involvement will increase project costs, and "educating the public" does not lead necessarily to acceptance (Farhar and Fitzpatrick 1990). However, a public involvement program, tailored to requirements of an individual project, is the approach social scientists recommend to avoid community polarization and enhance the probability of community acceptance. This includes initiating public information programs, citizen advisory committees, and mechanisms for input by the public; listening and responding to constituency opinion; and implementing a compensatory mechanism for disbenefits if these are supported by adequate information. Research that will answer questions raised by citizens and organizations may also be appropriate. Providing trained project personnel to work with community concerns also may be appropriate (Reinking et al. 1995).

Formal decision processes that protect public interests and respond to public concerns lead to greater community satisfaction with the decision outcome. Figure 2-6 of Reinking et al. (1995) illustrates one concept of the stages in the weather modification decision process; factors affecting community response to cloud seeding are listed. All these community response factors feed into the decision-influencing factors listed previously.

The following is according to the CSU study as mentioned by Reinking et al. (1995):

> [T]he primary factor that determines whether cloud seeding technology will be accepted and applied is the informal influences in the project area at hand. If the informal power brokers in the community favor its use or continuance, then a project will tend to go forward. Those power brokers left unconsulted, uninformed, and their concerns unattended to, become the seedbed of opponent action.
>
> The second factor . . . is the relative advantage that adopting cloud seeding provides the community's members, as compared with not doing so or with doing something else. Cost-effectiveness and benefits to the local economy without undue risks (guaranteed by adequate safeguards) are essential to implementing and continuing projects. These benefits must be perceived by the local people, not merely asserted by proponents, scientists, or officials (Farhar and Fitzpatrick 1990).
>
> *Observation* of the project's effects is the third key factor. The effects of seeding will be observed by community members with interest, and they will come to conclusions about what cloud seeding is doing to their weather. If scientists bring sound evaluation data forward, this will carry some weight. However, the effects that the people themselves experience will be decisive. These observations are tied to belief in efficacy. If community members attribute [perceived or actual] positive effects—more rainfall and less hail for agriculture and more snow for ski areas—to cloud seeding, then project continuance is more likely to occur (Farhar and Fitzpatrick 1990).

This indicates that it would be wise for those introducing the cloud seeding technology, the broker/change agent in Reinking et al. (1995), to provide community representatives with observational experiences by means of available observing or numerical modeling technology and laboratory or limited-scale field demonstrations.

Safeguards, for example, might be suspension criteria for operations when snowpack is some defined level above normal or when avalanches are predicted. Compensatory mechanisms for clear liabilities have appeared to be more important in winter than in summer projects.

Other factors (not listed) that influence community response and consequent decisions are obviously important. For those who will listen, scientific answers about the efficacy of cloud seeding do exist, but science is ever advancing and "final and complete" conclusions are elusive. This aspect often confounds the public, as noted earlier. What would be acceptable as proof of increased water? It is important to have a practical answer to this question. To speculate, using statistical terms, for example, scientists may require broadly based evidence of a measurable effect at the 99% significance level, whereas the user or the public may be satisfied with significance at the 80% level (Reinking et al. 1995).

The perception of drought conditions as a predominant decision-influencing factor has stirred some scientific concern. Interest increases when cloud seeding is perceived as an effective drought-relief technology; this is not a surprising finding of the CSU study. Conversely, opponents have often cited cloud seeding as a cause of drought. However, scientists generally agree that the most soundly based approach to stabilizing water supplies is to conduct sustained rather than crisis-reactive cloud seeding projects (Farhar and Fitzpatrick 1990). Drought is normally caused by abnormally persistent flow patterns in the global-scale atmospheric circulation; this in itself suggests that the persistent pattern may potentially result in continued dry weather and, hence, reduced cloud seeding opportunity and also means to scientists that cloud seeding is not a cause of drought. Drought conditions commonly (but not always) offer fewer suitable clouds; seeding in such conditions can be counter to the scientific basis. One cannot expect to make scientists of the populace in a public meeting or two. However, only efforts to educate those concerned can establish a soundly based belief in the technology's efficacy and counter the all too accurate cliché that "interest in cloud seeding is soluble in rainwater."

2.2.6 Public Participation Procedures

Decision processes that promote public participation create a climate in which the community is satisfied with the decision regarding whether to go forward with the project. Community members themselves should agree with the decision processes employed. If they believe these processes to be

Table 2-1. Actions Managers Can Take to Foster Project Acceptance

1. Regard proposed projects as pilots and provide time to learn from implementing them.
2. Involve community stakeholders and local organizations with high credibility.
3. Form citizen review committees, keep them apprised, and listen to them.
4. Convey accurate and complete information to the public, repetitively, through familiar and trusted channels.
5. Explain limitations in knowledge or technique.
6. Identify any potential risks and their magnitude and develop mitigation strategies.
7. Alert the citizen group and the public to anticipated problems and enlist community members to devise solutions.
8. Listen to feedback, acknowledge it, and modify project design accordingly.
9. Continue work with the community during the project's implementation.
10. Build evaluation components into the project and provide feedback to the citizen group and the public on actual project effects.

Source: Reinking et al. (1995).

fair, equitable, and responsive to community needs and concerns, they are more likely to accept the decisions resulting from them. Taking the time to receive and respond to public input contributes to a more socially acceptable outcome. Steps that project managers can take to reach this outcome are noted in Table 2-1.

2.3 ENVIRONMENTAL ASPECTS

The management of any natural resource, including precipitation, leads to potential ecological changes. Therefore, potential ecosystem changes resulting from increased interactions of precipitation and cloud seeding materials with the environment must be addressed in weather modification projects. Several factors that complicate easy identification and quantification of cloud seeding effects on the environment are discussed here. A brief history of the research on ecological effects of weather modification shows the motivation for pertinent studies. The pertinent concept of cumulative effects is explained. Two case studies are examined that deal with potential issues; these exemplify research on ecological impacts of cloud seeding and environmental impact documentation for a prototype snowpack augmentation program (Reinking et al. 1995).

2.3.1 Historical Perspective

Several federally funded, multiyear ecology projects have provided vitally needed information on environmental processes that go beyond the immediate topic of cloud seeding effects on precipitation. The projects included the Medicine Bow Ecology Project (Knight et al. 1975), San Juan Ecology Project (Steinhoff and Ives 1976), Uinta Ecology Project (Harper 1981), and Sierra Ecology Project (Berg 1988; Berg and Smith 1980). All dealt exclusively with cloud seeding for snowpack enhancement, and all were located in the western United States. A Project Skywater (U.S. Department of the Interior, Bureau of Reclamation) impact assessment included environmental aspects of winter-orographic snowpack augmentation (limited to the higher altitude parts of mountainous regions) and summertime convective rainfall or shower augmentation (mainly in context of plains regions but may also be in mountainous regions) (Howell 1977; USDI 1977a). Other landmark documents include a technological assessment of winter orographic snowpack augmentation in the Upper Colorado River Basin (Weisbecker 1974), a more general discussion of ecological effects of weather modification (Cooper and Jolly 1969), and a comprehensive assessment of potential impacts of artificial ice-nucleating agents (Klein 1978).

Aside from the Sierra Ecology Project (SEP), the bulk of the research on environmental effects was completed by the early 1980s. The focused investigations addressed concerns, such as the direct effects of added snow on large and small mammals and indirect effects through change in type and abundance of food supply, possible physical and biological changes in aquatic systems, and impacts on vegetation. Thereby, the sensitivities of various ecosystems were estimated (see, e.g., Table 2-2). Some of the specific studies and results from the ecology projects are reviewed in the 1983 edition of these guidelines (Committee on Weather Modification of the Irrigation and Drainage Division 1983).

The essence of the results is that changes that might be expected in the environmental factors (i) were most often subtle, nil, or indiscernible in relation to other natural influences (e.g., effects of fire or insects on forest vegetation); (ii) would be of the same type and magnitude as would result from a sustained increase of a corresponding percentage in natural precipitation (e.g., as a gradual change in herb species composition might occur in a wetter climate); (iii) might be beneficial as often as not and depending on point of view (e.g., as when fish habitat increases with lake level); and (iv) would have net outcomes that strongly affect ecosystem management practices (e.g., as when increased weed growth and grassland productivity occur together). During the 1970s, the most common seeding agents, chemical complexes of silver iodide (AgI), were examined for ecological effects (Klein 1978; Cooper and Jolly 1970). Conclusions from

Table 2-2. Sensitivity Matrix for Selected Environmental Issues

	Environmental setting			
Environmental issue*	Alpine	Forest	Rangeland	Agricultural
Erosion				
Surface erosion	1		1	
Mass wasting	2	1	2	2
Avalanches	2	2		
Microclimate				
Snow duration	2	2		
Soil moisture	1	1	1	1
Water yield	2	2	1	2
Water quality				
Physical	1		1	2
Chemical		1	1	2
Channel processes	1	1	1	2
Sediment yield	2		1	2
Vegetation productivity		2	2	
Nutrient loss	2	2		

*Presumed environmental responses to prolonged precipitation augmentation of 20%. 1 = detectable but insignificant; 2 = readily detectable, sometimes important. Source: USDI (1977b); Reinking et al. (1995).

those studies point to little or no effects on terrestrial or aquatic biological communities, either immediately or after many years of silver or iodide application in the small dosages possible from cloud seeding (Reinking et al. 1995).

The 1970s ecology studies have credibility, but caution may be appropriately exercised in accepting the conclusions outright. New scientific advances in assessment of ecological response, if applied to cloud seeding, might render earlier results outdated. Even if extreme environmental shifts are not to be expected, potential lesser changes are to be respected. Just as a cultivated crop may respond to enhanced precipitation, so may certain elements in a natural ecosystem. The responses can be manifolding, possibly unexpected, and may follow multiple pathways. The past two decades also have seen changing interpretations of and more rigorous adherence to regulatory statutes. For example, implications of NEPA regarding cumulative effects that were completely unaddressed as recently as the early 1980s now often require extensive analysis and documentation. Litigation on environmental issues associated with land management in general also has expanded multifold (Reinking et al. 1995).

The very nature of environmental effects make them largely site specific. The myriad geologic, pedologic (soil), biologic, hydrologic, and climatic conditions that combine to form the environment of any cloud seeding project area are not necessarily duplicated elsewhere. Although changes in precipitation in the American River Basin of central California may not be expected to induce significant increases in mass wasting, similar changes in precipitation at a more geomorphically sensitive area could be damaging. Equal time must be given to the possibility of positive outcomes. Although most research has focused on conceivable environmental impacts in the negative sense, added precipitation or stabilized annual precipitation indeed may be beneficial to the ecology in many instances, except where stabilization or change of any kind in ecology might be regarded as negative (e.g., designated wilderness areas) (Reinking et al. 1995).

Other aspects of the status of the knowledge on environmental effects of cloud seeding directly influence the rigor of projections. These aspects include the research orientation of some of the major ecology projects and the burden of proof. The Sierra Ecology Project (SEP), for example, was tied directly to the Sierra Cooperative Pilot Project (SCPP). The SCPP was a multiyear research program designed to examine the potential for snowpack enhancement but not as a long-term operational cloud seeding program. SEP, therefore, did not consider the effects of an operational seeding project of unlimited duration and seeding intensity. Also, statistical proof often lacks the results of the ecology projects. Early observations emphasized the relatively large variation in both physical inputs (e.g., precipitation amount and timing) and biotic and abiotic responses. The magnitude of the commonly assumed 10 to 15% cloud seeding signal is well within year-to-year variability of natural precipitation. For example, both record low (462 mm) and high (1,704 mm) total annual snowfalls that were recorded at a monitoring station in the central Sierra Nevada occurred within the six-year duration of the SCPP. The signal is even more embedded in variations induced by longer-term climatic change. Given that ecosystem responses must react to these wide natural swings, it becomes extremely difficult to prove anthropogenic cause and environmental effect relationships. Time periods longer than the duration of the typical ecology project are needed to isolate the effects. This phenomenon of low signal-to-noise ratio, in combination with the often intricate and poorly quantified cause-and-effect networks of biotic and abiotic systems, leads to relative ignorance of the timing and magnitude of environmental response (Reinking et al. 1995).

The Snowy Precipitation Enhancement Research Project in Australia (Lincoln-Smith et al. 2011; Williams and Denholm 2009) commenced during 2004 following proclamation of the Snowy Mountains Cloud Seeding Trial Act 2004 (NSW). This legislation mandated the use of AgI as the seeding agent, permitted the use of indium oxide as an inert tracer, and required that cloud seeding operations be ground based only. It also required an environmental management plan to be developed and implemented for the project. That plan included an explicit obligation to monitor silver and indium concentrations across the study area.

Williams and Denholm (2009) indicated that an extensive review of the literature was undertaken prior to commencement of the project to determine if the use of AgI seeding agent would have an adverse effect on the environment. Although silver ions from water-soluble silver salts have been shown to be toxic to aquatic species, this is not the case for the insoluble AgI. Many studies have shown that the toxicity of silver ions in water is significantly ameliorated by the presence in water of chloride ion, carbonate ion, sulfide ion, and dissolved organic carbon. In addition, silver has been shown to strongly adsorb onto particulate matter in water. Recent research has shown that silver ion concentrations in natural waters are negligible, and an investigation in the study area has confirmed many of these ameliorating factors to be present.

Samples taken prior to the commencement of the trial showed measurable concentrations of silver and indium within all matrices (soil, moss, peat, water, sediment) and at all locations monitored. Routine sampling takes place each year during the winter months and following the cessation of cloud seeding experiments for the season.

Lincoln-Smith et al. (2011) examined trends in the concentrations of silver and indium in soil samples collected from 13 generator locations (the locations from which the seeding and tracer agents are dispensed) between 2004 and 2009. Comparison of the concentrations with the relevant environmental guideline trigger values showed mean concentrations, and the data indicated that temporal trends in concentrations were variable across locations.

The program of investigation described for the Snowy Precipitation Enhancement Research Project provided a powerful tool for environmental management and temporal patterns of variation in key response variables (i.e., concentrations of silver and indium in selected environmental matrices) and enabled rapid response by management well before concentrations could accumulate in the environment to levels of potential concern.

Brown (2011), discussing seeding activities in California, indicated that "it presently appears unlikely that cloud seeding activities will violate existing groundwater contamination or soil contamination laws and regulations. The California Regional Water Quality Control Board has previously stated that the maximum concentration limit of silver in soil is 5 mg/L when using proper testing methods. Under the current methods of cloud seeding, it is unlikely that this amount of concentrated silver would ever occur in soils. The silver iodide is released over a wide area and is unlikely to accumulate in concentrations which would be dangerous to humans."

2.3.2 The Concept of Cumulative Effects

Federal regulations (NEPA) define cumulative impact as (Reinking et al. 1995)

> The impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time.

The cumulative effects issue has particular significance, because cloud seeding typically takes place over extensive geographic areas, and ownership of entire catchments may be concentrated among a few individuals, companies, or public agencies. Increasing public and governmental concern makes this topic a focal point for formal appeal of proposed management actions (Reinking et al. 1995; Davis et al. 1980).

Several components of the cumulative effects definition warrant discussion. First, the phrasing on the timing of actions (past, present, and reasonably foreseeable future) dictates the need to consider future management activities, many of which are likely to be unknown. Second, because all relevant agencies or persons as potential parties to management actions are included, knowledge of the current and future plans of all parties is required. Private enterprises are not otherwise required to notify the public of their future plans. This often results in a major information void. In situations where both public and private lands are involved, as is typical for cloud seeding operations in the mountainous western United States, private landholders do not publicize their plans for future land management. Therefore, the "reasonably foreseeable future actions" clause is difficult to implement. Third, the definition forces assessment of combined (collective) effects of individually minor actions (e.g., cloud seeding) with other, potentially more drastic actions. It is conceivable that "minor" effects from cloud seeding become unacceptable in combination with effects from other, completely unconnected actions (Reinking et al. 1995).

The Board on Atmospheric Sciences and Climate workshop report (BASC 2001) recommended that a "watershed experiment" be conducted in the mountainous West using all of the available technology and equipment that could be brought to bear on a particular region that is water short and politically visible from a water resource management perspective. Boe et al. (2004) strongly supported this earlier recommendation, which was not then included in the NRC report. Also, the watershed experiment should include environmental impact studies including water quality; hazard evaluations, such as avalanches; stream flow standards; and protection of endangered species.

Boe et al. (2004) summarized the need for study of environmental impacts of cloud seeding programs: (i) nearly all orographic weather modification programs in the western United States involve public lands; (ii) all agencies both governmental and private that engage in these weather modification programs are confronted from time to time by concerned citizens and environmental groups with questions about the environmental impacts of weather modification and the chemicals used in these programs; (iii) in cases where seeding aerosol generators are to be located on public lands, the land manager (e.g., U.S. Forest Service) is required to issue an environmental assessment and negative declaration prior to issuing special use permits for generator sites; (iv) public agencies, such as municipal utility districts, and state water agencies often are required to issue environmental assessments, environmental impact statements, and declarations of negative effects to meet governing charters and law; (v) these environmentally driven requirements involve much time and resources; (vi) thus, research on environmental impacts of weather modification programs and seeding agents is also a definite need; and (vii) the development of a programmatic approach in this area could be highly beneficial.

2.3.3 Case Study–The Sierra Ecology Project

The 12-year Sierra Ecology Project (SEP) was designed to study the effects of precipitation augmentation on the central Sierra Nevada and Lake Tahoe area snowpack and forest ecosystems due to SCPP. SEP studies generally assumed a 15% maximum annual increase in precipitation in the context of a five to seven year randomized seeding experiment. Results were specific to the target area of SCPP. Background work on the climatologic and hydrologic regimes included evaluations of forest disease and insects (Smith et al. 1978a), deer and their habitat (Smith et al. 1978c), vegetation (Smith et al. 1978b), hydrologic processes (Berg et al. 1980), and lake and stream biota (Smith et al. 1980), as well as publication of a bibliography on environmental responses to weather modification (Smith and Berg 1979). Field studies and monitoring activities then addressed acidity of snowpack runoff, snow-vegetation dynamics, hydrologic consequences of rainfall on the snowpack, and hydrologic disposition of augmented snow cover (MacDonald 1986).

Two biological communities—subalpine meadow vegetation and mountain hemlock stands—were identified and studied as candidate systems that could change as a result of increased snowpack. These communities were thought to exist in microenvironments that received substantially more water than indicated by regional precipitation amounts. Hemlocks, for instance, occupy sites with cool and moist northern exposures, cold-air drainage, and abundant snow, often immediately below snow cornices. Meadows are often in drainage sumps that concentrate moisture. Among the findings were the following (Reinking et al. 1995):

1. Mountain hemlock stands would increase at the expense of other subalpine vegetation types if snowpack increased over the long term.
2. Some types of hemlock stands would become increasingly less species rich, and the size-structure patterns of hemlocks would be altered.
3. Snow cover duration was a principal control of subalpine meadow plant development, productive success, and existing vegetation patterns.
4. Long-term effects of snowpack increased by 30% every year might result in dramatic vegetation changes, but longer-term studies would be needed to substantiate this assertion.

The hydrologic effect of an extended snow cover was investigated in a field experiment by sprinkling water on 1,000 m^2 plots in a small basin for 11 days after natural snowmelt ended (MacDonald 1986). Rises in ground water were observed, but once the simulated snowmelt ceased, piezometric pressures appeared to decline more rapidly than before. Other data supported the contention that increases in streamflow resulting from snowpack augmentation would not extend appreciably beyond the time of soil desaturation.

Although the aim of snowpack augmentation projects is not to enhance rainfall, potential impacts from increased rainfall stood out in the SEP as the single most critical concern. In uncommon circumstances (e.g., increased rainfall on steep, disturbed, saturated soils), an increase in soil erosion by splash, sheet, or rill, and even gullying erosion is possible. Similarly, if snowpack augmentation resulted in a thin snow cover on ground that would otherwise have been bare, snowmelt during subsequent rainfall would lead to greater runoff than would have occurred naturally. Although these concerns are real, routine adherence to suspension criteria that guard against rain-induced flooding would reduce the likelihood of appreciable negative impacts (Reinking et al. 1995).

SEP recommendations included the monitoring of environmental situations anticipated to concentrate the effects of snowpack increases. Subalpine meadows and mountain hemlock stands were identified as candidate biotic communities. Snow banks and spring/seep communities were also candidate index sites for long-term monitoring.

2.3.4 Case Study–Environmental Impact Statement for a Prototype Project

The Lake Oroville Runoff Enhancement Program was a five-year prototype project underway in the Feather River drainage of California's Sierra Nevada. It was designed to augment snowpack by cloud seeding from ground-based generators with liquid propane as the seeding agent. The Plumas National Forest and the California Department of Water Resources (CDWR), the lead public agencies responsible for the proposed project USDA (1990, 1991), completed a comprehensive joint environmental impact statement/environmental impact report (EIS/EIR) in September 1990. The document was written to allow tiering to similar projects (should they be proposed). A wide range of potential environmental issues was assessed. These included water resources (e.g., rain-snow level, length of winter, snowpack, extent of delayed snowmelt, ground water, avalanches, runoff and floods, water use, and downwind precipitation depletion), erosion, water quality, plant communities, rare plants, wildlife, fish and aquatic life, endangered and threatened animals, cultural resources, aesthetic values, transportation, and safety (e.g., floods and avalanches, hazardous material spills, and fire hazard). Within these somewhat broad categories, a wide variety of specific sub-issues were identified, such as those associated with the installation and use of the propane ice-nucleating generators.

Some results from the joint EIS/EIR elucidate the extent of the investigation (Reinking et al. 1995):

1. Temporary facilities (the propane generators) installed on land allocated to semi-primitive management by the Forest Service will be removed in summer, painted white to reduce aesthetic impact, and located away from the hiking trails.
2. Land-disturbing activities (e.g., regarding the propane dispensers and precipitation gauges) can be minimized by the careful replacement of the disturbed soil as near to original conditions as possible, to reduce the possibility for increased erosion.
3. Changes in the amount and intensity of the snowpack and rainfall are expected to be well within natural variations.
4. The contribution of noncombustive propane seeding to the greenhouse effect is negligible in the anticipated seeding environment.
5. A delay in snowmelt of 0 to 3 days is estimated.
6. The propane seeding of cold winter storms will not have a depletable (negative) effect on precipitation downwind of the seeding area.
7. There should be no measurable direct effect on erosion from an augmented snowpack within the project area.

8. Plant species with extremely limited habitats, including narrow tolerance to soil moisture regimes, may be affected. Because precipitation would not be altered from the normal range, sensitive plant populations within the project area are not expected to change.
9. Cultural resources (e.g., prehistoric petroglyphs and historic buildings) have weathered the natural, extreme ranges of measured snowfall in the area and will not be affected by the probable increase in snowfall.

The joint EIS/EIR was appealed to the regional forester of the Forest Service's Pacific Southwest region on numerous issues, many dealing with a lack of site specificity and inadequate analysis of direct, indirect, and cumulative impacts of the proposed project. In response to the appeal, the regional forester affirmed six issues raised by the appellants. The issues were these:

1. The EIS/EIR did not adequately describe the existing known data that related to the watershed condition and fisheries habitat of the third-order streams.
2. There was not an adequate description of the cumulative effects and the factors used in the cumulative watershed effects analysis on the third-order drainages.
3. The effects of the project on sensitive, threatened, and endangered wildlife species needed to be better addressed.
4. A further analysis needed to be made on the potential effects of flooding on small streams.
5. Identification was necessary for any municipal supply watersheds within the project area, and, if they existed, what were the effects of the project on water quality in these watersheds.
6. Assurance was needed that the California Department of Fish and Game and the U.S. Fish and Wildlife Service were consulted on this project.

A supplement to the EIS/EIR for the project summarized the original EIS/EIR and successfully addressed these issues (USDA 1991). In all, several stages of development, response to identified issues, and levels of approval were required in the EIS/EIR process. A negative (no effect) declaration (which was not accepted), the original EIS/EIR (which was appealed), and the supplement EIS/EIR (which received final approval from the Forest Service in November 1991) required approximately one year each to prepare in succession at a total cost of $400,000 or more. At an additional cost of some $100,000 annually, continuous environmental monitoring of watershed effects was put in place for the prototype cloud seeding project.

2.4 ECONOMIC ASPECTS

Every effect of added rain or snow is unlikely to be anticipated, but efforts should be made to predict as many changes and impacts as possible (Stroup 1973). Rational decision making still calls for a valid benefit-cost analysis. Evaluating economic benefits and liabilities of weather modification accurately requires an understanding of the technology itself (Davis et al. 1980). In all, the practitioner has much better information than existed in the past, but the following general assessment, without regard to an indexed year for the reported dollar amounts, still remains in force (Keyes 2006).

2.4.1 Deciding the Goal and Scale of Economic Analysis

Many studies highlight the complexities of identifying and weighing anticipated economic benefits and costs to various segments of society and elements of the economy. "Failure to distinguish between net economic benefit and transfer effects [as in redistribution of wealth] has given rise to endless difficulty in the analysis of water projects in the past." Crutchfield (1973) advises, "There is no need to perpetuate the confusion in assessing new technologies." Appropriate measures of desirable or undesirable financial effects of enhanced precipitation are possible but depend on point of view, whether local, national, or global, and the geographical extent and nature of economic impact is a critical issue (Reinking et al. 1995; Davis et al. 1980).

Uncertainties in the technology add to uncertainties in the economic evaluations, but to some degree this is true in any area of interest. A global view of aspects appropriate to consider is stated by Sonka (1979):

> Because weather events can have severe adverse effects on economic activity, the gross benefits of successful weather modification activities are apparently very high. And, in general, the operational costs of modification activities are small relative to those gross benefits. [But] the existence of such positive net benefits does not insure that some individuals would not suffer substantial decreases in welfare. Probably the most important aspect in determining the credibility of any economic analysis, however, is the viewpoint of that analysis . . . . [I]t should be clear that the goal of the analysis is to determine the effects of the modification activity on the entire economy of a region, not just impacts on those sectors which derive benefits from the planned activity.

This view of a comprehensive economic evaluation must be tempered by the scope of an operational project and the practical capabilities of the organization or enterprise conducting or proposing to conduct the operations. This view does not imply that private enterprise or other individual or collective sponsoring organizations have no role in providing cloud seeding services. It simply means that a thorough economic evaluation of cloud seeding must involve calculated socioeconomic costs and benefits much more comprehensive than those that may be appropriate concerns for the private operator or sponsoring organization (Reinking et al. 1995; Crutchfield 1969).

Economic analyses for the adoption of cloud seeding technology in specific situations do offer guidance not only for vested stakeholders:

> In view of the uncertainties that attend the application of weather modification by cloud seeding, one might inquire why it has been so widely adopted around the world. The answer, of course, lies in the large economic benefits it offers. Although difficult to measure exactly, the perceived benefits far outweigh the cost of implementing programs (Dennis 1980).

Although a certain economic objective might be attainable through cloud seeding, this is not in itself sufficient justification for launching an operational program (Dennis 1980).

In all, there are no simple answers or alternatives in assessing benefits and costs of cloud seeding. There are, instead, many gray areas of compromise that must be acknowledged and considered (Dennis 1980). This is illustrated in the following discussion, where the economics for two different situations are considered: when cloud seeding is applied to enhance direct rainfall on crops (generally summer cloud seeding) and when additional water from seeding is impounded and released in a controlled manner for later use (generally winter cloud seeding) (Reinking et al. 1995).

2.4.2 Economic Aspects of Summer Cloud Seeding

Several studies of economic effects of summer precipitation enhancement have been conducted in the United States, primarily for the High Plains and the Midwest. The approaches and results reveal appropriate response variables and the levels of sophistication possible in such assessments and fundamental differences dictated by geography (Reinking et al. 1995).

2.4.2.1 High Plains The economic effects of added growing season rainfall on High Plains agriculture were examined at the North Dakota Agricultural Experiment Station (Schaffner et al. 1983). Five objectives were specified:

1. Measure dollar values of direct benefits to farmers and ranchers of added growing season rainfall.
2. Determine enterprise adjustments needed on the farm and ranch to respond most profitably to increased rainfall.
3. Measure the total added direct benefits to the four farming areas and the state.
4. Examine the broader enterprise shifts within farming areas due to added growing season rainfall.
5. Measure the total impact of added growing season rainfall on the economy of the state.

Depending on the farming area, added rainfalls of 2 cm for June through July and 3 cm for June through August were used to determine crop, livestock, and economic responses. The rain increases would be realized over many consecutive growing seasons. The added quantities represent much larger percentage changes for the western than the eastern parts of the state, because the western area is normally much drier. Linear programming models were applied to select the most profitable farm enterprise plans with normal and added rainfall. Changes expected in yield from 15 different crops and forages and in livestock numbers were estimated. Five-year average prices for crop and livestock products in each farming area were used in the economic analysis. An input/output model based on actual expenditure of North Dakota businesses was used to account for spending and respending to estimate responses of other sectors of the economy (e.g., finance, wholesale, and agricultural processing; construction; retail; real estate; services; households; government) (Reinking et al. 1995).

In 1977 to 1981 average dollars, the assumed increases in rainfall produced increases in direct returns over variable costs to agriculture for the western, west central, east central, and Red River Valley (eastern) farming regions of, respectively, \$53.0 (19%), \$48.3 (14%), \$47.1 (10%), and \$29.2 (7%) in millions of dollars per year. To meet these economic enhancements, changes in relative acreages occurred in each area to accommodate the most profitable crops and forage. Livestock production increased significantly in all areas but progressively more from east to west (Reinking et al. 1995).

Direct purchases by farmers from the local economy resulting from increased farm income and expenditures totaled \$226 million for the state in the model estimates. This total when spent and respent generated another \$450.9 million of estimated gross business volume, and the largest increases occurred in the driest (western) part of the state (Table 2-3). Business volume in this simulation increased in all economic sectors, and the largest increases were associated with households and retail (Reinking et al. 1995).

Table 2-3. Estimated Increased Business Volume Resulting from Increased Farm Income and Expenditures in U.S. Dollars (millions) Generated by Added Growing Season Rainfall by Farming Areas in North Dakota

Economic Sector Receiving Added Business	Western	West Central	East Central	Red River Valley
Added Farm Income and Expenditures	67.3	59.6	58.6	40.5
Economic Sector to Which Business Volume Accrued:				
Agricultural livestock production	5.3	4.3	4.4	3.0
Agricultural crop production	3.3	1.7	2.2	1.3
Sand and gravel	0.0	0.3	0.3	0.2
Construction	5.7	5.0	4.8	3.1
Transportation	1.1	0.8	0.7	0.5
Communication and utilities	6.8	6.0	5.8	3.9
Wholesale and agricultural processing	6.7	2.6	4.2	2.1
Retail	51.9	46.1	47.1	33.8
Finance, insurance, and real estate	12.3	10.2	9.7	6.8
Business and personal services	5.3	7.0	3.8	3.9
Professional and social services	8.0	6.5	6.4	3.9
Households	93.0	81.6	79.8	51.1
Government	6.8	5.9	5.7	3.8
Total Added Business Volume	206.2	178.0	174.9	117.4

Source: Schaffner et al. (1983); Reinking et al. (1995).

A more recent evaluation of the North Dakota Cloud Modification Project (NDCMP) by Bangsund and Leistritz (2009) found significant benefits to the agricultural sector. The study analyzed the benefits based on rainfall enhancement of 5 and 10% and a 45% reduction in crop hail losses. These results are supported by independent evaluations of the NDCMP (Dennis et al. 1975; Johnson 1985; Schaffner et al. 1983; Smith et al. 1997; Wise 2005). The evaluation found that direct benefits to agricultural production for counties participating in the NDCMP ranged from $12 million to $19.7 million per year. When considering 2010 NDCMP costs of $801,000, the benefit to cost ratios ranged from 15–25 to 1. Further, gross economic benefits, which consider the turnover of additional dollars in the economy, were estimated at $37 million to $60.5 million annually (Schneider and Langerud 2011).

The Panhandle Groundwater Conservation District (Rhodes et al. 2010) conducted its 2009 Precipitation Enhancement Program marking the tenth year of cloud seeding in the Texas Panhandle. The season began with the first mission on April 26 and concluded on September 25 with the last mission. Typically, the season has run from April 15 until September 30. The 2009 seeding season contained 25 days with seeding events, which consisted of 32 seeding missions and 23 reconnaissance missions. Several days during the summer were marginal days for thunderstorm development, which resulted in more reconnaissance missions than any other year. According to Active Influence and Scientific Management (AISM), during the seeding events the program seeded 32 clouds, which consisted of nine small clouds, 10 large clouds, and 13 other clouds. The seeding of these clouds helped to produce an estimated 718,000 acre-ft of water, which translates to on average about 1.65 in. across the water district. Taking into account the raw rain gauge data, the 1.65 in. can be translated to a 10% increase per county in rainfall received. The economic value of this additional 10% of rainfall remained about the same as during the 2008 season. The total cost of the seeding program in 2009 was about $201,000. Considering this figure, plus what an additional 1.65 in./acre is worth, the district cost per acre is about 5 cents. Axisa (2004) also used work by AISM and Woodley Weather Consultants to arrive at a benefit/cost of 235/1 in west Texas and southeast New Mexico.

2.4.2.2 Midwest United States Rainfall variability and differential geographical effects on selected agricultural areas were considered in a study of the potential benefits of cloud seeding in Kansas. An assumed precipitation alteration scheme that varied changes in rainfall rate and amount from a 10% decrease to a 75% increase was applied to a 30-year series of rainfall observations. The simulated average growing season rainfall increased in a range from 3.8 cm in southeastern Kansas to 5.7 cm in northwestern Kansas. The expected changes in yield (Table 2-4) illustrate that not all crops respond proportionately, and the total response depends on the climatic and agricultural conditions of the region. Benefits of added grain crop production were linked to the price conditions assumed. In the western region, where benefits were potentially the largest, the 1978 estimates ranged from $99 million to $127 million (Smith 1978). The higher estimate assumed no reduction in crop prices from increased production; the lower estimate considered such a reduction. With lower prices, the

Table 2-4. Average Expected Yield Changes due to Assumed Precipitation Alteration in Kansas

Crop	Eastern Kansas	Central Kansas	Western Kansas
Fallow wheat	—	+0.46 bu/acre	+4.76 bu/acre
Grain sorghum	+0.47 bu/acre	+0.25 bu/acre	+3.15 bu/acre
Continuous wheat	−0.07 bu/acre	+0.88 bu/acre	+2.31 bu/acre
Forage sorghum	—	+0.18 ton/acre	+0.17 ton/acre
Soybeans	+0.36 bu/acre	—	—
Alfalfa	+0.09 ton/acre	—	—
Corn	−0.02 bu/acre	—	—

Note: bu = bushels
Source: Smith (1978); Reinking et al. (1995).

study noted, producers in areas not directly affected by cloud seeding might experience loss of income, or the western part of Kansas might gain at the expense of eastern Kansas if a successful rain enhancement program were instituted statewide (Reinking et al. 1995).

In a related unique field experiment in Illinois, the actual effects of enhanced rain on crop production were evaluated. Large (9 m × 48 m) mobile, plastic-covered shelters with sprinkler systems were used to exclude natural rain but otherwise expose crop plots to the prevailing weather. Watering was quantified and timed to the historical rain-day precipitation records for wet, dry, and average summers, and water was added to simulate modification. Initial results indicated that rainfall increases of 10 to 40% in Illinois increase corn and soybean yields by 4 to 20% if natural rainfall is below or near average (Changnon and Hollinger 1988).

Refined results showed that for 2.5 cm of rainfall added during a hot, dry summer, yields increased "10 bu/acre for corn and 4 bu/acre for soybeans." In a summer of average rain, increases are less, about "5 bu/acre for corn and 3 bu/acre for soybeans." Yields of both crops were shown to decrease when summer rainfall exceeded 36 cm. Rain increases of realistic percentages applied with sprinklers only on days when natural rainfall was less than 0.25 cm provided no detectable yield increases, whereas a 40% rain increase on all rain days produced the greatest increase in crop yield. Corn yields responded well to added rain on days with 0.25 to 2.5 cm of natural rainfall (Changnon and Hollinger 1990).

Yield trends and stability influence both microeconomic (e.g., single farm) and macroeconomic (e.g., aggregate Corn Belt) decision makers as they set priorities for investment in new technologies, such as cloud seeding (Garcia et al. 1987). It is not feasible for a single producer to have a cloud seeding program, but groups of producers might do so. Thus, it is appropriate to consider local and regional impacts (Dennis 1980), i.e., the level of aggregation in effort, area seeded, and economic effect (Reinking et al. 1995).

As yields have steadily increased with improving agricultural technology other than cloud seeding, variability of yields and the absolute yield risk to producers also have increased. These increases in variability and risk could be because of a heightened sensitivity of technology to weather or to temporal increases in weather variability. These findings have implications for estimating the economic effects of a fluctuating climate and society's response to mitigate adverse effects. Enhanced precipitation and consequent moderated crop heat stress might reduce risk by alleviating extreme year-to-year yield changes. However, yields are influenced by a broad set of agriclimatic conditions that must be considered in estimating the overall impact of weather. Therefore, differences in estimated weather effects on yields for similar aggregation levels must be accounted for. Lack of sensitivity to these differences can result in inappropriate measurement of the distribution of economic gains from activities such as cloud seeding. The effects of seeding are likely to be regionalized, and this can distort its relative attractiveness to user groups representing differing spatial aggregations, such as a few farms, a few counties, or a state (Garcia et al. 1987).

To aid in policy making, an effort was made to determine the economic beneficiaries of a functioning precipitation modification technology when applied at various spatial and temporal aggregations (Garcia et al. 1990). The results of the simulation illustrate potential distributions of economic effects, demonstrate the importance of careful planning in the use of weather modification technology, and provide information that is useful in determining the roles of local, state, and federal governments in support of weather modification (Reinking et al. 1995). Differences in soil types, climatic conditions, and crop response all influence producer revenues for a region of given size with precipitation enhancement over a given time period. According to the Garcia et al. (1990) study, producers within small target regions (with increased precipitation and crop yields) realize the largest revenue gains. Producers outside the small target regions experience only small revenue reductions due to the increased competition. The added revenue from a small area within a larger target region declines, and the revenues of producers in adjacent nontarget regions are reduced much more as the size of the total target region increases. The econometric simulation led to the conclusion that "for programs covering multistate areas, the change in total [producer] revenues to the target areas is negative." However, in the simulation, consumer savings increase with the size of the target area of successful precipitation enhancement. These results stem from changes in the regional and national balances of supply and demand. An increase in revenue for producers from added precipitation over time favors multiyear use of precipitation modification technology over one year of isolated use. However, it is cautioned that successful precipitation enhancement continued over several years may change production and technological responses within and outside the target areas and change consumer and producer benefits (Garcia et al. 1990).

2.4.3 Economic Aspects of Winter Cloud Seeding

Winter cloud seeding to augment snowfall in high-elevation areas is designed primarily to increase runoff for hydroelectricity and water supplies for lower-elevation, semiarid areas (Foehner 1983). In this situation, the primary beneficiaries usually do not reside in the project area. Projects conducted to enhance snow for winter sports activities are an exception. In either situation, the economic value of additional water can be calculated somewhat more readily than in cases in which crop response is directly involved (Reinking et al. 1995). Estimated benefit/cost (B/C) ratios of 23.5 : 1 (2002) to 9.7 : 1 (1999) for enhanced runoff for hydroelectric power production were reported by Griffith and Solak (2002, 1999).

Managed water is normally assigned a value equal to the cost of obtaining it, storing it, transporting it to the region of use, and distributing it to the users (Dennis 1980). However, water and electricity supply and demand also influence its value. Favorable effects on the net economic productivity of a hydroelectric utility system include more efficient use of storage capacity, a favorable change in the ratio of peak to average plant capacity, and a reduction in the overall capital intensity of the hydrogenerating system (Crutchfield 1969). Snowpack managed for the winter sports industry is used where it falls, and it directly benefits the many industries associated with skiing. The availability and direct benefits and costs of the managed additional snowpack or runoff will have ripple effects in other economic sectors.

The Western States Water Council (1982) indicated that a funding alternative being considered to pay for the U.S. Bureau of Reclamation Colorado River Enhanced Snowpack Test program was for Congress to levy approximately 1 mill/kwh on power generated at Colorado River system hydropower plants. Theoretically, the additional 1.5 maf/year of new snow melt would increase total power revenues enough to balance the 1 mill cost to power users. Proponents also asserted that the increased snowmelt runoff would improve water quality by diluting the present salt load.

Griffith et al. (2010) provide information about a feasibility/design study that determined an effective winter cloud seeding program can be established and operated for a portion of the Eastern Snake River Basin located in eastern Idaho. The program has the potential to enhance the snowpack by 5.5 to 7.6% during an average winter season, with the result of an additional average March through July runoff estimated of about 78 to 149 thousand acre-ft depending on whether ground-based seeding only or ground-based seeding plus airborne seeding is utilized.

The estimated costs to achieve these increases in March through July combined area streamflow are $2.95 to $4.51 per acre-ft. Conducting the proposed single winter season of area-specific meteorological monitoring prior to the start of operational seeding would serve to refine the preliminary program design. The estimated cost of this one season of observations was about $244,000.

Also, a review was conducted of the potential environmental impacts of the proposed program that included consideration of downwind effects, toxicity of seeding agents, avalanches, snow removal, and previous environmental impact studies. This review concluded that no significant environmental impacts would occur through implementation of this program.

One might think that factors affecting the value of additional water would be the same throughout the western United States. However, there is actually considerable diversity in the factors that determine the cost and value of (added) water (Reinking et al. 1995).

2.4.3.1 Arizona and Nevada Arizona receives some 90% of its renewable water supply from winter precipitation. This state relies on groundwater for 40% of its water supply, even with the newly opened aqueduct provided by the Central Arizona Project. According to the Arizona Department of Water Resources, overdraft of aquifers can be 2.5 million acre-ft/year; this can lower the groundwater level by several hundred feet, making it cost prohibitive to pump, causing land subsidence, and introducing water quality problems. New considerations are being given to water augmentation and reuse programs. Indeed, Arizona public policy, driven by economic and environmental considerations, officially acknowledges cloud seeding as a possible water augmentation method (Gelt 1992; Reinking 1992). The Salt River and Verde River watersheds contribute 1 million acre-ft/year; here alone, a 15% increase in runoff would meet the needs of 750,000 people annually. For Nevada, the Desert Research Institute indicates that the 1990 valuation of urban water rights is about $2,500/acre-ft, and runoff yields from precipitation enhancement at 0.025 cm/h for normal hours of precipitation would cost about $10/acre-ft (Reinking et al. 1995).

2.4.3.2 Utah Utah is the second driest state in the United States. The winter snowpack and associated runoff are necessary for agricultural and urban supplies and for the ski industry. The state spends some $8.5 million annually (1990 valuation) on water development, according to the Utah

Division of Water Resources (UDWR). Demands for urban use have increased with the state's population, an increase of about one-third since 1990. As in other states, early season snowfall is highly valued by the ski industry. The agricultural need is for late-season irrigation water, which is valued near $40/acre-ft, according to the UDWR, whereas the estimated direct cost of water from a hypothetical 8 to 12% increase in snowpack from cloud seeding in key mountain watersheds is $10/acre-ft. A comprehensive in-state study by UDWR (Stauffer and Williams 2000) estimated the cost of producing additional water by cloud seeding at about $1/acre-ft. In recent years, as many as 18 counties or water conservancy districts have contributed nearly $0.5 million to cost-share operational cloud seeding with the state (Griffith et al. 2009). This level of cost sharing has continued and has been considered a reasonable benefit-cost risk. The state has collaborated in the past with the federal government on research to determine the actual efficacy of cloud seeding (Reinking 1992; Reinking and Meitin 1989; Super 1999; Super and Heimbach 2005). In recent years, states in the lower Colorado River Basin have provided some financial support to upper basin states (Utah, Colorado, and Wyoming) to enhance existing operational seeding programs affecting areas around the Colorado River tributary.

Benefit-cost ratios of 3:1 to 10:1 were estimated for 10% mountain snowfall increases in the Sevier River Basin in Utah (Super and Reynolds 1991). The basis was the amount of additional water potentially produced, estimated value of the additional stream flow, and direct cost of conducting an effective operational program. Not accounted for were other benefits and costs that would affect an aggregate benefit-to-cost ratio. The 10:1 ratio reflects costs of the Utah operational seeding program as currently conducted, using a mixture of manually operated valley, canyon-mouth, foot hill, and low-mountain generators. The 3:1 ratio reflects the additional costs of using closely spaced, high-output generators high up the windward slopes to improve targeting. The National Weather Service River Forecast Center in Salt Lake City estimated that about 10,000 additional acre-ft (14%) would be produced in the mean annual runoff by the assumed 10% snowfall increase above the 2,440 m elevation. See Fig. 2-2 of Reinking et al. (1995). This estimate was derived with a snow accumulation and ablation model that numerically accounts for various physical processes taking place in the snowpack (Anderson 1973). The UDWR then estimated the value to the land areas along the Sevier River drainage at about $18/acre-ft. For the 880-ft/km^2, high-elevation target, $10,000 was the annual cost of the standard operation; $53,000 per season was the cost with the addition of the high-altitude seeding option (15 additional, remote-controlled generators, capital costs, and seeding materials) (Reinking et al. 1995). In more recent UDWR studies (Stauffer and Williams 2000; Stauffer 2001), it was estimated that the operational winter cloud seeding projects in Utah generate approximately 250,000 acre-ft of additional runoff. These UDWR studies estimate the cost of producing the additional water to be approximately $1/acre-ft via the current operational winter orographic cloud seeding program methodology used throughout Utah.

North American Weather Consultants (NAWC) had approximately 150 manually operated ground generators installed for the 2013–2014 winter season in Utah. NAWC (Griffith et al. 2009) does agree that cloud seeding from remotely controlled ground generators may be more effective under certain conditions, but the cost of implementing a large remotely controlled ground generator network to affect the large target areas in Utah is prohibitive. The cost of remotely controlled ground generators is approximately $40,000 each without any consideration of installation or maintenance costs. A network of 150 remotely controlled generators that would match the number of NAWC's lower-elevation generators would cost approximately $6 million just to cover the acquisition costs. There are additional complications regarding the implementation of a large, remotely controlled generator network. Suitable sites must be found and leases arranged for these locations. Often, these suitable sites will lie on National Forest or Bureau of Land Management lands, which may well make the approval for such use problematic. Remote locations may require over the snow or helicopter servicing during the winter, which can be an expensive proposition.

The design of programs using remotely controlled ground generators for smaller target areas, in Utah or elsewhere, where the resultant water has significant value (say, several hundred dollars per acre-ft or more) may be justified. Water in Utah for agricultural purpose is worth perhaps $10 to $15 per acre-ft and perhaps $50 to a few hundred dollars per acre-ft for municipal water supplies (Utah State Water Plan 2001). Contrast these values with the value of municipal water in parts of California, which may be worth several hundred dollars to near $1,000 per acre-ft (California State Water Plan 2013).

2.4.3.3 California Because precipitation in California varies extremely with latitude, and surface water is transported from the wetter north to the drier south, water values are typically much greater in the south. Economic analyses commonly segregate water value by use, with hydroelectric power generation, agriculture, and in-stream uses listed most often. The geographic distribution of each of these uses in addition to the dryness of the year partially determines water value (Reinking et al. 1995).

In 1992, a dry year, the California Department of Water Resources (CDWR) judged the average value of "new" water from the Feather River basin of northern California to be $30/acre-ft. The CDWR Drought Water Bank in 1992 paid $50/acre-ft for real, new water at the delta in the Sacramento Valley and marketed it for \$70 to \$75/acre-ft in the same location after accounting for conveyance losses and other charges. In 1991, also critically dry with larger urban shortages, the Water Bank paid \$125/acre-ft, which translated into a price of \$175/acre-ft plus transportation costs to users south of the delta. Water values are at least \$150/acre-ft in the south coastal area and even higher in some local areas in the south. One analysis listed total agricultural and hydrogeneration value of water for the Kings River (southwest slope of the Sierra Nevada) as more than \$320/acre-ft in 1986 (Romm and Ewing 1987). Henderson (2003) reported benefit/cost ratios of six long-running programs in California. Benefit/cost ratios were calculated to range from 13 : 1 to 61 : 1, based on precipitation increases of 2 to 9%. The study valued the additional water at \$60/acre-ft and additional electrical generation at \$20/MWh, both conservative estimates. Opportunities to generate additional water by cloud seeding are generally fewer in the south, but the higher value may make projects with lower yield worthwhile (Reinking et al. 1995).

Brown (2011) indicated that "California officials estimate that cloud seeding throughout the Sierra Nevada could easily produce another 300,000 to 400,000 acre-feet of water annually. It is easily foreseeable that California may determine that cloud seeding is far more economical than other methods of increasing water supply, such as desalination. It is, therefore, feasible that California may dramatically increase its use of cloud seeding in the near future."

2.4.3.4 Colorado Approximately 70% of Colorado's water is supplied by snowmelt runoff (Sherretz and Loehr 1983), and snow is extremely valuable while on the mountains, because winter sports have surpassed agriculture as the state's leading industry. Six major runoff-producing areas within the Colorado River Basin have a total high-water yield area of 58,500 km^2/ft. If cloud seeding could produce 1.43×10^6 acre-ft annually within the Upper Basin (approximately 10% of the average annual streamflow), and an additional 0.83×10^6 acre-foot in the lower and adjacent basins, of the total, "approximately ... 1.7×10^6 acre-feet would be available to reduce deficits and meet new demands. Valuing this water at ... \$30/acre-foot, the total benefit from additional water would be \$48.5 million/year" (Lease 1985). This estimate is based on a computer simulation of the impact of additional runoff produced by cloud seeding. The model of the Colorado River reflects water availability, salinity, and demands on water by municipal, industrial, energy, agricultural, and other users. On the basis of projected time and water demand relationships made for points along the river, the impact on river water supply and quality can be predicted (Lease 1985).

The possible increases in streamflow from cloud seeding could significantly increase the quantity and value of energy output from small-scale hydropower facilities in Colorado (Loehr et al. 1983). Given a value for electric power, Loehr et al. (1983) developed a method for evaluating the impact of weather modification from a run-of-river facility and a conventional dam. They found the wholesale value of power from such facilities ranged from $0.014 to $0.12/kWh, depending on the circumstances in which the energy is produced and used. For two sites studied, they estimated that a 15% increase in April 30 snow water equivalent increases electric energy output by 3.5 to 6.1% and its value by 5.0 to 9.9% annually (Reinking et al. 1995).

For the Colorado ski industry, any delay in opening-day/early-season snowfall or slow business at Christmas due to lack of snow substantially affects the state's economy. Sherretz (1983) statistically estimated that 15% snowfall increases for hypothetical dry winters at Colorado ski areas are associated with 2 to 8% increases in total season visits (skier visits equal the number of lift tickets sold). Sherretz's "conservative" estimates during the early 1980s of retail expenditures by these additional skiers were in the $0.5 to $10 million range for six ski areas. The activity in the Colorado ski industry has magnified manyfold since then, so early-season snow is all the more important to state economics. The antithesis is that "additional snow in the midseason probably does not significantly increase skier visits and attendant retail expenditures" (Sherretz 1984). The Colorado counties that do not host ski areas benefit from wages paid to residents who commute to jobs at ski areas (Reinking et al. 1995).

Snowmaking machines at the lower elevations of the ski slopes have greatly increased the stability of opening-day and low-snow periods. However, some ski areas do employ cloud seeding, especially to try to ensure reliable snow cover at the highest elevations. The relative value of the benefits might be estimated by determining the cost of meeting the requirements by these alternative methods (Reinking et al. 1995).

A frequently expressed concern of residents in cloud seeding project areas is that more snow will mean greater snow-removal costs. From a local viewpoint, it has been suggested that citizens whose lifestyles and incomes are negatively affected by enhanced precipitation may require compensation, which would be computed on variables such as wages lost or costs incurred from incrementally more adverse weather (Weisbecker 1974). However, it has been found to be very difficult to assess the cost of removing an additional increment of snow (Reinking et al. 1995).

Responding to such concerns, the Colorado Department of Natural Resources assessed county snow-removal procedures and developed a computer model to simulate snow-removal costs (Sherretz and Loehr 1983). Costs were simulated because most counties do not keep detailed records of snow-removal expenses. Information on wages, equipment, and removal procedures was obtained by interviewing road maintenance foremen. Variations in these factors and snow-removal strategies are reflected in the time required to remove a certain amount of snow in different counties (Reinking et al. 1995). Colorado Mountain and Western Slope counties were encouraged to develop procedures for collecting data of sufficient detail to compute snow-removal costs accurately. A large (25%) increase in snowfall owing to cloud seeding was assumed in one-third of the observed storms. Estimated costs per employee for removing snow from unseeded storms ranged from $1,300 to $11,000 in a winter of heavy snowfall. Additional snow from seeding was estimated to increase removal costs by 0.8 to 12.6% in a heavy snowfall winter. The average cost increase over all counties studied was 6.1% in winters with heavy and average snowfall and 4.9% in winters with low snowfall. Somewhat in contrast, the California Department of Transportation found that the increases in snowfall in near average or below average precipitation years are within the range covered by the major fixed costs for equipment and labor. In California, spring flooding can be a problem, so cloud seeding operations might be suspended in years when snow depths significantly exceed the average. Such aspects are aggregate effects, similar to those identified with summer seeding (Reinking et al. 1995).

A winter orographic cloud seeding program has been conducted in the Gunnison, CO, region for each winter season the past 12 winter seasons (through the 2013–2014 season). The intended target area is elevations above 9,000 ft MSL that provide streamflow to Blue Mesa Reservoir located in western Gunnison County. The goal of this operational program has been to augment higher-elevation winter snowpack, which subsequently contributes to spring and summer streamflow. This program has operated under permits granted by the Colorado Water Conservation Board. The program is supported by a number of local entities, and it also has received some funding support from the Colorado Water Conservation Board and the three Lower Colorado River Basin states (Arizona, California, and Nevada). A network of 20 to 25 ground-based AgI generators has been used to seed all storm periods thought to represent good seeding opportunities on the basis of targeting considerations and the likely presence of supercooled liquid water. A historical target/control evaluation technique was developed, based on NRCS SNOTEL April 1 snow water content observations to provide estimates of the potential effects of cloud seeding. These estimates indicate average seasonal increases in the 10 to 15% range. Calculations were made of increases in April through July streamflow on the basis of indicated increases in April 1 snow water contents. Increases in the range of 79,600 to 96,200 acre-ft in an average April through July runoff were indicated based on a 10% increase in April 1 snow water content for an average winter season. Costs of producing the augmented runoff based on these calculated increases in streamflow ranged from $0.94 to $1.13 per acre-ft (Griffith et al. 2011).

2.5 CONCLUSIONS

Social, environmental, and economic factors will determine whether or not a cloud seeding program is accepted. Benefit-cost and risk-benefit assessments are appropriate for each of these categories. Many levels of sophistication are possible in measuring, analyzing, and projecting the intertwined socioenvironmental and economic effects. Benefits of cloud seeding are determinable for increased hydropower generation, salinity reduction, enhanced snowpack for ski industries, and increased water supplies for fish and wildlife, recreation, municipal, industrial, and agricultural users. Also, each of these potential benefits carries some potential liabilities.

Silverman (2010) has indicated that the World Meteorological Organization (2007) recommended that "Confidence intervals should be included in the statistical analyses to provide an estimate of the strength of the seeding effect so informed judgments can be made about its cost effectiveness and societal significance."

The possibilities and costs of meeting the requirements by alternative methods and the consequences of having no such technology should be considered. Appropriate measures of possible direct and indirect effects and divisions of responsibilities for providing the analyses and dealing with their outcomes must be determined (Reinking et al. 1995).

The potential sphere of influence of the cloud seeding operation and the goals of the analyses are important considerations. The heterogeneity of the affected population gives rise to diverse goals and the potential for controversy. Awareness of public concerns, a responsive and well-guided public information/involvement program, a corresponding decision process, and ongoing evaluation of both the direct and indirect effects will provide many appropriate checks and balances as a cloud seeding program is brought from concept to application. The fundamental principles to be applied to successful siting and operation are not unique to cloud seeding projects. The same kinds of issues are encountered with power transmission lines, waste-to-energy conversion facilities, nuclear-waste disposal facilities, and a multitude of other less "newsworthy" endeavors that may benefit people if properly guided and managed. Whether to temper a view of the risks of conducting cloud seeding with a perspective for the risks of not understanding and developing alternative technologies for providing adequate water supplies is a matter of social choice. The startup and continuation of a cloud seeding program most likely will depend on the perceptions of the benefits and liabilities as derived from this whole process, the diligence with which effects are monitored, and how well public involvement is maintained (Reinking et al. 1995).

2.6 REFERENCES

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CHAPTER 3

LEGAL ASPECTS OF WEATHER MODIFICATION OPERATIONS

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3.1 INTRODUCTION

The weather is a key component of the natural environment that belongs to all of us. Any attempt to alter the weather for the benefit of some has important ramifications for others who live in proximity to them. Thus, we find the practice of weather modification is regulated in most of the United States, particularly in those regions along and west of the Mississippi River where cloud seeding has been employed over the years for the enhancement of precipitation (rain and snow) and, to a lesser extent, the suppression of deleterious elements, such as large hail. Regulation is also critical because history is replete with instances of purported "rain makers" who took money from the citizenry (especially desperate farmers and ranchers battling drought) only to be found out as charlatans. Government efforts to screen potential practitioners of weather modification activities are aimed at identifying such exploitation and protecting the public from it. Moreover, state regulation is justifiable, because governments regulate the allocation of water from waterways to users, and cloud seeding traditionally has been used as an intended means of water augmentation. In every instance, laws governing human behavior must be expressions of policy decisions intended to ensure an equitable balance between the opportunity to advance individual and collective interests and the need to consider the rights of others. A law is the mechanism by which such determinations about public policy are expressed and applied (Hurst 1950). This chapter has been adapted from Davis (1995) and Bomar et al. (2006) with

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adjustments to reflect recent developments pertaining to legal implications of the use of cloud seeding technology.

Laws relating to weather modification are formulated and implemented by all three branches of the federal government and state. The federal role in regulating weather modification is, at least to some, quite limited in scope. Federal involvement is summed up in Public Law 92-205 [Title 15 U.S. Code Anno. section 330-330(e) (West 1976; Supp. 1993)], which requires individuals and organizations performing weather modification activities to report them systematically so that the public's right to know is accommodated. This law expresses policy in the broadest sense, while leaving the responsibility to "fill in the details" with administrative entities (usually agencies) within the states, which possess rule-making authority. The scope of federal policy is limited to reporting. The National Oceanic and Atmospheric Administration (NOAA) is the agency designated to collect reports on weather modification activities among the states and issue a summary report annually on those activities.

It is at the state level where an array of weather modification rules and regulations are formulated and enforced. These legal constraints administered at the state level are designed, among other objectives, to protect citizens from incompetent or dishonest purveyors of weather modification technology [Section 3.7 Appendix (Davis 1995) has a list of state statutory and regulatory references]. More specifically, state regulation of weather modification is designed to ensure that (i) practitioners of the science are competent, and (ii) they have the resources to compensate anyone harmed by those practices. Individuals or organizations seeking to conduct weather modification operations must secure a license or a permit, or both, in some states. To obtain such authorization, applicants must demonstrate that the person or people to be in control and in charge of the operations have the requisite training and work experience. In most instances, states require those making day-to-day decisions about cloud seeding operations to possess academic degrees in meteorology or closely related fields. Applicants also must supply proof that they are financially responsible. This most often is done through the purchase of liability insurance or the posting of a bond.

Rules and regulations having to do with professional licensing and permitting within individual states have been promulgated by the pertinent state regulatory agencies [Section 3.7 Appendix of Davis (1995)].

Similar to the federal reporting requirement, various states have rules and regulations requiring licensed or permitted individuals or organizations practicing weather modification to provide data and other information about their activities to the appropriate state regulatory agency, usually on a monthly or quarterly basis. In many instances, though, the data and information required are more substantial and specific in content than those reportable to NOAA.

The court system has a role in defining atmospheric water rights and cloud seeding liability, although that role is not nearly as overt as that of the legislative branches. The courts have essentially formulated law by ruling on those rights and liabilities. This has been accomplished through case decisions made by the courts, including the writing of opinions justifying those decisions, thereby establishing precedents that often are followed in subsequent, similar court cases. Thus, any understanding of weather modification law must be gained from both judicial rulings and the work of the other two branches of government.

Although the role of the federal government may seem limited in gathering data and information about weather modification operations, its influence on the practice of weather modification policy can be far reaching. Federal appropriation measures, which make government funding available for research in and development of cloud seeding technologies, leave an indelible imprint on where and to what extent weather modification is performed. Such influence was first brought to bear in the 1970s, when the U.S. Congress not only enacted a law calling for a study of prospects and policies for atmospheric water management but also provided the funding for such a study. The investigation was duly carried out and reported (Weather Modification Advisory Board 1978).

The legal aspects of atmospheric water resource development and implementation are at play during three different phases in the life of a weather modification project: (i) preoperational planning, (ii) conduct of a project, and (iii) evaluation of the work accomplished.

3.2 PREOPERATIONAL PLANNING

The steps to be taken in preparing for a weather modification project usually include but may not be limited to the following: (i) obtaining a weather modifier's professional license; (ii) securing a weather modification operational permit; (iii) complying with environmental law stipulations, where relevant; and (iv) entering into a contract of sponsorship between the entity sponsoring the weather modification operation and the individual or organization conducting the project.

3.2.1 Role of Regulatory Entities in States

Nearly two-thirds of the states have, at some time and to varying degrees, implemented legislation about cloud seeding. The scope of these state laws varies from the rather complete North Dakota regulatory and funding scheme to the bare mention of atmospheric water in Hawaii (Beck 1991). In the vast majority of the states with weather modification regulatory responsibility, provisions exist to require people intent on performing weather modification work to submit to a regimen for gaining the necessary credentials.

3.2.2 Weather Modification Licenses

Because occupational competency is of fundamental public concern, the licensing of professionals in the United States is commonplace. Like doctors, lawyers, accountants, and engineers, those who practice weather modification must be licensed (including the regulators). In those instances where states require both a license and a permit, it is the request for a license that focuses attention on the credentials of the individual making day-to-day decisions about seeding operations.

3.2.2.1 A Basis for Occupational Competency Licensing criteria focus on two major factors: educational qualifications and operational experience. Generally, these are merely alluded to, if not mentioned, in various states' legislation. It is up to agencies implementing the statutes to ensure that they are fleshed out in administrative rules. Although competency criteria differ among the states, they most often list a minimum number of academic credit hours of college instruction in meteorology, mathematics, engineering, and other physical sciences, or combinations of these. They usually also require a certain number of years of experience working at weather modification projects. As a rule, integrity requirements are not so specifically delineated. However, at the very least, the criteria, when met, suggest the licensee has not been shown to be dishonest. A decision to license a meteorologist for work in a particular state sometimes relates to whether that individual has been certified by the Weather Modification Association (process available at http://www.weathermodification.org).

3.2.2.2 Initiating the Process for Obtaining a License Usually, where applications for weather modification licenses are concerned, licensing agencies have discretionary authority in deciding whether to grant or deny a license. Administrators have more than the power to determine whether the application process has been fully complied with. They can weigh qualifications as part of their decision-making process. Unless administrative fact finding is arbitrary or unreasonable, regulators have the final word on whether persons can practice weather modification in their state (Davis 1995). Courts will not overturn licensing decisions just because the judges disagree with the regulators (Pierce et al. 1985).

Whereas some state regulatory agencies have the prerogative to call for an interview of the applicant, most often face-to-face meetings are not necessary. Instead, regulators use information submitted by the applicant in the form of standardized applications, accompanying documents (e.g., diplomas, college transcripts, licenses from other states, lists of published papers, descriptions of work experience), and letters of recommendation and data otherwise unavailable to the licensing agency. Testing, like that employed by legal or accountancy board certification examinations, is rarely done.

Weather modification licenses most often are valid for one year, and license fees in most states are quite modest—a few hundred dollars at most per year. Renewal in most instances is virtually automatic.

Suspension or revocation of licenses, and refusal to renew, is all theoretically possible under most state weather modification statutes and agency rules. As a practical matter, though, the initial grant of the license (or its denial) is the most critical decision made by the regulator.

3.2.3 Weather Modification Permits

Governmental regulation of weather modification not only ensures that the interests of the public are protected by a somewhat vigorous licensing effort, but it also supports the implementation of the technology for the public's benefit. Permitting is designed to protect the public interest by excluding projects with inadequate technical merit and insufficient financial backing. By weeding out the unsavory projects, the worthwhile ones are helped. Moreover, permits are designed to ensure that adjoining projects do not interfere with one another.

To ensure that the public is adequately informed about efforts to control the weather, an integral part of the permitting process is the requirement in some states that planned weather modification activities be identified in "notices of intention" published in newspapers and/or electronically. The notice provides specific information on when, where, and how weather modification activities are to be conducted so that citizens can discern whether they are likely to be affected and can weigh in with any concern to the proper authority. The methodology is usually described in these notices, along with information about steps the public can take to seek more information, express a view, or ask for a public meeting on the matter.

Nearly half of all the states have in place regulatory provisions that require government approval of the "conceptual plan" of a weather modification project before cloud seeding can be lawfully carried out (see Table 3-1).

In most cases, state weather modification laws provide for exemptions to certain activities. These could include the following situations:

- Laboratory research and experiments;
- Activities of an emergency nature, for protection against fire, frost, sleet, or fog; and
- Research, development, and application of weather modification technologies conducted by state and federal agencies, institutions of higher learning, and bona fide nonprofit research organizations.

Table 3-1. States with Cloud Seeding Regulations, Legal Rights, and Liabilities Provisions

State	Public Funding	Project Regulation	Notice of Project	Reporting Seeding	Legal Rights and Liabilities
Arizona		X		X	
California	X		X	X	X
Colorado	X	X	X	X	X
Florida		X		X	
Idaho	X		X	X	
Illinois	X				
Iowa	X				
Kansas	X	X		X	
Louisiana	X	X			
Michigan		X		X	
Minnesota	X	X		X	
Montana	X	X		X	
Nebraska	X	X			
Nevada	X	X		X	
New Hampshire	X				
New Mexico	X	X	X	X	
New York	X				X
North Dakota	X	X	X	X	X
Oklahoma	X	X	X	X	
Oregon	X	X		X	
Pennsylvania		X		X	X
South Dakota	X	X		X	
Texas	X	X	X	X	X
Utah	X	X	X	X	X
Washington	X	X		X	
Wisconsin		X		X	
West Virginia		X		X	X
Wyoming	X	X	X	X	

Notes: Public Funding—government funding of cloud seeding projects; Project Regulation—requiring project permit and/or cloud seeding license as a condition of lawful seeding; Notice of Project—requiring publication of a notice of the project; Reporting Seeding—record keeping of projects and periodic reports of them; Legal Rights and Liabilities—legal liability for harm caused and legal rights in water.
Source: Bomar et al. (2006); Keyes (2003); New Mexico Law (2003); Langerud (2014); Solak (2014).

3.2.3.1 Criteria Considered during the Permit Process Before issuing a weather modification permit, administrative agencies in various states consider the following and want the answers to the questions listed:

1. *Personnel:* Will the project have licensed personnel on the premises? Are the meteorologists, pilots, and other employees well qualified for their respective roles?
2. *Methodology:* What cloud-seeding agents will be used? What are the rate, timing, and methods of dispersal?
3. *Equipment:* What types of dispensing gear will be employed (ground-based generators, aircraft)? Are the weather radar and other monitoring and measuring equipment adequate for the tasks planned?
4. *Project area:* Are the target, operational, and control areas well delineated?
5. *Operations plan:* Are the methodologies to be used of sound, scientific merit? Are there cloud-seeding suspension criteria to be followed?
6. *Data collection and archival:* What are the plans to obtain, process, and analyze data to evaluate the efficacy of the project?
7. *Assessment:* What methods will be used to evaluate the impact of cloud seeding? Will the planned work affect any other permitted weather modification operation?
8. *Contract and cost information:* What contracts will be negotiated?
9. *Liability insurance:* What types of insurance coverage will be furnished? Is such insurance adequate?

Some states require the sponsorship of a weather modification operation to be responsible for conducting preliminary studies to assess and quantify various impacts the proposed seeding operations may have on the environment. The resultant environmental impact statement (EIS) identifies various environmental consequences of "no action" and "proposed action" alternatives. The required scope of the assessment may address the likelihood that resultant increases in precipitation are actually occurring within a defined target area and potential effects on any changes in background precipitation in areas downwind of the target. It also could provide insight into the potential for seeding agents to have an adverse eco-toxicological effect on the study area environment. It may need to quantify, using hydrologic models, the impact of precipitation increases on stream flow and ground-water usage, and any deleterious effects on fish and other wildlife habitats.

By issuing permits, either as requested or in altered form, regulators are able to shape projects in ways best suited to protect the interests of the cloud seeder, sponsor, persons affected by the project, and the public. Many states have highly competent agency personnel who carry out their delegated tasks in a highly professional manner. These personnel may rely on advisory committees or boards of experts for needed expertise in processing requests for permits. In states where effective regulatory work is in doubt, the deficiency may well be because of inadequate funding.

Once an application for a permit is in hand, the relevant state agency decides what actions to take. Its strategy may be aided by the fact that its personnel already possess familiarity with the design of the project to be permitted. In most states one requirement of the permit applicant is that public notice of the permit application be published in newspapers in the area to be affected by the project. This enables the public to bring any concerns about the proposed project to the attention of the agency. The agency may determine that public hearings should be conducted to facilitate interaction with the public on various permit issues.

3.2.3.2 Site and Time Specificity In most instances a weather modification permit is issued for a single project for a specified period (from one season to several years in duration). Consequently, any appreciable delays in making permitting decisions can affect projects adversely. Decisions made by state agencies are subject to judicial review, and courts usually uphold administrative determinations. However, in cases involving errors of law or unreasonable findings of fact, courts may reverse agency decisions (Gellhorn and Levin 1990). Because long-term weather modification projects often involve substantial financial commitments, in some states regulatory agencies are given power to grant provisional approval (subject to annual review) to permit applications for longer periods of time. Permit fees are either set by state law as fixed amounts or as percentages of contracts.

The initial decision by an agency to grant or deny a permit is almost invariably the critical one. However, there are instances in which regulators refused to renew permits, and there is authority in regulating agencies in some states to modify permits while they are in force. A permit is a valuable right but one that can be administratively altered or expired at the end of its designated term.

3.2.3.3 Historical Overview of Permitting Controversies In recent years several permitting disputes have been particularly vigorous. Local opposition to hail suppression in the high plains of Texas led either to denials or revocation of weather modification permits, which in turn resulted in alterations to the Texas regulatory law, making it easier for protesters to block permit issuance where hail suppression was the objective (Kirby 1978). An appeal to the courts for judicial review of a permit decision in Colorado resulted in a decision by the regulating agency not to consider permit applications unless and until it was given a line-item appropriation to enforce its cloud seeding control law (Davis 1987).

Litigation headed off issuance of a permit in Montana for snowpack augmentation to the Bonneville Power Administration [Montana

Wilderness Association v. Hodel, 380F. Supp. 879 (D. MT 1974)]. Then, in 1992 litigation over the effort by operators of the North Dakota weather modification program to seed clouds resulted in issuance of a permit, ordered by a Montana court, to allow seeding inside Montana upwind from its North Dakota target area [North Dakota Atmospheric Resources Board v. Board of Natural Resource and Conservation, No. ADV-92-918 (MT 1st Judicial District Court, 1992)].

3.2.4 Impacts of Environmental Laws and Rules

With its goal of altering natural weather intentionally, the management of atmospheric water attracts scrutiny from people concerned over environmental quality. Sponsors and operators of weather modification projects must comply with applicable environmental statutes and regulations.

3.2.4.1 Adherence to Environmental Constraints State laws requiring a valid permit as a condition of lawful cloud seeding can be used to further environmental protection goals. During the permitting process, regulators can ascertain whether a project is environmentally sound (Davis 1995). Then, as cloud seeding projects are conducted, the reporting of activities (usually by the agency or some contractor working for the regulator) yields information that can be used to determine whether the projects have complied with environmental considerations (Davis 1975).

Where compliance with environmental laws is in question, public or court action can affect remedies. Possible changes in snowpack depth, for example, triggered expression of concern over wildlife by a Montana environmental group that went to court to stop the proposed cloud seeding project (Davis 1995). The group invoked environmental laws that it asserted would have been violated ([Montana Wilderness Association v. Hodel, 1974)] (Davis 1968).

3.2.4.2 Considerations for Environmental Impact Statement Federal agencies proposing to undertake projects having a "significant" impact on the "quality of the human environment" are required by the National Environmental Policy Act of 1969 to file a "detailed" environmental impact statement (EIS) [Title 42 U.S. Code Anno. section 4321 et. seq., Pub. L. 91-190 (1970)]. A few states, including some with active weather modification projects, have passed similar laws applying to state agencies. Because funding research and development of weather modification technology has been an important federal activity and using government money for operations has been undertaken in some jurisdictions by the state, its subdivisions, or both, requirements for impact statements can be important (Davis 1995). Such statements require appreciable time and money, and if they are not done correctly, the project could be enjoined until the EIS is acceptable.

Laws mandating environmental impact statements require that the EIS contain (i) the environmental impact of the proposed action, (ii) any adverse environmental effects that cannot be avoided should the proposal be implemented, (iii) alternatives to the proposed action, (iv) the relationship between local short-term uses of human environment and the maintenance and enhancement of long-term productivity, and (v) any irreversible and irretrievable commitments of resources that would be involved if the proposed action should be implemented (Plater et al. 1992; Davis 1995).

Preparing an EIS usually follows certain steps: (i) data collection concerning the elements of the EIS, which may be by borrowing from other statements relating to similar projects, by carrying out an "environmental assessment," or by conducting studies; (ii) preparation of a draft impact statement; (iii) circulation of the draft statement to receive comments from interested governmental agencies, groups, and persons; (iv) consideration of comments and reaction to them by altering the proposal or the final EIS, or both; and (v) filing the final statement with the appropriate governmental agency (Anderson 1973; Davis 1995).

There are cases in which snowpack augmentation has run afoul of bureaucratic interpretation of federal environmental policy. The Wilderness Act of 1964 established the Wilderness System, units of which are added by specific congressional inclusions of parcels of federal lands deemed appropriate for wilderness protection (Davis 1995). In wilderness areas, where many prime sites for snowpack augmentation exist, certain activities are banned. Officials of some federal agencies have taken the position that the law bars installation and monitoring of hydrometeorological data collection equipment, at least where mechanized means are used to install and service them (Davis 1975, 1995).

3.2.5 Contractual Agreements among Sponsors and Operators

Where a sponsor seeks to enlist the services of an individual or organization to conduct cloud seeding operations, a key step in the process is negotiation, preparation, and execution of a formal sponsorship contract.

3.2.5.1 Perspectives of Sponsors and Operators From the operator's perspective, a critical concern about the prospective sponsor is ability to pay the contract price. Some sponsors, such as utilities and ski areas, have adequate financial resources. So do governmental sponsors, although they must rely on the appropriations process of legislatures and comply with relevant fiscal laws to raise and spend taxpayers' money. Conversely, entities without ad valorem taxing authority, such as agricultural cooperatives, have a less attractive record of being able to fund projects over an extended period.

Reliance on governmental funding of weather modification has its drawbacks. Where taxpayers' funds for public works projects like cloud seeding are concerned, three types of funding laws are applicable to atmospheric water management: (i) general legislative grants of authority to spend appropriated funds, (ii) authority specially granted to the sponsoring agency by law to spend money on cloud seeding activities, and (iii) such special authority coupled with power to establish legal entities with taxing power to raise funds for weather modification (Changnon et al. 1977). Obviously, the availability of funds for a project is dependent on political support. In the absence of adequate appropriated monies, the project has to be terminated (Donnan et al. 1976).

From the sponsor's point of view, the ease or difficulty with which contracts are successfully negotiated is related to the availability of operators. Historically, the number of eligible individuals or organizations with the requisite experience and tools to perform cloud seeding is small. Personnel for whom services are contracted should have a weather modification license if the project is located in a jurisdiction requiring licensing. The Weather Modification Association (WMA) maintains information about certified operators and project managers, who are listed in its 2004 publication (p. 107), the *Journal of Weather Modification*, and on its website, www.weathermodification.org.

Contracts negotiated between sponsors and operators address the following concerns: Who will be responsible for obtaining the necessary licenses and permits? Who will supply needed weather forecasts and other relevant meteorological services? What seeding material delivery systems will be furnished and when? What records, including cloud-seeding data, weather information, and hydrological data, will be maintained and archived? What suspension criteria will be followed, and how will sponsors and operators convey their concerns about implementation of those criteria? Who will be responsible for writing and submitting to the proper authorities the requisite summary reports? Who will arrange for legal liability insurance coverage?

3.2.5.2 Ethical Standards Relating to Expectations and Claims As recommended by the ethics and standards policies of the WMA, operators should take measures to comply with professional ethical standards relating to sponsorship contracts (WMA, see http://www.weathermodification.org). This entails avoiding the following: (i) operators should not exaggerate their capabilities nor guarantee results, and (ii) operators should never contract for bonuses based on producing precipitation over and above certain thresholds, such as monthly normal or other arbitrary amounts. Such assertions and arrangements are detrimental to the weather modification industry. To say it another way, contingence fee contracts are never appropriate.

3.3 CONDUCTING OPERATIONS

Providers of cloud seeding services have certain legal obligations to meet during those times when weather modification activities are underway. These include (i) operating within the parameters and constraints of the approved operational plans; (ii) maintaining accurate and thorough records of their activities and the results and; (iii) reporting in a timely way about their activities to sponsors, the National Oceanic and Atmospheric Administration (NOAA), and relevant state regulatory agencies.

3.3.1 Operational Control

Great care should be exercised by those performing cloud seeding services. One reason for diligence is obvious: Every operation should be conducted in ways that avoid harming persons or property and that facilitate the successful pursuit of the objective (e.g., precipitation augmentation). But another reason has to do with avoiding the cultivation of any public perception that harm has or will result from cloud seeding or that no benefit has been or can be derived from such activity.

Those who manage weather modification projects can aid themselves and sponsors in avoiding these pitfalls by using public advisory groups and by operating only under predetermined (sometimes strict) operational controls. Such controls are often stipulated in the weather modification contract between sponsor and operator and in relevant permits. The controls consist of a clear designation of target and operational areas, a listing of cloud seeding criteria being observed, and a description of the policies and procedures in place to ensure that suspension criteria are observed when conditions warrant. Such controls should not, however, be so restrictive that they inhibit or prevent the successful capitalization of safe cloud seeding opportunities (Bluestein et al. 1986). The kinds of record keeping and reports required by contracts between cloud seeders and sponsoring groups usually will reflect the degree to which the project has conformed to the operational criteria established by the parties and regulators.

3.3.2 Archival of Data and Information

Anyone paying for cloud seeding services has a right to know what seeding materials and methodologies have been used and what results are believed to have been realized as a consequence of the weather modification activity (WMA, see http://www.weathermodification.org). After all, information is the lifeblood of effective government regulation and the key to keen public awareness of what is happening within a regulated industry such as weather modification.

Accordingly, operators must keep accurate and exhaustive records from which they can demonstrate compellingly that contractual obligations have been met. Such records will almost always satisfy regulators and address the dictates of government red tape and paperwork.

Officials representing the regulatory agencies have authority to visit onsite to obtain information about the project. In some instances, government employees may linger onsite to monitor day-to-day operations, although more often visits are made on an intermittent, even hit-or-miss basis. The visitorial power given to regulators by state laws is only used as an adjunct to police record keeping and reporting requirements (Gellhorn and Levin 1990). The type of reporting routinely done by the weather modifier, which entails gathering the data and entering them on proper forms, is less expensive and also less intrusive.

3.3.3 Reporting Procedures

Federal reporting is intended merely as a disclosure requirement. The periodic reports from cloud seeding operators are filed with NOAA in Silver Spring, MD. The federal government takes no action on the reports as it is not in the business of regulating weather modification activities.

Federal reporting is for information purposes only, not as evidence of any evaluation done on the project. Cloud seeding activities are reported but not the impacts from the seeding. Following submittal of an initial report to establish a federal record of a seeding project, the regulations, Part 908 of NOAA rules, require both interim (seasonal/annual) and final reports at completion of projects. These reports to NOAA include (i) the number of days each month when seeding operations were conducted and for what purposes (rain or snow enhancement, hail suppression, fog dispersal), (ii) hours of operation of each apparatus (airborne or ground-based) used in the project, and (iii) the types and amounts of cloud seeding agent used [Title 15 Code Federal Regulations section 908.8 (1987, Supp. 1991)].

In some states, the federal reporting forms suffice as the documentation required by state regulators. Other states insist on their own reporting forms, which usually are quite similar to the federal forms. The information provided by operators is used by regulators to verify conformance to provisions of the relevant licenses and permits and to keep the public fully informed. Those states without cloud seeding regulations do not require any reporting of activity.

3.4 EVALUATING OPERATIONS

Most law dealing with legal liabilities of weather modification activities to persons claiming harm from weather modification activities is judge-made law, which is law developed by courts following precedent set down in analogous situations. A large body of such so-called common law exists relating to liability for harm. Most of it comes from state courts or from federal courts applying state law (Davis 1995). Although the number of weather modification lawsuits historically has been few, by drawing on liability law developed from similar situations, a picture can be deduced of potential liabilities for damages for cloud seeding activities (Davis 1974).

3.4.1 Legal Liabilities for Sponsors and Operators

At present, only eight states have law dealing specifically with weather modification legal rights and liabilities. In five jurisdictions, at least one case in court has involved issues about atmospheric water rights or weather modifiers' liabilities (see Table 3-2). Although weather modifiers have been successful in responding to liability challenges, well-advised cloud seeders carry legal liability insurance. Such liability coverage may be required by statutes and contracts (Davis 1995). Legal defense expenses and judgments are payable from such insurance policies (Dobbyn 1989). Such costs can be quite substantial (Mann 1968).

Table 3-2. State Cloud Seeding Rights and Liabilities Provisions

State	Provisions
	Case Law on Atmospheric Water Rights and Liabilities
New York	Cloud seeding proper because property owner has no atmospheric water rights.
Texas	Operator can be liable because property owner has atmospheric water rights.
Pennsylvania	Cloud seeding proper if government authorized.
	Statute on Rights to Augmented Water
Colorado	Water can be appropriated.
Utah	Water use right is with next person with an unfilled water right.
North Dakota	Treatment as if it were natural water.
	Statute on Liability Theory
Texas	Cloud seeding is not regarded as an ultrahazardous activity.
Utah	Cloud seeding liability is possible only for negligence.
Pennsylvania	Liability if defendant's conduct harms plaintiff (no fault).
West Virginia	Liability if defendant's conduct harms plaintiff (no fault).

Source: Davis (1995).

Statutes on legal liability change the common law. In two states, statutes limit the theories on which liability may be based by limiting plaintiffs to suing for professional malpractice or intentional wrongdoing. This is done by stating that the cloud seeding is not an ultrahazardous activity for which there is liability without fault or by stipulating that there can be no liability either for trespass or nuisance merely for inserting cloud seeding agents into the atmosphere. Pennsylvania and West Virginia go the other way. Statutes in those states made proving liability cases easier by dropping the requirement that claimants establish that cloud seeders were at fault. Plaintiffs merely need to prove that they were harmed by the activity of the cloud seeder (Davis 1995; see Table 3-2).

3.4.1.1 Liability Theories It is not unusual for plaintiffs' lawyers to allege all of the liability theories. Proof of such allegations, however, is a real challenge. Plaintiffs have the burden of bringing evidence to court that will persuade the finder of fact that the defendants' conduct met the requirement of at least one such theory. To date, defendants have won almost all liability lawsuits.

One example of the difficulty faced by plaintiffs' lawyers in prevailing in liability cases is the Yuba City Flood Case, instituted in California during the 1950s and concluded the following decade (Davis 1995). Complainants alleged several theories on the basis of which they sought to have the court determine that the cloud seeding in question was the sort of inappropriate action on which the law would rest liability [Adams v. California, Civil No. 10112 (Superior Court Sutter County, CA, 1964)]. They asserted that the cloud seeders (i) were negligent in that their conduct was professional malpractice because it fell below the standard of conduct expected of professional cloud seeders; (ii) trespassed in that they caused intrusion of materials, rain/snow, and runoff, or combinations of these, on lands owned by the plaintiffs; (iii) committed a private nuisance in that on the balance, the gravity of harm from their conduct outweighed the benefit to the cloud seeders and their sponsor; and/or (iv) performed an abnormally dangerous activity in that cloud seeding is so dangerous that its performance should be liable for harm caused by them, even though they may not have been at fault by being careless, trespassing, or committing a nuisance (Mann 1968). Proof of at least one of these liability theories is one of the necessary elements of a plaintiff's liability case (Keeton et al. 1984).

3.4.1.2 Causation It is not enough for people seeking to recover damages in court for misconduct by others to allege and prove some theory of liability. Rather, it must also be shown that some causal connection exists between the conduct on which that theory is based and the harm that they assert has befallen them. It is on this requirement of proof of causation that most weather modification plaintiffs have floundered. For example, in a Michigan lawsuit, a farmer claimed that cloud seeding in an intended target area upwind from his farm caused a storm that had an adverse effect on his property [Reinbold v. Sumner Farmers, Inc., No. 2734 C (Tuscola County, MI, 1974)]. The jury, which found for the defendants, evidently concluded that either he failed to establish a liability theory or he had not proved causation (Davis and St. Amand 1975). Examination of the evidence indicates that the plaintiff did not show causation (Davis 1995). No wonder, then, why so few lawsuits have been filed. Failure to show causation is a major barrier to any effort to assign legal liability to cloud seeders.

3.4.1.3 Defenses Those sued for alleged harm from weather modification activities may prevail not only because of the great difficulty of plaintiffs to establish cases. A successful defense may also stem from the defendants proving an affirmative legal defense. The federal government and a few state governments are legally immune from liability, at least to the extent they have not waived that immunity. The Federal Tort Claims Act is a partial waiver of federal immunity, but it does not waive liability for abnormally dangerous activities where there has been no governmental fault and for so-called discretionary functions (e.g., project planning) (Jayson 1984; Keeton et al. 1984). Immunity is an important defense (Davis 1995).

The Federal Tort Claims Act was the basis on which the plaintiffs in Lunsford v. United States [570 F.2d 221 (1977)] sought to obtain a recovery from the federal government for the loss of life and property associated with the Rapid City flood in the early 1970s. Although reason existed to decide the case on its merits against the plaintiffs (Davis 1988), it actually floundered on the inability of the litigants to have their claims certified as a class action, whereby all of them could join together in a single suit. The procedural provisions of the Federal Tort Claims Act do not permit such a joiner. Those people suing under that law must comply with its procedural requirements and prove their tort claims. Certification as a class action also has been denied by a state court [Saba v. Counties, 307 N.W. 2d 590 (N.D., 1981)].

State defenses include the concept of public necessity, which deals with allowing conduct that might otherwise be the basis for liability if it is necessary to protect the public from an imminent public disaster. Typical cases involve blowing up houses to prevent the spread of conflagration (Kionka 1992). Might not drought relief by way of cloud seeding also fit?

3.4.1.4 Indemnity and Insurance The ultimate financial burden of liability can be arranged by contract between the weather modification operator and sponsor or among them and an insurance carrier. Some sponsors (for example, the federal government) may require weather modification operators working for them to agree to indemnify them for any losses incurred, including any legal liabilities. People in the weather modification business can buy legal liability insurance, which shifts the ultimate loss to the insurance carrier (Davis 1995). State laws and regulations often require liability insurance as a condition of receiving a permit. Obviously, the cost of the insurance premiums, like any other costs, gets passed on to the sponsors of the weather modification project.

3.4.2 Water Rights

Practically speaking, liability has seldom been a serious problem for practitioners of weather modification. But the threat of it, and the costs of litigation, continues to be a concern among some operators. The fact is, anytime a law is broached, those who do cloud seeding think of liabilities. Conversely, mention cloud seeding to a lawyer, and he or she will think of water rights problems. Yet, water rights problems are often more theoretical than practical. The same reasoning is applicable to water rights questions as that explaining the lack of success by liability claimants, in other words, proving causation. Until better means are available to establish the extent to which clouds have been "rustled" by being seeded and the amount by which cloud seeding efforts have augmented streamflow, it will be quite difficult to quantify whatever right a claimant might be asserting (Davis 1995). Of course, that day could come, and engineers and other scientists could play active roles in supplying the needed proofs and in drafting laws concerning quantification (ASCE 2004). Nevertheless, some law now exists on the subject of atmospheric water rights (see Table 3-2).

3.4.2.1 Atmospheric Water Three states (Pennsylvania, New York, and Texas) have case law dealing with ownership of atmospheric waters [Pennsylvania Natural Weather Association v. Blue Ridge Weather Modification Association, 44 Penna. District and County Rep. 2d 749 (Common Pleas, Fulton County PA, 1968); Slutsky v. City of New York, 197 Misc. 730, 97 N.Y.S.2d 238 (Supreme Court 1950); Southwest Weather Research, Inc., v. Duncan, 319 S.W.2d 940 (TX Civil Appeals Court 1958)]. Thus, the cases are scattered; they do not come from the top appellate courts of any of the three states, and they are contradictory (Davis 1995). One case states that the landowner has a right in atmospheric water passing above the surface of his land (Texas); another takes the position that he/she does not (New York); and the third says he/she does but that state-permitted cloud seeding can deprive him/her of such a right (Pennsylvania) (Davis 1974). Consequently, it is difficult to deduce any general rule from the cases directly in point.

It is reasonable to analogize rights in atmospheric waters to rights in surface water under the traditional riparian rights system of the eastern states, which would favor property owners holding riparian lands (persons with property under the clouds) or under the proper appropriation system of the western states, which supports claims by people first making beneficial use of water (sponsors of cloud seeding projects). It is also conceivable that atmospheric water rights might be based on the concepts of developed water, or imported water, which provide the basis for claims by those who bring new water to a basin (Getches 1990; Tarlock 1988). Obviously, reasoning from these and other analogies also leads to conflicting results.

3.4.2.2 Augmented Surface Water The scarcity of atmospheric water rights cases can be attributed to the real concern that water and weather resources management relates to water on the ground. In this instance, engineering measurement and evaluating data present difficult problems. Nonetheless, three states have statutes dealing with such water on the surface of the ground: Colorado (Colorado Legislative Council 1971), Utah (Dewsnup and Jensen 1977), and North Dakota. Under Colorado law, a permit can be obtained to appropriate the right to use surface water made available through cloud seeding (Davis 1995). With Utah law, the right to surface water is allocated to the most senior water appropriator whose allocation was not already filled by water naturally in the stream. North Dakota would treat the additional water like natural runoff (Jones 1991). Of course, three different solutions by the three states that have addressed the questions are inadequate bases for declaring any trend. A published Regulated Riparian Model Water Code could serve as one basis for a sponsor to claim a quantifiable amount of atmospheric water (ASCE 2004).

3.5 CONCLUSIONS

Those who develop and manage water resources possess considerable experience in dealing with governmental institutions, which both support their activities and administer legal constraints within which waters are administered. Thus, the development of atmospheric water resources tends to be treated consistently with surface and underground water development. Legal considerations ought not to inhibit decisions about developing this part of the hydrologic cycle any more than they do with other portions of the cycle.

As research into more effective strategies for altering atmospheric processes continues, society seems sure to benefit from advances in the ability to ameliorate drought and diminish the impact of floods and severe storms. Such progress will lead to a greater ability to demonstrate the efficacy of weather modification. That benefit will extend to our legal system in addressing the need to develop and refine laws and regulations governing all aspects of water resource management and planning.

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CHAPTER 4
THE SCIENTIFIC BASIS

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4.1 INTRODUCTION

Precipitation is produced naturally by either the collision–coalescence process, Wegener–Bergeron–Findeisen (i.e., Bergeron, or ice crystal) process, or both processes working in tandem. The opportunity for precipitation enhancement arises from the possibility that nucleation agents can be introduced at the right time and place to stimulate one, the other, or both processes to achieve precipitation efficiencies greater than what might have occurred naturally. This presumes that at least some natural clouds are inefficient in converting atmospheric water vapor into precipitation reaching the ground (Czys et al. 2006).

The efficiency of the precipitation process may be improved by seeding inefficient clouds. This seeding may be implemented to induce a microphysical response, termed *static-mode* seeding, or to invigorate cloud motions (typically vertical), termed *dynamic-mode* seeding. There is a growing awareness that static and dynamic processes work in harmony, making it nearly impossible to alter microphysical conditions without affecting cloud growth or vice versa. Hence, it has become more common to consider the scientific basis for seeding within the context of seeding technique. There are two commonly used seeding techniques:

1. Glaciogenic seeding, where the ice crystal process is the target for initial response; and
2. Hygroscopic seeding, where the collision–coalescence process is the target for initial response.

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This section describes the scientific basis for positive changes in the precipitation amount that applies to both seeding techniques. It borrows from previous versions of Chapter 4 (Czys et al. 2006; Grant et al. 1995), in some places verbatim. Extensive scientific literature exists on these subjects including scientific reviews by Bruintjes (1999), Super (1999), Czys and Bruintjes (1994), Reinking (1992), Warburton (1992), Woodley and Rosenfeld (1992), Braham (1986), Orville (1986), Dennis (1980), and others listed in the references provided at the end of this chapter.

4.2 THE NATURAL PRODUCTION OF PRECIPITATION

Knowledge about how clouds produce precipitation naturally is still limited, even though great advances continue to be made with regard to instrumentation, the amount and quality of empirical data, theoretical development, and computer simulations of clouds and precipitation. The discussion here is neither complete nor comprehensive but seeks to provide a basic description adequate to understand how precipitation enhancement might be achieved. The collision–coalescence, or warm-rain process, and the ice crystal process typically require the preexistence of a cloud in the atmosphere, with the possible exception of the ice crystal process. Ice crystals may form directly from the vapor state via homogeneous nucleation when the air temperature is near or below −40 °C. Cloud formation involves the formation of a condensate phase (i.e., liquid or ice) from the vapor phase (Section 4.2.1) and then the subsequent growth of the condensed phase to hydrometeor sizes smaller than those of precipitating hydrometeors (Section 4.2.2). The authors simply provide enough detail to support the discussion of the precipitation processes (Section 4.2.3). There are many references that describe the formation of clouds or the formation of cloud condensate in greater detail (e.g., Wallace and Hobbs 2006; Pruppacher and Klett 1997; Rogers and Yau 1997; Young 1993).

4.2.1 Formation of Cloud Condensate

The amount of water that can be held in the atmosphere in vapor form is small and dependent on temperature. Air holds less water as vapor at lower temperatures than at higher temperatures. Typically, the atmospheric water vapor actually present in the air near the Earth's surface is less than that required for condensation to occur. However, when an air parcel is cooled at a constant altitude the air cools *isobarically*, or when air is cooled by lifting it, because of converging winds or some other mechanism, the air expands and cools *adiabatically*. As this cooling takes place, the absolute amount of water in vapor form generally remains the same, but the capacity of the air to hold water in its vapor state decreases. When cooling is sufficient, a temperature is eventually reached at which the parcel saturates, that is, the amount of vapor available equals the carrying capacity of the air.

Additional cooling results in *supersaturation*, when the available water is greater than can be contained in vapor form in the air parcel. At supersaturation, the excess water vapor begins to be removed by condensation or deposition to form cloud droplets or ice crystals, respectively. Fog formation generally happens isobarically, for example. It follows, then, that the amount of cloud condensate in a cloud or cloud system is controlled (Czys et al. 2006) by the

1. Amount of water vapor in an air parcel being cooled;
2. Amount of cooling, which if accomplished by vertical air motion, i.e., lifting, determines the depth of the cloud;
3. Temperature difference through which condensation takes place; and
4. Extent of the area over which cooling occurs.

The total cloud condensate formed has been used to determine precipitation efficiency. The precipitation would be 100% if all of this condensate ends up as precipitation reaching the ground. Similarly, it would be 0% if none of the condensate ended up as precipitation reaching the ground. If precipitation efficiency is defined as the fraction of condensed water vapor that ultimately reaches the ground, then thunderstorms have an approximate 19% precipitation efficiency (e.g., Sui et al. 2007; Li et al. 2002; Young 1993; Fankhauser 1988; Houghton 1968; Wexler 1960; Braham 1952).

4.2.2 Cloud Initiation and Colloidal Stability

Supersaturation in our atmosphere usually only exceeds 100% by a few tenths of a percent. This condition usually is not sufficient to initiate condensation without assistance. The presence of aerosols, such as dusts, salt particles, bacteria and pollutants, reduces the supersaturation required for droplet nucleation by providing a surface to which the vapor molecules can attach. Hence, the characteristics of the aerosol population ultimately determine the initial cloud droplet concentration and size distribution. The characteristics of the aerosol population are strongly dependent on the underlying surface characteristics from which they originate, and the atmospheric (weather) processing during their advection from their source regions. For example, continental regions far from oceans are generally associated with high concentrations of small aerosols. In contrast, maritime regions are generally associated with broader aerosol size distributions with smaller concentrations overall. Another factor to consider is that aerosol concentration tends to increase as surface wind speeds increase.

Cloud condensate over land is often initially available in the form of many small droplets, but the droplet sizes and concentrations may be governed by the indigenous aerosol population or the cloud formation dynamics. This is true even when temperatures in clouds are well below 0 °C. As a cloud forms, its droplets are typically less than 20 μm in diameter, in concentrations of hundreds per mL. The competition for the water vapor excess among the droplets is strong, and further growth by condensation is restricted. Because these small droplets fall slowly (<0.3 cm/s), they essentially move with the turbulent air currents within the visible cloud and rarely if ever collide with one another. Such clouds are typically referred to as microphysically or *colloidally* stable because the droplets do not interact (Braham 1959) and are suspended in air as a cloud with a precipitation efficiency near 0%.

4.2.3 Initiation and Evolution of Precipitation

Three different mechanisms can disrupt *colloidal stability* and lead to measurable precipitation at the ground. The first mechanism involves *collision and coalescence* among the drops and droplets so that successively larger drops form. When a few large cloud droplets coexist with smaller ones, as determined by the input *nuclei* population, the larger drops have a significantly greater fall velocity than smaller droplets and can grow quickly by the collision–coalescence process. The efficiency with which collisions will occur is highly dependent on the relative sizes and concentrations of the large and small drops (e.g., Johnson 1982). Collisions subsequently become more frequent, and the collection more efficient as the large droplets become progressively larger, due to increasing sweep-out. The increased sweep-out is the combined effect of an increasingly greater cross-sectional area exposed to collisions and progressively greater fall velocities relative to the smaller droplets. The process accelerates when the drops grow so large that some begin to break up and thereby provide additional embryos for precipitation to evolve. This chain reaction-like process first discussed by Langmuir (1948) leads to progressively greater numbers of precipitation embryos and a growing population of large drops with sufficient fall velocities and mass to reach the ground.

The second mechanism that disrupts colloidal stability involves the coexistence of supercooled cloud droplets and ice crystals. Given that the saturation vapor pressure over ice is less than that over water, ice crystals in the presence of liquid cloud droplets are in an environment that is highly supersaturated with respect to their surface. Under this condition, the more numerous water droplets tend to maintain water saturation. Consequently, the ice crystals grow rapidly from the transfer of vapor from the numerous water droplets to the ice crystal surfaces by vapor deposition. The surrounding water droplets compensate for the vapor loss by evaporating. In turn, the droplets may be replenished by continued nucleation in updrafts. Hence, every potential precipitating cloud can be characterized by how its colloidal stability may be disrupted. There are those where (Czys et al. 2006)

1. Collision–coalescence may dominate at temperatures totally higher than 0 °C, and/or
2. Ice crystal process in the presence of supercooled droplets dominates at temperatures lower than 0 °C, or the
3. Overall precipitation process straddles the melting level and collision–coalescence process works in tandem with ice crystal process.

This ultimately influences the selection of a seeding technique for precipitation enhancement.

The third mechanism that may disrupt colloidal stability involves direct removal of supercooled cloud droplets by *accretion* to falling ice crystals. Although the smallest cloud droplets generally will evaporate to compensate for vapor loss to ice crystals growing by diffusion, larger ones survive and can be collected directly by the ice crystals. This rimes the ice crystals and removes substantial quantities of cloud liquid condensate. Intensive riming of crystals leads to graupel. Riming also facilitates removal of cloud condensate by increasing ice particle size, mass, and fall velocity, which proportionally increases the sweep-out of cloud drops. Additional interactions among ice crystals, referred to as *aggregation*, also promotes development of precipitation-size particles, which may lead to higher precipitation efficiency.

Precipitation efficiency might be negatively influenced if the cloud forms on a large number of aerosols (e.g., continental clouds), or if the amount of aerosols ingested into a preformed cloud increases due to a mechanism separate from the mechanism that formed the existing cloud (e.g., Warner 1968; Rosenfeld 1999, 2000; Ramanathan et al. 2001; Andreae et al. 2004; Givati and Rosenfeld 2004). Air pollution was observed in one situation to mask the added rainfall produced due to cloud seeding (Givati and Rosenfeld 2005). In contrast, there have been examples of a positive influence on precipitation efficiency from the injection of aerosols into a cloud system (e.g., Hobbs et al. 1970; Hindman et al. 1977a, b; Mather 1991). These observations are consistent with the conceptualization that increasing the aerosol burden will retard the precipitation process unless the infusion is accompanied by an amount of water vapor sufficient to accommodate the additional loading, or the infusion reaches a level sufficient to initiate a precipitation process.

Precipitation efficiency is not only dependent on the disruption of colloidal stability and creation of hydrometeors that are large enough to achieve fall velocities in excess of the updraft velocity but also on the fraction of liquid hydrometeor mass that survives evaporation and/or *sublimation* during the fall toward Earth through dry air beneath cloud. Precipitation efficiency can be reduced to zero if the drops or ice particles (graupel, aggregates, or snowflakes) completely evaporate or sublimate beneath cloud to result in virga (precipitation that does not reach the surface). Model calculations have indicated that for equal precipitation-particle mass, more of the mass survives the fall in the dry air beneath cloud if the particle starts its descent with a frozen component (Srivastava 1987).

While collision–coalescence and *glaciation* processes are the primary focus for reducing colloidal stability, there are interdependencies among mechanisms that are important. For instance, collision growth can provide very large drops that will freeze more readily because as drop volume increases, the probability that it will contain a natural ice-forming nucleus also increases. It has also been shown that when some larger cloud droplets ($>$24 μm diameter) coexist with highly rimed ice particles or graupel in the temperature range from about −3 °C to −8 °C, accretion can lead to the production of ice splinters, also known as *ice multiplication* (Hallett and Mossop 1974). The splintering process can enhance ice crystal concentrations by three to four or more factors of 10 above background to make it an effective mechanism to further promote precipitation efficiency.

However, when definite mechanisms for growth of hydrometeors large enough to fall out are not operative, great amounts or even all of the cloud condensate can evaporate before any precipitation is formed; thus, there is very low precipitation efficiency. Clouds that have significant cloud condensate but do not have appropriate mechanisms for particle growth in the cloud lifetimes available are naturally inefficient and can be considered to have potential for increased precipitation via cloud seeding.

4.3 CLOUD SEEDING TO AUGMENT RAINFALL

Cold and warm cloud precipitation processes potentially are augmented through cloud seeding techniques. The augmentation is a function of a complex set of processes and their interactions that influence the following factors, among others: (i) persistence and effectiveness of seeding material, (ii) dispersion (transport and diffusion), (iii) seeding agent concentration, (iv) background cloud microstructure (hydrometeors and nuclei), and (v) the air-mass characteristics (e.g., state variables, gas, solid, and aqueous phase composition) in which the cloud was formed (e.g., Bell et al. 2008; Rosenfeld et al. 2005; Rosenfeld and Woodley 2003).

Glaciogenic and hygroscopic cloud seeding techniques commonly are used to augment the precipitation process. Glaciogenic seeding is the most commonly employed technique where the cold cloud process is the target for initial response, whereas hygroscopic seeding is the most commonly employed technique where the warm cloud process is the target for initial response. Chapter 5 covers both techniques in detail.

4.3.1 Seeding to Enhance the Warm Cloud Process (Hygroscopic Seeding)

Hygroscopic seeding is becoming a more popular consideration for modifying summer (convective) clouds. A review of hygroscopic seeding experiments has been provided by Czys and Bruintjes (1994). It has one of two primary objectives:

1. Initiate the warm rain process when it would otherwise not occur, or
2. Initiate the warm rain process sooner than if not treated.

Although it is possible to distinguish between many clouds that will initiate the collision–coalescence process and those that will not (Czys and Scott 1993), it is more difficult to determine the onset of the collision–coalescence process.

Hygroscopic aerosols and seeding agents have an affinity for water vapor and readily allow for the nucleation of water drops. In the case of hygroscopic seeding, an optimum size for the seeding nuclei exists such that they will nucleate preferentially over much smaller ambient natural aerosols. The artificially nucleated droplet may grow initially by condensation, then grow by collision–coalescence to precipitation sizes or may be large enough to immediately initiate the collision–coalescence process. Model simulations indicate that hygroscopic nuclei around 2 μm in diameter might be optimal (e.g., Segal et al. 2004; Cooper et al. 1997). Model simulations also suggest that hygroscopic seeding could result in a net loss of precipitation, even though precipitation may be initiated earlier than naturally expected due to *updraft loading*, which consequently weakens or potentially reverses updraft flow that would have otherwise promoted continued cloud growth and more overall precipitation (Segal et al. 2004; Caro et al. 2002).

When hygroscopic seeding concepts were first introduced, the methodology involved delivering fine sprays of saline solutions, ground salt, or smoke from flares. These methods proved to be impractical, and hygroscopic seeding consequently has not gained widespread use. They either involved transport of prohibitively massive amounts of solutions or the generation of particle sizes that could not be adequately controlled. Neither could they be targeted precisely enough to desired cloud volumes, as is the case with AgI (silver iodide) seeding.

"New" hygroscopic seeding flares have been developed that allow for delivery of hygroscopic aerosols at cloud base in size ranges that would positively affect the collision–coalescence process. When delivered to the inflow region just beneath the cloud, the nuclei can be ingested and processed along an upward and then downward drop growth trajectory. Mather et al. (1997) discussed the use of such flares in the conduct of a South African cloud seeding experiment.

Summer clouds suitable for seeding are those that either would not have an active coalescence process or those that would have delayed initiation of the warm rain process. Seeding usually occurs early in the cloud's lifetime before the warm rain process is firmly established. Hence, clouds suitable for hygroscopic seeding would show strong potential for vertical development, possess moderate updrafts that are strong enough to support the precipitation hydrometeors, and would probably have a fairly narrow drop size distribution (but no more so than in the cloud without seeding). Hygroscopic flares could be expended just below cloud base in the area of maximum updraft to ensure that the cloud ingested the seeding agent (Mather et al. 1997).

Hygroscopic seeding may have desirable secondary effects to promote the production of precipitation. For example, if hygroscopic seeding leads to the production of precipitation-size drops prior to the cloudy air parcel reaching the 0 °C isotherm in updrafts, then artificially created, supercooled rain drops may participate in raindrop freezing to benefit latent heat release, and promote secondary ice production. These secondary effects are objectives in glaciogenic seeding.

4.3.2 Seeding to Enhance the Cold Cloud Process (Glaciogenic Seeding)

The primary purpose of glaciogenic seeding is to initiate the ice process earlier (at somewhat higher temperatures) than would have occurred naturally. This is done (Czys et al. 2006) to

1. Disrupt colloidal stability by artificially freezing droplets and creating ice crystals that may grow by vapor diffusion and/or accretion, and
2. Invigorate cloud dynamics through the release of the latent heat of fusion associated with the conversion of supercooled water vapor and droplets to ice crystals.

It is difficult to identify situations where both (1) and (2) are not working in conjunction with one another. The primary active ingredient in the seeding material of choice is AgI. Silver iodide is desirable because it has a molecular structure very similar to ice and greatly reduces the excess energy required to create an ice surface from the vapor and liquid phases. Silver iodide seeding in summertime situations is commonly applied as aerosols created from burning flares dropped into cloud updrafts or from ice nuclei generators mounted beneath an airplane's wings. The material is then dispersed as the airplane flies through or under the cloud. Dry ice has been used, but it is comparatively more difficult to (i) generate dry ice particles of consistent size and concentration and (ii) disperse. Chapter 5 contains discussions of the various seeding agents and modes.

Clouds that contain large amounts of supercooled liquid water and low concentrations of ice are most suitable for the application of glaciogenic cloud seeding. Clouds with a weak collision–coalescence process and containing small to moderate concentrations of supercooled drizzle and raindrops may be optimal candidates for seeding because the nucleated ice particles could grow by *accretion* within the vast reservoir of supercooled cloud water in which they reside. Care must be taken to ensure that seeding such clouds does not yield sleet or hail in cases of extremely unstable atmospheres.

Vertically developing cloud tops are suitable for seeding shortly after they rise above the 0 °C level. Therefore, the cloud does not have to be precipitating (internally) before seeding begins. Developing cumulus clouds are especially suitable for seeding if their cloud tops show potential for growing colder than −4 °C or −5 °C because AgI is not very active at temperatures between 0 °C and −4 °C. It takes time for the AgI nuclei to transform into ice crystals large enough to remain within the growing cumulus and fall through it as precipitation. Some glaciogenic nuclei have hygroscopic properties allowing them to function through the *condensation-freezing nucleation* mechanism or the *submersion-freezing nucleation* mechanism. A condensation-freezing nucleus acts to form ice when water vapor condenses on its surface and immediately freezes. A submersion or immersion-freezing nucleus acts to form ice after the nucleus acts as a cloud condensation nucleus forming a drop, or it becomes incorporated into a cloud droplet, which ultimately moves into a region of a cloud were the air temperature is at the freezing point of that submerged or immersed nuclei.

Laboratory experiments have shown that when a drop freezes, a thin ice shell forms almost immediately (e.g., Schaefer and Cheng 1971). Concurrently, the release of latent heat raises the mean temperature of the drop to near 0 °C. The ice shell then acts as a barrier to the dissipation of heat to the environment and thus slows the rate at which the freezing drop converts to a solid ice hydrometeor. For larger, millimeter-size drops, freezing times can occur on the order of 5 to 10 minutes (Czys et al. 2006). Therefore, the buoyancy enhancement is nowhere near as dramatic as would be suggested if the drops froze instantaneously.

When glaciogenic seeding material is introduced into cloud volumes where no larger drops are present, seeding generally leads to relatively small ice crystals. The crystals begin to disrupt colloidal stability as their growth releases additional latent heat, which increases cloud buoyancy. However, when loading is negligible and ice hydrometeor growth does not involve growth by accretion, the invigorated cloud may pump condensate into the upper troposphere reducing precipitation efficiency to nil. Hence, it is important that cloud characteristics be determined prior to seeding exercises and that "seedability" criteria be adhered to during operations so that only clouds with the best chance for positive reactions are selected for treatment.

4.3.3 Seeding to Enhance Development of Individual Convective Clouds

The scientific basis for augmenting precipitation by increasing the precipitation efficiency of clouds has been considered in the previous sections. Increased precipitation efficiency implies a disruption to the colloidal stability of the cloud, either by adding ice crystals to a mix of supercooled drops and vapor, and/or by an induced cloud buoyancy increase from the release of latent heat (fusion) causing the cloud to become larger and consequently provide the opportunity for longer hydrometeor growth periods. This section discusses means by which cloud seeding might enhance cloud development and, consequently, increase precipitation. Other advertent and inadvertent modification methods may be more important than cloud seeding for enhancing cloud development, including human-induced alterations, such as surface albedo changes, urban heat islands, or changes in boundary-layer moisture from large-scale irrigation projects. Each of these alterations, under some circumstances, could lead to changes in boundary-layer heat and moisture fluxes that potentially create significant changes in cloud formation, development, and possibly precipitation efficiency (e.g., Pielke 2001; Anthes 1984). Xue et al. (2013a, b), Chen and Xiao (2010), Curic et al. (2007), Rosenfeld and Woodley (1993), and Orville (1986) further address the effect of cloud seeding on the processes associated with cloud formation, development, and possibly precipitation efficiency.

The basic concept for enhancing the development of individual convective clouds is, in itself, not complicated. Full consideration of the details of the process, however, is quite complex. The simple consideration involves the rapid conversion of large amounts of supercooled cloud water to ice particles. This adds heat to the cloud with respect to the cloud environment, at least in a different place than it would be released by natural ice-nucleating processes through the release of the latent heat of fusion. In clouds with substantial amounts of supercooled water, this can involve a substantial amount of sensible heat added to the cloud. Cloud model calculations suggest that increases of a few tenths of a degree centigrade or so in appropriate cloud regions can result in modest increases in cloud size and duration. Because the heated cloud air becomes even less dense than the cooler surrounding air, it will become more buoyant and thus rise farther than it would have without the additional heating. This can lead to greater (vertical) cloud development. If the air mass in which the convective cloud is embedded is quite stable, the additional heating and buoyancy might have little overall effect. If cases for treatment are selected where the atmosphere is only slightly stable, a slight cloud temperature increase can permit cloud growth to altitudes much higher than those that would be attained by the cloud without the additional heating (Czys et al. 2006). This was the basic precept of the Florida Area Cumulus Experiment (Woodley et al. 1983; Woodley and Sax 1976).

Geographical regions where this type of cloud seeding is feasible are not well defined. Some subtropical areas near the ocean appear to be suitable as do some continental regions with access to boundary layer moisture. Clouds that occur in these areas are characterized by warm cloud bases and contain large amounts of supercooled liquid water with appreciable supercooled drizzle and precipitation-size drops. Air masses in such areas can also have slightly stable atmospheres that restrict cloud growth but are not so stable that they preclude deep cloud growth when a small amount of additional heating is added. In contrast, in many continental areas in the mid-latitudes, cloud droplet spectra are much narrower and are composed almost completely of very small cloud droplets. Clouds in these regions also frequently have low liquid water contents. An additional limitation to this type of cloud seeding in such areas is that frequently the thermal stability is not great, and the *heat of vaporization* released when the cloud droplets are formed is already sufficient to permit cloud growth through the full depth of the troposphere (Czys et al. 2006). The cloud seeding strengthens the updraft, leading to increased condensation rates that may lead to greater precipitation amounts.

4.3.4 Expansion of Glaciogenic Seeding Concepts to Mesoscale Systems

The chain of events hypothesized by Woodley et al. (2003a, b) includes evidence of area-wide effects. DeFelice et al. (2014) present evidence for enhanced precipitation, or a direct seeding effect, in the target area and in "extra-area" regions from the conduct of seeding programs. The spatial extent of the positive extra-area seeding effects may extend to a couple hundred kilometers. Both microphysical (static) and dynamic effects of seeding appear to be contributors to the extra-area effects. They did not reveal regional impacts to the water balance, nor to the natural precipitation on a regional scale, suggesting that cloud seeding should not dry up the atmosphere or lead to summer drought, contrary to a popular belief. The understanding of such cloud seeding enhancement processes is poor due to limited understanding of the linkage between individual cumulus cloud systems and mesoscale processes.

Conceptual and numerical models have been used to study how cloud seeding affects cloud processes (e.g., Xue et al. 2013a, b; Saleeby et al. 2011; Chen and Xiao 2010; Curic et al. 2007; Caro et al. 2004; Farley et al. 2000; Orville 1996; Meyers et al. 1995; Orville and Kopp 1990; Orville 1990, 1986; Orville and Chen 1982; Fritsch and Chappell 1981). The various mechanisms that have been proposed require a careful balance between cloud development rates and the movement of the gust front formed from the downdrafts associated with the various cloud towers as these downdrafts reach the surface (Czys et al. 2006). The environmental wind field that is essentially independent of any cloud seeding effect may substantially control the characteristics and movement of the gust front. Thus, expansion of dynamic seeding effects to the mesoscale is likely to be dependent on environmental conditions. The authors advocate further research on extra-area effects and the development of new tools to better understand clouds and their response to seeding. Seeding in a target area that might exist downwind of other target areas is considered in Chapter 6. For the sake of the current discussion, we would suggest employing a combination of confirmatory measurements and modeling to determine the magnitude of the extra-area effect on that downwind project area and adjusting operations accordingly. This will ensure an optimal result for the downwind target area at potentially minimal extra project cost, because the increased cost of the additional satellite, airborne and/or ground measurements, and their analysis could be offset by reduced operational costs. Furthermore, the added measurement infrastructure potentially could be used to more effectively evaluate the project effectiveness on meeting its goal and help maximize the efficiency of the operation.

4.4 THE NATURAL PRODUCTION OF SNOWFALL

Most attempts to augment wintertime precipitation focus on increasing snowfall from orographic clouds subject to the generation of supercooled liquid water via orographic lift up windward slopes. Winter clouds associated with deep cyclonic storms and mesoscale systems, but that do not benefit from orographic influences, have not been the subject of snow augmentation. This has occurred for the most part because additional water to replenish watersheds and increase streamflow is derived from mountainous regions. Therefore, the primary focus of this section is on winter orographic clouds and their potential for precipitation augmentation by seeding.

4.4.1 Formation of Cloud Condensate

The basic physics of the formation and evolution of condensate in winter orographic clouds is very similar to that for other cloud types. Lifting and cooling of air to supersaturation results in the nucleation of droplets on available condensation nuclei resulting in cloud development. A primary difference in the process for winter clouds compared with that of summer clouds has to do with the fact that the air is often mechanically lifted over upslope barriers rather than lift, which results from positive buoyancy driven by surface and/or latent heating. Supercooled cloud droplets are created when cloud formation occurs where air temperatures are $<0\,^{\circ}C$.

Similar to summer clouds, clouds with very few initial ice crystals—because of an absence of natural ice nuclei—make the best candidates for treatment. Winter clouds are quiescent compared with their summer counterparts; many remain a suspension of supercooled cloud droplets for prolonged periods, producing little if any precipitation that reaches the ground.

4.4.2 Cloud Initiation, Colloidal Stability, and Evolution of Precipitation

Cold clouds are typically colloidally stable because they are usually composed of a population of many supercooled droplets characterized by relatively small mean diameters (e.g., 10 microns, μm) and a very narrow size range (e.g., 4 μm), and few if any naturally nucleated ice crystals. Cloud development that progresses from the lee of a mountain range often eventually evaporates once it detaches from the lifting mechanism, thus producing little, if any, snowfall. Other natural clouds might develop with initial populations of supercooled droplets that are less colloidally stable or perhaps initiate ice earlier because they are colder but are still suboptimal for natural precipitation production. Although these clouds may produce some snow at the ground, only a small fraction of the available supercooled water is converted to precipitation (low efficiency). These less efficient clouds are primary candidates for seeding.

4.5 CLOUD SEEDING TO AUGMENT SNOWFALL

The primary purpose of glaciogenic seeding to augment snowfall, as it is for summer clouds, is to convert supercooled liquid to ice and thereby disrupt its colloidal stability. As has been pointed out in an earlier section, ice has a depositional growth advantage over liquid at the same temperature and pressure. Thus, over any fixed period, crystals will grow at a faster rate than their liquid droplet counterparts. The initial population of crystals may then follow one of three growth trajectories, any of which may become more or less important as the precipitation evolves. In the first path, the ice particles may simply grow by deposition, depleting the surrounding population of liquid drops to sizes large enough that they can gain fall speeds larger than the vertical motions within and below the cloud to eventually reach the surface as a fine crystalline snow (Czys et al. 2006). In a second path, ice crystals grow large enough to gain a differential fall speed relative to the population of droplets. Once this happens, they begin to collect droplets through accretion (or riming). This results in precipitation in the form of heavily rimed snowflakes. This accretion growth may also result in the production of secondary seeding by rime splintering (Hallett and Mossop 1974) to further promote the conversion of liquid to ice. In the last but not the least important path, the ice crystals may attain a sufficiently broadened size distribution that they interact among themselves and aggregate so that snowflakes eventually reach the surface. Some processes from these three basic scenarios may occur in conjunction with each other, for example, aggregation and riming are an especially favorable combination to increase precipitation efficiency. For any of these scenarios, the introduction of a seeding agent facilitates ice initiation, allowing depositional growth, riming, and/or aggregation when it otherwise would not occur or would be weaker under natural conditions.

4.5.1 Snow Augmentation Methods

Two techniques are commonly used to augment snowfall. Seeding material in the form of silver iodide (AgI) aerosol is either released directly into suitable clouds using wing-tip-borne ice nuclei generators or burn-in-place flares on aircraft, or it is released from ground-based generators. Ground-based generators can either be manually operated at lower elevations in populated areas or operated remotely at higher elevations. Each type of generation system has advantages and disadvantages, some of which are discussed in Chapter 5. Dry ice particles may also be dropped by aircraft into regions of clouds containing supercooled liquid water. Although a less commonly used material/technique, dry ice seeding from aircraft can offer some specific advantages over AgI in terms of targeting and the temperature of the supercooled liquid water that can be treated.

4.5.2 Expansion of Snow Augmentation Concepts to Larger Scales

Winter orographic clouds often contain significant amounts of supercooled liquid, and because seeding is intended to convert much of this liquid to ice, the potential exists for the release of latent heat that may be comparable to that in summer convective clouds. This release of latent heat may either initiate or enhance isolated convective elements embedded within the cloud system. These elements may act to increase cloud depth (Dennis and Orville 1997). Greater cloud depth may convert more water vapor to supercooled liquid, provide larger cloud volumes over which precipitation processes may act to produce more snow, and serve to preserve the cloud for a longer duration than it would have existed naturally. These are all characteristics that may promote greater snowfall at the surface. That said, as the cloud depth increases, there also may be an increasing number of naturally active ice nuclei with height above cloud base. The air temperature typically decreases with height above cloud base, and the activity of ice nuclei (artificial and natural) increases with decreasing air temperature.

Previous research conducted in mountainous regions of the western United States has demonstrated that supercooled liquid water frequently occurs in winter stratiform clouds over the upwind sides of mountain barriers (e.g., Breed et al. 2014; Super 1999; Reynolds 1988; Warburton and DeFelice 1986). This supercooled liquid water often is confined to lower elevations in the vicinity of the top of the mountain barrier. Temperatures within these layers can, in some situations, be only slightly less than 0 °C, which presents challenges to effective seeding with glaciogenic seeding agents (Czys et al. 2006).

Several observational and theoretical studies have suggested that there is a cold temperature "window" of microphysical opportunity for cloud seeding. Studies of both orographic and convective clouds have suggested that clouds with tops colder than −25 °C have sufficiently large concentrations of natural ice crystals such that seeding can either have no effect or even conceivably reduce precipitation (e.g., Griffith et al. 2013; Grant 1986; Gagin et al. 1985; Gagin and Neumann 1981; Grant and Elliott 1974). It is possible that seeding such cold clouds could reduce precipitation by creating so many ice crystals that they compete for the limited supply of water vapor and result in numerous, more slowly settling ice crystals that sublimate before reaching the ground (Czys et al. 2006). There are also indications that there is a higher temperature limit to seeding effectiveness (Cooper and Lawson 1984; Gagin and Neumann 1981; Grant and Elliott 1974). This is believed to be due to the slow rates of ice crystal vapor deposition growth at warm temperatures and, from a practical standpoint, low efficiency of ice crystal production by silver iodide at temperatures higher than −4 °C. Thus, there appears to be a "temperature window" from about −4 °C to −25 °C at which clouds may respond favorably to silver iodide seeding (i.e., exhibit seedability). Dry ice (frozen carbon dioxide) seeding via aircraft extends this temperature window to temperatures just lower than 0 °C (Czys et al. 2006). Liquid propane or other compressed gases, when released directly into a supercooled cloud, can initiate ice formation at temperatures similar to those of dry ice (perhaps −2 °C or lower), but the release must occur within a cloud. Ice crystal growth rates at such warm temperatures are, however, typically less than those at colder temperatures. This is among the considerations when determining treatment windows and targeting.

Orographic clouds are less susceptible to a time of treatment window because they typically exist in a quasi–steady state for long periods; therefore, they offer a greater time opportunity for successful precipitation enhancement than cumulus clouds. A time window of a different type does exist for orographic clouds, which is related to the time it takes the vapor in a parcel of air to condense to form supercooled liquid water and ascend to the mountain crest. If winds are weak and clouds are relatively deep (e.g., cold cloud tops), there may be sufficient time for natural precipitation processes to occur efficiently. Stronger winds may not allow efficient natural precipitation processes, but seeding may speed up precipitation formation. Even stronger winds may not provide enough time for seeded ice crystals to grow to precipitation sizes before being blown over the mountain crest and sublimating in the sinking subsaturated air to the lee of the mountain. A time window related to the ambient winds, however, is much easier to assess in a field setting for orographic clouds than for cumulus clouds.

If clouds upwind and over mountain barriers containing supercooled liquid water are routinely seeded to produce appropriate concentrations of ice crystals exceeding 10 to 20 per L of cloudy air, snowfall increases can be anticipated in the presence or absence of natural snowfall (Czys et al. 2006). The latter depends on the amount of supercooled water and the microstructure and dynamics of the seeded system, for instance. Seeded snowfall rates are usually light, on the order of 1 mm/h or less, although consistent with median natural snowfall rates in the intermountain west (Super and Holroyd 1997).

4.6 TECHNOLOGICAL ADVANCES

Recent advances in the technologies that support weather modification beyond those reported in Czys et al. (2006) are worth a mention. The evaluation of seeded storms may now include selecting variable target/control areas or individual cells with improved radar analysis tools (Woodley and Rosenfeld 2004; Woodley et al. 2003a, b). A new era in cloud and aerosol characterization measurements, beyond DeFelice (1998), for example, is on the horizon that involves the use of unmanned airborne platforms. Models to support a greater understanding of the effects from seeding efforts must continue to be developed, validated, and refined because their strategic use in real-time numerical cloud models combined with continuous, real-time remote sensing data offers great potential for predicting and recognizing seeding opportunities and monitoring and determining cloud seeding effects (e.g., DeFelice et al. 2014; Woodley and Rosenfeld 2004; Reinking 1995).

4.7 CONCLUSIONS

The scientific basis of precipitation enhancement by cloud seeding has advanced minimally beyond the levels discussed by Grant et al. (1995). The basic principles of cloud seeding for precipitation augmentation are reasonably well understood, but the great natural variability in the factors affecting natural precipitation development leaves much room for further investigation toward refining cloud seeding methodologies. Cloud seeding does not dry up the atmosphere or lead to summer drought, contrary to a popular belief, and typically increases the areal extent of the precipitation that reaches the surface compared with the condition without cloud seeding (e.g., DeFelice et al. 2014). The spatial extent of the positive extra-area seeding effects may extend to a couple hundred kilometers. Both microphysical (static) and dynamical (dynamic) effects of seeding appear to be contributors to these extra-area effects.

Numerical models have become increasingly proficient at simulating cloud processes and the effects of seeding (e.g., Xue et al. 2013a, b; Saleeby et al. 2011; Chen and Xiao 2010; Curic et al. 2007; Caro et al. 2004; Farley et al. 2000; Orville 1996; Meyers et al. 1995; Orville and Kopp 1990; Orville 1990, 1986; Orville and Chen 1982; Fritsch and Chappell 1981). However, if further progress is to be made, vigorous use of the available new instrumentation, improved seeding agents, and models must be accelerated. Some case studies have taken advantage of field measurements, such as tracers for targeting and plume dispersion, as well as fine-scale precipitation data, for comparison and validation of numerical model output, particularly for orographic systems over complex terrain (see, e.g., Breed et al. 2014; Xue et al. 2013c; Bruintjes et al. 1995). Further discussion of some acceptable directions is provided in Chapter 5.

This chapter borrows from previous versions of Chapter 4 (Czys et al. 2006; Grant et al. 1995). The authors thank the authors of the previous versions of Chapter 4 for providing a firm foundation for this update.

4.8 REFERENCES

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CHAPTER 5

CLOUD SEEDING MODES, INSTRUMENTATION, AND STATUS OF PRECIPITATION ENHANCEMENT TECHNOLOGY

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5.1 INTRODUCTION

This chapter is largely based on Section 5 in the 2006 version of this manual (Griffith 2006). Updates have been made to account for more recent information that became available since 2006.

Once the decision has been made to implement a precipitation augmentation cloud seeding project, consideration needs to be given to the project design. A project design is needed to systematically address the fundamental aspects of setting up, conducting, and evaluating a project. The project design should include (i) a statement of goals; (ii) definition of the project area, which may include target and adjacent affected areas and possible control area, if any; (iii) specification of an operational period; (iv) specification of cloud seeding modes; (v) project instrumentation requirements; (vi) cloud seeding criteria; (vii) seeding suspension criteria; and (viii) evaluation criteria. Such a design can provide an excellent source of information for the preparation of a solicitation requesting the work to be performed. Relevant aspects relating to project design are examined in Chapter 6.

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5.2 CLOUD SEEDING MODES

Cloud seeding mode is a term that denotes the choices available in selecting the appropriate cloud seeding agent and the methods available for dispensing these agents. Two basic modes of seeding are possible: one that predominantly affects processes warmer than 0 °C (hygroscopic seeding) and another that affects processes colder than 0 °C (glaciogenic seeding). There are several questions to be asked to determine the best cloud seeding mode for a particular project. What cloud seeding agent to use—dry ice (CO_2), silver iodide (AgI), liquid propane (C_3H_8), a hygroscopic agent, or some organic compound? Should ground-based seeding, airborne seeding, or a combination of the two be used? At what rate should the seeding agent be applied? How many ground generators or seeding aircraft are required to adequately seed the specified target area? These questions are best answered when the meteorology and cloud characteristics for the area have been defined and used by meteorologists with expertise in the field of weather modification. Sometimes the most desirable cloud seeding mode will prove to be too costly when compared with probable economic benefits, which will necessitate the specification of a more economical but still reliable cloud seeding methodology.

5.2.1 Cloud Seeding Agents

Experiments conducted at the General Electric (G.E.) Laboratories in Schenectady, NY, in 1946 and 1947 by Schaefer (1946) and Vonnegut (1947) demonstrated that certain materials are quite effective in converting supercooled liquid water droplets (droplets at temperatures lower than 0 °C) into ice crystals. Schaefer demonstrated that dry ice (solid CO_2) particles, when dropped through a supercooled cloud, produce ice crystals because of spontaneous or homogeneous nucleation (Mossop 1955). Additional experiments conducted by Vonnegut were concerned with the possible identification of materials that might serve to promote heterogeneous nucleation. *Heterogeneous nucleation*, which is by far the dominant process in nature, can result either from direct deposition to ice from the vapor phase or the direct contact nucleation of supercooled liquid water. Aerosol particles (e.g., wind-carried soil particles) can promote both heterogeneous nucleation processes. These particles are known as ice-forming nuclei. In the case of supercooled liquid water, such aerosol particles can significantly raise the temperature at which the droplets would otherwise freeze by homogeneous nucleation. Among the most effective freezing nuclei identified by Vonnegut were silver iodide and lead iodide (AgI and PbI). The temperature threshold at which pure particles of these substances began to produce a few ice crystals was in the range of −3 °C to −4 °C, much higher than with most naturally occurring substances in the atmosphere.

Later research (Fukuta 1966, 1963) demonstrated that several organic materials can also provide effective ice-forming nuclei. Two examples of such materials are 1,5-dihydroxynaphtalene and metaldehyde. *Pseudomonas syringae* (Ward and De Mott 1989), a bacteria thought to reduce frost damage in plants, has also been shown to be an effective heterogeneous ice-nucleating agent. Different classes of cloud seeding agents (homogeneous, heterogeneous, and organic, either homogeneous or heterogeneous) will be discussed separately. A fourth class of cloud seeding agents, which consists of an array of hygroscopic (water absorbing) materials, were covered in Griffith (2006).

5.2.1.1 Homogeneous Nucleating Agents Homogeneous nucleation is the physical process by which water molecules come together to form a stable water droplet or ice crystal without the assistance of a condensation or freezing (or ice-forming) nucleus. No seeding agents exist for the homogeneous nucleation of water droplets, so homogeneous nucleation in cloud seeding exclusively refers to the nucleation of ice from the vapor phase.

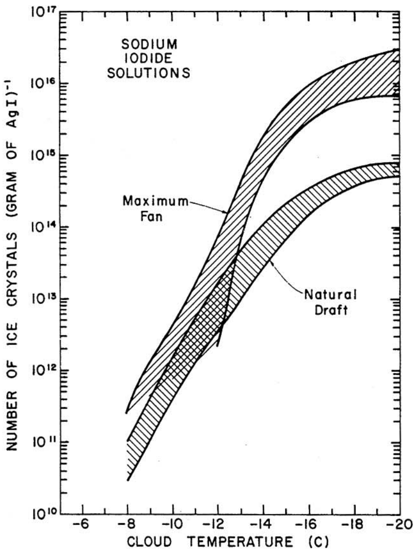
Dry ice (solid CO_2) is an effective homogeneous ice-nucleating agent, because its temperature is well below the temperature threshold of spontaneous (homogeneous) freezing of water (about −40°C). It is capable of producing 2×10^{11} to 8×10^{11} ice crystals per gram of dry ice dispensed, and its effectiveness is relatively independent of temperature in the range from −1°C to −11°C (Holroyd et al. 1978). Other research (e.g., Horn et al. 1983) indicates that these numbers may be several orders of magnitude low, with definite temperature dependence. Although dry ice has several advantages, such as rapid transformation of supercooled water vapor and cloud water droplets to ice, good effect near the melting level, a total lack of any toxic residuals, and low cost, it must be dispensed directly into the supercooled region of the cloud and, thus, usually requires an airborne delivery system. Dry ice was frequently used in cloud seeding projects in the United States in the 1950s and early 1960s but was slowly replaced by silver iodide as convenient storage and dispensing capabilities for generation of silver iodide nuclei were developed.

Liquid propane, when vented to the atmosphere, is a freezing agent much like dry ice. It produces almost the same number of crystals per gram as does dry ice (Kumai 1982). It cannot be dispensed from aircraft, because it is a flammable substance. However, it can be dispensed from the ground if released at elevations that are frequently within supercooled clouds. The U.S. Air Force has used liquid propane dispensed from ground-based sites to clear supercooled fog at military airports for more than 35 years. Liquid propane seeding to augment precipitation was tested in a California research program that utilized remotely operated ground-based dispensers (Reynolds 1992, 1991). Two winter seasons of liquid propane seeding experimentation were also conducted on the Utah/NOAA Atmospheric Modification Project (Super 1999) and a single season program (2003–2004) sponsored by the Bureau of Reclamation (Super and Heimbach 2005) in the Wasatch Plateau region of central Utah. The 2003–2004 experimentation indicated some statistically significant snowfall increases in seeded 2 h experimental units. Future experimentation needs to demonstrate that this technique can increase precipitation over a sizable fixed target area for a significant period (e.g., a winter season).

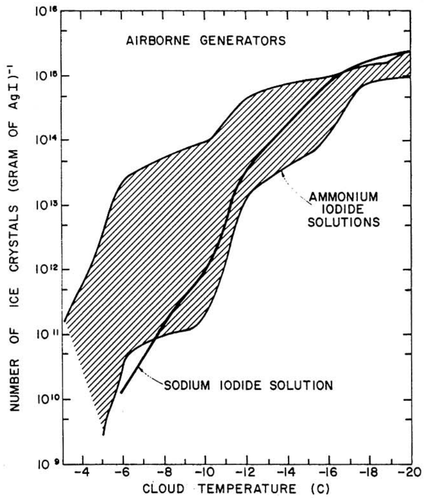
5.2.1.2 Heterogeneous Cloud Seeding Materials Heterogeneous cloud seeding agents can be either those that promote the nucleation of water drops to affect the warm-rain processes of collision–coalescence or agents with molecular structures similar to ice to facilitate the nucleation of ice crystals.

Both silver iodide (AgI) and lead iodide (PbI) particles, in size ranges between 0.1 μm to 1 μm are highly effective as freezing nuclei. Because of environmental concerns related to the release of lead into the atmosphere, PbI generally has not been utilized as a cloud seeding agent. However, silver iodide does not suffer from these environmental constraints and has been the preferred seeding agent in many cloud seeding projects. This has been the case for projects and/or programs conducted in the United States and other countries, such as Australia and Canada, for decades. Correctly sized particles of AgI usually are produced through some combustion process followed by rapid quenching, which forms literally billions of effective freezing nuclei per gram of AgI consumed if temperatures are lower than −4°C. Methods of generating properly sized particles of AgI were covered in Section 5.2.2 of Griffith (2006) and are in the same subsection herein.

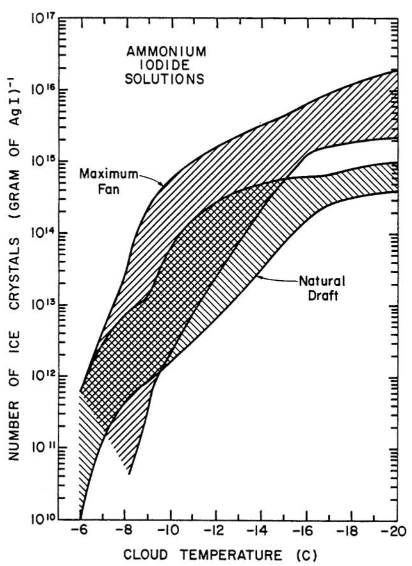
Cloud chambers have been constructed at several research facilities, such as Colorado State University (1969–2004), to test, among other things, the effectiveness of different generating techniques in producing freezing nuclei. Figure 5-1 provides plots of the number of effective freezing nuclei produced per gram of AgI consumed in a variety of seeding material generation methods as a function of the temperature of the cloud chamber (Garvey 1975). All of the curves in Fig. 5-1 exhibit an increase in activity with decreasing temperatures. Studies of naturally occurring freezing nuclei exhibit the same characteristic but with even fewer active natural nuclei in the regions warmer than −10°C to −15°C. The presence of either ammonium or sodium iodide in solutions of AgI and acetone mixtures is prompted by the need for a catalyst to allow dissolving AgI in acetone. Note the relative increase in effectiveness of silver iodide–ammonium iodide mixtures over that of silver iodide and sodium iodide. The differences in activity from solutions involving sodium and ammonium iodide are attributed to more hygroscopic



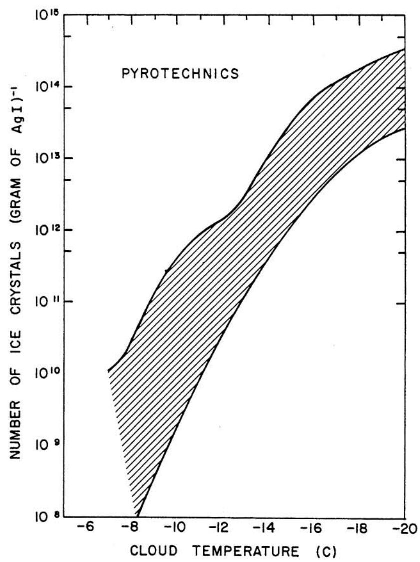
Ranges of effectiveness values for the aerosols produced by five ground generators burning solutions of AgI-NaI in acetone for two conditions of ventilation.



Range of effectiveness values for the aerosols produced by three airborne generators burning various solutions of AgI-NH_4I and one solution of AgI-NaI.



Ranges of effectiveness values for the aerosols produced by six ground generators burning solutions of AgI-NH_4I in acetone for two conditions of ventilation.



Range of effectiveness values for the aerosols produced by ten kinds of pyrotechnics.

Fig. 5-1. Ranges of effectiveness values for aerosols produced by various methods Source: Garvey (1975), reproduced with permission from American Meteorological Society.

complexes being formed using sodium iodide solutions. This decreases the effectiveness of AgI particles produced from these solutions (Donnan et al. 1970). This finding caused a switch from sodium iodide to ammonium iodide as the preferred catalyst. Differences also occur due to the difference in airflow past the cloud seeding generator. This effect is shown in the upper left-hand image of the figure, where maximum fan production is greater, which might be expected to occur under cloud seeding conditions.

Later research by DeMott et al. (1983) in cloud chamber tests indicated that the addition of ammonium perchlorate (NH_4ClO_4) to the standard silver iodide, ammonium iodide, acetone solution further increases the number of effective freezing nuclei produced per gram of silver iodide. Other research (DeMott 1988) indicated that the addition of sodium perchlorate ($NaClO_4$) to the aforementioned solution apparently produces a hygroscopic nucleating agent. The complex produced through the burning of these mixtures exhibits significantly faster reaction times in producing ice crystals than by other means of producing AgI freezing nuclei. Finnegan (1999) provides further documentation that the addition of chlorine to seeding solutions provides increased activity at higher temperatures, and perhaps more important, faster rates of nucleation than solutions that generate pure AgI. Finnegan indicated that the addition of chlorine can be accomplished by adding sodium or potassium perchlorate or paradichlorobenzene to silver iodide-acetone seeding solutions. These results suggest that choices are available in the design of cloud seeding projects that utilize AgI in terms of the potential number of ice crystals that can be produced per gram of AgI utilized and also in the rates at which these ice crystals are produced. Different cloud seeding project designs may be able to effectively utilize these choices to a definite advantage.

It has been shown that field observations of nucleation efficiency from aircraft wingtip acetone generators or ground-based silver iodide generators in clouds with temperatures below 0 °C may exhibit even higher efficiencies (Finnegan and Pitter 1987). This is because of the production of water vapor in the combustion process providing transient supersaturations. Deshler et al. (1990) reported on such a phenomenon from aerial seeding in clouds over the Sierra Nevada.

The potential toxicity of AgI and possible environmental impacts have been investigated extensively (CardoENTRIX 2011; Williams and Denholm 2009; Klein 1978; Cooper and Jolly 1969; Douglas 1968). Findings indicate little concern over the short term (measured in decades), with some possible impact in the long term (hundreds of years). The Weather Modification Association issued a "Position Statement on the Environmental Impacts of using Silver Iodide as a Cloud Seeding Agent" (WMA 2009).

5.2.1.3 Organic Cloud Seeding Materials Several organic materials (compounds of carbon) have been identified as effective freezing nuclei. Phloroglucinol appears to have been the first organic freezing nucleant identified (Langer et al. 1963). Several other compounds, including trichlorobenzene, raffinose, trimesic acid, melamine, 1-leucine, 1-tryptophane, metaldehyde, and 1,5-dihydroxynaphtalene have been shown to provide effective ice-forming nuclei (Fukuta 1966, 1963; Langer et al. 1963; Power and Power 1962). Some of these compounds exhibit higher threshold activation temperatures, which hold promise for potential future applications where activation near the melting level is advantageous. Most organic nucleants have received little field testing to date; therefore, their acceptance for use in operational precipitation enhancement projects probably will be delayed until tested in research-oriented cloud seeding projects. The exception is liquid propane, which has been previously mentioned. Its efficiency is similar to that of dry ice (Griffith et al. 1995).

Several potential advantages are associated with organic nucleants, which should encourage consideration for testing in research projects. These plentiful materials are biodegradable, have lower costs (especially when compared with silver iodide), and have comparatively high temperature activation thresholds. Some organic materials, unlike dry ice, can undoubtedly be adapted to ground-generation techniques (similar to propane).

5.2.1.4 Hygroscopic Materials Numerous precipitation enhancement projects have used AgI complexes as their primary nucleating agent since the 1950s (ASCE 2004). Nevertheless, the injection of hygroscopic agents that may alter the initial cloud droplet spectra or create raindrop embryos immediately may be an efficient method for treating warm-based continental cumulus clouds in which the vertical distance from cloud base to the melting level can be as much as a few kilometers. Ludlam (1958) and Appleman (1958) described the concepts involved in hygroscopic seeding with salt particles by dropping large numbers of salt particles into cumulus clouds. Salt seeding was used experimentally in a North Dakota pilot project, a combination hail suppression and rainfall enhancement project, in 1972. In that experiment and others conducted in South Dakota, finely ground salt particles were released near the bases of moderate-sized cumulus clouds to create raindrop embryos around the salt particles. Experiments carried out in South Africa in the early 1990s underscored the potential effectiveness of seeding with hygroscopic agents in increasing precipitation from cumulus clouds (Mather and Terblanche 1994). A two-season, follow-on experiment was conducted in Mexico (Bruintjes et al. 2001). A three-season experiment was conducted in Thailand (Silverman and Sukamjanaset 2000). Following these experimental programs, hygroscopic seeding began to be applied on more operationally oriented programs such as those in Texas (Rosenfeld et al. 2010) and India (Krishna et al. 2009).

Hygroscopic agents deliquesce (that is, become liquid by absorbing moisture from the air) at relative humidity values significantly less than 100%. Mather et al. (1997) made use of flares containing primarily potassium perchlorate, which when burned produced potassium chloride (KCl) particles with mean diameters of about 0.5 μm. The hygroscopic flares contained about 1 kg of seeding material. These flares were burned near the base of cumulus clouds in an attempt to alter the cloud droplet spectra through the "competition" effect. Although there are many naturally occurring hygroscopic substances, KCl particles have an advantage of only requiring a relative humidity on the order of 70 to 80% to deliquesce and readily act efficiently as cloud condensation nuclei (CCN).

Project planners should bear in mind that the hygroscopic flare method is relatively new and is not yet used as widely as the AgI complexes. These flares do, however, potentially offer an opportunity to increase precipitation from clouds whose temperatures are entirely above 0 °C, temperatures at which freezing nuclei (e.g., silver iodide) are ineffective.

5.2.1.5 Other Seeding Methods and Inadvertent Weather Modification Over the years, there have been a number of proposed techniques to produce increases in precipitation. Some of these techniques are based on plausible physical principles and may offer potential (though yet to be proven through modeling and field testing). An example could be the alteration of the albedo of an area through the installation of a surface that absorbs the sun's energy, thereby creating increased convection near the Earth's surface, possibly leading to enhanced cloud development. An inadvertent effect appears to have been detected during the Metromex project (Changnon et al. 1971) conducted in the St. Louis area, although in this case, the effect was hypothesized to have been because of urban pollution or heat island effects. Research performed by Rosenfeld and Lensky (1998) indicated that "natural and anthropogenic aerosols can substantially modify clouds not only in pristine environments, as was already demonstrated by the ship tracks, but they can also produce a major impact on cloud microstructure and precipitation in more continental environments, leading to substantial weather modification in densely populated areas."

An increase in the aerosol burden within a cloud may retard the precipitation process unless the infusion is accompanied by a direct or indirect amount of water vapor to accommodate the additional loading (see Chapter 4). For example, substantial reduction in the rainfall efficiency of clouds observed when plumes of smoke caused by biomass burning due to agricultural practices or forest fires (e.g., Rosenfeld 1999; Andreae et al. 2004), cooking and heating, and industrial processes

(Rosenfeld 2000; Ramanathan et al. 2001) were entrained into these clouds was manifested as actual loss of 15 to 25% of the winter precipitation from orographic clouds downwind of major coastal urban areas (Givati and Rosenfeld 2004). Air pollution was observed to mask the added rainfall because of cloud seeding (Givati and Rosenfeld 2005). Therefore, the opposing effects of air pollution and cloud seeding need to be separated for proper assessment of the anthropogenic impacts on precipitation amounts.

Clouds formed in polluted air with suppressed precipitation processes could regain their rain-producing ability once they incorporate sufficient additional water vapor, large hygroscopic particles originating as sea spray (Rosenfeld et al. 2002), or salt dust particles from salt flats, such as the anthropogenically dried Aral Sea (Rudich et al. 2002), because large hygroscopic particles mixed into the clouds may override the detrimental effect of the smoke particles. Dust in Saudi Arabia also was found to modify convective clouds. Under dusty conditions, when a large concentration of coarse-fraction mineral particles was in the aerosol, cloud drop concentrations were lower and droplet diameters larger than under regional background conditions when the aerosol was dominated by submicrometer sulfate particles (Posfai et al. 2013).

Rosenfeld and Givati (2006) established that reductions in precipitation in mountainous areas located downwind of large cities are occurring in the western United States. The authors attributed these reductions to artificially made aerosols interfering with the natural precipitation formation processes. Griffith et al. (2005) demonstrated similar reductions are occurring in mountainous areas downwind of Salt Lake City, UT. A field experiment in the California Sierra Nevada mountains found that the aerosols transported from the coastal regions are augmented greatly by local sources in the Central Valley, resulting in high concentrations of aerosols in the eastern parts of the Central Valley and Sierra foothills, consistent with the detected patterns of suppressed orographic precipitation in the southern and central Sierra Nevada. The precipitation suppression occurs mainly in the orographic clouds that are triggered from the boundary layer over the foothills and propagate over the mountains (Rosenfeld et al. 2008).

Rosenfeld et al. (2012) claimed, "Dust and pollution aerosols, through their effect on precipitation forming processes, redistribute latent heat in a way that weakens tropical cyclones. Therefore, incorporating these aerosol effects in models has the potential to improve the predicted storm intensities."

Another example of inadvertent weather modification revolves around the question of what happens to precipitation outside the intended cloud seeding target areas. This issue is frequently raised during the conduct of weather modification programs. A recent paper (DeFelice et al. 2014) examined this question. The conclusion was that the results summarized in the paper made a strong case for enhanced precipitation, or a direct seeding effect, in extra-area regions from the conduct of precipitation enhancement seeding programs.

5.2.2 Delivery Systems

Two broad options, ground-based and aerial, exist regarding cloud seeding delivery systems. Most systems currently in use are designed to dispense silver iodide nuclei, hygroscopic particles, or particles of dry ice. The choice of the delivery system (or systems) should be made on the basis of the project design, which should establish the best system for the specific conditions and requirements of a given project area. This requires a good climatology of the target areas clouds.

5.2.2.1 Aerial Application Commonly available aircraft can be modified to carry an assortment of cloud seeding devices. Silver iodide nuclei dispensers include models that burn a solution of silver iodide dissolved in acetone, or through pyrotechnic devices (flares), either ejectable or burn-in-place units. A typical silver iodide solution burner has a solution tank and a nozzle configuration. The silver iodide acetone solution is forced through the nozzle into a combustion chamber where the atomized solution is ignited, and the silver iodide crystals formed through combustion are expelled along with the other combustion byproducts into the atmosphere (ASCE 2004; Griffith 2006).

Pyrotechnics are similar to ordinary highway flares that are typically ignited at one end and designed to burn for periods varying from several seconds to several minutes. Silver iodide cloud seeding pyrotechnics (often referred to as flares) are impregnated with varying amounts of silver iodate ($AgIO_3$); $AgIO_3$ is used because this compound provides the oxygen needed to burn the flare formulation. Other flares can be utilized that burn some type of salt (e.g., calcium chloride) to produce small hygroscopic particles. These flares are classified as Class 1.4 s explosives, which require some restrictions in the way they are transported. Cloud seeding pyrotechnics (silver iodide and hygroscopic) can be burned from racks mounted on an aircraft near the trailing edge of the wing or can be ejected (silver iodide) from the underside of the aircraft. In the latter case, the flare is ignited as it leaves the aircraft and then falls for approximately 600 to 1,800 m (depending on the designed burn time) before being completely consumed. An aluminum casing containing the ejectable pyrotechnic mixture remains in the dispensing rack on the aircraft when the cloud seeding mixture is expelled by a propellant charge. Pyrotechnics typically produce 10 to 100 g of active seeding agent per minute of burn, whereas aerial acetone generators typically produce 2 to 3 g of active seeding agent

Fig. 5-2. Example of an acetone-silver iodide generator mounted on a wing tip Source: Courtesy of North American Weather Consultants, Inc.

per minute. The rate at which the seeding agent is dispersed is not the only important factor, however. Cloud chamber tests indicate that, in general, acetone generators produce about 10 times as many effective ice nuclei per gram of AgI burned as do pyrotechnics. In addition, the activation temperatures and nucleation mechanisms also may vary. All of these factors should be considered when selecting the type of generation method to be used. Laboratory cloud chamber test results can be highly informative in this regard. Figures 5-2 through 5-4 provide common installations of a silver iodide acetone dispenser, a pyrotechnic burn-in-place rack, and a rack for ejectable silver iodide pyrotechnics.

Dry ice is frequently dispensed through openings located through the floor of baggage compartments or extra passenger seat locations on modified cloud seeding aircraft. Dispensers have been designed to disperse "pelletized" or small particles of dry ice. Dry ice pellets, available commercially in some of the larger cities of the United States, with diameters of 0.6 to 1 cm and 0.6 to 2.5 cm in length are the appropriate size. The goal of dispensing dry ice is to have the particles fall 1 to 2 km before they sublime completely, thereby creating a sizable "curtain" of seeded cloud area. Other dispensers have been developed that either dispense precrushed dry ice or actually crush dry ice slabs onboard the aircraft. Figure 5-5 provides a

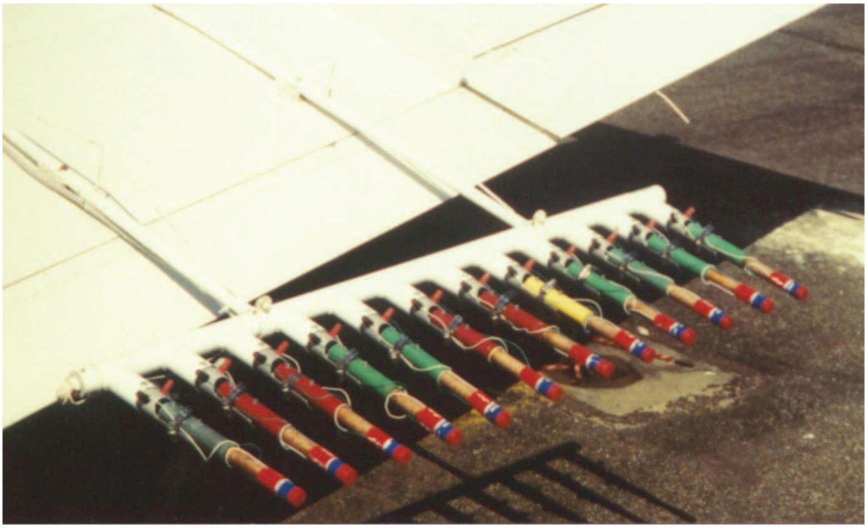


Fig. 5-3. Example of a wing-mount silver iodide pyrotechnic rack
Source: Courtesy of Weather Modification, Inc.

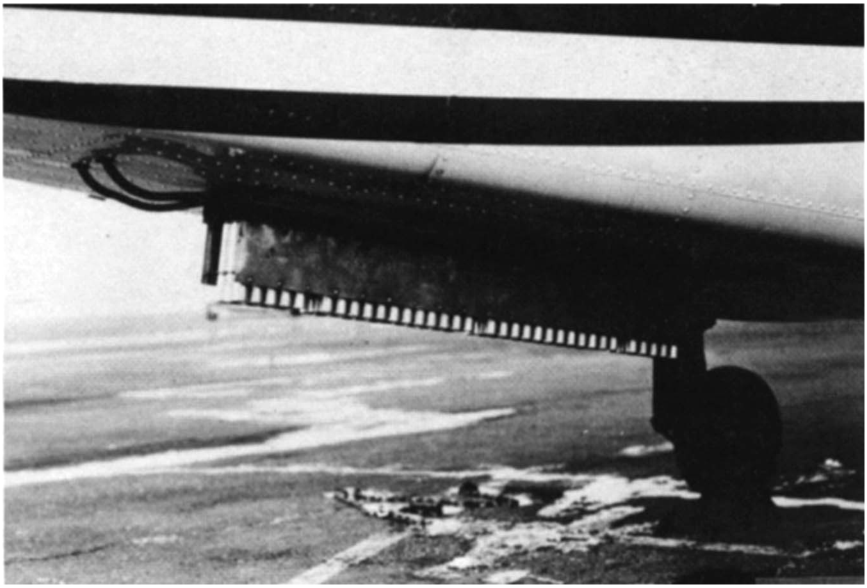


Fig. 5-4. Example of an ejectable silver iodide pyrotechnic rack
Source: ASCE (2004); © ASCE.

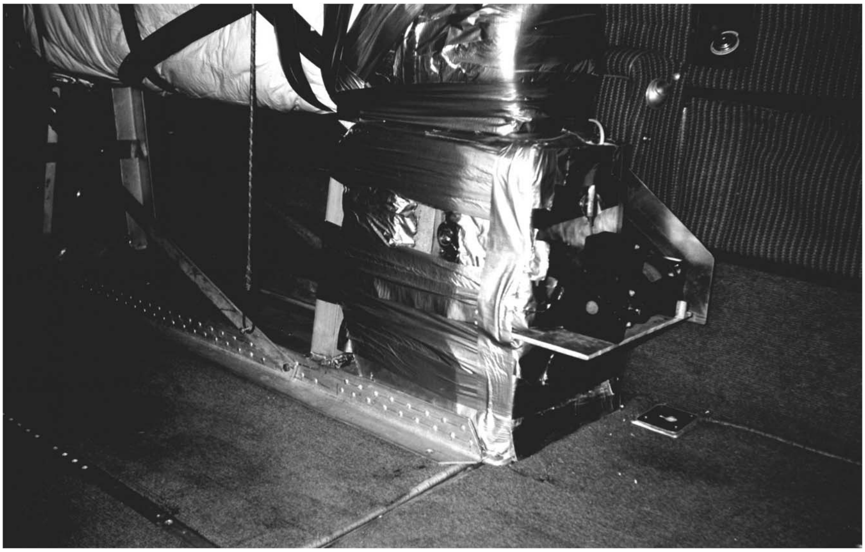


Fig. 5-5. Example of a dry ice dispenser mounted in an aircraft
Source: ASCE (2004); © ASCE.

photograph of a dry ice dispenser mounted in an aircraft. A third type of dispenser developed for Air Force research in the 1960s (Vickers and Church 1966) manufactured dry ice pellets from containers of pressurized liquid carbon dioxide.

Some prototype organic and hygroscopic dispensers have been developed on various projects. Fukuta et al. (1977) reported on an organic dispenser that received some field testing in South Dakota. Some agricultural spray dispensers have been modified to dispense hygroscopic materials. One disadvantage of most hygroscopic materials is that they are corrosive, requiring special care to avoid damage to the cloud seeding aircraft. They also tend to clump in humid conditions, requiring careful storage and handling techniques.

Types of aircraft utilized in operational cloud seeding projects range from single engine aircraft (such as a Cessna 182 or Piper Comanche) to larger twin-engine aircraft (Piper Twin Comanche, Aztec, Navajo, Seneca, and Cheyenne; Cessna 310, 340, 411, 414, and 421; or Aero Commander 690). Any modification of an aircraft incorporating cloud seeding equipment must be certified by the relevant aviation authority. This certification usually places them in a restricted category. As the name implies, certain restrictions govern the use of such aircraft including a limitation on the type of personnel authorized to fly in such aircraft.

The type of cloud seeding agent and delivery system used may dictate the type of aircraft used. Dry ice or ejectable AgI flares usually are dispensed at cloud top. However, this is only possible if cloud tops are accessible to seeding aircraft, tall enough to contain supercooled water (0 °C to −10°C), and positioned such that proper targeting of the cloud seeding effects is possible. Cloud seeding flights that are likely to entail flying through supercooled portions of clouds should be conducted with aircraft with de-icing capabilities.

For AgI acetone burners and end burning flares (AgI or hygroscopic), the aircraft can be operated in updraft regions below cloud base. However, when using silver iodide as the seeding agent it is advantageous to inject the seeding agent directly into supercooled clouds. With possible flight durations of 4 h or more, the aircraft should be fully de-iceable or frequent descents below the melting level will be required to shed ice buildup.

Research in winter orographic cloud seeding utilizing aircraft suggests that AgI acetone wingtip generators provide the simplest and most effective way to seed from aircraft. This is because (i) a 30-L solution tank holds enough cloud seeding solution for a 5 h flight; (ii) silver iodide solutions with a chlorine additive can effectively seed at temperatures near −5°C, with the silver iodide becoming more effective as the seed line rises to higher levels in the cloud; and (iii) the cloud seeding agent can be released outside a supercooled cloud, and when the seeding plume subsequently encounters the supercooled cloud, nucleation can occur (ASCE 2004).

5.2.2.2 Ground Applications Most ground generators utilized in the United States to date have relied on the generation of silver iodide freezing nuclei. Several different techniques have been developed to generate correctly sized silver iodide particles, including electric arc generators (a technique that is no longer used operationally), acetone solution generators, and pyrotechnics. Electric arc generators produce silver iodide particles by passing electricity through an electrode of silver in the presence of iodine. The most common type of ground generator in use today consists of a tank that holds an acetone solution with a given concentration (usually in the range of 1 to 5% by weight) of silver iodide. Other components include a means of pressurizing the solution tank, a nozzle, and a combustion chamber. Frequently, such systems employ a propane tank with a pressure reduction regulator to pressurize the solution tank and serve as a combustible material into which the silver iodide-acetone solution is sprayed. Other systems have been developed that utilize nitrogen to pressurize the solution tank, which directly burns the silver iodide-acetone solution.

Ground-based generating systems have been developed that are operated either manually or by remote control. Manually operated units often are sited at local residences at lower elevations upwind of the target area.

Fig. 5-6. Example of a manually operated, ground-based silver iodide generator Source: Courtesy of North American Weather Consultants, Inc.

Local residents are instructed in the operation of these units and then are called from a central location to turn the generators on or off. Figure 5-6 provides an example of a typical installation. Remotely controlled units are often desirable if suitable residences are not located upwind of the target area and to facilitate location of units in higher elevations upwind of the target to ensure the seeding agent reaches elevations cold enough for nucleation to occur. Both acetone burners and pyrotechnic systems have been developed for remote control applications using radio, cell phone, and satellite communications systems. Figure 5-7 provides an example of a remotely controlled system.

Pyrotechnics, similar to the end-burning type described for aerial applications, also can be used at surface sites. Again, these units dispense silver iodide nuclei. Racks are built to hold a number of pyrotechnics, which can be ignited via an automated control system to burn units at a predetermined rate. These units can be operated remotely using the same communications systems as those used to operate the remotely controlled acetone generators. Figure 5-8 provides an example of a typical installation.

The following comments are oriented toward winter programs, but some of these concepts apply to summer clouds as well. Defining the

Fig. 5-7. Example of a remotely controlled, ground-based silver iodide generator Source: Griffith (2006), © ASCE.

proper amounts and release locations of a seeding agent is a rather complex proposition. The authors certainly have effectiveness production curves like those from Colorado State University in Fig. 5-1. The desired concentrations of nuclei in a given cloud volume can vary based on considerations such as natural ice nuclei concentrations and whether a static or dynamic seeding response is sought. Concentrations could range from $\sim 1-10/l$ up to $\sim 100/l$. Other considerations come into play; for example, should the seeding agent act quickly (condensation freezing) or slowly (contact nucleation)? Where should the material be released? Is it near the

Fig. 5-8. Example of a ground-based silver iodide pyrotechnic dispenser
Source: Courtesy of North American Weather Consultants, Inc.

barrier, as is often the case with liquid propane resulting in short crystal growth times, or is the release farther upwind potentially offering longer growth times? What are the likely locations and temperatures of the supercooled liquid water? What type of plume rise is likely? If the plume rises, it encounters lower temperatures, and therefore more nuclei become active based on data like that provided in Fig. 5-1. At what temperature are the artificial ice crystals created? Although propane seeding is advocated to seed supercooled liquid water contents found at higher temperatures between −2°C to −4°C or −5°C, the growth rates of such crystals are much slower than ones created at lower temperatures, say, in the range of −6°C to −10°C. Ice crystals, or really by then snowflake masses, are important because mass determines fall velocities. Higher fall velocities of snowflakes may have the ability to affect the barrier, whereas those with low terminal velocities may not. Mass also translates into amounts of additional precipitation potentially reaching the ground. Wind velocities are important during seeding events. For example, high wind speeds result in shorter crystal growth times. Wind directions are also important: are the winds impacting the barrier in a perpendicular fashion or at some angle? Perpendicular winds probably will produce higher supercooled liquid water contents but may result in shorter ice crystal growth times. More oblique angles may have lower supercooled water contents but longer ice crystal growth times. This brief discussion is provided as an example of why a project-specific design study (refer to Chapter 6, Section 6.3) is highly desirable so that complexities such as these can be addressed in a fashion that is customized to represent a specific target location.

5.2.2.3 Advantages and Disadvantages of Aerial and Ground Systems The most critical portion of any cloud seeding project is the proper delivery of cloud seeding material to the appropriate portion of the cloud. Concentrations of the cloud seeding agent must be adequate to modify a sufficient volume of cloud to significantly affect the precipitation process in the desired manner (Griffith et al. 1995). To date, this has been and continues to be the greatest challenge in developing a reliable and economically meaningful precipitation enhancement technology.

The complexities of wind flows over mountain barriers and within actively growing convective clouds and cloud complexes make delivery of cloud seeding material and the determination of the fallout of cloud seeding effects very difficult. Major research projects conducted during the last 30 years have spent millions of dollars and applied the most sophisticated measuring equipment to determine the transport and dispersion of seeding material and to quantify the effects due to cloud seeding. Results have emphasized that delivering seeding material to the appropriate portions of clouds in sufficient quantities is, at best, limited with current seeding methodologies.

To adequately treat supercooled regions of clouds requires producing from a few to tens per liter of additional ice nuclei after the material has had time to diffuse within the cloud. Much of the available supercooled liquid water in clouds is between the 0 °C and −10°C levels (Super 1999; Reynolds 1988; Reynolds and Dennis 1986). On the basis of the effectiveness levels of various cloud seeding agents in this temperature range, seeding rates can be determined. A part of this calculation requires knowing how much dispersion occurs from either aerial or ground release of cloud seeding agents.

The choice of a cloud seeding delivery system (aerial or ground based) and the accurate targeting of the cloud seeding effects are complex issues. In some cases, several seasons of in-situ measurements of cloud types, liquid water concentrations and temperatures, wind flows, and transport mechanisms may be needed before a cloud seeding design can be finalized.

Project design needs to consider the relative advantages and disadvantages of aerial and ground systems and select the systems that are best suited to meeting the goals of a specific project. Sometimes a combination of aerial and ground systems is a reasonable choice to gain many of the advantages of both types of systems while offsetting some of the disadvantages of each of the systems when used separately. For example, the winter operational program being conducted in Santa Barbara County, CA, frequently has utilized both ground-based and aerial seeding modes (Griffith et al. 2005). Aerial systems offer advantages in terms of enhanced targeting of the cloud seeding material into specific regions of the storm or cloud systems, the ability to deliver higher dosage rates into given volumes of cloud, and the ability to seed stable atmospheric situations, which may not be possible using ground-based systems. Disadvantages include higher costs than ground generator operations. Also, it is difficult to maintain an effective amount of cloud seeding material feeding into the supercooled clouds affecting a target area of substantial size over long periods (i.e., multiple aircraft and crews may be required). In addition, there are potential hazards of flying in icing or extreme turbulence and possible flight restrictions near major airports and within military operations areas (MOAs).

Advantages of ground generator systems include lower costs of operation and the ability to operate continuously for extended periods (Griffith 2006). Disadvantages include an inability to operate ground generators successfully during periods of atmospheric stability (if lower elevation dispensers are used), thus losing some cloud seeding opportunities. Greater targeting uncertainty exists, because assumptions have to be made regarding the combined horizontal and vertical transport of seeding material prior to nuclei activation, ice crystal growth, and fallout. The high cloud seeding rates possible with aircraft at effective cloud seeding heights (i.e., temperatures lower than about −4°C) probably are not possible using ground generator systems. Maintenance of remotely controlled generators in isolated locations often requires regularly scheduled maintenance trips involving over-snow vehicles or helicopters, which can be a labor-intensive and costly proposition.

A remotely operated liquid propane dispenser has been shown to be a reliable method of seeding small volumes of supercooled clouds, even at temperatures near 0 °C (Super and Heimbach 2005; Reynolds 1991). Figure 5-9 shows a photograph of a propane dispenser. However, propane dispenser units must be located at elevations known to be in cloud and at temperatures lower than 0 °C during winter storms, which is not a consideration when using silver iodide dispensers. This may require close proximity to the target area and subjects the seeding effects to the complexities of flow over mountains, including rapid updrafts and downdrafts, and limited horizontal dispersion of the seeded cloud volume. Site selection is critical when positioning these dispensers. No experimental projects conducted to date have demonstrated that precipitation can be increased over a sizable fixed target area using this technique. This technique has, however, been used successfully in supercooled fog-clearing operations (ASCE 2013).

Fig. 5-9. Example of a propane dispenser
Source: Griffith (2006), © ASCE.

The efficacy of ground-based generating systems in summertime applications is uncertain. Some utilization may be possible in mountainous areas with "seedable" cumuli. Applications in flat terrain, such as the Great Plains, face complex targeting and cloud seeding rate problems that render aerial seeding a much more certain seeding approach.

5.2.3 Deployment of Cloud Seeding Systems

A project design should consider the deployment of a seeding system. Choices of types of generators to be used and seeding rates influence the deployment strategy. Spacing of ground generators or the type of aircraft flight plans to be flown are also an important aspect in specifying a cloud seeding mode. The goal in static mode seeding operations is to achieve concentrations of 1 to 10 nuclei per liter of supercooled cloud. For dynamic seeding, 50 to 100 or more nuclei per liter may be needed.

5.2.3.1 Dispersion of Cloud Seeding Materials in Winter and Summer Clouds There has been a concentrated effort during the last 15 to 20 years to document both the horizontal and vertical dispersion of aerial and ground release seeding agents (Super 1999, 1991). These results

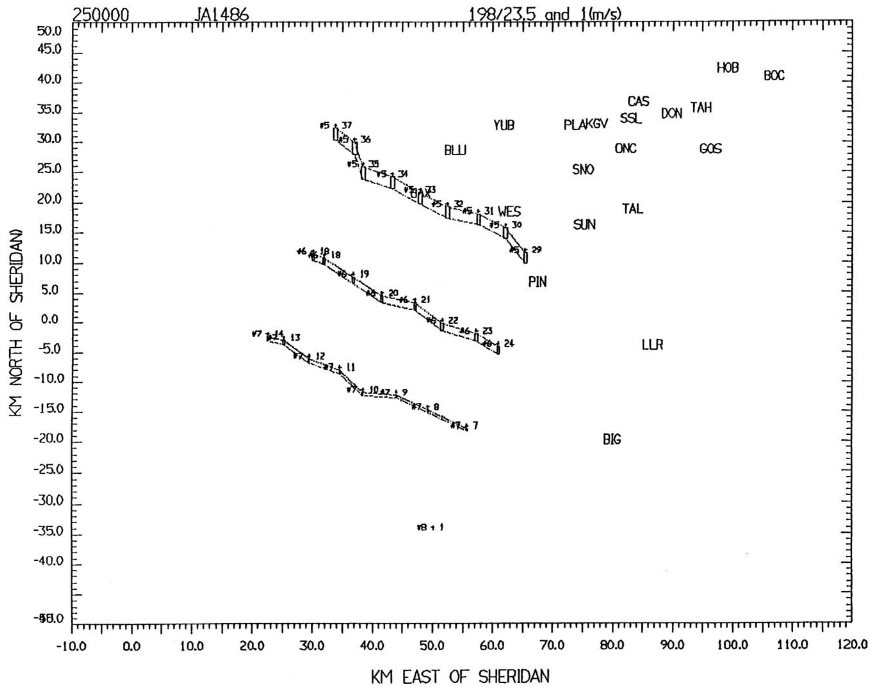


Fig. 5-10. Graphical depictions of a seed line produced from silver iodide seeding at 10, 20, and 30 minutes downwind
Source: Reynolds (1988), reproduced with permission from American Meteorological Society.

indicate that the dispersion rates for AgI from either wing-tip generators or end-burning flares on aircraft is about 1 m/s horizontally and 0.1 m/s vertically in most wintertime clouds. Figure 5-10 is a graphical depiction of the predicted downwind transport of one seed line at 10, 20, and 30 min following release (Reynolds 1988). Wind speeds of 50 knots are not atypical for this elevation within wintertime clouds. Note the limited volume of cloud that is actually affected by cloud seeding. Results would indicate that in some situations (e.g., large target areas) it may be difficult to seed the upwind cloud effectively over a watershed with a single aircraft. Two or more coordinated aircraft flying simultaneously may be required.

Ground seeding plumes also have limited horizontal and vertical dispersion. Studies (Super 1999; Griffith et al. 1992) indicate that plumes typically spread out horizontally in a 15 to 20 deg arc and diffuse vertically to about 1,000 m above the release elevation. Careful placement and activation of the ground-based generators is required if the AgI nuclei plumes are to reach the −5°C to −6°C level some 30 min upwind of the seeding target area. The plumes should disperse horizontally and merge before reaching the target area, yet maintain a minimum concentration of some 1 to 10 nuclei per liter. Griffith et al. (1992) suggest the spacing between ground generators should be in the 5 to 10 km range.

There has been some research conducted on the dispersion of seeding materials in summer clouds. An inert atmospheric tracer (sulfur hexafluoride, SF_6) was used in experiments conducted in North Dakota and Texas summer clouds. The SF_6 was released either at the base or at mid-levels of growing towering cumulus clouds. The dispersion of the tracer was studied through repeated penetrations of the cloud at different altitudes. A real-time SF_6 analyzer on board the research aircraft documented the presence and concentrations of the tracer gas. Tracer plumes detected at mid-levels of the cloud were found to be somewhat narrow and embedded within updrafts or downdrafts. Tracer plumes with diameters comparable to the cloud diameters were found in the upper 20% of the clouds. These observations suggested only limited dispersion of the plumes in the clouds, with greater mixing occurring at cloud top (Stith et al. 1986; Rosenfeld et al. 2010).

5.2.3.2 Aerial Cloud Seeding Modes Various aerial cloud seeding modes are available to choose from, depending on the seeding concept, type of clouds to be seeded, seeding agent, and type of dispenser (e.g., flares, acetone-silver iodide burners). Choices of flight levels include seeding at cloud base, in-cloud seeding, or cloud top seeding (Griffith et al. 1995).

Cloud-base seeding is frequently used in summertime situations when either silver iodide-acetone generators or burn-in-place pyrotechnics are used. Cloud seeding rates vary in the range of tens to hundreds of grams of AgI per hour. Seeding is usually carried out in the inflow or updraft regions because these regions normally contain the highest concentrations of water vapor and will carry the agent up to the desired range of temperatures in the clouds.

In-cloud seeding is a frequent seeding mode in wintertime projects where the aircraft fly at or near the melting level (to avoid icing) or in the −5°C to −10°C region where cloud seeding materials function quickly and where there are often higher concentrations of supercooled liquid water. In-cloud seeding is also utilized in summer operations, although weather radar is usually required (either on board the aircraft and/or at a ground support site) to permit avoidance of potentially dangerous thunderstorms. Various seeding techniques (i.e., dry ice, ejectable AgI flares, end-burning flares, or acetone-AgI generators) can be used for in-cloud seeding. Cloud seeding rates are normally on the order of 250 to 3,000 g/km of flight path in cloud when using dry ice or in the tens to hundreds of AgI g/km.

Cloud top seeding can be employed in both winter and summer operations, although this seeding mode is more commonly used in summer programs. Typical seeding targets consist of growing cumulus clouds. Cloud seeding aircraft can penetrate towering cumulus cloud tops (usually in the −5°C to −10°C range) to locate and seed updrafts that contain high supercooled liquid water concentrations. Either dry ice or ejectable AgI pyrotechnics can be dispensed into these growing tops. Cloud seeding rates are similar to those for in-cloud seeding unless dynamic cloud seeding is called for in the project design. AgI consumption can range from hundreds to thousands of grams per hour during a dynamic cloud seeding operation. Such situations require close coordination with the relevant aviation authority. Often routine flight patterns to be used can be approved by the controlling authority prior to operations, allowing quick clearances for seeding.

5.2.3.3 Ground-Based Cloud Seeding Modes Ground generators frequently have been utilized in wintertime cloud seeding projects or programs in the western United States and other mountainous regions of the world over the past 50 to 60 years. A network of generators is established upwind of a mountain barrier. The number of generators, the spacing between, and their distance upwind of the barrier are determined from target area size, expected temperatures in cloud, and the anticipated transport and dispersion of the cloud seeding material. Using ground-based AgI generators requires reliance on vertical dispersion of seeding material caused by atmospheric instability and turbulence associated with naturally occurring storm systems and the barrier. Cloud seeding material is not "shot" or projected into storm clouds, contrary to frequent public perception of how ground generators function. Output rates are lower than with airborne seeding, typically on the order of 5 to 35 g of AgI consumed per hour of operation. Some use has also been made of ground-based burn-in-place AgI pyrotechnics to achieve higher output rates from the ground. The latter seeding technique formed the basis of the Santa Barbara II Phase I research project in California (Brown et al. 1974), where 400 g of silver iodide was consumed every 15 min during the passage of a convective band over the seeding site. The cloud seeding in this project was directed at a dynamic response, thus the high seeding rates. Operational applications of this technique that began in 1981 have continued in this area to the present (Griffith et al. 2015).

Ground-based rockets and artillery shells loaded with silver iodide or some other seeding agent have been used extensively in several of the former Soviet Bloc countries and China on hail suppression and precipitation enhancement projects. The projectiles are launched with directions from radar and targeted to the supercooled tops of the growing cloud elements. Although these methods appear to offer the advantages of both ground and airborne delivery systems in some countries, they are costly and unacceptable for use in regions where there are numerous private or commercial aircraft operations.

5.2.3.4 Studies Related to Proper Targeting of Seeding Materials If financial constraints allow and program goals indicate a need to do so, targeting during initial seasons of operational programs can be verified by releasing various tracers, such as sulfur hexafluoride (SF_6) or indium sesquioxide (In_2O_3) along with the seeding agent or by tracing the ice nuclei themselves with an ice nuclei counter. This has been done in several operational programs in the American West, for example, California (Stone and Marler 1993; Chai et al. 1993), North Dakota (Boe et al. 1992), and Utah (Super and Huggins 1992). Such physical verification of targeting lends credence to the methodology employed by the program and may contribute significantly to the program's longevity. Perhaps more important, improper targeting can be corrected, and program efficacy improved.

A useful, but expensive means of verifying the targeting is to test the snowpack within and outside the target area for traces of those chemicals used in the seeding. Typically, testing is done for silver, as silver iodide is usually a primary component in the ice nucleant used. The presence of silver in snow does not by itself directly translate into quantitative estimates of increases in precipitation. Tracers such as indium sesquioxide (In_2O_3) also are seeing increased use, for the indium is not a nucleant, and when released simultaneously from the same location with the silver-iodide-based seeding agent at known rates, the final ratio of indium to silver in the snow indicates the fraction of the silver that *was* active as a nucleant, confirming a physical linkage between seeding and ice production. This kind of physical process (not statistical) evidence strengthens the argument that seeding was the cause of indicated increases in precipitation. Work with indium sesquioxide in the Lake Almanor watershed of the Sierra Nevada showed annual silver/indium ratios as high as 8.4:1 at the higher, colder elevations of the target area under westerly flow (Stone and Marler 1993; Chai et al. 1993). This research suggests that an active ice nucleation process produced new ice crystals, and additional precipitation was linked with more than 85% of the silver detected in the target area snowpack. Also, it was found that the amount of indium was related linearly with precipitation amount, implying that the indium aerosol particles were being removed directly by the number of cloud droplets the plumes encountered. The indium particle size distribution of the indium-containing aerosols emitted by the source was known, which allowed a direct estimate of the amount of precipitation that would have fallen naturally (because a new ice crystal nucleated by the seeding agent has an extremely small chance of collecting both a silver and indium particle). The difference between the total precipitation and the nonseeded component provides an estimate of the amount of seeded precipitation. Case studies conducted in the Nevada/NOAA federal state cooperative program at Lake Tahoe, NV, showed that the seeded precipitation can be a large fraction of some precipitation samples. Specialized source-receptor experiments showed that the Ag:In ratio could exceed 10 : 1 and was correlated with enhanced precipitation rates of up to 6.0 mm h^{-1} (Stone and Huggins 1996). In an analysis of a winter research program conducted in the Snowy Mountains of Australia (Manton and Warren 2011), it was found that "the primary analysis of the targeting of the seeding material is unequivocally successful, with the maximum level of silver in the primary target area found to be significantly greater in seeded than un-seeded experimental units. A secondary analysis of the ratio of silver to indium supports the proposal by Chai et al. (1993) that there has been a microphysical impact on cloud precipitation processes."

Another tool that is available is cesium-tagged, ice-nucleating seeding agents. Although the concept is not new, the efficiency of the seeding agents now make them a viable option for use in operations. The additional expense of adding cesium to the seeding agent is not great, especially given the added confidence it provides in targeting verification. The expense, however, of silver and cesium and silver analyses can be significant. The newer formulations have been shown to outperform older "standard" AgI seeding agent yields by as much as a factor of 30 at temperatures of –8°C. Applications are numerous, including testing of new generator locations or techniques while minimizing impacts on existing operational seeding programs, detecting impacts on control areas and extended areas downwind of primary target areas, measuring the (contamination) impacts of neighboring seeding programs, and determining the relative contributions of aircraft versus ground-based seeding components of individual programs. Each of these applications involves detecting cesium to uniquely identify the source of the seeding materials. Unlike the indium control tracer—which requires the duplication of seeding agent release facilities—cesium can be added to seeding materials and released without the need for additional operational apparatus. Cesium has a natural background level equal to or lower than silver, so detection of cesium and silver in samples located downwind of their release point provides physical evidence of the source of the materials. Cesium also can be readily incorporated into modern pyrotechnics. McGurty (1999) provided results of a winter research program that successfully utilized this tagging technique in the San Joaquin watershed located in the southern Sierra Nevadas. The tagging allowed the differentiation of the source of the seeding material, whether it came from ground or airborne seeding.

5.3 INSTRUMENTATION AND ATMOSPHERIC MODELS

There are two basic needs for meteorological or hydrometeorological information and atmospheric models to support a project. Real-time data are needed for decision making and monitoring functions. Past cloud seeding research has identified certain situations during wintertime or summertime precipitation episodes that respond favorably to cloud seeding, whereas others appear either not to respond or to respond unfavorably. Consequently, the project design must consider the development of "seeding criteria" to achieve a favorable response (ASCE 2004).

The presence of supercooled liquid water generally is a necessary but not sufficient condition for initiating a cloud seeding project that utilizes glaciogenic seeding agents. Liquid water is highly variable both in space and time in wintertime storms and cannot be correlated well with any specific meteorological variable (Reynolds 1988). This is also true of summer convective clouds where entrainment of dry air can rapidly erode a convective element's liquid water before cloud seeding can affect the supercooled water. In-situ or remote measurements of supercooled liquid water, therefore, are desirable to allow informed decisions.

As discussed in the previous sections, delivering cloud seeding material to the appropriate place and time can be difficult. Information on atmospheric stability and vertical wind profiles is required to assess the potential of ground-released seeding material to reach appropriate levels in cloud and to determine the expected fallout region of enhanced precipitation (i.e., targeting).

Information on movement of storms, the likelihood of a storm affecting the project target area, the likely ending time of precipitation in the target area (i.e., forecasting), etc., is also an important component of real-time decision making. This type of information provides input to establishing such things as personnel schedules, maintenance schedules, and supply logistics.

Project monitoring also includes a need for information concerning possible hazardous situations during which cloud seeding should not be performed. Suspension criteria should be defined as part of project design.

Postproject assessments of results are a second basic need for data from various types of instrumentation. It is quite important to the continued viability of an operational cloud seeding project to consider methods of assessing and reporting the estimated effects of the seeding. Ideally, a project design completed prior to the initiation of the project will consider, among other topics, the question of assessing the effects of cloud seeding. An assessment of the effects of cloud seeding in an operational project where every favorable seeding event is seeded is not a simple matter. Many projects without some method of assessment or indication of the achievement of a positive effect are abandoned within three or four years because of lack of support.

Types of instrumentation of potential value in satisfying each of these general requirements (i.e., real time and postproject) are examined separately in the following sections.

5.3.1 Real-Time Decision-Making and Monitoring Tools

An array of hydrometeorological instrumentation of potential value exists in the day-to-day conduct of a cloud seeding project. A considerable amount of information that can be utilized in cloud seeding projects is in place at many locations serving other functions. Examples include the National Weather Service network of data collection, data assimilation, data processing, and data and analyses dissemination functions (Griffith et al. 1995). Depending on the location of the target area in relation to existing data collection points and the specific needs of a particular project for certain types of instrumentation (as established in the project design), it is possible that some additional project-specific instrumentation may need to be acquired, installed, and operated in support of the project. Such installations may be of use in terms of real-time project operations and postproject assessments. The various types of data and instrumentation of potential value to a cloud seeding project for real-time decision making and monitoring functions will now be discussed.

5.3.1.1 Publicly Available Weather Data The National Weather Service (NWS) collects various meteorological data and issues weather forecasts to a diverse group of users. Basic data and analyzed data and forecasts are available to cloud seeding projects from the NWS or private companies that provide data via the Internet. Types of data available by these means include rawinsonde data from a national network of stations on a twice daily basis. Such data, if collected in close proximity to the project area, are useful in trying to establish the "seedability" of a given situation and "targeting" the effects of cloud seeding. Hourly observations from a large number of reporting stations are also available. These observations include information on cloud cover, surface winds, temperature, humidity, and present weather. This type of information is useful in developing a knowledge of the structure of a particular storm as it affects a given target area.

In recent years weather cameras have proliferated throughout the United States. These cameras provide visual information at diverse locations that can help determine the type of cloud cover and precipitation that may be occurring. Such input is only available during daylight hours.

Analyzed NWS data include surface pressure patterns and constant pressure charts at upper levels and forecasts of these pressure fields at 6 or

12 h intervals out through 72 h and beyond. Current weather can best be observed via weather radar and satellite images. The NWS or the same companies that provide weather data can provide images from both local weather radar and geostationary satellites. Such images can be stored and displayed in sequential fashion (looped) on video monitors allowing extrapolation of weather features into the target area ("nowcasting").

Project suspension criteria may require meteorological or hydrological data to be monitored. These might include telemetered river and reservoir levels, weather radar observations, and precipitation data from special telemetered gauges designed to monitor heavy precipitation and to alert water managers and the NWS automatically of threatening weather conditions. The NWS also issues special weather statements and weather watches and warnings as conditions warrant. These can be obtained via NOAA weather radio, the NWS, or through the same data stream providing weather data. For winter projects it may be necessary to contact the U.S. Forest Service via a special recorded phone message that warns of potential avalanche hazards.

The National Weather Service has approximately 136 Next Generation Weather Radar (NEXRAD) sites in the contiguous United States (Baer 1991; Klazura 1993). The NEXRAD (WSR-88D) is a Doppler radar, which provides high-resolution reflectivity and velocity information and has recently been upgraded to provide polarimetric data. This capability allows for improved data quality and better differentiation among different types of precipitation (e.g., rain, snow, hail, and mixed hydrometeors). The NWS has developed approximately 40 categories of analysis products. A number of these products are available in near real time from various Internet providers, including data available directly from the NWS. Success of the Collaborative Radar Acquisition Field Test (CRAFT) project enables users to access the full-resolution database in near real time from any NEXRAD site via data compression techniques. Volume scans from NEXRAD sites take approximately the same amount of time as scans from TITAN-equipped project-dedicated radar (TITAN is discussed in Section 5.3.1.5), that is, about 5 min. Therefore, if data are acquired from NEXRAD sites shortly following the completion of each volume scan they can be used as effectively as TITAN-equipped project radar to make real-time seeding decisions.

The NWS has utilized weather satellites since the 1960s to provide information on cloud cover. Weather satellites have become increasingly sophisticated since then. Both orbiting and geostationary satellites (satellites that remain in a "stationary position" over the Earth's equator) are used. Sensors routinely carried on these satellites provide, for example, visible images, infrared images, and information on atmospheric moisture and temperature. Data are available at approximately 10 to 15 min intervals, and sometimes more frequently when severe weather is occurring.

Satellite information is useful in the conduct of cloud seeding projects to determine the location and movement of the cloud system of interest. The infrared data capability provides this information during nighttime hours and also can be used to estimate cloud top temperatures, which are of interest in assessing the potential seedability of winter storms. The data provided by satellites also can be analyzed to provide estimates of different quantities, such as the water content of the atmosphere (Guillory et al. 1993) and even supercooled liquid water (Roskovensky et al. 2011). These quantities are of interest in the real-time conduct of cloud seeding projects.

An evolving technique uses multispectral analyses of satellite imagery. With timely satellite imagery, it is possible to calculate the evolution of the effective radii of convective cloud particles with respect to temperature, which provides information about precipitation-forming processes in the clouds (Martins et al. 2007; Rosenfeld and Lensky 1998).

The usefulness of polar orbital satellites is limited by the number of times these pass over the areas of interest. Usefulness of both polar orbital and geostationary satellites is limited by the horizontal resolution of the sensors.

5.3.1.2 Weather Research and Forecasting Models Continuing improvements are being made to atmospheric models. For example, the Weather Research and Forecasting (WRF) model is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research. It features multiple dynamical cores; a three-dimensional, variational (3DVAR) data assimilation system; and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers.

The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), National Oceanic and Atmospheric Administration [National Centers for Environmental Prediction (NCEP) and Forecast Systems Laboratory (FSL)], Air Force Weather Agency (AFWA), Naval Research Laboratory, University of Oklahoma, and the Federal Aviation Administration (FAA). WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. WRF provides operational forecasting with a model that is flexible and efficient computationally while offering the advances in physics, numerics, and data assimilation contributed by the research community.

NOAA's Earth Systems Research Laboratory recently developed the High Resolution Rapid Refresh (HRRR) version of the WRF model. This model has a 3 km grid spacing compared with the more standard grid model spacing of 13 km (e.g., the NAM model), plus it is reinitialized every hour using the latest radar observations. The NAM and GFS NOAA models, in contrast, are currently reinitialized every 6 h. Hourly forecast outputs from the HRRR model are available for a variety of quantities out to 15 h. Table 5-1 provides a summary of forecast variables of potential interest in assisting real-time decision making in the conduct of precipitation enhancement programs.

A silver iodide cloud-seeding parameterization has been implemented into the Thompson microphysics scheme of WRF to investigate glaciogenic cloud-seeding effects (Xue et al. 2013a). The sensitivity of the parameterization to meteorological conditions, cloud properties, and seeding rates was examined by simulating two-dimensional idealized moist flow over a bell-shaped mountain. The results verified that this parameterization can reasonably simulate the physical processes of cloud seeding with the limitations of the constant cloud droplet concentration assumed in the scheme and the two-dimensional model setup. This scheme was then implemented in WRF over southern Idaho during the 2010–2011 winter season. The seeding effects of both ground-based and airborne seeding and the impacts of model physics, seeding rates, location, timing, and cloud properties on seeding effects have been investigated (Xue et al. 2013b). It was found that glaciogenic cloud seeding increased orographic precipitation by less than 1% over the simulation domain, including the Idaho Snake River Basin and by up to 5% over the target areas. The local values of the relative precipitation enhancement by seeding were up to ~20%.

A numerical modeling study was conducted to explore the ability of the WRF model-based, large-eddy simulation (LES) with 100 m grid spacing to reproduce silver iodide (AgI) particle dispersion by comparing the model results with measurements made over the Medicine Bow Mountains in Wyoming (Xue et al. 2014). AgI cloud-seeding parameterization was applied in this study to simulate AgI release from ground-based generators. Qualitative and quantitative comparisons between the LES results and observed AgI concentrations were conducted. The results showed the following:

1. Despite the moist bias close to the ground and more than 4 km above ground level (AGL), the LES with 100 m grid spacing captured the essential environmental conditions except for a slightly more stable planetary boundary layer (PBL) relative to the observed soundings.
2. Wind shear is the dominant turbulent kinetic energy (TKE) production mechanism in wintertime PBL over complex terrain and generates a PBL of about 1,000 m depth. The terrain-induced turbulent eddies are primarily responsible for the vertical dispersion of AgI particles.

Table 5-1. HRRR Forecast Variables of Interest

Variable	Application
1 km above ground level reflectivity	Forecast of lowest elevation radar returns 1 km above ground
Composite reflectivity	Forecast of composite radar returns using reflectivity values from different scan elevations
Maximum 1 km above ground level reflectivity	Forecasts that pinpoint the location of maximum reflectivity cores
1 h accumulated precipitation	Forecasts of radar-derived estimates of precipitation reaching the ground in a 1 h period (QPF)
Total accumulated precipitation	Forecasts of radar-derived estimates of precipitation reaching the ground for a specified time period, for example 1 to 6 h in the future (QPF)
850 mb winds	Forecasts of the 850 mb (~4,000 ft) wind direction is useful in targeting of seeding material determining if and when wind directions go out of bounds in regard to suspension criteria (e.g., avoiding burn areas)
700 mb temperature	This level, which is ~10,000 ft, is often a good estimate of the steering level for storms and is also a good indicator in winter orographic programs whether silver iodide nuclei will activate because this level is often near the barrier crest height
700 mb vertical velocity	Forecasts the strength of the upward or downward movement at the ~10,000 ft level; stronger updrafts favor transport of seeding material to colder, more effective cloud regions
Echo top height	Forecasts of cloud echo tops; can be useful in determining whether the cloud tops are forecast to be cold enough for silver iodide to be effective (~ −5°C) and perhaps too cold < −25°C to produce positive seeding effects

3. The LES-simulated AgI plumes were shallow and narrow, in agreement with observations. The LES overestimated AgI concentrations close to the ground, which is consistent with the higher static stability in the model that is observed.
4. Non-LES simulations using PBL schemes had difficulty in capturing the shear-dominant turbulent PBL structure over complex terrain in wintertime. Therefore, LES models of wintertime orographic clouds with grid spacing close to 500 m or finer are recommended.

5.3.1.3 Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) The HYSPLIT model is the newest version of a complete system for computing simple air parcel trajectories in complex dispersion and deposition simulations. As a result of a joint effort between NOAA and Australia's Bureau of Meteorology, the model was recently upgraded. New features include improved advection algorithms, updated stability and dispersion equations, a new graphical user interface, and the option to include modules for chemical transformations. Without the additional dispersion modules, HYSPLIT computes the advection of a single pollutant particle or simply its trajectory. This model has provided the capability to predict the transport of seeding plumes in real time. Input data include the latest NAM model data, release location, source strength, and duration of the requested output (e.g., 1 h, 2 h, etc.). Both ground and airborne releases can be simulated. The model can be run for previous conditions and use archived NAM model data.

5.3.1.4 Special Project Precipitation Gauges In some situations the number and/or location of existing NWS or other public agency's precipitation gauges are inadequate for a specific cloud seeding project's requirements. This may dictate the need for installation of additional gauges to support the project. Typical uses of special precipitation gauges are determining the onset of precipitation and thus possible cloud seeding potential, monitoring for excessive precipitation periods, and collecting precipitation data for postanalysis. Installation of additional precipitation gauges for project evaluation of seeding effectiveness is only useful if randomization is employed; otherwise, there will not be any unseeded database from which regressions could be developed (ASCE 2004).

Types of gauges available include weighing-type precipitation gauges and tipping bucket gauges. The type preferred depends on whether it is a summer or winter project and the intensities of precipitation that can be expected in a given target area. Sometimes it is desirable to provide data in real time to the project meteorologist, in which case telemetry of some type is needed.

Special provisions are required if the gauges are to be used to measure snow. This includes mounting on towers, shielding the orifice from wind to increase catch efficiency, and provision to melt the snow. Weighing gauges are the only satisfactory method of measuring the water equivalent of snowfall. Tipping bucket gauges must be heated to operate in snow, but it is well known that the heat rising from the gauge is sufficient to raise the trajectory of ice crystals, causing them to pass over rather than into the gauge, thus under-sampling precipitation. An antifreeze solution must be added to the weighing gauge to melt the snow as it is collected. An evaporation suppressant (usually mineral oil) also must be placed into the antifreeze solution to prevent the antifreeze from evaporating. Special mixtures of methanol and glycerin, which are nontoxic, have been tested and found to work as well as glycol (toxic) mixtures (Price and Rilling 1987).

A second problem in snow measurement is capping of the gauge orifice by accumulating snow. It is recommended that the gauge have at least a 30 cm orifice and that the sidewalls of the gauge be minimized to avoid snow sticking to the side of the gauge and bridging over the orifice. A newer design, the optical rain gauge, offers an attractive alternative in measuring snow that may have some advantages over the weighing or tipping bucket gauges (DeFelice 1998).

Gauge resolution is also important. For wintertime projects, the gauge should be able to resolve precipitation accumulations to within 0.3 mm. This is on the order of what seeding produces in about an hour. Because of the requirement for high resolution and a large orifice, servicing of the gauge will be frequent unless the catch can be drained automatically and a fresh antifreeze charge placed into the gauge. Figure 5-11 shows a photograph of a weighing-type rain/snow gauge that automatically drains and recharges itself, requiring few or no visits during a winter season.

5.3.1.5 Special Project-Specific Weather Radar Different types of weather radars are available as project-dedicated radars. Some radars are Dopplerized (a technique that provides hydrometeor direction and speed information in addition to the precipitation intensity), providing both reflectivity and radial velocity data (Pasqualucci et al. 1983). Dual-polarization radars can provide information about hydrometeor types and can be used to track chaff (a tracer) to follow dispersion of seeding material. Radars are available in a variety of wavelengths (K_a-, X-, C-, S-band), each of which can serve a slightly different function in cloud seeding projects. K_a-band (1 cm) radars, pointed vertically, can provide information on cloud top heights in winter storms. They also may be sensitive enough to directly observe cloud seeding effects. K_a- and X-band (3 cm) radars can detect light to heavy snowfall and light to moderate rain but are attenuated during heavy rainfall. By far, the most commonly used radars in cloud

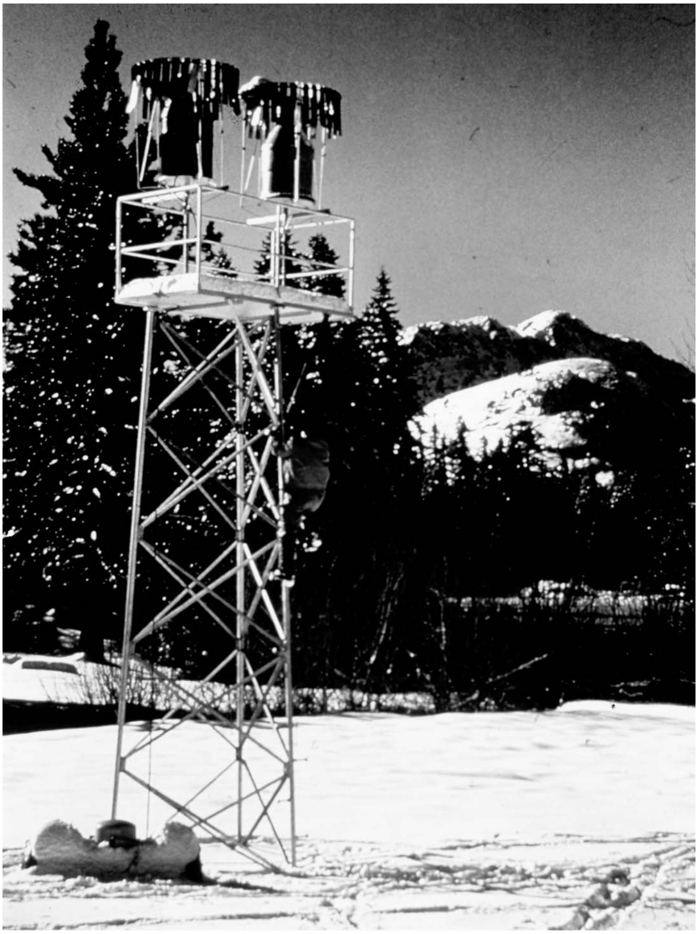


Fig. 5-11. Example of a weighing bucket recording precipitation gauge
Source: Griffith (2006), © ASCE.

seeding projects are C-band (5 cm) radars. They provide sufficient sensitivity in rain events but decreased sensitivity in snow events. They also can be Dopplerized and polarized as needed. S-band (10 cm) radars are superior in heavy rain and hail situations but may lack sensitivity in measuring snow.

Normally radars are operated in either plan position indicator (PPI) or range height indicator (RHI) modes. The PPI mode provides a horizontal depiction of the precipitation out to a range of perhaps 180 to 360 km. Multiple PPI scans at different elevation angles can be accumulated over a 4 to 5 min period, forming a volume scan. The RHI mode provides a vertical

Fig. 5-12. Example of a self-contained, project-dedicated weather radar installation in the field
Source: Griffith (2006), © ASCE.

presentation of precipitation the radar sees along an azimuth from the radar. Radar digitizing is readily available and can be specified for a project if real-time processing, storage, and retrieval of data are of benefit. Project-specific weather radars frequently are used in summertime cloud seeding projects. In summertime operations, they can be used to keep track of high reflectivity and potentially hazardous areas (i.e., convective bands or probable hail regions) to be avoided by the cloud seeding aircraft and to identify areas of new echo development of potential interest as cloud seeding targets. They are used somewhat less frequently in wintertime projects, especially if aircraft are not used.

The utility of weather radars in aerial seeding operations can be enhanced considerably if they are equipped with an aircraft tracking capability, which utilizes a radio modem to transmit a Global Positioning System (GPS) aircraft location to a ground-receiving site (typically the project radar). When the project radar is equipped with such a unit, the operator can track the location of the cloud seeding aircraft visually in relation to cloud echoes and ground terrain (of special interest in mountainous areas). In some cases, radar information can be utilized as input to suspension criteria. Figure 5-12 contains a photograph of a typical project-specific field radar installation.

Automated radar analysis is the family of capabilities for the identification and tracking of individual storms through systematically recorded volumetric radar data. An example of this is the package called TITAN (Thunderstorm Identification Tracking, Analysis, and Nowcasting) developed in South Africa; versions have been used and made available to the public by the National Center for Atmospheric Research (NCAR) and Research Applications Laboratory (RAL). TITAN has been described by Dixon and Wiener (1993). Storms are identified on each volume scan (a collection of individual PPI scans taken at different elevation angles in a short period of time) as volumes enclosed by an envelope composed of a specified surface of threshold reflectivity, and a complex algorithm associates a storm cell on one scan with its position on the next. For each volume scan, quantities such as storm height, volume, and mass are estimated for each storm, and the time history of these constitutes a description of their life cycle. Storm outlines can be overlaid on the radar display at each scan time for several past scans in one color, the present in another color, and extrapolated future times in yet another. The prognostic cell positions are computed from a forecast algorithm. The TITAN software also can be used to display the location of the seeding aircraft in relation to the weather echoes.

The National Severe Storms Laboratory has developed an improved NEXRAD cell-tracking algorithm (known as SCIT) that was implemented on the NWS Advanced Weather Interactive Processing System (AWIPS) computer workstations.

Geerts et al. (2010) describe some airborne flights conducted in conjunction with an ongoing winter cloud seeding research program being conducted in southern Wyoming. A downward pointing lidar was used to detect seeding signatures produced from upwind ground releases of silver iodide.

5.3.1.6 Special Project Rawinsondes Rawinsondes (balloon-borne weather instrument packages) are a common addition to an operational cloud seeding project. Balloon-borne (helium or hydrogen filled) instrument packages transmit back (via radio) pressure, temperature, and humidity data to a surface site. By tracking the balloon using either triangulation with LORAN, GPS, or radio signal strength (radiotheodolite), program operators can obtain a vertical profile of wind direction and speed (Griffith 2006).

Data are acquired from the surface to varied heights (up to 15 km), depending on the project requirements. Observation times are also on an as-required basis, varying from 3 h, 6 h, 12 h, or 24 h releases during active weather conditions. For winter projects the site should be located upwind of the target area, especially in mountainous regions. For large mountain barriers, two rawinsonde sites may be needed, one on the upwind edge and one near the crest of the barrier to adequately measure the complexities of the flow. Figure 5-13 shows a photograph of a typical rawinsonde receiver system. Near real-time rawinsonde data are valuable inputs in a variety of ways.

Fig. 5-13. Example of a rawinsonde receiver system
Source: Courtesy of Weather Modification, Inc.

In wintertime rawinsonde data can be used to indicate whether any low-level stability exists in the atmosphere, which may limit or preclude ground-based seeding with AgI. Targeting guidance is also available from upper-level wind data. Data from upwind and, if available, crest or downwind sounding data can be input to simple kinematic and microphysical models to predict the transport, nucleation, and fallout of seeded ice crystals.

In summertime the convective potential of the air mass can be determined. The location of a rawinsonde field site is not as critical for summertime projects as for wintertime projects. This same sounding can be used as input to numerical cloud models, which can provide information on the dynamic cloud seeding potential for the particular air mass. In a creative application, Czys and Scott (1993) used rawinsonde data to diagnose occurrence, height, and coalescence activity of summertime convective clouds in the 1989 Precipitation Augmentation for Crops Experiment. Data from rawinsondes can be utilized to initiate project suspension if, for instance, extreme instability is indicated, which would suggest a high likelihood of hail formation or other damaging weather.

5.3.1.7 Supercooled Liquid Water Observations One of the observations particularly useful in the conduct of wintertime snowpack enhancement projects is the observation of supercooled liquid water (SLW). It is also an important quantity in summer rainfall enhancement projects, but in that case it can only be derived from in-situ aircraft measurements. This will be discussed more later.

An important instrument applied to the measurement of SLW in winter mountain clouds is the dual channel microwave radiometer (Hogg et al. 1983). Radiometers originally were used as a research tool but in recent years have been used operationally. Radiometers provide valuable information on both the SLW and water vapor passing over a given mountain range. The instrument passively detects the presence of both condensed cloud water and water vapor in a narrow beam above the radiometer. When operated at elevations where the temperature is less than 0 °C, only SLW due to cloud droplets is observed. When operated at lower levels with higher temperatures, melting crystals and cloud liquid at temperatures above 0 °C can contaminate the system's data. Considerable work has gone into the development of small, portable microwave radiometers in the past several years. These radiometers can provide continuous profiles of temperature, relative humidity, and liquid water. Figure 5-14 shows a photo of a unit installed in the field.

Another remote-sensing method (based on satellite information) has been developed to help identify the presence of supercooled liquid in cloud tops (and thus the potential for glaciogenic seeding and identifying seeding signatures). This method has been described by Woodley et al. (2000). Roskovensky et al. (2011) describe the development of an automated algorithm for estimating the potential cloud supercooled water from satellite data.

A more inexpensive approach to measuring SLW is the installation of an icing rate meter at mountain top. The device is similar to ice detectors used on aircraft or by power and telephone companies operating equipment subjected to severe rime icing. The detector has a small 25 cm probe protruding from a small hemisphere. The probe vibrates at a known frequency. When ice accumulates on the probe tip by a process known as accretion, it changes the vibration frequency, causing a heater to switch on at a predetermined ice mass, thus melting the accumulated ice. By knowing the number of de-icing cycles, wind speed, and mass of ice required to cycle the heater, liquid water content can be calculated (Hindman 1986).

This type of detector has been used successfully as a real-time indicator of SLW. Mounted on a mountaintop having commercial or other power sources, the data can be telemetered via satellite or telephone to the project operations center. It is useful to have additional observations at this same site. These would include temperature, wind speed, and direction. Temperature would be useful to determine a particular cloud seeding agent's

Fig. 5-14. Example of a portable microwave radiometer
Source: Courtesy of Radiometrics, Inc.

activity level and wind speed to quantify liquid water amounts. Solak et al. (2005) and Yorty et al. (2012) provide analysis results obtained from icing rate meters installed at three different exposed locations in Utah. Figure 5-15 shows a photo of a typical unit, and Fig. 5-16 shows a photo of a field installation.

5.3.1.8 Special-Project Cloud Physics Instrumentation Specially instrumented cloud physics aircraft frequently are used in research-oriented cloud seeding studies, but their application to operational cloud seeding projects has been rather limited. The primary prohibiting factor is cost, because fully equipped aircraft are expensive to configure and operate.

Weather Modification, Inc. (WMI) of Fargo, ND, has installed sophisticated cloud physics instrumentation on a variety of aircraft. Figure 5-17 shows a photograph of a WMI-instrumented King Air 200. The significant costs to equip and fly such aircraft are justifiable on research projects where the need to understand basic processes is a primary goal. A compromise situation is possible, however, especially when a cloud seeding project utilizes one or more cloud seeding aircraft. This compromise consists of the

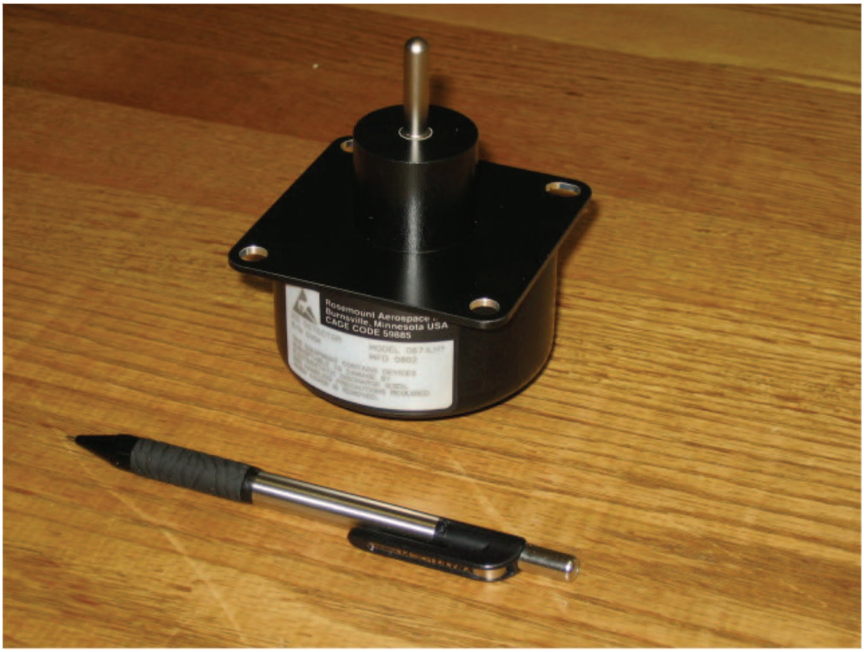


Fig. 5-15. Ground-based Goodrich icing rate meter
Source: Courtesy of North American Weather Consultants, Inc.

installation of somewhat basic cloud physics instrumentation on the seeding aircraft. The quantity of perhaps greatest interest is SLW, which is directly related to the seedability of a cloud system. Other variables of interest include some measure of the concentration of ice particles (an indication of how naturally efficient the system is), temperature, and some water vapor measurement (i.e., dew point or relative humidity).

5.3.1.9 Other Instrumentation and Equipment It is critical that confidence be gained that the cloud seeding agent is reaching the appropriate regions of the intended cloud in sufficient concentrations to be effective. Obviously this applies more to ground-based seeding than to aerial seeding. Several methods are available to do this. Tracer studies during the first one to two years of a project may be used to build confidence that seeding material reaches the appropriate SLW-rich cloud levels the majority of the time. Tracer studies require both a good understanding and observation of the general wind flow and the release of an aerosol that can simulate the trajectory of the seeding agent.

It is critical that the environmental winds be observed during these experiments. Rawinsondes already have been discussed. More continuous

Fig. 5-16. Field installation of an icing rate meter and support instrumentation Source: Courtesy of North American Weather Consultants, Inc.

observations can be obtained from sodars and wind profilers (Weber and Wurtz 1990). Sodars, or acoustic sounders, are much less expensive but provide vertical profiles of the horizontal winds within only the lowest kilometer above the device. Profilers (Hogg et al. 1983) provide winds to the top of the troposphere but at a somewhat degraded resolution in the lowest levels compared with the sodar. Doppler weather radars and properly equipped research aircraft also can provide horizontal wind measurements, but their applications are limited over mountainous terrain because of terrain blocking and aircraft flight level restrictions, respectively (Griffith et al. 1995).

At least three methods are available for tracing the trajectory of aerosols. The first is the use of an ice-nucleus counter (Langer 1973) to directly measure the presence of AgI. This detector can be operated in either a fixed or mobile configuration. For mobile configurations, it can be mounted either in a van or on an aircraft. In either configuration, it acts as a portable cloud chamber cooled to −20°C. When ice nuclei are injected into the chamber, crystals grow and fall out onto an acoustic detector. By counting the number of acoustic emissions, program operators can obtain a qualitative estimate of ice nuclei concentrations. The response time of this system

Fig. 5-17. King Air 200 cloud physics research aircraft
Source: Courtesy of Weather Modification, Inc.

is slow, thus smearing the plume. Also, it can be quite difficult to operate unless specialized training is obtained. Its main advantage is that it is sampling the actual seeding plume and not a surrogate.

The second tracer method is through release and detection of rare gases that can be measured down to parts per trillion (PPT). One such tracer gas used extensively in past air pollution work is sulfur hexafluoride (SF_6). Fast response analyzers (Benner and Lamb 1985) provide a means to measure the gas concentrations in PPT. It is applicable for both winter and summer cloud seeding projects and has been used successfully on both (Stith et al. 1986; Griffith et al. 1990, 1992; Rosenfeld et al. 2010). In recent years concerns about releasing fluorocarbons into the atmosphere has limited these types of tracer studies.

A research technique has evolved using circularly polarized X-band radar (Martner and Kropfli 1989). The technique is based on the principle that hydrometeors scatter radiation both horizontally and vertically, and this type of radar measures both components. By releasing small pieces of reflective material (chaff) that scatter only the horizontal component, it is possible to track the material through a cloud, even if the cloud is precipitating moderately. This is because the depolarization signal from the chaff is much greater than that from precipitation particles. By scanning through the cloud in which chaff has been released, it is possible to obtain a three-dimensional view of transport processes in cloud. The chaff does not remain suspended in the cloud but has a fall speed of about 30 cm/s. This gradually separates seeding materials from the chaff. Experimentation continues using other material that would not have such high fall velocity.

5.3.2 Measurements of Potential Value in Postproject Assessments

The major requirement for instrumentation measurements other than real-time decision and monitoring functions is providing data for postproject assessments of the cloud seeding effect. There are again a variety of measurements that have been investigated and used for this purpose (Griffith et al. 1995).

Assessment of the effects of seeding in operational cloud seeding projects presents a challenge to people's ingenuity. The question of precisely how much rain or snow would have occurred in a given situation without seeding may appear doable, yet has not been achieved with the precision needed for verification of seeding effects. The obstacle is the large natural variability in precipitation from day to day, month to month, and year to year. Imposed on this large natural variability may be a seeding signal of 5 to 10%, which usually proves to be within the data noise levels. An approach utilized in research projects involves randomization, whereby normally one-half the seedable events are left unseeded for comparison with the seeded ones. Statistical tests can be applied and if the seeding signal is large enough and the experiment is conducted long enough, some convincing statements can be made concerning success or failure.

Sponsors of operational projects are normally unwilling to forego one-half the potential benefit of a cloud seeding project to establish the effectiveness of seeding with a high degree of statistical significance. Consequently, other assessment approaches are required. The most common approach is a target and control comparison (Dennis 1980), where a control area is selected such that the effects of seeding should not affect it (this selection is ideally made prior to the beginning of seeding). A historical period is selected during which a regression analysis can relate measurements, such as precipitation, snowpack water content, or streamflow, to similar measurements in the target area. This historical period should not include any periods with previous seeding in either the control or target areas. These regression relationships are then used to predict the amount of natural precipitation to target for comparison with the observed values. Griffith et al. (2009) provide an example of the application of this assessment technique to four winter orographic cloud seeding programs conducted in Utah.

Unfortunately, target-control analyses can suffer from changes in relationships from the target to control from year to year and especially for various prevailing wind (storm track) regimes. These types of assessments are more prone to statistical errors than are purely randomized experiments. Historical comparisons via simple regressions are intended to reveal systematic changes in target-control relationships and might mix effects of cloud seeding with climatic fluctuations and changes because of other causes. Use of additional controls at different geographic directions and orographic situations may reduce this risk (e.g., Ben-Zvi and Langerman 1989).

Other assessment techniques have been utilized to determine possible cloud seeding success. These techniques are generally concerned with documenting the physical links in the chain of events from cloud seeding leading to increased precipitation at the ground. Even if only limited physical studies, such as transport and diffusion, are performed, they may provide more credibility to purely mathematical techniques (e.g., target/control analyses). Certain effects due to cloud seeding are hypothesized, such as a decrease in SLW and an increase in ice crystal concentrations, and these hypotheses can be verified via physical measurements. The various types of measurements of potential value in seeding assessments are discussed more later.

5.3.2.1 Precipitation Gauge Data Measurements from precipitation gauges provide the most common form of data from which target-control assessments are made. Target-control relationships should be established at the beginning of seeding activities to avoid possible bias in the selection of control areas after the fact. Typically, monthly or seasonal regressions are developed. A common problem encountered in performing such assessments in mountainous areas of the United States is a lack of gauge sites at higher elevation locations. Another problem is one of historical gauge movements or changes in the type of gauge, which can alter the precipitation measurement, making long periods of record incompatible. Installation of additional precipitation gauges for the project is only useful if randomization is employed; otherwise, there would be no historical database from which regressions or seed comparisons could be developed. Information already has been described on the necessity for high-gauge resolution, depending on the length of the experimental units outlined in the project design. In parts of the United States, assessments also are hindered by the designation of certain higher-elevation areas as "wilderness areas," meaning accessibility is limited if not excluded altogether. Analysis of ground gauge records need not be limited to rainfall amounts. Enhancement of rainfall intensity, duration, and spatial correlation can help in detecting and assessing seeding effects (e.g., Ben-Zvi and Fanar 1996; Ben-Zvi 1988, 1989; Gagin and Gabriel 1987; Sharon 1978).

5.3.2.2 Remote Sensor Data Weather radar measurements (overlays, time-lapse photography, or digitized data) have been utilized in assessments of summertime rainfall enhancement projects. Weather radar has not yet provided quantitative measurement of snowfall (especially in mountainous areas) and, therefore, has not been used successfully in evaluating the end result of wintertime orographic cloud seeding projects. This is partly because the radar is much more sensitive to a few large snow particles than to the many small snow particles that are commonly produced by cloud seeding. The use of project-specific radar data from sites established for the cloud seeding project suffers from the same lack of any historical unseeded database for comparison purposes. To study the behavior of the clouds in two areas, analysis of unseeded clouds outside a seeded region may be warranted.

In summer programs, information on echo size, echo height, height and timing of first echo, echo intensity, and echo duration for the seeded and unseeded clouds may suggest certain significant systematic differences. Beall et al. (2009) discussed some results of an analysis of this type performed in the state of Texas. Digitized radar data can be used to crudely estimate the rainfall rates at cloud base. These calculated rates are often a more accurate indicator of rainfall in isolated thundershowers than widely spaced precipitation gauges. Dual-polarization and dual-wavelength radars offer better possibilities for hydrometeor-type identification and precipitation (rain and snow) measurement. The recent upgrading of NEXRAD to include dual polarization may assist such evaluations in the future. There has been a comparison of NEXRAD rain accumulation algorithms with numerous rain gauge measurements for different types of horizontal gradient events (Klazura et al. 1999).

Other types of remote sensors are also available. Microwave radiometers can detect water vapor and liquid water along a viewing path continuously; these instruments may be used to monitor weather conditions. For example, when placed upwind of a mountain barrier, they can signal the presence of SLW and thus an opportunity for orographic cloud seeding for conversion to precipitation. Lidars with polarization capability have been used to detect the location and phase (water or ice) of clouds. Wind-profiling radars and radio acoustic sounding systems (RASS) have been operated in a demonstration network over the central United States and Alaska by NOAA's Forecast Systems Laboratory; these data are available in near real time via the Internet.

5.3.2.3 Cloud Physics Data If cloud physics data are available for a project, an analysis of the data can provide a physical understanding of a portion of the sequence of events in the production of precipitation. It may be possible in these analyses to interpret the presence of a possible seeding effect. For instance, a systematic decrease in SLW content and a corresponding increase in ice crystal concentrations following cloud seeding strongly suggests a seeding effect within the cloud, although the resultant impact at ground level would not be explicitly addressed. In winter projects, ground level observations of ice crystal types and the degree of riming (collection and freezing of supercooled water drops on ice crystals) can provide additional information of the likely regions of ice crystal formation (temperature dependent) and the relative efficiency of the system. These data then can be analyzed before, during, and after seeding to investigate possible differences that may be attributable to seeding (e.g., Warburton and DeFelice 1986). The same instruments used on aircraft for measuring ice crystal concentrations (two-dimensional optical array probes) can be used at the ground to count and size ice crystals (Super and Heimbach 2005; Super 1999). Either aspirating a fixed site probe or mounting the probe on a vehicle and driving it through the desired area can provide data similar to that collected from aircraft.

5.3.2.4 Streamflow Data Streamflow measurements, typically compiled by the U.S. Geological Survey, can be utilized to make cloud seeding assessments. The Kings River Project in California (Henderson 1981) utilized a target/control assessment based on historical seasonal runoff amounts having correlation coefficients in the 0.95 to 0.98 range (Hastay and Gladwell 1969). Even with high correlation coefficients, decades may be required to assess the cloud seeding effect with a statistical significance in the 0.05 range because only one measurement per seeded year is acquired. Silverman (2010) reported on the evaluation of 11 different long-term operational programs conducted in the Sierra Nevada of California. Silverman utilized target and control analyses based on annual streamflow.

One problem often faced in streamflow assessments is either the lack of unimpaired runoff measurements or a change from an unimpaired measurement point to one with new dams or diversions constructed upstream at some time in either the historical or the seeded period. Some techniques are available to calculate natural flows, taking such factors as evaporation from lake surfaces into account. Another problem is the potential for carryover flow from one year to another, which impairs the independence between different annual records, thus complicating the assessment (e.g., Ben-Zvi and Langerman 1995).

5.3.2.5 Snow Course and SNOTEL Data Following Church's (1918) historical work on the development of techniques to measure snow water content in the Reno, NV, area, an extensive snow course measurement network was organized in the western United States and numerous foreign countries. Beginning in December or January and continuing through April or May, monthly measurements of snow depth, water content, and density were acquired at a large number of sites. Most sites also had standpipe storage gauges, which were read on approximately a monthly basis beginning in December at the same time the snow course measurements were made. More recently, the Natural Resources Conservation Service using its SNOw TELemetry (SNOTEL) system has automated such observations. This automated system now provides hourly observations, both snowpack water content and accumulated precipitation. These data are available in near real time via the Internet. These data can be utilized either separately or combined with precipitation data to perform cloud seeding assessments using the target and control approach. SNOTEL/snow course measurements can fill some of the voids in precipitation gauge measurements in higher mountainous areas. For snow water content target and control evaluations, measurement sites should be at or near the same elevation, because melt rates can vary by elevation, which could lead to the development of lower correlations than might otherwise be possible. Movement of snow course measurement sites over the years must be kept in mind. This may have a significant impact on subsequent relations between target and control areas.

5.3.2.6 Snow Sample Data Occasionally, samples of newly fallen snow are collected for an analysis of silver content. This is an evaluation technique encountered more frequently in research projects due to the expense involved. Snow samples collected prior to cloud seeding or from nonseeded storms are analyzed to establish the natural background silver content (if measurable with available analysis techniques) for comparison with snow samples taken from seeded storms. This technique is only valid for projects using AgI as the cloud seeding agent, although some analysis techniques are applicable to other possible cloud seeding agents as well (e.g., PbI). Several analysis techniques have been developed for use in such analyses, including neutron activation, proton excitation, and flameless atomic absorption. An example of an analysis of the downwind transport of AgI outside of primary target areas is given by Warburton (1974). Warburton et al. (1996) demonstrated how trace chemical assessment techniques strengthen traditional target and control precipitation analyses.

A modification of this trace chemistry assessment technique involves the simultaneous release of a control aerosol along with an active seeding aerosol (Warburton et al. 1996; Lincoln-Smith et al. 2011). Such a tracer has properties very similar to the seeding agent, with the key exception being that it does not nucleate ice. It is insoluble in water, has an extremely low natural background in precipitation, and is only removed from the atmosphere by passive precipitation scavenging mechanisms. Both the seeding agent and tracer are transported and scavenged in very similar manners when conditions are not conducive to effective seeding. Given similar release rates, detecting the same concentrations of silver and, say, indium in precipitation samples at downwind locations indicates that the two aerosols most likely were removed from the atmosphere solely by scavenging. Conversely, when sufficient SLW exists and temperatures are low enough for the active seeding material to nucleate new ice crystals, the ratio of silver to tracer in target area precipitation samples can be much greater than unity. This indicates that some fraction of the seeding material was directly responsible for the nucleation of ice crystals that eventually produced additional snowfall.

5.4 STATUS OF PRECIPITATION ENHANCEMENT TECHNOLOGY

The current status of precipitation enhancement technology has been addressed by four of the major organizations that have dealt with weather modification during the past 50 to 60 years: American Society of Civil Engineers (ASCE), Weather Modification Association (WMA), American Meteorological Society (AMS), and World Meteorological Organization (WMO). The position or policy statements of these organizations on weather modification regarding precipitation augmentation are summarized as follows.

5.4.1 American Society of Civil Engineers

The ASCE Policy Statement #275 was approved by the ASCE Board of Direction in July 2012 (ASCE 2012).

> ***Policy:*** 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.
>
> ***Issue:*** Atmospheric water management capabilities are still developing and represent an evolving technology. Longer-term commitments to atmospheric water resource management research and operational programs are necessary to realize the full potential of this technology.
>
> ***Rationale:*** Water resources worldwide are being stressed by the increasing demands placed upon it 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.

5.4.2 Weather Modification Association

The WMA's (2011) Capability Statement on winter and summer precipitation augmentation is provided as follows. Also see http://www.weathermodification.org for more details on the 2011 version of its statement.

Winter Precipitation Augmentation

The capability to increase precipitation from wintertime orographic cloud systems has been demonstrated in a number of research experiments. The evolution, growth, and fallout of seeding-induced (and enhanced) ice particles have been documented in several mountainous regions of the western United States. Enhanced precipitation rates up to about 1 mm per hour have been measured in seeded cloud regions. Although conducted over smaller temporal and spatial scales, research results tend to be consistent with evaluations of randomized experiments in larger project areas as well as a substantial and growing number of operational projects. Increases of 5%–15% in winter season precipitation have been consistently reported in target areas that are effectively treated by cloud seeding projects, and generally accepted by the scientific community. Similar results have been found in both continental and coastal mountain regions. The consistent range of indicated effects in many regions suggests widespread transferability of the estimated results for supercooled orographic clouds.

Wintertime snowfall augmentation projects can use a combination of aircraft and ground-based dispersing systems. Although silver iodide compounds are still the most commonly used glaciogenic (ice forming) seeding agents, dry ice is used in some warmer (but still supercooled) cloud situations. Liquid propane also shows some promise as a seeding agent when dispensers can be positioned above the freezing level on the upwind slopes of mountains at locations sufficiently far upwind to allow growth and fallout of precipitation within the intended target areas. Dry ice and liquid propane expand the window of opportunity for seeding over that of silver iodide, since they can produce ice particles at temperatures as warm as

−0.5°C. For effective precipitation augmentation, cloud seeding methods and guidelines need to be adapted to regional meteorological and topographical characteristics.

Technological advances have aided winter precipitation augmentation projects. Fast-acting silver iodide ice nuclei, with higher activity at warmer temperatures, have increased the capability to augment precipitation in shallow orographic cloud systems. Computer models have been developed to simulate atmospheric transport, as well as meteorological and microphysical processes involved in cloud seeding; and these models are coming into use in operations. Finer scale atmospheric computer models are currently showing skill in predicting the amount of natural precipitation down to short time intervals such as individual storm periods. High resolution airborne radar and lidar systems are being used to study the fine scale structure of air motion and cloud and precipitation particle evolution in the boundary layer over mountainous terrain. These airborne remote sensing instruments are capable of documenting changes in cloud structure that may be occurring due to cloud seeding processes and in the cloud regions that are the most difficult to observe by in situ aircraft probes or ground-based radar. Improvements in computer and communications systems have resulted in a steady improvement in remotely controlled ground-based silver iodide generators, permitting improved positioning and reliable operation in remote mountainous locations. Equipment improvements include solution flow control and atomization technology. There have been improvements in silver iodide flare rack designs and flare sizes. Also, improvements in weather prediction and remote meteorological measurement telemetry are advancing capabilities in weather modification technology.

Traditional statistical methods continue to be used to evaluate both randomized and nonrandomized wintertime precipitation augmentation projects. Highly accurate quantitative precipitation prediction, especially for orographic situations, is providing a promising option for evaluation of cloud seeding experiments. Results from similar seeding projects are also being pooled objectively to obtain more robust estimates of cloud seeding efficacy. Objective evaluations of nonrandomized operational projects continue to be a difficult challenge. Some new methods of evaluation using the trace chemical and physical properties of segmented snow profiles have been used to establish targeting effectiveness and estimate precipitation augmentation over basin-sized target areas.

Summer Precipitation Augmentation

The capability to augment summer precipitation from convective clouds has been demonstrated in some project areas, and the scientific community places a lower degree of confidence in the indicated effects of these efforts compared to that for winter precipitation augmentation for a number of reasons, especially their cloud dynamical differences. Augmentation of summer precipitation normally involves delivery of either hygroscopic (water-attracting) or glaciogenic (ice-forming) aerosols into the updraft regions at the bases or above the freezing level of the subject clouds with the intention of modifying the clouds' internal microphysical structure to enhance the growth of precipitation particles. The modification of cloud microphysics and precipitation inevitably feeds back to cloud dynamics such that the two processes combined alter the precipitation further. The outcomes of the seeding depend strongly on the initial conditions.

Results from research projects conducted on summertime cumulus clouds are encouraging but somewhat variable. Part of the resulting uncertainty is due to the variety of climatological and microphysical settings in which experimentation has been conducted. Other important factors include the spatial scale at which the investigations are conducted and the seeding mode. A research project that combines the statistical results with microphysical documentation of the way in which rain enhancement is achieved is still lacking.

Assessments of some operational and research projects that have seeded selected individual clouds or clusters of clouds with either glaciogenic or hygroscopic nuclei have found that seeded clouds tend to last longer, expand or travel farther to cover larger areas, and are more likely to merge with nearby clouds and produce more precipitation. Both dynamic and microphysical changes appear to be involved.

Most summertime seeding projects have been evaluated using radar data, making it possible that some of the seeding results have been confounded by seeding-induced changes in the drop sizes that will in turn affect the radar reflectivities and the inferred rainfall rate. This would tend to exaggerate the seeding effect. This uncertainty applies especially to hygroscopic cloud seeding efforts in which the goal is to increase the droplet sizes.

Evaluations of operational summer precipitation augmentation projects present a difficult problem due to their nonrandomized nature and the normally large temporal and spatial variability present in summertime rainfall. Recognizing these evaluation limitations, various methods for the evaluation of such projects have been developed and used, ranging in scale from individual clouds to floating targets of varying sizes to area-wide analyses. The results of many of these evaluations at the single cloud scale through floating target areas up to 2,000 km^2 have indicated a positive seeding effect in precipitation. Area-wide effects can be more difficult to discern due to the large temporal and spatial variability in summertime rainfall noted earlier. In some instances, apparent positive effects of seeding have also been noted outside the specific targets. Thus, the apparent effect of seeding is not necessarily confined to the directly treated clouds. The physical mechanisms leading to those effects outside the directly treated clouds are not yet fully understood.

Technological advances have aided summer precipitation augmentation projects. These include fast-acting silver iodide ice nuclei, new hygroscopic seeding formulations, polarimetric radars, satellite-based microphysical observations of the clouds, sophisticated radar, and satellite data processing and analysis capabilities, advancements in airborne cloud physics instrumentation, and full bin microphysics numerical modeling. (WMA 2011, reproduced with permission)

5.4.3 American Meteorological Society

An information statement of the American Meteorological Society (adopted by the AMS Council on 2 November 2010):

1. Introduction
Increasing population, urbanization, and the impacts of a changing climate require that water resources be managed to most effectively alleviate the shortages that manifest themselves, from time to time, in various geographic settings. At the other extreme, precipitation processes on occasion may be so intense and prolonged that damage results to crops and structures, and there can be injuries and loss of life. In addition, nonprecipitating clouds may obscure visibility to the extent that transportation and other human activities are significantly hindered. One tool available for mitigating some of these weather impacts is planned weather modification through cloud seeding. In its most common form, specially formulated aerosols or very cold materials are dispersed in targeted locations within clouds to achieve precipitation enhancement, hail damage mitigation, fog clearing, and other intentional effects. Cloud seeding techniques have been developed over nearly 70 years through experimentation and trials. In this statement we focus on the policy issues that pertain to local-scale application of these techniques covering areas from a few to several hundreds of square kilometers. Larger-scale efforts to intentionally modify weather and climate using these or other techniques are discussed in a separate AMS policy statement on geoengineering.

2. Uncertainty
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.

3. Risk Management

Unintended consequences of cloud seeding, such as changes in precipitation or other environmental impacts downwind of a target area have not been clearly demonstrated, but neither can they be ruled out. In addition, cloud seeding materials may not be always successfully targeted and may cause their intended effects in an area different than the desired target area. This brings us to the ethical concern that activities conducted for the benefit of some may have an undesirable impact on others. At times unintended effects may cross political boundaries. Weather modification programs should be designed to minimize negative impacts. International cooperation may be needed in some regions.

Precipitation augmentation through cloud seeding should be viewed cautiously as a drought relief measure. Opportunities to increase precipitation are reduced during droughts. A program of precipitation augmentation is more effective in cushioning the impact of drought if it is used as part of a water management strategy on a long-term basis, with continuity from year to year, whenever opportunities exist to build soil moisture, to improve cropland, and to increase water in storage.

From time to time methods have been proposed for modifying extreme weather phenomena, such as seeding severe thunderstorms with aerosols to diminish tornado intensity, or seeding tropical cyclones to cause changes in their dynamics and steer them away from land and/or diminish their intensity. Some experimentation has taken place in these areas, but current knowledge of these complex weather systems is limited and the physical basis by which seeding might influence their evolution is not well understood.

Weather modification techniques other than cloud seeding have been used in various areas of the world for short periods of time to achieve goals similar to those of cloud seeding. Much less is known about the effects of these other techniques, and their scientific basis is even further from being demonstrated, either statistically or physically, than it is for cloud seeding. Application of weather modification methods that are not supported by statistically positive results combined with a well-understood physical chain of processes leading to these results and that can also be replicated by numerical cloud modeling, should be discouraged.

4. Recommendations

As with weather forecasting, significant progress has been made in the science of weather modification in the last half-century. There remain limits to the certainty with which desired changes in cloud behavior can be brought about using current cloud seeding techniques. Continued effort is needed toward improved understanding of the risks and benefits of planned modification through well-designed and well-supported research programs.

In particular, the following specific recommendations are made:

1. Efforts should continue to improve understanding of the targeted cloud and precipitation processes in planned modification.
2. Because predictability is a limiting factor in the assessment of weather modification efforts, well-designed (randomized) and well-supported research programs should be conducted that improve the predictability of the undisturbed weather and the magnitude of weather modification effects.
3. It is necessary to comprehensively address the risks, benefits and ethical issues associated with planned weather modification and to develop policy approaches that can help the implementation and conduct of future experiments and operations.
4. Research into modification of extreme weather systems, such as tornadic thunderstorms, tropical cyclones, etc., should be limited to numerical simulations until such time as there is sufficient knowledge to lay the foundation for safe experimentation in the atmosphere. (AMS 2010, reproduced with permission)

5.4.4 World Meteorological Organization

The following are excerpts from the WMO Statement on Weather Modification.

3. Precipitation (Rain And Snow)

3.1 This section deals with those precipitation enhancement techniques that have a scientific basis and that have been the subject of research. Other non-scientific and unproven techniques that are presented from time to time should be treated with the required suspicion and caution.

Orographic Mixed-Phase Cloud Systems

3.2 In our present state of knowledge, it is considered that the glaciogenic seeding of mixed-phase clouds formed by air flowing over mountains offers good prospects for increasing precipitation in an economically-viable manner under suitable conditions. These types of clouds attracted great interest in their modification because of their potential in terms of water management, i.e., the possibility of storing water in reservoirs or in the snowpack at higher elevations. There is statistical evidence that under certain conditions precipitation from supercooled orographic clouds can be increased with existing techniques.

3.3 Observations supported by numerical modeling indicate that supercooled liquid water can exist in amounts sufficient to explain the observed precipitation increases and could be tapped if proper seeding technologies were applied. The processes culminating in increased precipitation have also been directly observed during seeding experiments conducted over limited spatial and temporal domains. While such observations further support the results of statistical analyses, they have, to date, been of limited scope. The cause and effect relationships have not been fully documented.

3.4 This does not imply that the problem of precipitation enhancement in such situations is solved. Much work remains to be done to strengthen the results and produce stronger statistical and physical evidence that the increases occurred over the target area and over a prolonged period of time, as well as to search for the existence of any extra-area effects. Existing methods should be improved in the identification of seeding opportunities, targeting of the seeding material, and the times and situations in which it is not advisable to seed, thus optimizing the technique, reducing inadvertent risks, and maximizing the cost effectiveness of the operations.

3.5 It should be recognized that the successful conduct of an experiment or operation is a difficult task that requires qualified scientists and operational personnel. It is also difficult to target the seeding agent from either ground generators or from broad-scale seeding by aircraft upwind of an orographic cloud system. The accurate and timely identification of regions of sustained supercooled liquid water and the ability to target these regions in often times varying wind conditions with seeding material are critical to the success of these experiments and is often a major challenge.

Synoptic-Scale Cloud Systems

3.6 The seeding of cold stratiform clouds began the modern era of weather modification. Under certain conditions shallow stratiform clouds can be under certain conditions made to precipitate, often resulting in clearing skies in the region of seeding.

3.7 Cloud systems associated with mid-latitude synoptic fronts can contain supercooled liquid water. When these systems pass over mountain ranges, the pre-existing supercooled liquid water can be enhanced, leading to conditions suitable for cloud seeding.

3.8 A number of field experiments and numerical simulations have shown the presence of supercooled water in some regions of these clouds and there is some evidence that precipitation can be increased.

Cumuliform Clouds

3.9 In many regions of the world, cumuliform clouds are the main precipitation producers. These clouds are characterized by strong vertical velocities with high condensation rates. They hold the largest condensed water contents of all cloud types and can yield the highest precipitation rates. Seeding experiments with cumuliform clouds have produced variable results, which are at least partly due to the high natural variability of convective clouds.

3.10 Because cumuliform clouds can occur in many different conditions, the resulting precipitation can develop through rain drop coalescence (warm cloud) or through ice (cold cloud) processes or in combination of these processes (mixed-phase clouds). Thus, glaciogenic or hygroscopic techniques may be used to modify this type of cloud. Precipitation enhancement techniques by glaciogenic seeding are utilized to affect ice and mixed phase processes, while hygroscopic seeding techniques are used to affect warm and mixed phase processes. Evaluation of these techniques has utilized direct measurements with surface precipitation gauges, as well as indirect radar-derived precipitation estimates. Rainfall patterns produced by cumuliform clouds have complex spatial and temporal characteristics that are difficult to resolve with rain gauge networks alone.

3.11 The responses to seeding, based on reviews of historical experiments, seem to vary depending on changes in natural cloud characteristics and in some experiments they appear to be inconsistent with the original seeding hypothesis. Experiments involving heavy glaciogenic seeding of warm-based convective clouds (bases about +10°C or warmer) have produced mixed results. They were intended to stimulate updraughts through added latent heat release, which, in turn, was postulated to lead to an increase in precipitation. Some experiments have suggested a positive effect on individual convective cells. Conclusive evidence that such seeding can increase rainfall from multicell convective storms has yet to be established. Many steps in the postulated physical chain of events have not been sufficiently documented with observations or simulated in numerical modeling experiments.

3.12 In recent years, the seeding of warm and cold convective clouds with hygroscopic chemicals to augment rainfall by enhancing warm rain processes (condensation/collision–coalescence/breakup mechanisms) has received renewed attention through model simulations and field experiments. Two methods of enhancing the warm rain process have been investigated. First, seeding with small particles (artificial CCN with mean sizes about 0.5 to 1.0 micrometers in diameter) is used to accelerate precipitation initiation by stimulating the condensation–coalescence process by favorably modifying the initial droplet spectrum at cloud base. Second, seeding with larger hygroscopic particles (about 30 micrometers in diameter) is used to accelerate precipitation development by stimulating the collision–coalescence processes. A randomized experiment utilizing the latter technique indicated statistical evidence of increases in radar-estimated precipitation increases. However, the increases were not as indicated by the conceptual model but seemed to occur at later times (one to four hours after seeding). The cause of this apparent effect is not known.

3.13 Recent randomized seeding experiments with flares that produce small (0.5 to 1.0 micrometers in diameter) hygroscopic particles in the updraught regions of continental, mixed-phase convective clouds have provided statistical evidence of increases in radar-estimated rainfall. The experiments were conducted in different parts of the world and the important aspect of the results was the replication of the statistical results in a different geographical region. In addition, limited physical measurements were obtained suggesting that the seeding produced a broader droplet spectrum near cloud base that enhances the formation of large drops earlier in the lifetime of the cloud. These measurements were supported by numerical modeling studies. Although the results are encouraging and intriguing, the reasons for the duration of the observed effects obtained with the hygroscopic particle seeding are not understood and some fundamental questions remain. Measurements of the key steps in the chain of physical events associated with hygroscopic particle seeding are needed to confirm the seeding conceptual models and the range of effectiveness of these techniques in increasing precipitation from warm and mixed-phase convective clouds.

3.14 Despite some statistical evidence of changes in radar-estimated precipitation changes in individual storms using both glaciogenic and hygroscopic techniques, there is no evidence that such seeding can economically increase rainfall over significant areas. (WMO 2010, reproduced with permission)

5.5 CONCLUSIONS

Various cloud seeding modes and types of instrumentation are available for application in precipitation augmentation cloud seeding projects. The selection of a particular cloud seeding mode, instrument, or atmospheric model to be used will vary depending on the unique characteristics of a given project area and project goals. Factors affecting these selections include time of operations (winter, summer), target area size, topography, accessibility, funding available, and other project-specific aspects. It is highly desirable to consider these factors thoroughly prior to initiating an operational cloud seeding project. A project design performed for a particular project should specify cloud seeding modes and instrumentation to be used and provide additional information necessary for the conduct of the project.

Specification of a cloud seeding mode includes considerations of the type of cloud seeding agent to be used and the type of dispensing technique to be used to disperse the cloud seeding agent. A variety of seeding agents have received varying degrees of attention since 1946. Among the most commonly used agents in operational projects are silver iodide and hygroscopic materials. Other agents are available, including liquid propane and dry ice, but several others suffer from one or more of the following limitations: (i) lower seeding effectiveness than silver iodide, (ii) some attendant environmental concerns that might be associated with the release of agents such as lead iodide, or (iii) the lack of demonstrated seeding capability in the atmosphere instead of that indicated solely through laboratory trials (e.g., some organic substances).

Dispensing systems can be categorized as either for ground-based or aerial use. Ground-based systems are most useful in wintertime projects in mountainous areas; they have limited utility in summertime projects. Aerial dispensing systems are ideally suited to summertime cumulus seeding either at cloud base, in cloud, or at cloud top. Silver iodide, hygroscopic agents, and dry ice can be dispensed aerially; silver iodide and liquid propane can be dispensed from the ground, but dry ice cannot. There are both advantages and disadvantages associated with silver iodide, hygroscopic agents, and dry ice, and with ground and aerial dispensing systems. Decisions regarding which to use depend significantly on the requirements and design of a specific project.

Results from research programs conducted in South Africa, Mexico, and Thailand on individual clouds have generated renewed interest in hygroscopic seeding to affect the collision–coalescence processes in clouds or portions of clouds where temperatures are higher than 0 °C. The viability of this technique to generate increases in precipitation over a fixed target area for a summer season has yet to be established through the conduct of a research program.

Instrumentation for precipitation enhancement projects can serve dual functions: (i) real-time project monitoring and (ii) postproject assessments. Instrumentation, both existing and serving other functions, or installations directly related to the project, provides needed input to real-time decisions, such as the forecasting of probable seeding opportunities, the determination of seedable situations, the conduct of seeding operations, and the exercise of project suspension criteria. The application of sophisticated atmospheric models also can be of assistance in accomplishing the aforementioned objectives. Instrumentation measurements also can serve in a postproject assessment of the probable effects of cloud seeding based on critical variables, such as precipitation, snow water content, or streamflow.

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CHAPTER 6

HOW TO IMPLEMENT A CLOUD SEEDING PROGRAM

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6.1 INTRODUCTION

The common design elements underlying the different aspects of a cloud seeding program necessitate that water resource managers collaborate with public officials, meteorologists, environmental scientists, and the local populace when designing operational cloud seeding programs. Local climatology, hydrology, land use, water storage facilities, and environmental concerns must be viewed as a single interconnected whole. The hydrologist quantifying streamflows, the environmental scientist assessing the effects of precipitation changes and seeding agents, the populace that might be affected by those effects, the meteorologist studying precipitation patterns, the farmers and ranchers conducting operations, and the biologist monitoring wildlife and vegetation within and beyond the program area should be consulted when creating the cloud seeding program plan (Section 6.2.2). This will help ensure support of the planned operations, that the evaluation portion of this plan (Section 6.4.2) is comprehensive enough to determine the success of the program adequately, and that future researchers will be helped in evaluating changes potentially associated with the cloud seeding program. Such a team may provide the best

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basis for determining the long-term future of each program (see Chapter 2, Section 2.2).

Given a well-constructed plan, the next step is to secure the resources it stipulates and ready them for the implementation phase. The implementation of a cloud seeding program, regardless of size, is not as easy as it may sound and should begin with an all-hands meeting. This meeting lays out the roles and responsibilities of project team members and program objectives, feasibility study, factors governing implementation, program control, and program management. The sections following provide more detail on how to implement a cloud seeding program. Armed with this information, a prospective cloud seeding sponsor can decide what elements of the process to assume individually or institutionally and whether or when to enlist the services of an expert weather modification consultant.

6.1.1 Feasibility Study

Before a cloud seeding program is implemented, a feasibility study, as described in Section 6.3, should be conducted to assess the probability of the program becoming successful. Should the feasibility study indicate that the program (e.g., cold cloud precipitation augmentation, warm cloud precipitation augmentation) would likely be unsuccessful, there should be no implementation phase (Boe and Keyes 2006).

6.1.2 The Factors Governing Implementation

Cloud seeding programs to increase precipitation are implemented primarily because a need exists for additional water. The need and feasibility study help define how much additional water is desired and how likely the existing technology and its science will ease the water shortfall without creating problems from excess water. Thus, a goal is defined and the steps of the planning and implementation should follow as provided in Fig. 6-1.

The feasibility study (Section 6.3) estimates the amount of additional water that can be expected from a program. It considers the local climatology, any seeding technologies to be applied, and any known operational constraints that may exist.

If the findings from the feasibility study reveal no insurmountable difficulties, then the program needs and goals can be clearly defined. The program design, in addition to maximization of economic benefits, must protect the public interest and safety and avoid (or minimize) any adverse effects. There should also be an evaluation plan (assessment) to quantify the results of the program in terms appropriate to the program sponsor's needs. An assessment or estimation of program effectiveness is very important to the longevity of any program.

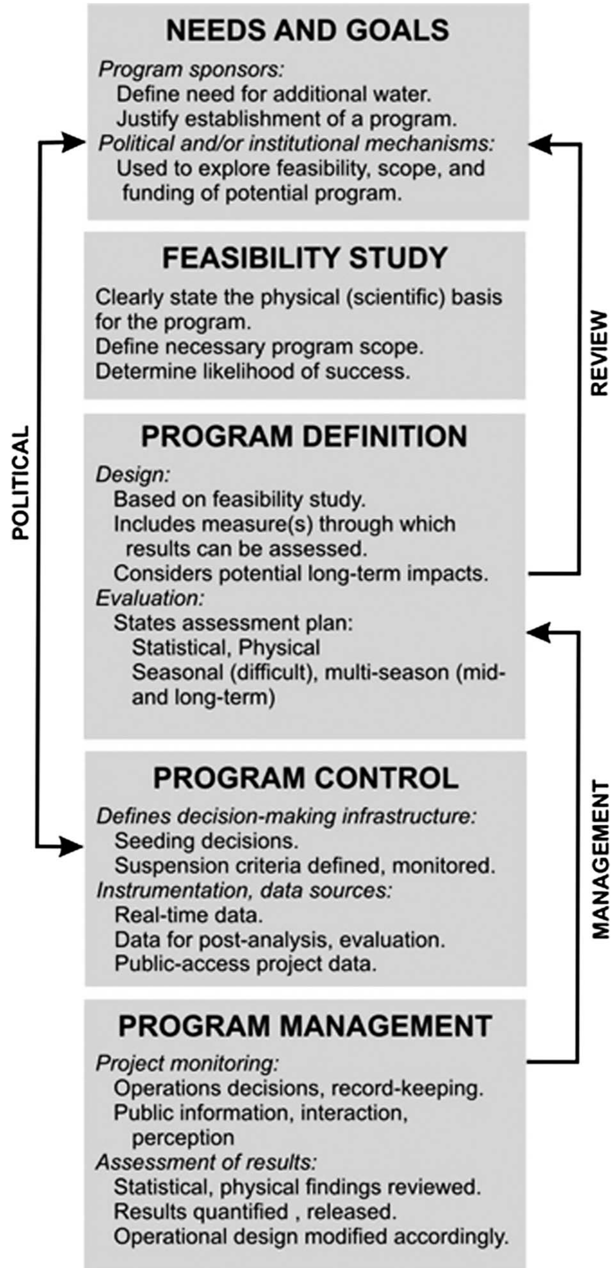

Fig. 6-1. The steps involved in the planning and implementation of a cloud seeding program
Source: Boe and Keyes (2006), ©ASCE.

Program controls are then set in place defining the program infrastructure. Program controls, as shown in Fig. 6-1, imply communications (flow of information) and the criteria for seeding and for suspending seeding. Program controls are both scientific and political, the latter because it is usually the will of the people (politics) that leads to the creation of programs. Program controls also may affect program goals. For example, suspension criteria may necessarily be conservative, which is then reflected in the stated program goals.

Program management has direct input in the program design and evaluations but is also responsible for other essential functions, including public relations, assessment, record keeping, and day-to-day operations (Section 6.6).

6.2 NEEDS AND GOALS

The primary objective of cloud seeding programs designed to increase precipitation is to help meet the water resource needs of society. This section describes how program sponsors might approach the assessment of need and the formulation of goals (Boe and Keyes 2006).

6.2.1 Origin of Need and Program Justification (Program Sponsors)

Humanity's existing water development technologies have resulted directly from need and humankind's ingenuity to anticipate and act to meet those needs. Cloud seeding (weather modification) is but one case in point. Society must assess all the alternatives for development of water supplies in its local area and determine which will be implemented. Common water resource development tools include conservation; reuse; dam, reservoir, and irrigation system construction; inter-basin diversion; and weather modification. These tools may be applied singly or in almost any combination.

Social needs are first articulated by those in need, and awareness grows. With awareness comes dialog and discussion, as may be heard when people speak publicly or as may be found in the printed media. Such needs are sometimes formally addressed through legislation. Most governments are responsive to their constituencies, and some will develop weather modification programs to address expressed water development needs, if the government leaders are convinced of the feasibility of the development of the cloud seeding project. In many (if not most) instances, the initial impetus for a prospective program comes directly from the water resource community (e.g., water districts, hydroelectric utilities, etc.).

The identified needs then must be translated into achievable engineering and scientific objectives. In other words, program viability must be assessed and the costs of such programs estimated. If the potential sponsors can afford to conduct the program and the program benefits are projected to significantly exceed the costs, then a desire for program implementation usually follows.

6.2.2 Political and/or Institutional Mechanisms

Water resource engineers, meteorologists, hydrologists, economists, and their respective organizations must recognize the need for an interdisciplinary approach to decision making and apply this approach beginning with the earliest stages of program design and development.

In many cases state and federal laws will place restrictions and/or reporting requirements on proposed programs. Often, public meetings are required. Governing agencies must be identified and those offices having jurisdiction in the program area contacted. If laws exist, it is likely that licenses and/or permits may be required. Complete descriptions of the program, methodologies, seeding agents, and safety criteria usually are required as part of the licensing/permitting process. Considerably more information in this regard is provided in Chapter 3.

In some cases it may be helpful to establish a citizens' advisory committee, comprising representatives of the area's stakeholder groups. Such a committee normally would represent the major economic interests of the region, local governmental officials (persons not involved in program regulation, such as city council members), environmental and public interest groups, and perhaps the news media.

6.3 THE FEASIBILITY STUDY

Planning has been defined as the orderly consideration of a program from the original statement of purpose through the evaluation of alternatives, to the final decision on a course of action (Linsley and Franzini 1964). There is no predefined process that always leads to the "best" decision, because each cloud seeding program is unique in its physical and financial setting. There is no substitute for professional judgment in program planning, design, and management. Each individual step toward a final program design should be supported whenever possible by quality quantitative analyses rather than estimates, according to Boe and Keyes (2006).

6.3.1 Feasibility Study Considerations

The term "feasibility study" refers to the examination of the local climate and cloud characteristics to determine whether cloud seeding technology has a reasonable expectation of increasing precipitation sufficiently to justify developing a program. The term "program assessment" refers to the evaluation of the program itself when it is actually conducted.

The feasibility of a program largely depends on two factors. First, is there a scientific basis for the work proposed that could yield the desired additional precipitation? This is discussed in detail in Chapter 4. Second, even if such a basis exists, is the cost of implementing a program based on the known science affordable and justifiable? The latter heavily depends on the combination of available financial resources and the expected return in additional water, in other words, the benefit–cost ratio.

When possible, the feasibility study for a program should draw significantly from previous research and well-conducted operational programs that are similar in nature to the proposed program (e.g., similar topography, similar precipitation occurrences, etc.). Percentage increases obtained from such programs can be used in the development of benefit–cost analysis for the proposed program (see Chapter 2, Section 2.4). The professionals collect and analyze the requisite weather, climate, operational aspects, and funding information. In so doing, the literature searches should include engineering, meteorological, social, environmental, and legal publications on weather modification technology.

6.3.2 Feasibility Study Technical Considerations

The primary purpose of the feasibility study is to answer two questions. First, does it appear that a cloud seeding program could be implemented in the intended target area that would be successful in achieving the stated objectives of the program? Examples include increasing high elevation snowpack or increasing summer rainfall directly on croplands. Second, are the estimated increases in precipitation expected to produce a positive benefit–cost ratio? The answers to these two questions will determine whether the proposed program appears to be technically and economically feasible.

Answering the first question involves assessing whether the climate and cloud characteristics of the region of interest will normally produce sufficient numbers of clouds amenable to effective treatment. In "normal" seasons there must be enough suitable clouds to make a program worthwhile. That number depends on the increase in precipitation likely to be obtained from each event and on the value of the additional water thus reaching the surface. Background climatological studies of the weather typical of the intended target areas can help address these questions. In addition, the clouds must be treatable, that is, there must be a means of consistently treating the cloud volumes with enough seeding agents to achieve the desired effects. Contributing factors include how seeding agents are transported and dispersed by the airflow and/or convection relative to the locations of the seedable clouds. For orographic seeding, the transport and dispersion primarily is studied relative to the terrain. For airborne seeding, the locations of aircraft bases, the aircraft performance, and the locations climatologically favored for the development of suitable clouds are the primary considerations.

The feasibility study should also address other potential concerns, for example, the environmental effects of seeding agents, such as silver iodide (AgI), and the possibility of measurable downwind effects. References to all relevant research should be summarized for the benefit of both the potential program sponsors and the public. Numerous studies have shown repeatedly that adverse environmental effects are unlikely even with long-term programs. Data potentially useful in these studies include the following (Boe and Keyes 2006):

- *Precipitation data*. Time-resolved precipitation data are extremely helpful. Daily totals are useful; hourly data are even better. If researchers know what time precipitation fell, they can correlate the event with the weather conditions correctly at the time. Data can be in water equivalents, as from precipitation gauges, or in snow depth, as from snow boards. Snow pillow data also are useful, but there is a time lag between snowfall and response of the sensors in the pillows of which analysts must be aware.
- *Temperature.* Temperatures at the surface and aloft are very useful, for supercooled cloud is necessary for glaciogenic seeding to be effective. Again, time-resolved data are preferred; however, upper air soundings normally are made just twice daily and then usually only from fixed locations. Greater time resolution of upper air temperatures can be obtained from prognostic numerical models, but researchers must remember that such estimated temperatures are from atmospheric models, not actual measurements.
- *Winds.* Wind speed and direction, both surface and aloft, are very helpful. In programs proposing to treat orographic clouds (clouds produced by the flow of moist air over hills or mountains), the wind direction usually is strongly correlated with storm conditions, most always when the mid-level horizontal winds are close to perpendicular to the axis of the hills or mountain range. In programs planning to seed convective clouds, the wind speed and direction play a large role in cloud motion.
- *Humidity.* Humidity measurements at the surface and aloft are highly useful, for drier air masses will not produce suitable clouds. Once again, time-resolved data are preferred; however, unless data from ground-based instrumentation sited on mountains in the area of interest are available, humidity data aloft may be limited to extrapolations from the twice-daily soundings, if available.

- *Satellite and radar data.* In many locations, satellite and/or radar data may be available. Satellite imagery may offer verification of cloud extent and temperature (at cloud top with infrared imagery) during storm periods. Likewise, radar data may be helpful, especially during warmer seasons when the precipitation is not primarily snow.
- *Streamflow data.* If long-term streamflow data are available, it may be possible to establish correlations between streamflow and snowpack or precipitation (Stauffer 2001). Such correlations not only are useful in derivation of estimates of streamflow increases but also may be helpful in designing program safety criteria.

One possible source of estimates of potential program effects on precipitation is previous research and operational programs conducted in similar climatological settings using the same seeding techniques and seeding agents proposed for the new program. Some examples are the Climax I and II research experiments (Mielke et al. 1981) conducted in the Central Colorado Rockies, the Bridger Range Experiment conducted in southwest Montana (Heimbach and Super 1988; Super and Heimbach 1983; Super 1986), and the High Plains and Edwards Aquifer convective cloud seeding programs of West Texas (Woodley and Rosenfeld 2004).

If climatological studies provide ample evidence for the existence of suitable clouds, the feasibility study then must address the means through which seeding agent is best delivered to the clouds. This task is commonly referred to as "targeting." The importance of proper targeting cannot be overstated.

There are two means to deliver seeding agents to those clouds deemed amenable to treatment. One is with aircraft, the other from ground-based facilities. Both techniques, outlined as follows and described in more detail in Chapter 5, can be effective, but both also have limitations.

- *Airborne seeding*. This can be done from aircraft in several ways. One advantage of airborne seeding is the flexibility of the targeting; seeding agents can be released at almost any coordinates, subject to the restrictions imposed by aircraft performance and the underlying terrain. In winter orographic programs, these restrictions can be significant.
- *Ground-based seeding*. This can be done from manned fixed sites or from remotely operated fixed sites. The primary advantage of ground-based seeding is that releases can be more or less continuous from a fixed location, such that a "plume" of seeding agent is consistently transported and dispersed by the wind and air motions to locations downwind. To achieve full coverage of an area, multiple sites usually are required.

Air motions at and near the surface generally are complex, especially near and over hills and mountains, or when convection (thermally driven vertical air motion) is present. Therefore, it is not easy to predict where the seeding agent will be transported, especially given the wide range of possible environmental wind and temperature (stability) profiles. This task could be investigated by three-dimensional numerical modeling, although it is important that the output of the model to be used has been or is subjected to independent verification (e.g., atmospheric tracer studies). Though not inexpensive, both may impart greater confidence in the targeting strategies being used operationally. Such verifications need not continue indefinitely but rather only long enough to gain the needed evidence. Various models are available, from somewhat simple air flow models that can be run on a personal computer (PC) or through an Internet interface (e.g., HYSPLIT), to more sophisticated models such as the WRF (Weather Research and Forecasting model) that require greater effort and a workstation or workstation cluster. The real-time utility of the use of such models to assist in operational decision making during the actual conduct of the program may be limited if several hours are required to perform a run on a supercomputer (Boe and Keyes 2006).

Climatological analyses of available rawinsonde data may also be conducted to determine the mean wind, stability, and vertical temperature profiles that accompany the development of seedable clouds. Hourly observations of available surface wind data may be examined to determine when up-barrier wind components are present. Such information can be used to aid the siting of ground generators in winter programs and to identify the primary moisture advection regimes for convective programs. For example, a climatological analysis for a winter orographic program might indicate that the predominant wind flow during a majority of seedable situations is associated with mid-level winds from the south through southwest. The analysis might also indicate that these conditions are frequently accompanied by low-level inversions at around the 800 hPa level. Such information would suggest that an array of ground generators should be established south through southwest of the proposed target area at elevations above 800 hPa. In other words, seeding material dispensed from generators sited using this information would be expected to have up-barrier trajectories over the intended target area because the seeding material typically would be released above existing stable layers in the lower atmosphere in winds that are heading over the target area.

6.3.3 Feasibility Study Cost Considerations

If the aforementioned analyses indicate that a cloud seeding program appears to be technically feasible, then the second question can be answered: would the program be expected to be economically feasible? To answer this question, the value of the expected increase in precipitation must be estimated. For example, in the case of a program to enhance hydropower production, the estimated increase in precipitation will need to be converted to an estimate of increases in streamflow. These estimates of increases in streamflow can be converted into an estimated dollar value, usually drawing on the potential sponsor's knowledge of the impact of the estimated streamflow on power generation, assuming all additional streamflow can be captured in existing water storage facilities (reservoirs). Program sponsors may well have computer models that can be used to estimate these impacts. Griffith and Solak (2002) provided an example of this type of economic analysis.

The cost of the planned program then needs to be estimated. This may begin as a preliminary estimate, based on a preliminary program design, that is later refined based on the outcome of the formal design of the proposed program (see Section 6.4). A preliminary benefit–cost ratio then may be calculated. Program sponsors may expect a favorable ratio of perhaps 5:1 or even 10:1 for the program to be considered economically feasible.

If the preliminary program design is not found to be cost effective, program designers and sponsors may wish to consider revisions to the initial program design. If such is the case, two questions need to be addressed.

First, what components (if any) of the preliminary design may not be essential to still have a reasonable probability of achieving the intended goals of the program? Should the initial estimated benefit–cost ratio not be favorable, program designers might ask, "Are there components of the preliminary design that are not absolutely essential to achieving the goals of the program?" In other words, are there elements that might be "nice to have" but not essential? One way to address this question is to start with a basic core program design and then rank any potential additions to the program in terms of its perceived ability to "deliver additional precipitation on the ground." A point of diminishing returns may be discovered when this type of analysis is applied, and the program then can be redesigned accordingly (see Chapter 2, Section 2.2.6 and Tables 2-1 and 2-2). Once the appropriate adjustments to estimated program costs have been made, the benefit–cost ratio can be recalculated. If a favorable ratio is obtained, the steps outlined in the following section can proceed (see Section 2.4.3.2). If a favorable ratio is not obtained, then this planning process should be terminated.

Second, what fraction of the program cost will be directed at evaluating (assessing) the effects of the program? Some evaluation of the effects of the seeding is strongly encouraged and very probably essential to the long-term survival of the program (see Chapter 2, Sections 2.2 and 2.4).

The effort spent on the evaluation ultimately will reflect the level of proof the program sponsors feel they need to realize. Larger programs, especially those conducted with public funds, often require a greater level of proof (more evidence, either physical, statistical, or both) that the program is effective.

6.3.4 Statement of Program Expectations (Likelihood of Success)

A clear statement of the program scope and how the objectives fit within the overall role and goals of the sponsoring entities is essential. For example, a public utility might have as its primary objective, "the comprehensive development of hydropower, maximizing the benefits to the company while minimizing environmental impacts." A weather modification program conducted during the winter months to increase snowpack (and ultimately runoff) may be an alternative that would supply additional streamflow and generating head. A program conducted during the warm season to increase rainfall (and ultimately soil moisture) or to recharge aquifers may be an alternative that would supply additional crop needs and reduce irrigation requirements, including the mining of groundwater. In many cases, implementation of a cloud seeding program may offer the least costly means to meet such objectives. Before the program is designed, the sponsors should thus state what the program is expected to accomplish and how it will fit into existing water management programs and goals.

Evaluation (assessment) of cloud seeding programs is imperative. A reasonable plan for evaluation should be devised for every program, even if the plan initially only provides for the collection of relevant data. Without meaningful long-term program assessments, cloud seeding programs are invariably discontinued for lack of evidence of effectiveness.

Comprehensive program planning and development need not be the purview of a single agency or entity. In fact, a consortium of groups and various governmental agencies could in many instances carry the development forward faster. This is especially the case if the program sponsors include public entities, such as municipalities or counties.

Water development decisions pertaining to cloud seeding must be fact based. Emotion, suppositions, or political ambition should not govern the final decision (Linsley and Franzini 1964). The design of most cloud seeding programs requires the accumulation and study of a substantial body of meteorological, hydrologic, economic, environmental, and social data. The services of specialists in each of these fields are needed to collect and interpret these data (Keyes et al. 1995). For most programs, the data are primarily historical, for example, long-term temperature, wind, and precipitation data. The longer the periods of record, the greater is the value of the data.

6.4 PROGRAM DESIGN

After the completion of the feasibility study, the prospective program sponsors will know if local cloud characteristics and estimated benefit–cost ratios warrant implementation of a precipitation increase cloud seeding program. The scope of the program will be defined by the findings of the feasibility study and should include measures for assessment of the program's results. Potential long-term effects should also be weighed. A comprehensive program design then should be developed that addresses the following items according to Boe and Keyes (2006).

6.4.1 Seeding Modes and Agents (Design)

The design, which is based on the feasibility study, will define the following (Boe and Keyes 2006):

- *Seeding modes.* Plans will incorporate ground-based and/or airborne seeding, as described in Chapter 5, according to the findings of the feasibility study. Many programs use both but not necessarily at the same time. For example, a winter orographic seeding program might deploy ground-based seeding devices to target the majority of the supercooled liquid water found at low altitudes over the mountain crests but might augment this seeding with treatment by aircraft flying upwind of the barrier over a valley, at or near the altitude of the crestline. The aircraft also might be used to target specific convective cloud elements, common in the fall and spring, that may not always be targeted reliably with ground-based facilities. Programs intended to treat convective (warm season) clouds with few exceptions rely on aircraft-based delivery systems.
- *Siting of equipment.* Ground-based equipment may be sited in accordance with climatological and model-guided assessments of the prevailing weather factors important to the transport and diffusion of the seeding material over the intended target area. Validation of the siting could be achieved during program operations through silver and/or trace chemistry analyses as discussed in Chapter 5, Section 5.2.3.4. In many locations, particularly in the United States, many of the preferred ground-based generator sites are located on public (Forest Service) lands. Access to and permission to use these sites can require a great deal of paperwork, and the final permission (or denial) sometimes can be determined by the personalities of those involved. In general, it is easier to site equipment on private land, when quality, privately owned sites can be found.
- When considering the locations of ground-based seeding facilities and the probable flight tracks of airborne seeding runs during the design phase for winter orographic programs, individuals are

encouraged to use numerical modeling and/or tracers to ensure effective placement, assuming there are adequate financial resources to do so and program goals include that level of effort on the issue. In modeling simulations, it is not sufficient to model only a single wind regime. As many wind profiles associated with precipitation and/or the presence of supercooled clouds should be modeled as possible. This will allow the design of a targeting plan that will maximize the coverage of the target areas under varying wind conditions.

- *Aircraft base of operations*. The basing of aircraft is also of some concern so that the aircraft can safely depart from and return to the airport selected during weather conditions typical of operations. Suitable alternate airports must be available, in the event that the "home" airport is not accessible. In programs conducted in warmer locales or during the warm (convective) season, aircraft that accumulate significant ice simply can descend to warmer levels, shed the ice, and return to operations. However, in many wintertime programs, particularly those in higher latitudes or the interior of continents, this is not possible, for the temperature of the atmosphere all the way to the surface may be less than 0 °C. In this case, the option of descending to shed ice does not exist, and the aircraft must cease operations once the pilot believes the aircraft has accumulated all the ice it can safely handle. This is true even of aircraft certified for flight in known icing conditions.[1] For programs using multiple aircraft, basing decisions must consider minimizing time from deployment to arrival at the target cloud, as the seeding "window of opportunity" is small in convective clouds. For larger project areas, distribution of aircraft at multiple bases (as available airport facilities allow) is the preferred method in this scenario (Langerud et al. 2010).
- *Seeding agents.* Various cloud seeding agents are discussed in detail in Chapter 5. The design will identify which agents should be used and when.

6.4.2 The Evaluation Plan

When a cloud seeding program is designed, an evaluation plan should be part of the design. Most operational cloud seeding programs for the last 30 or more years in both warm and cold seasons, especially those in the United States, have decided to seed every cloud or storm meeting their program design criteria as being treatable. This means that with these programs, the only avenue left for evaluation has been to compare the precipitation received within the target area to that received in a nearby, climatologically similar control area. If a long-term positive correlation in precipitation between the target and control areas can be established for those years when no seeding was done in either area, then a subsequent relative change in the target can be attributed to seeding. The risk in drawing such a conclusion is that climates change, although changes in the relationship between nearby areas may be less than changes in the overall precipitation climate, or one area or the other may have been affected by an extreme event that didn't affect the other. Such things could lead to the wrong conclusion—either positive or negative—being drawn about the effects of seeding. Multiple seasons of cloud seeding that exhibit systematic differences lend credence to drawing qualified conclusions about the effectiveness of the seeding program.

A second option, seldom used in operational programs, is to randomize treatment for the intended area of effect, that is, to decide randomly which days or storms should be treated and to compare them to those that were not. This is usually the approach adopted in scientific experiments, but this course has its drawbacks as well. Although it can eliminate the possibility that climatological changes were the reason for any observed changes in precipitation, the chance of a single extreme event (seeded or not seeded) having a dominant effect on the conclusion still exists. Another drawback is that to randomize, some fraction of all suitable clouds must not be treated. This, of course, diminishes the overall effects and thus the benefit–cost ratio of the program.

Randomization of treatment for a few seasons as a program is first started should perhaps be considered if the sponsor is sincerely interested in establishing the strongest possible evidence of program effectiveness (Mooney and Lunn 1969). Historically, most randomized programs have been conducted as research programs, but nothing precludes a serious operational program from randomizing treatment if its sponsors choose to do so. Randomization need not be 50:50, that is, one case seeded for every case not seeded, but could be two-thirds: one-third, wherein two out of every three cases is seeded. This lengthens the period needed to draw firm conclusions, but allows most seedable cases to be treated, increasing the program's immediate impact.

Barring this, one is usually compelled to examine observable differences between those clouds or systems that are seeded and other clouds or systems, presumably of similar nature and potential, that are not seeded. Problems often arise because persons involved in seeding programs naturally seed those situations perceived to have the greatest potential to produce precipitation, and other biases sometimes known and sometimes unrecognized exist (Woodley and Rosenfeld 2004).

The initial step in program evaluation is the collection of relevant precipitation, snowpack, or streamflow data, and whatever supporting atmospheric data are obtainable. Some scientists believe that proper evaluation of a weather modification program can occur only if the program is randomized (see, e.g., National Research Council 2003). Others hold that meaningful results can be obtained for properly designed nonrandomized programs, especially if such programs are coupled with physical measurements that verify some of the key processes involved, such as those related to targeting and nucleation (Orville et al. 2004). Such physical data may include cloud physics measurements, radar and satellite data, numerical modeling to aid targeting, and trace chemistry measurements (see, e.g., Changnon et al. 1979). Some of these techniques may be more readily applied to research rather than operational programs.

Some newer approaches thus combine the target versus control approach with physical measurements, computer modeling, and/or trace chemistry to validate program operations and verify that the clouds intended to be seeded were suitable candidates and were actually seeded (Boe and Keyes 2006). For example, when the project finds silver concentrations above background amounts in snow within the target that fell during a period of seeding, the argument that seeding increased the snowfall is strengthened (McGurty 1999). This alone does not constitute unequivocal proof as it is possible that the silver was "scavenged" by falling snowflakes and was not the origin of the ice crystals that formed the snow. The tracer techniques discussed in Chapter 5 can resolve that question.

New, higher-end computer models, such as WRF and HYSPLIT, may allow predictions of where seeding agents released from specific locations should travel and be deposited. Thus, the use of a numerical model on even a nonrandomized seeding program could allow improved definition of both target and control areas and allow for storm-by-storm evaluations to be made. For example, the model might identify situations in which the control area was contaminated by an agent drifting out of the target region or in which the target area was not well targeted. Before relying on any model for such finer-scale applications, however, some validation should be performed for the region of interest. For example, this could be done by checking for silver or other tracers in new "seeded" snow where the model says it should be found. Without adequate model validation, the comparatively small anticipated differences in precipitation because of seeding will fall within the level of uncertainty associated with the modeling guidance, yielding inconclusive results.

Correlations between target and control areas normally are weaker the shorter the sampling interval. In other words, correlations for individual storm periods are weaker than those for individual months, which are weaker than those for an operational season of several months or longer. The degree of correlation determines the ability of a target/control evaluation method to discriminate the seeding signal from the natural variability of precipitation measurements (i.e., a signal-to-noise problem). If affordable, even on a temporary basis, modeling is a helpful tool that can reduce the "noise" in the signal by clarifying which areas actually were targeted during a given storm event.

In many long-term cloud seeding programs, seeding may have been conducted in various ways for 10 to 20 years, and the data collected then studied to evaluate the program effectiveness. Greater consistency of the operational methodology would reduce the "noise level" in evaluation, although few would argue that a desire for consistency should impede the adoption of improved technology in an operational program. In many cases it has taken years to analyze the different methodologies, with much debate about the findings. Often, no final conclusion has been reached regarding program efficacy.

It is very important that the quantities on which evaluation (assessment) is to be based be defined before the program begins, and any necessary equipment (e.g., precipitation gauges) be deployed. The addition of measurements, such as those obtained from precipitation gauges, will only be useful in a systematic program evaluation if, for example, a similar number of gauges is also deployed within the proposed control area and the project is *randomized*. Without randomization, there likely will be no unseeded data available for comparison with the seeded data from the newly installed gauges. In such a case, siting criteria (elevation, exposure) must be the same for all supplemental gauges.

Selection of target and control stations to be used in the evaluation of operational programs should be done prior to the commencement of seeding activities if at all possible. This approach can then result in an a priori evaluation as long as the target and control sites remain the same. This step also will remove questions of bias that may arise if such selections are made several years after the beginning of seeding. In other words, no one can be accused of selecting a set of target and control sites that provide positive indications, whereas a different set of sites might indicate little or no effect. Changes in the site groups should be made only when necessitated by the decommissioning of a target or control measurement station.

In addition to examination of precipitation data, other techniques also are available. Any physical measurements made during both natural and seeded storms help document the development of precipitation. Sampling of snow in and around the target area for evidence of seeding agents can help verify correct targeting and further strengthen results, although this expense is not trivial.

Radar reflectivity data can be used to estimate precipitation, especially during warm-season programs when most of the precipitation is in liquid form at lower levels. Such estimates are derived from empirical relationships between radar reflectivity, Z, and rainfall rate, R, termed *Z-R relationships*. These relationships can be "tuned" for a best fit to each local area, or even on a storm-by-storm basis. This is accomplished by comparing the radar-estimated precipitation with that actually observed by surface gauges and then "adjusting" the radar estimates to make them agree with the surface observations. The *Z-R* relationships generally should hold for those storms that form under similar conditions to those present when the relationships were developed. *Z-R* relationships that yield poor estimates should be reported to the program manager, who should inform the scientists so that they can develop better relationships for future operational use in the area of interest (Boe and Keyes 2006). Once the *Z-R* relationships are established for a particular storm, the radar can be used to estimate precipitation, providing estimates of *total* rainfall amount over the area covered by the radar (e.g., Woodley et al. 2001). The radar technique is attractive because such area-wide estimates are difficult to make solely with rain gauges, because they are normally many kilometers (miles) or tens of kilometers (miles) apart.

A radar-based technique that utilizes the advantages of the WSR-88D 10 cm (S-band) wavelength NEXRAD weather radars operated by the National Weather Service in the United States has been described by Woodley and Rosenfeld (2004). This technique uses "floating" target units that are tracked by the radars.

Because weather patterns vary considerably from season to season, and invariably program sponsors and operators learn how to conduct various program facets better, operational and evaluation plans should be flexible and seasonally subjected to review and modification if appropriate. During the initial season or two, procedural modifications may be made even more frequently. The risks associated with making programmatic modifications should be estimated and passed on to the program sponsors prior to their implementation. Usually the greatest complication arises from the need to evaluate operations differently if they are conducted differently. Early on, this may not be a major issue, but if significant changes are made a year or more into the program, it may be necessary to reevaluate the program to ensure that "apples" are not compared with "oranges."

Evaluation of weather modification programs has proven to be difficult. The primary difficulty arises from the unavoidable fact that no two clouds or even two storm systems are exactly the same, and researchers cannot simply treat (seed) one and not the other and then observe the differences. Evaluations on a cloud or storm basis are now possible with the use of analytical numerical cloud models that can provide forecasts (or even hindcasts) of specified response variables. Evaluation statistics comprising differences between observed and forecast variables should be less noisy than the observed variables themselves. Such models are becoming increasingly helpful, but the answers are only as good as the model and the input data. As previously stated, program-specific validation/verification of the model should be performed. For examples, see Orville et al. (1984), Helsdon and Farley (1987), Rasmussen and

Heymsfield (1987), Farley et al. (1989), Kopp et al. (1990), Orville and Kopp (1990), Kopp and Orville (1994), Stith et al. (1994), Wilhelmson and Wicker (2001), and Xue et al. (2013a, b).

Sponsors of operational programs often do not expect to conduct evaluations that might be considered necessary by the scientific community to "prove" that cloud seeding is working as intended. A quote from a paper by Bruintjes (1999) illustrates this point:

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

Another quote from Silverman (1978) supports the quote from Bruintjes: "Users of weather modification are shrewd business people. They understand that they are, in many cases, taking a gamble when they use weather modification, but it is no greater risk than they take in other aspects of their business."

The Weather Modification Association's Code of Ethics (Weather Modification Association 2012) states, "Evaluations of projects are strongly encouraged. Any limitations to evaluation will be reported to the client. Procedures to be used in evaluations should be specified in advance."

6.4.3 Quantification of Findings

It is important to assess the effectiveness of cloud seeding for precipitation augmentation. Evaluation (assessment, at times estimation) of the effects of seeding efforts might seem at first thought to be a somewhat straightforward exercise. However, the more commonly stated percentage increases, unfortunately, fall well within the normal range of natural precipitation variability. Thus, quantifying the differences attributable to cloud seeding becomes a challenging enterprise. The difficulty in doing so does not mean that evaluations should not be done. Rather, it indicates that the whole matter should be addressed from a perspective that reflects an understanding of (i) the evaluation possibilities (statistical and physical) and their limitations, (ii) some primary pitfalls involved, (iii) the costs of the various methods and what they can realistically be expected to provide, and (iv) a balanced plan for evaluation that fits the program's goals and needs. This is an issue worthy of careful consideration. At the heart of the matter lies the "level of proof" issue and fundamental benefit–cost considerations.

As previously noted, most operational programs are not randomized. Thus, after the completion of a month's or a season's seeding activities, the precipitation recorded within the target areas often is compared with that observed in the control areas. Judging program outcome by comparing data from just a single month or season is risky, as natural variability can be considerable, and it is possible that one or two large events over either the target or control areas could greatly affect the perceived program impact. For example, a large event over the control areas when no event of similar scale occurred over the targets could wrongly lead to the conclusion that the effect of the program was negative. Conversely, a large event over the target(s) when none occurred over the control(s) could lead analysts to conclude incorrectly that an exaggerated positive effect resulted from seeding. In either case, the apparent conclusion is inaccurate but simply as the result of a "bad draw," which are naturally large events not occurring over both target(s) and control(s). For example, consider a program wherein mountain storms moving from west to east are usually seeded. Suppose a deep low pressure center passes to the south of the target, creating much upward vertical motion, condensation, and precipitation over the target area, along with *easterly* winds. If the program's seeding systems are set up to seed storms passing from west to east, seeding a storm characterized by easterly flow certainly will have little impact in the target area(s). If precipitation is considered on a storm-by-storm basis, such storms can be identified and excluded from the analysis. If it is not, then the resulting precipitation would be included—even if most of it fell outside the target area(s), perhaps even over the control(s). The likelihood of a "bad draw" diminishes with increasing numbers of units (clouds, storms, seasons). As a consequence, indications of results from long-term programs are more credible than those from shorter-term programs (Silverman 2010).

Because of the potential for suggestion of bias or conflict of interest in evaluations, statistical and/or physical evaluations of operational programs could be conducted by qualified but disinterested third parties, in other words, people with no stake in the outcome. Such individuals are more readily able to identify possible sources of bias and are more likely to offer criticism (often constructive) when it is warranted. The independence associated with third-party evaluation may strengthen program credibility. The sponsors and public may be more accepting of a third-party report than an in-house document, regardless of the degree of honesty and expertise with which the in-house report was assembled. The WMA Statement on Standards and Ethics (http://www.weathermodification.org) encourages program evaluations. It should be recognized and emphasized that if a third-party evaluation of a nonrandomized program is to be undertaken, the evaluation methods and procedures should be established in advance (a priori) of the seeding period to be evaluated. For example, if a target and control winter analysis is proposed, the stations making up the target and control and the historical period to be used should be specified in advance. This is important, because otherwise there could be a question of bias in the evaluation of a nonrandomized program if the basis for the evaluation is established only after the fact (a posteriori).

Care must be taken in the selection of the party doing the evaluation to ensure that the party is (i) qualified and (ii) truly disinterested in the result. The Weather Modification Association maintains a list of members, many of whom are highly capable of such analyses.

Collectively, there are many ways to assess operational weather modification programs, even without randomization. The critical issues are to incorporate evaluation methods that are *appropriate* to a program's needs and goals and to consider carefully the "level of proof" that is required for program support decision making. Analysts must remain mindful of the fact that every evaluation method known has one or more limitations that can be noted. Thus, absolutely conclusive quantitative proof of cloud seeding effects currently is not achievable in the realm of nonrandomized operational programs. Recognizing that, at this time in the evolution of cloud seeding technology, it is not possible to deal in absolutes regarding the evaluation question; a program manager can survey the spectrum of assessment possibilities and, perhaps with the help of an expert weather modification consultant, select an evaluation method that best fits program needs. For new programs, it is advantageous to establish and state what methods are being used before seeding begins, thus helping to avoid obvious biases and bolster program credibility. New technologies for assessment can be considered and incorporated if deemed appropriate and cost effective (Boe and Keyes 2006).

6.5 PROGRAM CONTROL

An operational program design should include the infrastructure of operations that clearly should be set forth in an operations plan, written well in advance of the onset of seeding operations, and reviewed by the sponsor, contractor, and any regulatory agencies having jurisdiction over weather modification. Such operations manuals describe the communications "chain of command," operations procedures, seeding suspension criteria, and reporting requirements along with operational theory and the theoretical (scientific) basis for the program. In addition, a summary of the program's environmental review often is included, or if no program-specific review was conducted, an overview of the environmental findings from similar programs may be provided. Thus, the operations plan is a one-stop source of information about the program (Boe and Keyes 2006), containing most program-related information, apart from results, which will be determined later.

6.5.1 Seeding Decisions

Program operations. Operational weather modification programs are controlled by guidelines and other criteria established by the sponsor and conveyed to the program operator (contractor), usually in the person of an operations director or program manager. The general flow of information, as described in ASCE (2003), is illustrated in Fig. 6-2.

The daily flow of program decision making generally is focused at an operations center. For warm season (summertime) programs, this also is often the program radar site. For cold season programs, it may be a room dedicated for the purpose within the sponsor's offices, a remote field location where other program equipment is sited (e.g., a microwave radiometer), or if aircraft are involved, an office at an airport.

In Fig. 6-2, the core group involved in the actual day-to-day conduct of operations includes those at the operations center, the operations personnel, and those responsible for the maintenance and servicing of program facilities. The people in these three groups typically communicate at least daily and often many times per day when the program has the potential for seeding activities. Maintenance and servicing of field sites usually is conducted when inclement weather is not occurring. Therefore, the maintenance personnel are generally most active when the operations personnel are not and vice versa.

Additional input is received frequently at the operations center from the program sponsors. Often this communication relates to updated hydrological data (reservoir levels, streamflows, etc.), or updated rainfall or snowfall reports, including snow surveys. The program sponsor always has the prerogative to suspend operations, in addition to the program

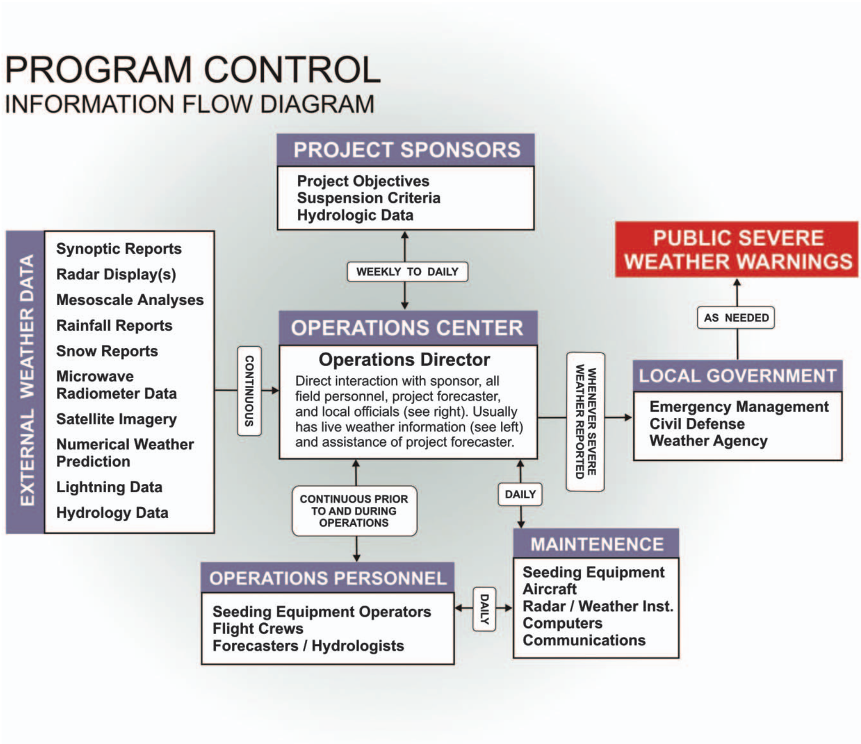

Fig. 6-2. This diagram illustrates the communications infrastructure of a typical weather modification program; some items shown are season dependent
Source: Adapted from Fig. 4-1 in ASCE (2003), ©ASCE.

seeding suspension criteria that are preestablished in the program design. It also is prudent to grant the seeding operations director unilateral real-time suspension authority as a safeguard against rapidly developing hazardous conditions when communication among the usual parties may not be readily accomplished. An example of the value of this arrangement is shown later in this chapter.

6.5.2 Data Collection and Access

Data collection is a critical part of any evaluation program, as discussed in Section 6.4. The data collected and archived are invariably a function of the design of the evaluation plan, restrictions on the data collection (frequency of snow sampling, for example), and the funding level of the program. Additional instrumentation and data collection over and above what was done prior to the onset of the program may help evaluate the program efficacy, and ultimately, the economics of the program, but often are not affordable. Chapter 5 contains additional discussions on this topic.

It can be helpful to establish a public access website offering access to real-time program data. Typically, such sites include real-time program radar imagery, status of seeding (aircraft or ground-based), seasonal seeding and precipitation statistics, the daily program forecast, frequently asked questions (FAQ) and answers, and an e-mail address to which inquiries and comments can be sent. Such websites provide interested people with real-time information, imparting real knowledge of what is occurring. This reduces speculation and eliminates any sense of secrecy or covertness about the program. If a frequently updated program site is not considered practical by the sponsors, they may find another way to provide regular, timely program information, if appropriate to program goals and needs. In some cases, a project sponsor agency may handle project information and inquiries through its own public relations mechanism.

Some programs have ended because of lack of evaluation and/or lack of a rapid communication during potentially hazardous conditions. The program protocol should have clearly defined operational criteria and restrictions related to short-term and long-term suspension of the programs and equally clear evaluation objectives.

6.5.3 Seeding Suspension Criteria

Chapter 2, Section 2.2.4, and Chapter 3, Section 3.2.3, of this manual both point to the need for programs to implement safeguards that will ensure public safety and environmental well-being. The most common such safeguard is a well-designed set of criteria that, when satisfied, triggers an immediate cessation of seeding activities. Such safeguards differ for warm season (convective) and cold season (orographic) seeding programs but share common goals.

6.5.3.1 Warm Season Suspension Criteria Warm season programs designed to increase precipitation deal most commonly with convective storms. These storms range in scale from cumulus congestus (towering cumulus) clouds that produce little, if any, precipitation that reaches the ground, to heavy thunderstorms capable of producing extreme precipitation volumes in very short periods of time. Rainfall rates from deep moist convection commonly exceed 25 mm (1 in./h) (Lamb 2001) but sometimes are far greater. For example, 305 mm (12 in.) of rain fell in Holt, MO, on June 22, 1947, in just 0.7 h (Lott 1954). The hazard implications for such heavy rainfalls are further complicated by the fact that such storms are often slow moving and release much of their precipitation over the same area, as in events that have resulted in extreme natural floods like that which occurred in Rapid City, SD (Maddox et al. 1978; Doswell et al. 1996), and the Big Thompson Canyon of Colorado (Maddox et al. 1978). Such storms/convective systems ought not to be seeded. Thus, suspension criteria need to provide for the early identification of storms with such potential so that seeding may be called off in advance of the event.

Some factors that alert program forecasters to the potential for warm season flooding by convective storms are listed as follows. The likelihood of potential flooding increases as more of these factors are present. They include (Boe and Keyes 2006)

- Convective instability as indicated by upper air soundings (large convective available potential energy, or CAPE),
- Atmospheric dynamics that favor storm development,
- Precipitable atmospheric water in excess of 25 mm (1 in.),
- Low-level wind shear profiles that favor moisture advection in the low levels and "ventilation" of the storms aloft,
- Light to moderate mid-level winds that will favor slow storm movement,
- Saturated or near-saturated soils, and
- Reservoirs or other water control structures that are at or near storage capacity.

Together, these and other local factors can alert the program forecaster to the increased probability of localized flooding and the potential need to suspend seeding. A rule of thumb often used by program managers is that if the forecaster sees enough signs to become concerned about localized flooding, sufficient cause exists to suspend seeding, even in the absence of any storms. Such decisions usually are made by the program manager (operations director) after consultation with the program forecaster and the program sponsor. A good example of prestorm suspension of warm season seeding occurred in June 2002 in a Texas precipitation enhancement program (Resler et al. 2002), when the program operations director (and also forecaster) became concerned early in the day about flooding potential. This particular event occurred in the Abilene area on a weekend, and the program sponsor could not be contacted. The operations director consulted with his immediate supervisor within the company, and the decision was made to ground all seeding aircraft, thus suspending all seeding even before any clouds formed. Later that afternoon and evening, numerous slow-moving, heavy precipitation-producing thunderstorms developed that produced the flooding of numerous streets and basements in portions of Abilene, but no seeding had been done. In this case, the program sponsor was not contacted before the decision to suspend was made, as would normally be the case. However, the "when in doubt, suspend" rule of thumb was appropriately applied, and the value of well-considered suspension criteria and protocols was demonstrated.

There are additional real-time indicators that warm season seeding operations to increase rainfall should be suspended. These include (Boe and Keyes 2006)

- Flood watches or warnings issued by local authorities, such as the National Weather Service.
- Radar indications of slow-moving or stationary thunderstorms that are producing heavy rains.
- Radar-derived precipitation estimates that indicate excessive rainfall, particularly if soils are known to be saturated or nearly saturated.
- Train echoing, when a series of storms follow the same path, one after another; although no single storm may produce enough rain to result in flooding, the collective effect of a series of storms often does. Train echoing, (or "training") often occurs along stalled or slow-moving surface frontal boundaries.
- Tornadic storms are not seeded in some programs but are in others. One school of thought holds that operations managers should do nothing (i.e., seeding) that could be perceived as contributing to a dangerous situation; another is that because there is no direct evidence in the literature that indicates seeding can cause or exacerbate tornadic storms, seeding should continue.

The seeding suspension criteria developed for any warm season program should address all of these factors and should clearly state the threshold for suspension. Some suspensions (as noted) occur before any storms even develop, whereas others occur when storms with flooding potential actually are observed. In either event, thorough records should be kept of all suspensions, including the time they were ordered and the reasons why. Some programs have determined that local news media should be notified when suspensions occur. Others have even sought the visual verification of suspension of operations by local authorities; for example, local law enforcement has been asked to visit an airport to verify that aircraft are not flying. The latter is not generally required unless there are known to be individuals present in the program area who would seek to blame any natural misfortune on the seeding program, in which case verification of inactivity by law enforcement or other civil authority will dispel any such claims.

6.5.3.2 Cold Season Suspension Criteria Cold season programs designed to increase precipitation deal most commonly with orographically induced, often synoptically aided clouds and storms. Such storms range in scale from simple "cap clouds" that barely enshroud the mountain tops to energetic synoptic-scale winter storms capable of producing extreme precipitation volumes (rainfalls or snowfalls) in somewhat short periods.

Suspension criteria also are needed for cold season programs to avoid even the appearance of exacerbating severe winter conditions.

Common negative consequences of better-organized cold season storms include snowy, icy, and/or blocked roadways, reduced visibilities, heightened avalanche potential, increased roof loading, and additional snow removal costs. All of these effects can occur with large natural storms as well. Some winter programs are conducted to increase rainfall, not snowfall. As a consequence, some of the same type of suspension criteria developed in summer programs may be needed in these operations.

The cold season suspension criteria are intended to avoid (Boe and Keyes 2006)

- The appearance of contributing to extreme precipitation events, which are usually naturally efficient. To do this, operation managers must identify potential extreme snow and/or severe winter weather events prior to their development over the target so that they are not seeded.
- Contributing to already heavy snowpack, such that spring runoff may become excessive and/or unmanageable.
- Seeding very warm storms that may produce heavy rains on existing snow packs at high elevations.

Suspension for naturally occurring high-intensity precipitation producing storms is generally based on the program forecaster's experience with the local climatology, prognostic charts (especially numerical models), and real-time observations of developing storm conditions. The last of these is aided greatly by real-time satellite imagery.

Suspension to avoid contributing to excessive snowpack is more readily accomplished. Available snow course data are compared periodically to "normal" snowpack to determine the percentage of normal snowpack present. Program-specific criteria should be established (and set forth in the operations plan) that specify when seeding is to be suspended. For example, early in the snow season (say, December), the snowpack (in a northern hemisphere program) is usually a small fraction of the annual total. Therefore, seeding may not be suspended until measured snowpack water content exceeds perhaps 200 or 250% of "normal" for that date. As the season progresses and the total snowpack increases, the suspension threshold may then drop such that by the end of January the suspension threshold might be 175% of normal and by the end of February 150% of normal. By the first of April, seeding may be suspended if snowpack exceeds 125% of normal. These specific numbers are provided simply as examples, and specific appropriate values should be determined by hydrological studies of each local area. Suspension of seeding because snowpack meets or exceeds a certain percentage of normal does not necessarily mean that the program is shut down for the balance of the season, only that seeding operations should cease until such later time that the percentage of normal drops below the given threshold for the date. If the weather pattern remains wet for the duration of the winter, seeding may not resume, but if drier conditions persist for a time, as is often the case, seeding then resumes.

6.6 PROGRAM MANAGEMENT

The program management has certain ongoing responsibilities, some of which continue beyond the operational season. Although some program sponsors prefer that the individuals or entity (contracting company) conducting the actual seeding make most day-to-day decisions with minimal oversight, others are more hands on and desire more direct involvement in day-to-day decision making. Such determinations are made by the program sponsor. Invariably, it is the responsibility of the program sponsor to ensure the following (Boe and Keyes 2006):

- *Oversight of operational decision making*. This need not be micromanagement but should include a mechanism through which operational decisions are reviewed periodically.
- *Record keeping*. In most cases the sponsor requires that detailed records be kept of operations. In many cases, such records are required by law. For example, in the United States, the National Oceanic and Atmospheric Administration (NOAA) requires that the type, location, and duration of operations be reported periodically, along with quantities of the seeding agent dispensed. Further, many U.S. states require additional reporting, usually as a part of their operations permitting.
- *Public information and outreach*. Program sponsors often have public relations staff available who can include information about cloud seeding efforts and effects in their presentations or who at least can be prepared to answer questions. Many sponsors also include the expertise of the contractor in this effort. This might entail public talks, management of a project website (see Section 6.5.2), or the preparation of nontechnical program informational brochures.
- *General assessment (evaluation) of the program*. Although some sponsors are satisfied with program evaluations conducted by the contractor, others choose to retain expertise from outside the program to evaluate program efficacy. The reasons for the latter are twofold. First, even if an "in-house" evaluation is done with utmost care and effort to avoid biases, it is common for such evaluations to be called into question simply because they were conducted by the same party doing the seeding. Some people dismiss in-house evaluations as being self-serving. The second reason is that evaluation by a qualified

individual or team that has no direct stake in the outcome is less likely to be biased (consciously or unconsciously) and more likely to be accepted by the public. In either case, the key is that those conducting the evaluation be qualified and unbiased.

- *Disclosure of findings*. Once an evaluation is completed, the findings should be reported to the program sponsors. Then, they can determine whether and to what extent the results are to be released to the press and made readily available to the interested public. Evaluations often are posted on the sponsor's or contractor's websites. Evaluation based on a single year's efforts will, in most cases, be very difficult, as the magnitude of the anticipated effect is within that of natural variability. This is most certainly true of nonrandomized programs. Therefore, disclosures concerning operations after the first few seasons may be limited to a summary of operational days and any physical measurements made that reflect on program efficacy.
- *Modification of operational design*. If difficulties are discovered concerning the design of the program, it is within the sponsor's purview to ensure that the difficulties are corrected. If seeding criteria or methodology are modified, it might complicate comparisons of findings from the initial season or seasons with those of future seasons, but it is more important to correct problems.

The importance of open program information dissemination cannot be overstated. Beyond a program website as described in Section 6.5.2, weekly or monthly program updates and educational news releases for decision makers, such as county commissioners, legislators, governors, and administrative staffs, can be used to keep the program visible and the public informed.

ENDNOTES

1. Certification for flight in known icing does not mean that an aircraft can carry an infinite amount of ice, nor that the aircraft can rid itself of ice sufficiently to remain in icing conditions indefinitely. Rather, certification for "known icing" means that the aircraft has demonstrated the ability to safely fly within cloud conditions known to produce icing long enough to safely pass through the icing level.

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CHAPTER 7
GLOSSARY

Glossary terms with an asterisk (*) are copyrighted by the American Meteorological Society (AMS 2014) and used with permission. Alternative glossary entries are indicated with *italics.*

2D-TD—Two dimensional–time dependent

Abnormally dangerous activity—Activity involving a high degree of risk that is not a matter of common usage and for which there is legal liability for resulting harm, even though utmost care has been taken to avoid such harm

Accretion—In cloud physics, the process of growth or enlargement of an ice crystal or particle by the accumulation of supercooled droplets

Adiabatic—The expansion or compression of a gas (such as air) occurring without loss or gain of heat

Advection—The process of transport of an atmospheric property (i.e., air temperature, water vapor content, or moisture) caused solely by the velocity field of the atmosphere. This movement is usually considered to be in the horizontal direction but may be used in terms of vertical movement. Vertical advection implies motions are predominately vertical and driven by buoyancy forces. It may operate in conjunction with radiation, and it may lead to the formation of clouds or possibly enhance the precipitation process under the right atmospheric conditions.

Advertent weather modification—Weather modification resulting from intentional efforts by humans to change the weather

AES—Atmospheric and Environmental Service

AgI—See *silver iodide*

Air mass—A large body of air (hundreds to thousands of square kilometers) that possesses similar temperature and dew point characteristics as a function of height

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

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

ASOS—Automated surface observing station

AWIPS—Advanced Weather Interactive Processing System

BAMS. *Bulletin of the American Meteorological Society*, 45 Beacon Street, Boston, MA 02108-3693

Broadcast seeding—The release of a 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 also is a routine practice to increase precipitation within winter clouds in mountainous areas.

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

CCN—Cloud condensation nuclei. Tiny solid and/or liquid (not predominantly pure water) *nuclei* upon which water vapor first condenses as the relative humidity approaches 100%. These *nuclei* are the seeds for cloud droplets.

Cell*—A convective element (cloud), which, in its life cycle, develops, matures, and dissipates, usually in about 20–30 min. A cell in radar usage is a local maximum in radar reflectivity that undergoes a life cycle of growth.

Certified Weather Modification Manager—Certification of weather modification project managerial experience and skills granted by the WMA

Certified Weather Modification Operator—Certification of weather modification project operational experience and skills granted by the WMA

Cloud condensate—Liquid and ice water present in clouds

Cloud droplets—Liquid water droplets that are too small to precipitate because they typically range from 1–10 μm in diameter. Such droplets suspended in the atmosphere with other droplets form a cloud. Note: Human hair has an average thickness of about 65 μm.

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.

Cloud type—Cloud conditions with distinctive physical characteristics (cloud depth, temperature, wind, stability, etc.) such that different types may have different responses to seeding.

CO_2—See *dry ice*

Coalescence*—In cloud physics, the merging of two colliding water drops into a single drop. Coalescence between colliding drops is affected by the impact energy, which tends to increase with the higher fall velocities of larger drops.

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

Colloid—A mixture composed of two phases of matter, the dispersed phase (or colloid) and the continuous phase (or the dispersion medium). Colloids do not settle. In the case of a cloud, the dispersed phase is liquid and the continuous phase is air making it a colloid. But because the cloud droplet components are generally greater than 1 μm in diameter it is not technically a stable colloidal system, because the liquid components would settle, albeit slowly, without coagulating. A population of airborne liquid (not of pure water) and/or solid *nuclei* (i.e., a population of aerosols) is closer to being a stable colloid, compared with a cloud.

Colloidal stability—A theory advanced in the 1940s by Derjaguin, Verway, Landau, and Overbeek concerning the likelihood of components in the dispersed phase coagulating. In the case of *supercooled fog*, the dispersed phase is supercooled droplets, which are approximately the same size and unlikely to coagulate naturally, exemplifying a stable colloid.

Conceptual model—A model of precipitation, hail, and/or fog development and the seeding methods to enhance or mitigate that development based on current knowledge and scientific concepts. See also *cloud model*.

Contact-freezing—A nucleus that, when it makes contact with a supercooled droplet at temperature below 0 °C, will cause it to change to ice

Contamination—The inadvertent distribution of seeding agent into areas that, according to project design, was not to have been seeded

Continental air mass—A large body of air that forms over a continent and consequently has the basic continental characteristic of relatively low water vapor content. See *air mass*.

Control area—Areas where cloud seeding operations do not take place, preferably similar in character and near to the *target area*. The behavior of storms over the control area is compared with those treated over the target area to assess differences and thus estimate project effectiveness. See also *target area and seeding area*.

CONUS—Continental United States

Convective cloud—A cloud characterized by organized, fluid motion, including both upward and downward motions. This term generally is interchangeable with a *cumulus cloud*.

CPR—Cardiopulmonary resuscitation

CRAFT—Collaborative Radar Acquisition Field Test

CRBPP—Colorado River Basin Pilot Project

Crossover design—A project that employs areas that alternate between target and control. This crossover reduces the possibility of geographically induced bias in the evaluation.

Cumulus cloud*—A principal cloud type in the form of individual, detached elements that are generally dense and have characteristically sharp, nonfibrous outlines. These elements develop vertically, appearing as rising mounds, domes, or towers, the upper parts of which often resemble a cauliflower.

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

Drizzle drop*—A drop of water with diameter between 0.2 mm and 0.5 mm, which usually (but not always) falls from stratus or stratocumulus clouds. Drizzle is sometimes popularly called mist.

Droplet spectrum—The numbers and sizes of the droplets within the cloud volume of interest

Dry ice—Frozen or solidified carbon dioxide (CO_2). Dry ice pellets have an equilibrium surface temperature of −78 °C (at ambient pressure) and a cloud seeding operational temperature range colder than −2 °C. Dry ice is used fairly often, especially in applications where environmental concerns about silver doses are heightened or the temperature is between 0 °C and −5 °C.

Dynamic seeding—The treatment of clouds with the intent of using the latent heat produced by additional 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*.

Entrainment*—The mixing of environmental air into a preexisting organized air current so that the environmental air becomes part of the current; for example, the entrainment of air into cumulus clouds. Entrainment of air into clouds, especially cumulus, is said to be inhomogeneous when the timescale for mixing of environmental air is very much greater than the timescale for droplet evaporation. Entrainment deepens the mixed layer in the absence of advection effects.

Environmental impact statement (EIS) —A document prepared by or for a governmental agency proposing a project that states the environmental impacts that may affect the quality of the human environment

Evaporation-mixing—Denotes a process in which condensation occurs following the mixture of two different air parcels. The mixture is commonly driven by the diffusion of the vapor from the warmer mixture into the other and may also be associated with fog formation.

EWRI—Environmental and Water Resources Institute, American Society of Civil Engineers, Reston, VA (http://www.ewrinstitute.org)

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

FACE—Florida Area Cumulus Experiment

Fog droplets—See *cloud droplets*

Geostationary satellite*—A satellite in a west-east orbit at an altitude of 35,786 km above the equator. At this altitude, its orbit matches the Earth's rotation such that the satellite can be maintained over the same ground location. A geostationary satellite orbit is not necessarily the same as a geosynchronous orbit.

Geosynchronous satellite*—A satellite in an equatorial or near equatorial orbit that orbits at the same angular velocity as the Earth, making one revolution in 24 h. A geosynchronous orbit is not necessarily the same as a geostationary orbit.

Glaciation—The conversion of water phase to the ice phase

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, satellite-based navigation positioning system that provides consistently accurate positions, based on a constellation of 24 low Earth-orbiting satellites with very accurate clocks and the computational resources to triangulate the positions near the Earth's surface. The system was developed by the U.S. Department of Defense for one satellite to determine position with an accuracy of 30–100 m and an accuracy within mm of a known reference position if two satellites are used and integration times are sufficiently long.

Graupel*—White, opaque, heavily rimed snow particles that are about 2–5 mm in diameter. Also known as snow pellets, they form in convective clouds when supercooled water droplets freeze to an ice particle on impact. Graupel are sometimes distinguishable by shape, such as conical, raspberry, and lump (irregular) graupel.

Heat of vaporization—The heat absorbed per unit mass of a given material (water) at its boiling point that completely converts the material (water) to a gas at the same temperature; equal to the heat of condensation

Heterogeneous nucleation—The phase change of a substance to a more condensed state (i.e., a lower thermodynamic energy state) initiated by nuclei with different physical and chemical properties than the substance. For example, the nucleation of ice crystals from supercooled water vapor using silver iodide as the nuclei. See *nucleation.*

HIPLEX—High PLains EXperiment, part of the Bureau of Reclamation's Project Skywater

Homogeneous nucleation—The phase change of a substance to a more condensed state (i.e., a lower thermodynamic energy state) initiated by nuclei with the same physical and chemical properties as the substance. That is, the nucleation system only contains one component, for example, the nucleation of ice crystals from supercooled water vapor. See *nucleation.*

Hydrometeor*—Any product of condensation or deposition of atmospheric water vapor, whether formed in the free atmosphere or at the Earth's surface, including being derived from a wind-blown water surface. Thus, for example, hydrometeors are cloud drops or ice particles of any size and shape, either suspended in the air or precipitating.

Hygroscopic*—Pertaining to a marked ability to accelerate the condensation of water vapor; the ability of nuclei to absorb vapor but at a low enough rate that it does not completely dissolve under most conditions. This term is principally applied in meteorology to those *CCN* composed of salts that yield aqueous solutions of a very low equilibrium vapor pressure compared with that of pure water at the same air temperature.

Hygroscopic seeding—Treatment of clouds with hygroscopic materials that encourages the formation of larger droplets, changing the cloud droplet spectrum in such a way as to enhance development of precipitation through coalescence

Ice-forming nucleus. See *ice nucleus*

Ice nucleus. An aerosol, typically solid, that serves as a nucleus for the formation of ice crystals in the atmosphere. The subset of atmospheric particles (essentially all airborne matter) upon which ice crystals will form. These *nuclei* are typically water insoluble particles and may be classified as hydrophobic condensation *nuclei*. These are sometimes abbreviated *IN* or *IFN*, which stand for *ice nuclei* or *ice-forming nuclei*, respectively.

Ice process—The process by which cloud particles grow large enough to fall out as ice-phase precipitation. This often occurs where there is coexistence of ice and supercooled water droplets. The ice particles can grow rapidly at the expense of the supercooled water droplets.

ICPMS—Inductively coupled plasma-mass spectrometer, a somewhat new technique to determine the concentration of trace elements in solution

IFN—Ice-forming nucleus. See *ice nucleus*.

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

Immunity—In a legal liability action against a government, a defense based on the concept that the government cannot legally be sued

IN—See *ice nucleus*

Inadvertent weather modification—The unintentional modification of the weather through some aspect of human activities, such as the production of cloud nuclei or ice nuclei from various industrial or manufacturing processes

Indemnification—Payment to a person or agency of an amount of money equal to any loss it may have incurred including any legal liability payment made

In-situ measurements—The gathering of information from within or on a medium. That is, they are made in the actual location or environment of the object or entity measured. Such measurements are still the most common type of measurements, although *remote sensing measurements* are becoming more prevalent.

JWM—*Journal of Weather Modification*, the official journal of the Weather Modification Association. See *WMA.*

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. Simply, it is the heat released into the surrounding air or absorbed from the surrounding air when water changes its physical state. For example, the heat released when water vapor condenses is called latent heat of condensation; the heat released when a liquid water droplet freezes is called the latent heat of fusion.

License—Document issued by a government agency to an individual authorizing the holder to practice a profession.

Lidar*—Light detection and ranging. An instrument combining a pulsed laser transmitter and optical receiver (usually a telescope) with an electronic signal processing unit used for the detection and ranging of various targets within the atmosphere, such as atmospheric particles; analogous to the principles of operation of a microwave radar.

LORAN—Long-range navigation

Maritime air mass—A large body of air that forms over an ocean. See *air mass.*

MOA—Military operations area

MSDS—Material safety data sheet(s)

NaCl—See *sodium chloride*

NASS—National Agricultural Statistics Service

NAWMC—North American Weather Modification Council (http://www.nawmc.org)

NCAR—National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO, 80305 (www.ncar.ucar.edu/ucar/index.html)

NDTP—North Dakota Thunderstorm Project

Necessity—In a legal liability action a defense against liability based on the privilege to undertake activities to prevent an imminent public disaster

Negligence—Careless conduct falling below the standard of reasonable, prudent care

NEXRAD—Next Generation Radar. See *WSR-88D*.

NH_4I—Chemical formula for ammonium iodide

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 30 min

Nucleation—Any process of initiating a phase change of a substance to a more condensed state (or a lower thermodynamic energy state). Some examples include the process of initiating the ice phase in a supercooled liquid water drop and the process of initiating the liquid phase from its vapor. The nucleation may be *homogeneous nucleation* or the more common *heterogeneous nucleation*.

Nuclei—Airborne aerosols, droplets, or vapor/gas molecules on or through which a phase change may occur; a basis for future development and growth; a kernel. See *CCN and ice nuclei.*

Nuisance—Conduct that significantly harms the right to use and enjoy properly and that, on balance, is less desirable than the benefits obtained from it

NWS—National Weather Service. See *NOAA*.

Operational area—The area encompassing the target area and any surrounding upwind areas employed for treatment so that the effect from seeding covers the target area and for evaluating the project (excluding the control area as long as these areas have not had seeding conducted in them)

Operational cloud seeding project—A cloud seeding project conducted for a specific purpose, such as optimizing the production of precipitation within a target area

Opportunity recognition—The identification of those clouds or cloud systems suitable for seeding according to the conceptual model

Orographic*—Relating to mountains or mountain effects. Most often refers to the influences of mountains or mountain ranges on wind field, but also to describe the effects on other meteorological quantities such as air temperature, humidity, or precipitation distribution.

Overseeding—A condition that results from the application of too much glaciogenic seeding agent, in which case too many small ice crystals may form, none of which are large enough to precipitate or aggregate

Permit—A document issued by a governing or regulatory agency to an individual, group, or entity authorizing a holder to carry out some activity as specified therein

Placebo—Treatment with an inert substance without the knowledge of those applying the treatment. In a randomized cloud seeding program, clouds are treated with live seeding agents or a placebo. The placebo seeding might be only an audible event such as a recorded "bang" that sounds like a flare firing, or involve release of a flare containing sand to simulate as closely as possible the release of true seeding agents without the operator discerning the difference.

Potassium chloride—KCl, a simple salt often used as a primary ingredient in hygroscopic cloud seeding pyrotechnics

PPI—Plan position indicator

PPT—Parts per trillion (or it would be ppt)

Precipitation efficiency—The efficiency at which condensed water within a cloud is transformed into hydrometeors that can fall out and reach the ground as precipitation

Project area—The area covered by all the equipment used for operations within all other areas used in evaluation or assessment by the contractors and/or sponsors

Pyrotechnic—Fireworks, i.e., a flare that burns to produce either AgI or hygroscopic nuclei

Radiation—The transfer of heat energy without the involvement of a physical substance, such as air molecules. For example, the heat from a stove burner is an example of radiation, because the heat would flow away from this burner regardless of whether there were air molecules, no air molecules (as in space), a body of water, water and a piece of metal, or a piece of metal between the burner and the receptor. Radiative cooling of an atmospheric layer could lead to additional cloud formation and possibly precipitation, given specific circumstances.

Radiosonde (or rawinsonde)—An expendable meteorological instrument package that senses and transmits temperature, dewpoint temperature, and pressure at various altitudes during its ascent into the atmosphere. These quantities can be converted into relative humidity. Radiosondes are carried aloft by weather balloons twice daily from many sites around the world and may also be employed by projects to bolster forecasting or research efforts. If their position is tracked in time, then they will also reveal the vertical wind field profile. The radiosonde that is tracked in time to also obtain wind field is known as a rawinsonde.

Raindrop*—A drop of water of diameter greater than 0.5 mm. See *drizzle drop.*

RAP—Research Applications Program

RASS—Radio Acoustic Sounding System

Remote sensing*—A method of obtaining information about properties of an object or environment without coming into physical contact with that object or environment. Compare *in situ measurement.*

Remote sensing devices—Refers to any sensor(s) on satellite, airborne, or ground-based platforms that either directly (active) or indirectly (passive) infer information about a property of an environment without being in or attached to that environment. Examples of ground-based remote sensing devices include lidars, radars, radiometers, acoustic sounders, and sonic anemometers. Satellites have radiometers sensitive to one or more spectral regions of the electromagnetic spectrum onboard a satellite. Some of the latest satellite platforms include radar and will include a lidar in the near future. These devices can also be mounted on aircraft. Contrast with *in-situ measurements*.

Remote sensing measurements—Refers to the measurements from *remote sensing devices*

Research cloud seeding projects—Cloud seedng projects organized primarily to acquire additional knowledge on how "seedable" the clouds in a given location might be; the precipitation processes that occur naturally and how they may be altered by seeding; the testing of different seeding modes, etc. Assessment of seeding effects is a primary interest. These projects are typically sponsored by government agencies because of their cost.

Response time—Time that elapses from identification of a seeding opportunity until the release of a seeding agent actually begins. In the case of instrumentation used during operations or to evaluate operations, the response time, with respect to measuring devices, refers to the time interval necessary for the measuring device exposed to a change in an atmospheric property to reach the fraction [1 – (1/e)] or 63.2% of the total environmental change in that atmospheric property that it would exhibit after an infinitely long time.

Revocation—Permanent cancellation of a license or permit

RHI—Range height indicator

Riming—The growth of an ice crystal by the collection of supercooled droplets that is said to have grown by riming

SAD—Seasonal Affective Disorder

SCPP—Sierra Cooperative Pilot Project

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

Seeding area—The area over which cloud seeding operations are permitted. This includes the *target area* and additional area outside the target area to allow for seeding upwind for intended effect in the target. See also *control area* and *target area*.

Seeding criteria—A set of conditions established for a cloud-seeding project that are designed to optimize the augmentation of precipitation. Typical indices used are cloud temperatures, wind flow, atmospheric stability, and water content.

Seeding hypothesis—A statement of expectations that identifies certain assumptions and predicts an outcome in terms of a seeding effect, given the specifics of a seeding project, such as seeding mode and a project location and duration

Silver iodide—A common *glaciogenic* seeding agent. Its chemical symbol is AgI. See *ice nucleus.*

SLW—Supercooled liquid water, which means the amount of water at temperatures below 0 °C

SODAR—Sonic detection and ranging. These systems are used to remotely measure the vertical turbulence structure and wind profile of the lower layer of the atmosphere.

Sodium chloride—NaCl, the chemical composition of common table salt. Salt powder is being used for hygroscopic seeding because of its hygroscopic properties.

Static cloud seeding—Cloud seeding to alter the precipitation by changing the efficiency with which existing cloud water is converted into precipitation-size particles. This terminology is no longer contemporary.

Stratiform clouds—Descriptive of clouds with limited vertical development and extensive horizontal development, as contrasted to the vertically developed cumuliform cloud types

Stratus clouds—Clouds that are uniformly stratified and nearly always have a uniform base. They are normally precipitation free, but occasionally drizzle, or light mist, will fall out of stratus clouds. There are weather reports of light to moderate continuous rain from stratus clouds that form near oceans.

Supercooled fog—A fog containing supercooled water droplets. See *supercooled water*.

Supercooled water—Water that remains in the liquid state despite air temperatures colder than 273 °K (32 °F). Some pure water droplets may exist in a supercooled state to temperatures well below 23 °K (−40 °F). Such have been called solution drops, which contain dissolved salts from cloud condensation nuclei. The dissolved salts lower the temperature for freezing compared with the freezing temperature for drops containing only water molecules. Drops that contain only water would freeze at temperatures at or colder than 233 °K (−40 °C).

Suspension—Temporary cancellation of a license or permit associated with cloud seeding. A temporary halt of seeding operations to avoid undesirable results. See *suspension criteria.*

Suspension criteria—Criteria developed for a specific cloud seeding project to avoid seeding during undesirable periods. Examples include excess snowpack accumulation, excess rainfall forecasts, and National Weather Service forecasts of severe weather.

Target area—The region for which cloud seeding operations would normally occur

Targeting—The releasing of artificial cloud seeding material in a manner that allows adequate dispersion of the material, interception of supercooled liquid water droplets, growth of ice crystals, and fallout of augmented precipitation in a specified target

Terminal fall velocity*—The particular falling speed, for any given object (i.e., a raindrop) moving through a fluid of specified physical properties (cloudy air), at which the drag forces and buoyant forces exerted by the fluid on the object (i.e., a raindrop) just equal the gravitational force acting on the object (i.e., a raindrop)

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; it is widely used in operational convective cloud seeding programs.

Trespass—Intended intrusion upon the land or property of another person

Turbulence—Irregular atmospheric motion, especially when characterized by upward and downward currents

USAF—United States Air Force

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, sometimes used in hailstorm research programs, will degrade with prolonged exposure to UV radiation and are either covered with foil or painted.

Wilderness area—Area formally designated by federal statute as one that must be kept in wilderness status

Wind field—The three-dimensional space (i.e., vertical and horizontal) and temporal values of wind speed and wind direction over a surface on the Earth

Wing-tip generator—Cloud seeding generators mounted at or near the tips of aircraft wings.

WMA—Weather Modification Association, P.O. Box 845, Riverton, Utah 84065 (http://www.weathermodification.org)

WMO—World Meteorological Organization, 7 bis Avenue de la Paix, CP 2300-1211, Geneva 2 - Switzerland (http://www.wmo.ch/index-en.html)

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

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