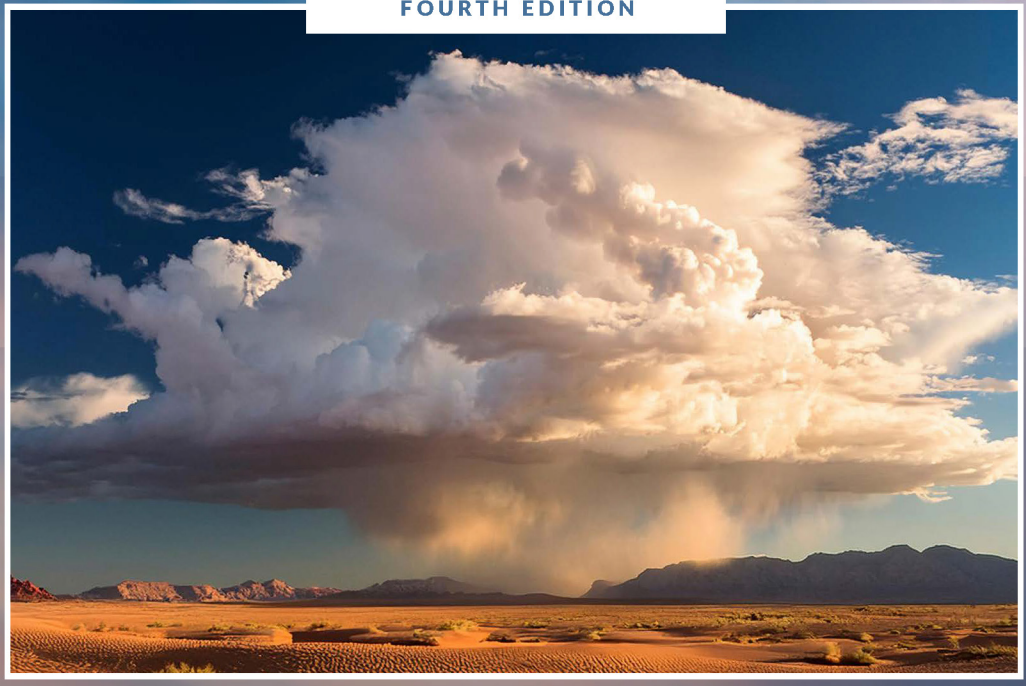
ASCE MANUALS AND REPORTS ON ENGINEERING PRACTICE NO. 81

GUIDELINES FOR CLOUD SEEDING TO AUGMENT PRECIPITATION

FOURTH EDITION



Edited by

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ASCE

EWRI ASCE ENVIRONMENTAL & WATER RESOURCES INSTITUTE

Guidelines for Cloud Seeding to Augment Precipitation

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Guidelines for Cloud Seeding to Augment Precipitation

Fourth Edition

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Sponsored by the
MOP 81 (4th Ed.) Task Committee 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 manual 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 https://ascelibrary.org/topic/ascebookseries/b-mop.

DEDICATION

This manual is dedicated, posthumously, to the following coauthors of the March 1983 guidelines (ASCE Journal of Irrigation & Drainage Engineering), in 1995 (ASCE Manuals and Reports on Engineering Practice {MOP} #81), in 2006 (ASCE/EWRI MOP 81, 2nd Edition), and in 2016 (ASCE/EWRI MOP 81, 3rd Edition) versions. They, and others, made significant contributions, as dedicated volunteers, to the development and publication of the guidelines.

Prof. Ray Jay Davis was an academician throughout his 45-year legal career, which 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 the chair for a mammoth 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 served as the chair, a member, a principal investigator, or an adviser to innumerable committees to governmental agencies of states and the federal government. Ray authored the draft *Model State Water Allocation Code* and the textbook *Law in Action: American Government*. He represented the United States at the United Nations Conference on International Legal Principles for Weather Modification. 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]). He served the Weather Modification Association (WMA) as its "legal eagle," earning the organization's Thunderbird Award in 1978. He was also the author of Section 3—Legal Aspects of Weather Modification, ASCE MOP #81 (1995); as well as the initial version of the guidelines for cloud seeding to augment precipitation in March 1983.

Robert "Bob" D. Elliott was a key participant in several landmark weather modification research projects, most notably, the US Bureau of Reclamation's Colorado River Basin Pilot Project and the Sierra Cooperative Pilot Project. He was instrumental in developing computerized targeting models effective in calculating the transport of cloud seeding materials, their interaction with cloud microphysical processes, and the resultant precipitation. In 1961, the American Meteorological Society (AMS) honored Bob with an Award for Outstanding Contributions to the Advance of Applied Meteorology. He was elected Fellow of the AMS, and he was a member of the Society's original Board for Certified Consulting Meteorologists. He served on the Committee on Weather Modification of the ASCE that developed the guidelines for cloud seeding to augment precipitation in the *Journal of Irrigation & Draining Engineering* in March 1983. He provided Section 1—Summary for the guidelines on cloud seeding. Bob was the coauthor of Section 1—Summary in the 1st Edition of ASCE MOP 81 (1995). He helped found the Weather Modification Association (1951) and was the first recipient of the association's prestigious Thunderbird Award in 1973 and later of its Schaefer Award in 1978.

Olin H. Foehner Jr. had a leading role in the planning and design of the Bureau of Reclamation's Sierra Cooperative Pilot Project (SCPP). He later directed the Colorado River Enhanced Snowpack Test (CREST), when the project's Auburn field office was established, and the Sierra Ecology Project was launched with the Forest Service Pacific Southwest Forest and Range Experiment Station. He participated in numerous other collaborative activities in weather modification with California and Nevada, and his dedication to the long-term objectives of the Bureau of Reclamation's SKYWATER contributed to the development of the agency's Division of Atmospheric Water Resources Management. He was the original author of Section 2—Societal, Environmental, and Economic (SEE) Aspects in Weather Modification of ASCE's guidelines for cloud seeding to augment precipitation that was published in March 1983.

Prof. Lewis "Lew" O. Grant was an emeritus professor at Colorado State University (1993 to 1998), where he earlier had helped to establish the institution's Atmospheric Science Department. As an author, or coauthor, of more than 100 publications and/or scientific conference papers, he was honored with the university's Andrew Clark Award for excellence in research. As a Fellow of the AMS, he served on the Society's Cloud Physics, Water Resources, and Weather Modification committees. He also was a member of the National Science Foundation (NSF) Advisory Committee for Atmospheric Science, and he served as president of the Consortium for Atmospheric Resource Development. He earned the WMA's Schaefer Award in 1991, and the US Farm Bureau's conferred on him its "Cloud

Squeezer" Award in 1977. Lew provided some of the initial work in Section 4—The Scientific Basis of the March 1983 journal article of the *Irrigation & Drainage Irrigation* version of the guidelines and he was a coauthor of the same section in ASCE MOP 81 (1995).

Dr. Archie M. Kahan, First Director of the US Bureau of Reclamation's Project SKYWATER. He directed the development of the agency's Division of Atmospheric Water Resources Management. He participated in numerous collaborative activities in weather modification with the Western United States and his dedication toward the long-term objectives of the Bureau of Reclamation's SKYWATER. He used his expertise, gleaned from his role with OPHIR and the earlier involvement with the US Bureau of Reclamation's Project SKYWATER, to coedit ASCE MOP 81 (1995).

Dr. Harold "Harry" D. Orville helped establish the Department of Meteorology at the South Dakota School of Mines and Technology, where he served as department head for 20 years (1974 to 1994). He was eventually named Distinguished Professor Emeritus by the school, for which he also served as interim vice president in 1987 and 1993. A Fellow of the AMS, he was awarded by the Society in 1993 its highest award for service, the Charles Franklin Brooks Award. The WMA honored him with its Thunderbird Award in 1993 and its Schafer Award in 2003. Harry was a coauthor of Section 4—The Scientific Basis, 1st Edition of ASCE MOP 81 in 1995.

Dr. Roger F. Reinking devoted his entire, distinguished career as a scientist specializing in weather modification for the National Oceanic and Atmospheric Administration (NOAA). An avid outdoorsman, he was an accomplished photographer, often focusing on wildflowers and landscapes. He devoted much of his time later in life in advancing causes that promoted global sustainability and clean energy, writing prolifically on these topics to lawmakers and other decision-makers. He was honored with the WMA Thunderbird Award in 1999. Roger was a coauthor of Section 1 (Summary), the lead author of Section 2 (SEE Aspects), and a coauthor of Section 4 (The Scientific Basis) in ASCE MOP (1995).

Donald "Don" Rottner cofounded the OPHIR Corporation, a research and instrumentation company that focused on atmospheric sciences. He used his expertise, gleaned from his role with OPHIR and an earlier involvement with the US Bureau of Reclamation's Project SKYWATER, to coedit ASCE MOP 81 (1995). With the Bureau's Division of Atmospheric Water Resources Management, starting in 1972 as a researcher with USBR Project SKYWATER, Don led the effort to collect data, promote quality control, and archive data produced by a 5-year, multimillion-dollar weather modification research program in southwestern Colorado.

Dr. Paul L. Smith was instrumental in developing the Institute of Atmospheric Sciences (IAS) at the South Dakota School of Mines and Technology (SDSMT) into an internationally recognized research organization. He oversaw the successful deployment of an armored T-28 aircraft in many field-research projects, the nation's only aircraft capable of deliberate penetration of hailstorms. He coauthored numerous statistical and observational analyses of data collected from prestigious research initiatives such as the National Hail Research Experiment (NHRE), the High Plains Cooperative Program (HIPLEX), the North Dakota Cloud Modification Project (NDCMP), and Grossversuch (in Switzerland). Paul helped the National Science Foundation establish its Lower Atmospheric Research Facility, which provided support for observing facilities at universities and the National Center for Atmospheric Research (NCAR). He played a key role in the development of NOAA's Atmospheric Modification Program (AMP). He served on the International Commission on Clouds and Precipitation (1988 to 1996), as well as several National Research Council advisory boards, including the NEXRAD Technical Advisory Committee. Paul was a Fellow of the AMS, which also designated him as its prestigious Remote Sensing Lecturer. The WMA honored him with its Thunderbird Award in 1995. Paul was one of the four final reviewers from the Blue-Ribbon Review Panel of the EWRI Standards Development Council for the 2nd Edition (2006) and the 3rd Edition (2016) of ASCE/EWRI MOP 81.

Dr. Joseph "Joe" A. Warburton, with advanced degrees in physics of the lower atmosphere from the University of Queensland, earned a senior scientist position with the University of Nevada's Desert Research Institute in 1965, in which he later served as president, and served as executive director of the university's Atmospheric Sciences Division. The university awarded Joe the Emeritus Status in 1993. His work in 11 countries and Antarctica led to more than 120 papers published in journals. He was made a Fellow of the Australian Institute of Physics, and awards given him included the Antarctic Service Medal and the WMA Schaefer Award in 1985 and the WMA Thunderbird Award in 2002. He was honored with a landmark in the Antarctic named after him, Warburton Ledge, in the Britannia Range near Mount McClintock. Joe was a coauthor of Section 4—The Scientific Basis and of Section 6—How to Implement a Cloud Seeding Program, 1st Edition of ASCE MOP 81 in 1995.

Dr. William "Bill" L. Woodley began his lengthy career as a key investigator for the Florida Area Cumulus Experiment (FACE), a multifaceted study in the 1970s of the dynamics and microphysical processes of cumulus clouds—and how they are influenced by seeding. He was integrally involved in the establishment of a long-running rain

enhancement endeavor for the King of Thailand. In the 1980s, as chief scientist for Texas' research initiative to invigorate summertime cumulus clouds by seeding them with silver iodide, Bill formulated a conceptual model that served as the foundation for the construction of 12 rain enhancement projects in Texas in the late 1990s. He also developed a method for evaluating short-term, nonrandomized operational cloud seeding projects on a floating-target-area basis, using Next-Generation Radar (NEXRAD) mosaic radar data. He partnered with Hebrew University's Daniel Rosenfeld in exploring the efficacy of finely milled salts, from the Dead Sea, in nudging young thunderstorms in West Texas to produce more rainfall over larger areas. He, and his son Christopher, pioneered the use of videography in describing the practice, and efficacy, of cloud seeding for rain enhancement. The WMA honored him with its Thunderbird Award in 1992 and with its Schaefer Award in 2005. Bill was one of the four individuals who served on the Blue-Ribbon Review Panel of the EWRI Standards Development Council for the 2nd Edition (2006) and the 3rd Edition (2016) of ASCE/EWRI MOP 81.

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PREFACE

Traditional water resource management pertains to making efficient use of available fresh water, treated effluent, desalination of ocean water and brackish water, and reducing loss by way of floods. Minimizing water loss includes augmenting water supply by other means that could include atmospheric water management by cloud seeding.

Some areas of the United States and the world need to increase water supplies. These updated guidelines provide water resource managers and others with information they will need for decision-making regarding the use of cloud seeding to augment water supplies.

This manual incorporates background on the scientific basis and practice of cloud seeding to augment precipitation for both summer and winter clouds. 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. All this is intended to give water resources managers the broad background behind what is involved in utilizing cloud seeding to augment the supply of fresh water.

The American Society of Civil Engineers (ASCE) Weather Modification Committee (1960 to 1985) and the Climate and Weather Change Committee (1985 to 1996) of the ASCE Irrigation & Drainage (IR) Division assembled dedicated experts in the field of weather modification who volunteered a great amount of time to write each edition of this valuable document. The ASCE IR committees are grateful for the contribution made by everyone who has been involved for nearly four decades that has culminated in this edition.

The Fiscal Year (FY) 1982 Weather Modification Committee and the FY 1982 and Executive Committee 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.: Social, Economic, and Environmental Issues in Weather Modification; Ray Jay Davis: Legal Aspects of Weather Modification; Lewis O. Grant: The Scientific Basis; Don A. Griffith: Seeding Modes and Instrumentation; and Conrad G. Keyes Jr.: How to Implement a Cloud Seeding Program).

The original task committee appreciated the extensive technical editing of each section of the manual by the personnel of the 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 to 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 P. DeFelice, and Don A. Griffith; (5) Don A. Griffith; and (6) Bruce A. Boe and Conrad G. Keyes Jr. Most of these individuals had been long-standing members and/or officers of the Weather Modification Association (WMA). The final reviewers from the Blue-Ribbon Panel for the EWRI Standards Development Council included Darin W. Langerud, Paul L. Smith, Mark E. Solak, and William L. Woodley.

The 2016 (third) edition of the manual was produced by those listed within each chapter and such was approved for publication by the Atmospheric Water Management (AWM) Standards Committee (SC). The editors from the 2016 EWRI Revision of Manual 81 Subcommittee were Chief Editor Conrad G. Keyes Jr., and Coeditors George W. Bomar, Thomas P. DeFelice, and Don A. Griffith. The other authors of the chapters were Robert Czys and Bruce Boe (both were lead authors in 2006). The other subcommittee reviewers from the AWM SC and/or the Weather Modification Association were Joseph H. Golden and Maurice D. Roos. The final reviewers of all sections from the Blue-ribbon Panel for the EWRI Standards Development Council were 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 sections before all sections were provided to the Chair of the EWRI Standards Development Council for approval toward publication by ASCE.

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CHAPTER 1
EXECUTIVE SUMMARY

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1.1 INTRODUCTION

Modern cloud seeding technologies can be successfully applied to help resolve community water resource demand–related issues and have been used for more than 70 years. The terms *cloud seeding* and *weather modification* are often used interchangeably. Recent technological and scientific advances have strengthened the impetus for seeking applications of modern cloud seeding technologies that could benefit society, primarily in regions where additional precipitation is viewed as an economic asset. The potential augmentation is in the range of 5% to 15% in winter cloud seeding projects (WMA 2016). Operational cloud seeding projects can be conducted to augment both winter and summer precipitation. Different cloud seeding techniques and seeding agents are often used in winter versus summer projects driven by the prevailing natural precipitation processes in winter versus summer clouds. Historically and currently, a large majority of operational cloud seeding projects being conducted in the United States are winter projects. Cloud seeding technologies are not without limitations, which must be recognized and incorporated into decisions regarding their use. Technology has changed greatly since DeFelice and Keyes (2016). The most significant changes in technology that are beginning to transfer into operations from the very recent past is the use of artificial intelligence/machine learning (AI/ML) techniques in streamlining operational decision support, analysis tools that aid the identification of seedable conditions and support project evaluations (e.g., Xue et al. 2016; Rauber et al. 2019; Tessendorf et al. 2019; Khain et al. 2022).

The GOES East and West satellites now offer higher resolution and operationally available data compared to previous versions, improving