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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



ENVIRONMENTAL &  
WATER RESOURCES  
INSTITUTE

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Sponsored by the  
Atmospheric Water Management Standards Committee of  
the Standards Development Council of the  
Environmental and Water Resources Institute of the  
American Society of Civil Engineers

**ASCE** AMERICAN SOCIETY  
OF CIVIL ENGINEERS



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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 exists 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 Antarctic 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<sup>1</sup>; and  
Conrad G. Keyes Jr., Sc.D., P.E., D.WRE, Dist.M.ASCE<sup>2</sup>*

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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