NOAA Technical Memorandum ERL WPL-231

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

THE NOAA FEDERAL/STATE COOPERATIVE PROGRAM IN ATMOSPHERIC MODIFICATION RESEARCH—COLLECTED PUBLICATION TITLES AND ABSTRACTS

Roger F. Reinking (Editor)

Wave Propagation Laboratory
Boulder, Colorado
April 1993

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THE NOAA FEDERAL/STATE COOPERATIVE PROGRAM IN ATMOSPHERIC MODIFICATION RESEARCH— COLLECTED PUBLICATION TITLES AND ABSTRACTS

Roger F. Reinking (ed.)

ABSTRACT

This volume contains the titles and abstracts of technical publications through fiscal year 1992 that are the products of the NOAA Federal/State Cooperative Program in Atmospheric Modification Research. The program is focused on the very interdisciplinary science of purposeful cloud modification for precipitation enhancement and hail suppression, and unintentional modification of clouds and precipitation. The publications serve to record and disseminate the knowledge gained from the research. This collection makes available under one cover the program's reference material to date, for use by those who need or desire to access state-of-the-art information pertaining to this field. The audience includes, for example, water managers, policy makers, scientists, practitioners in the field, and the interested public. Listed are publications on topics including but not limited to

(i) cloud and precipitation processes,
(ii) numerical cloud and atmospheric mesoscale modeling,
(iii) atmospheric and storm monitoring instrumentation and technologies,
(iv) aerosol transport and dispersion in clouds and over complex terrain,
(v) cloud seeding technologies and effects,
(vi) agricultural responses to cloud modification,
(vii) weather economics and societal aspects of cloud modification,
(viii) unintentional weather and climate modification, and
(ix) precipitation and hydrological assessment and forecasting.

ABOUT THE PROGRAM

Purposeful weather modification, in its very broad sense, has many facets that are so common they are often overlooked. In small ways that become large and influential in the collective sense, for comfort and productivity, we have created ideal indoor weather in which to live, work, travel, and entertain ourselves—from that in our homes, shopping malls, automobiles, and domes that cover athletic fields to that in our greenhouses, computer facilities, and space shuttles. Beyond this, we have created improved weather regimes in frost-protected orchards and in irrigated, shaded, and wind-sheltered gardens and farmland; we have created man-made snow for early season skiing (now a major industry) and cool oases with reservoirs and golf courses in the desert, and we power our industry and light our cities with the hydroelectricity developed from runoff. We place a high value on the optimal environment; we always have and always will demand to modify it accordingly. In this context, given many potential benefits, it is as natural for us to want to enhance precipitation or suppress hail by cloud seeding as it is to want to enhance plant growth by fertilizing the soil in our otherwise optimized greenhouses or farmland. Such cloud seeding, and the science behind it, defines purposeful weather modification (or more explicitly, cloud or precipitation modification) in the narrow sense.

Desires and demands to predict and "do something about" the weather in general, and precipitation in particular, have probably existed as long as humanity. Currently, among potential beneficiaries, who are generally quite apart from the scientists who would develop appropriate technologies, an unrelenting demand persists to apply purposeful precipitation modification with whatever knowledge is available. The numerous operational cloud seeding programs around the world attest to this demand. It is driven primarily by our ever-present, ever-growing need for fresh water and only a few alternative means to provide it, and further by a desire to alleviate hail damage to crops in many susceptible, agriculturally significant regions around the globe. The parallel to this is that precipitation is influenced unintentionally by many other anthropogenic activities, with unclear and uncontrolled consequences to our water resources.

To resolve quantitatively the real potential for purposeful precipitation modification and the effects of unintentional modifications to the hydrologic cycle is to offer one meaningful alternative for formulating better plans and means to supply and allocate water resources (*i*) during persistent shortages caused by population growth in water-limited climates, (*ii*) during extreme events, or (*iii*) for stabilization as for optimal crop production where precipitation is normally sufficient but highly variable. We know that cloud seeding acts according to basic scientific principles in simple cloud systems. Understanding when and how cloud seeding works in complex cloud systems, and how well, is important to the policy makers, practitioners, the users and beneficiaries, and those affected indirectly. Understanding the agricultural, economic, societal, and environmental aspects of precipitation changed by any means is important to all concerned with water resources. Precipitation management is the goal. Scientific investigation followed by technology transfer is the fundamental means to achieve that goal. This is what the NOAA Federal/State Cooperative Program in Atmospheric Modification Research (hereafter the NOAA Atmospheric Modification Program, AMP) is all about.

The mission of the NOAA AMP is to support, conduct, and coordinate basic and applied research to understand cloud and precipitation processes and their role in the hydrologic cycle, under natural influences and with purposeful and inadvertent modifications. A recent change of the name of the program from "weather" to "atmospheric" modification better reflects the broad intent of the program.

In 1978, a national Weather Modification Advisory Board ("the Cleveland Committee") carried forward to the Secretary of the U.S. Department of Commerce, and then to the President of the United States, a report defining priorities for national weather modification policies and programs (Cleveland, 1978; Secretary of Commerce, 1979). Among its many findings, the Board resolved that "locally controlled operational projects . . . offer an excellent opportunity for increasing scientific knowledge and technology development . . . Proper design, well-conducted operations, and careful data collection will permit useful evaluation of the effectiveness of selected multi-year operational projects. The resulting scientific gains will be sizable, and most local users, sooner or later, will appreciate federally sponsored scientific evaluation of the operational projects locally supported." This resolution served as a charter for the NOAA AMP. With funding for research administered by NOAA, atmospheric and water resources agencies in North Dakota and Utah joined to establish the program in FY 1979. Nevada joined in FY 1983, followed by Illinois in FY 1984, Arizona in FY 1990, and Texas in FY 1993. Each of these states finances operational cloud seeding and corresponding applied research (in some cases jointly with its counties), has passed laws that require investigation of alternative sources of water including precipitation enhancement, and/or has a demonstrated need to know the potentials and effects of changes in rain or hail on crops and related economics. Each has an atmospheric or water resources research institute or agency where it is recognized that investigation of cloud seeding or unintentional weather and climate modification offers potential benefits to the state, the region, and the nation.

In the same era as the "Cleveland report," purely statistical evaluations of cloud seeding effects with often disappointingly unclear results were gradually abandoned in favor of "back to basics" research to better understand the multiscale meteorology and physics of cloud and precipitation processes with and without the influence of seeding. Research in the area of agricultural and economic impacts of changes in precipitation also began to achieve greater depth and broader significance. The research in the NOAA AMP reflected this shift.

In the last decade, weather science has witnessed massive advances in computing power, remote sensing and airborne technologies for atmospheric measurement, multiscale numerical atmospheric and cloud models, air motion tracer technologies, chemical means to evaluate cloud processes and seeding effects, techniques to determine directly the influence of precipitation changes on soil moisture and crop growth, and complex agroeconometric models. Thus, our measurements and numerical simulations of atmospheric water substance, cloud system processes, and causes and impacts of changes in precipitation have been taken to levels only fantasized a decade or two ago. The NOAA AMP has shared substantially in this trend, and indeed set the pace for a significant part of it. Our accomplishments and fundamental scientific understanding, pertinent to the NOAA AMP mission, have increased accordingly, and dramatically, a tribute most of all to the small but diligent community of participating scientists, and to the continuity of their financial support as mustered by their managers in the participating States and administered through NOAA. Collaboration of scientists with support from other Federal and State agencies occurred in many instances in the NOAA AMP projects; those contributing scientists, their published results, and their funding agencies are heartily acknowledged.

Ms. Karen Martin deserves very special recognition; she patiently and professionally assembled this volume from my collage of tedious input, and the task and her effort were indeed monumental. Merlin Williams is to be congratulated for creating the NOAA AMP; he was its first manager. William Woodley preceded me in the management role, and his thrust helped to enhance the science in the program. I deeply appreciate the wisdom of Vernon Derr, Robert Mahler, William Hooke, Steve Clifford, and Robert Kropfli of NOAA, all of whom effectively steered me through difficult times and cheered with me in good times during my tenure as program manager. And it is the principal investigators in the participating states, Stanley Changnon, Joseph Warburton, Bruce Boe, Barry Saunders, Dennis Sundie, Paul Summers, and Lynn Rose, and their staffs and consortiums of scientists who have made me proud to put my name on this volume.

To date, more than 200 researchers have contributed by reporting their results in some 400 publications. The knowledge we have gained and published is available to whomever will accept it, as listed in these collected publication titles and abstracts from the NOAA Federal/State Cooperative Program in Atmospheric Modification Research.

Dr. Roger F. Reinking
Director
Atmospheric Modification Program
FY 1983-FY 1992

HOW TO USE THIS VOLUME

Literature produced from research funded totally or in part by the NOAA AMP is listed. Primarily the period from FY 1983 to FY 1992 is represented, but many earlier reports to or generated within the NOAA Weather Modification Program Office that existed before FY 1983 are included for preservation of the record. In all, most publications since the FY 1979 inception of the NOAA AMP are included. Collaborative publications resulting entirely from other-agency support are equally important, but it was not possible to collect and include them here. Omissions are inevitable but not intentional.

The listings are alphabetical by primary author, with most recent publications by each primary author presented first. Titles only are listed for unreviewed publications and reports. Abstracts, when available, are added for those publications that appeared in the formal, peer-reviewed literature. To assist those unfamiliar with scientific journal titles and technical nomenclature, the reference material has not been abbreviated. An author index is included for convenience in locating works by non-primary authors, as well as the primary ones. Final project reports to NOAA AMP have been filed with the National Technical Information Service (NTIS), as indicated in the specific listings. The journals are generally available in technical libraries. Other publications are available from the publishers or the authors. The NOAA AMP is currently managed by Dr. Joseph H. Golden, Office of Oceanic and Atmospheric Research, National Oceanic and Atmospheric Administration, SSMC1, 1335 E-W Highway, Silver Spring, MD 20910 USA. Further information may be obtained from his office.

AUTHOR INDEX

THE COLLECTED PUBLICATION TITLES AND ABSTRACTS

Achtemeier, G. L., S. A. Changnon, G. L. Dzurisin, A. R. Jameson, D. B. Johnson, P. Kennedy, and R. C. Semonin, 1983: Pre-experimental studies during 1980-1982 for Precipitation Augmentation for Crops Experiment. Final Report, NOAA Contract NA80RAC00072. Illinois State Water Survey, Champaign, IL, 480 pp.

No abstract.

Achtemeier, G. L., S. A. Changnon, G. L. Dzurisin, A. R. Jameson, D. B. Johnson, and R. C. Semonin, 1980: Precipitation Augmentation for Crops Experiment (PACE)—Pre-experiment studies. Final Report, NOAA Contract NA79RAC0114. Illinois State Water Survey, Champaign, IL, 121 pp.

No abstract.

Ackerman, B., and N. E. Westcott, 1986: Midwestern convective clouds; A review. *Journal of Weather Modification*, 18:87-94.

Studies of Midwestern convective clouds and precipitation spanning some 40 years have contributed information addressing many aspects of weather modification experimentation and operation. In this paper, we have focused on the studies which provide insight into the microphysical and dynamical characteristics of these clouds, with a view toward assessing the state of our current knowledge and providing the information base needed for the development of physical hypotheses for natural and modified cloud behavior and for design of future experimentation.

Ackerman, B., S. A. Changnon, P. Garcia, S. Gould-Stewart, S. E. Hollinger, F. Huff, C.-F. Hsu, A. Jameson, S. Kidder, S. Offutt, M. Pinar, K. Sigh, and N. E. Westcott, 1985: Precipitation Augmentation for Crops Experiment. SWS Report 365, Annual Report to National Oceanic and Atmospheric Administration, May 1984-April 1985. Illinois State Water Survey, Champaign, IL, 171 pp. + appendices (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Ackerman, B., and R.-Y. Sun, 1985: Predictions of two one-dimensional cloud models: A comparison. *Journal of Climate and Applied Meteorology*, 24:617-628.

Two one-dimensional steady-state models of cumulus convection in common use in weather modification research, the NOAA Experimental Meteorology Branch model (EMB) and the Great Plains Cumulus Model (GPCM), differ in their formulations in several ways. Some of the differences arise from the conceptualization of the convective phenomenon which is modeled in each and some from the physical parameterizations utilized. Predictions of cloud top and dynamic modification potential (seedability) by the two models for 57 midday radiosondes in the Midwest, differed significantly, with the EMB values consistently higher. GPCM simulations provided a better overall estimate of observed radar echo tops, while EMB consistently overestimated, by largest amounts when tops were below 12 km. Study of the impact of temporal and/or spatial separation between sounding and cloud area emphasizes the need, in the Midwest, to consider factors other than thermodynamic stratification (e.g., forced lifting, convergence) on the synoptic and mesoscale when applying the model for prediction of cloud development. However, it was also found that the average difference in predictions by the two models, for the same sounding, was of the same order as the average difference in predictions arising from spatial or temporal separation.

Anantharaj, V. G., 1990: An exploratory study of the summertime observations by a dual-wavelength microwave radiometer at Dickinson, North Dakota in 1987. M.S. thesis, Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 116 pp.

No abstract.

Blackmore, W. H., III, 1992: A summary of weather modification activities reported in the United States during 1990. *Journal of Weather Modification*, 24:130-131.

No abstract.

Boatman, J. F., and R. F. Reinking, 1984: Synoptic and mesoscale circulations and precipitation mechanisms in shallow upslope storms over the western high plains. *Monthly Weather Review*, 112:1725-1744.

It is generally believed that synoptically driven storms, with lifting induced or enhanced by upslope flow over the high plains, produce most of the winter precipitation in eastern Colorado. Two extremely different circulations, the fully developed extratropical cyclone and the shallow arctic anticyclone, bound the range of upslope circulations. Two cases involving shallow upslope circulations were studied in detail for this work.

Aircraft, standard synoptic scale, and selected mesoscale data were available for the case studies. The synoptic and (in one case) mesoscale circulations, characteristics of the consequent upslope and overlying midlevel stratiform clouds, and the microphysical processes that generated the precipitation from these events were examined. Dynamically and microphysically, these cases were among the simplest of the varied upslope storm systems. The arctic air masses were about 100 mb in thickness. The troposphere in and above the arctic air was potentially stable in both cases. The upslope clouds resulted from topography-induced upward air motions associated with easterly flow. The easterly flow was caused by horizontal pressure gradients within the anticyclones. In one case, mesoscale analyses revealed that the local topography retarded and diverted the approaching arctic air until it became deep enough to flood the entire area.

The observed upslope cloud layers formed within the cold air mass. The limited available moisture was derived from local sources and the arctic air itself. Water contents were generally ~0.1 g m^{-3} or less in all cloud layers. Some aircraft icing confirmed the presence of the liquid, and water saturation prevailed in the clouds. Heterogeneous nucleation (primary ice generation) was the most likely source for ice particles in both cases. Ice multiplication could be neither confirmed nor denied. Once nucleated, ice crystals grew predominantly by vapor deposition, to produce some crystals with diameters as large as 2 mm. However, aggregational growth was observed in the storm with the warmest cloud temperatures, and accretional growth was possible in the storm with the greatest water contents. Natural seeding of the upslope clouds by ice particles falling from the midlevel clouds occurred in both cases. Survival of the crystals in descent between the cloud layers was strongly regulated by the atmospheric ice saturation ratio. Crystal growth in the clear air occurred in one case, whereas substantial sublimation occurred in the other.

Boe, B. A., 1992: Hail suppression in North Dakota. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 58-62.

No abstract.

Boe, B. A., 1992: Ongoing studies of convective storms in North Dakota, and analyses of the data set collected during the North Dakota Thunderstorm Project. Final Report, NOAA Cooperative Agreement NA90AAH0A176. North Dakota Atmospheric Resource Board, Bismark, ND, 21 pp. + appendices and project bibliography (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Boe, B. A., J. L. Stith, P. L. Smith, J. H. Hirsch, J. H. Helsdon, Jr., A. G. Detwiler, H. D. Orville, B. E. Martner, R. F. Reinking, R. J. Meitín, and R. A. Brown, 1992: The North Dakota Thunderstorm Project: A cooperative study of High Plains thunderstorms. *Bulletin of the American Meteorological Society*, 73:145-160.

The North Dakota Thunderstorm Project was conducted in the Bismarck, North Dakota, area from 12 June through 22 July 1989. The project deployed Doppler radars, cloud physics aircraft, and supporting instrumentation to study a variety of aspects of convective clouds. These included transport and dispersion; entrainment; cloud-ice initiation and evolution; storm structure, dynamics, and kinematics; atmospheric chemistry; and electrification.

Of primary interest were tracer experiments that identified and tracked specific regions within evolving clouds as a means of investigating the transport, dispersion, and activation of ice-nucleating agents as well as studying basic transport and entrainment processes. Tracers included sulfur hexafluoride (SF_6), carbon monoxide, ozone, radar chaff, and silver iodide.

Doppler radars were used to perform studies of all scales of convection, from first-echo cases to a mesoscale convective system. An especially interesting dual-Doppler study of two splitting thunderstorms has resulted.

The objectives of the various project experiments and the specific facilities employed are described. Project highlights and some preliminary results are also presented.

Boe, B. A., 1991: The North Dakota Thunderstorm Project, a final report. NOAA Cooperative Agreement NA89RAH09088. North Dakota Atmospheric Resource Board, Bismark, ND, 28 pp. + appendices (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Boe, B. A., and H. L. Johnson, 1990: Destabilization antecedent to a tornadic northern High Plains mesoscale convective system: A case study. Preprints, 16th Conference on Severe Local Storms, Kananaskis Provincial Park, Alberta, Canada, October 22-26, 1990. American Meteorological Society, Boston, MA, 538-541.

No abstract.

Boe, B. A., and J. A. Jung, 1990: 1988 Final Report (on convective cloud/cloud physics research). NOAA Cooperative Agreement NA88RAH08115. North Dakota Atmospheric Resource Board, Bismark, ND, 27 pp. + appendices (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Boe, B. A., and J. A. Jung, 1990: 1985 Final Report (on convective cloud/cloud physics research). NOAA Cooperative Agreement NA85RAH05084. North Dakota Atmospheric Resource Board, Bismark, ND, 22 pp. + appendix (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Boe, B. A., and J. A. Jung, 1990: The application of geostationary satellite imagery for decision-making in convective cloud seeding in North Dakota. *Journal of Weather Modification*, 22:73-78.

A McIDAS (Man-computer Interactive Data Access System) workstation was employed to monitor the development, movement, and eventual decay of convective clouds over target areas totalling 366,000 km^2 in western North Dakota. Information relevant to cloud seeding strategies for both rainfall enhancement and hail suppression was relayed to the field meteorologists at their radar sites in near real-time, where the operational decisions were made. Both the utility and the timeliness of the information were evaluated. Shortcomings are also discussed.

Boe, B. A., 1989: 1986 Final Report (on transport and diffusion experiments in cumulus clouds). NOAA Cooperative Agreement NA86RAH06058. North Dakota Atmospheric Resource Board, Bismark, ND, 29 pp. + appendices (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Boe, B. A., and J. A. Jung, 1989: 1987 Final Report (on convective cloud/cloud physics research). NOAA Cooperative Agreement NA87RAH07088. North Dakota Atmospheric Resource Board, Bismark, ND, 21 pp. + appendices (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Boe, B. A., P. L. Smith, H. D. Orville, N. C. Knight, M. Hjelmfelt, D. A. Griffith, J. L. Stith, and R. F. Reinking, 1989: North Dakota Thunderstorm Project Field Operations Plan. North Dakota Atmospheric Resource Board, Bismark, ND, 75 pp.

No abstract.

Boe, B. A., R. L. Rose, and M. L. Schultz, 1988: The North Dakota Atmospheric Resource Program. Preprints, Conference on Irrigation and Drainage, Lincoln, NE. American Society of Civil Engineers, New York, 5 pp.

No abstract.

Brown, K. J., 1984: The role of operational weather modification in a developing science. Extended Abstracts, 9th Conference on Weather Modification, Park City, UT, May 21-23, 1984. American Meteorological Society, Boston, MA, 43-44.

No abstract.

Bruintjes, R. T., T. L. Clark, and W. D. Hall, 1992: Comparisons between observations and numerical simulations of a winter storm episode over complex terrain. Proceedings, 11th International Conference on Clouds and Precipitation, Montreal, Canada, August 17-21, 1992. International Commission on Clouds and Precipitation, International Association of Meteorology and Atmospheric Physics, Innsbruck, Austria, 467-470.

No abstract.

Bruintjes, R. T., T. L. Clark, W. D. Hall, and R. Gall, 1992: The use of sophisticated three-dimensional numerical models in water orographic weather modification efforts. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 121-125.

No abstract.

Bruintjes, R. T., G. K. Mather, and D. E. Terblanche, 1992: Additional evidence of increases in precipitation due to cloud seeding of summertime convective clouds over South Africa. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 115-120.

No abstract.

Bruintjes, R. T., R. Gall, and T. L. Clark, 1991: The evolution of the flow field and cloud structures over complex terrain during a winterstorm episode. Extended Abstracts, Symposium on Lower Tropospheric Profiling: Needs and Technologies, Boulder, CO, September 10-13, 1991. American Meteorological Society, Boston, MA, 29-30.

No abstract.

Bruintjes, R. T., R. Gall, T. L. Clark, and W. D. Hall, 1991: Comparisons between modeling and observations of precipitation over mountainous terrain in Arizona. Abstracts, IAMAP Symposium M9, Vienna, Austria, August 11-24, 1991. International Union of Geodesy and Geophysics, Brussels, Belgium, 168.

No abstract.

Campistron, B., A. W. Huggins, and A. B. Long, 1991: Investigations of a winter mountain storm in Utah. Part III: Single-Doppler radar measurements of turbulence. *Journal of the Atmospheric Sciences*, 48:1306-1318.

This Part III of a multipart paper deals with the analysis of turbulent motion in a winter storm, which occurred over the mountains of southwest Utah. The storm was documented with a long duration single Doppler radar data set (~21 h) comprised of volume scan observations acquired at 10-min intervals. Turbulence parameters were determined using a new technique of volume processing of single Doppler radar data.

Physical analysis of turbulence is restricted to three particular storm regions: a prefrontal region far removed from a cold frontal discontinuity, a frontal zone aloft, and a low layer in the post-frontal region where a long lasting (~6 h) wind-maximum existed. The prefrontal period showed enhancement of turbulent parameters near 2.6 km height, apparently due to disturbed flow caused by an upwind

mountain range. Turbulence parameters in this prefrontal region showed good agreement with *K*-mixing length theory. Within the frontal zone, most turbulence parameters reached peak values, but were generally less than orographically induced turbulence values in the prefrontal period.

Turbulence in the low-level postfrontal period experienced periodic oscillations consistent with precipitation and kinematic variables described in Parts I and II, and associated with mesoscale precipitation bands. Acceleration of the valley-parallel wind component was apparent in prefrontal and postfrontal periods and was related to the specific valley configuration through a Venturi effect.

Campistron, B., A. B. Long, and A. W. Huggins, 1991: A method of retrieving turbulence parameters from volume processing of single-Doppler radar measurements. *Journal of Atmospheric and Oceanic Technology,* 8:491-505.

In previous work, the derivation of turbulence parameters from single-Doppler radar observations was performed with data acquired along a horizontal circle. Here the technique is extended to all the radar data within a horizontal cylindrical slice of finite depth using the same basic assumptions of linearity of the mean wind field and horizontal homogeneity of the turbulence. The method allows the extraction of the six Reynolds stress components, together with their vertical derivatives, and the turbulent fluxes of a scalar quantity deduced from the reflectivity data.

Experimental data were used for the performance evaluation of the methodology. A simple testing procedure was carried out to remove erroneous results. The statistical uncertainty in the measured Reynolds stress terms was found to be about 0.05 m^2 s^{-2}, except for the variance of the vertical component, which was poorly retrieved because of an absence of data at high elevation angles. Calculations showed that contamination of the vertical momentum flux measurements by the scatterer fall speed was negligible. An analysis of the response function of the technique to the atmospheric scales tended to show that the diameter of the processing slices corresponded to the largest turbulent scale dimension involved in the measured turbulence quantities.

Chai, S., W. G. Finnegan, R. L. Pitter, and J. A. Warburton, 1989: A mechanistic interpretation of a winter orographic cloud seeding program. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:179-183.

No abstract.

Changnon, S. A., 1992: Are we doomed to fail in drought management? Proceedings, National Forum on Water Management Policy. American Water Resources Association, Reston, VA, 1-17.

No abstract.

Changnon, S. A., 1992: Inadvertent weather modification: Its status and relevance to global climate change. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 63-69.

No abstract.

Changnon, S. A., 1992: Inadvertent weather modification in urban areas: Lessons for global climate change. *Bulletin of the American Meteorological Society*, 73:619-627.

Large metropolitan areas in North America, home to 65% of the nation's population, have created major changes in their climates over the past 150 years. The rate and amount of the urban climate change approximate those being predicted globally using climate models. Knowledge of urban weather and climate modification holds lessons for the global climate change issue. First, adjustments to urban climate changes can provide guidance for adjusting to global change. A second lesson relates to the difficulty but underscores the necessity of providing scientifically credible proof of change within the noise of natural climatic variability. The evolution of understanding about how urban conditions influence weather reveals several unexpected outcomes, particularly relating to precipitation changes. These suggest that similar future surprises can be expected in a changed global climate, a third lesson. In-depth studies of how urban climate changes affected the hydrologic cycle, the regional economy, and human activities were difficult because of data problems, lack of impact methodology, and necessity for multidisciplinary investigations. Similar impact studies for global climate change will require diverse scientific talents and funding commitments adequate to measure the complexity of impacts and human adjustments. Understanding the processes whereby urban areas and other human activities have altered the atmosphere and changed clouds and precipitation regionally appears highly relevant to the global climate-change issue. Scientific and governmental policy development needs to recognize an old axiom that became evident in the studies of inadvertent urban and regional climate change and their behavioral implications: Think globally but act locally. Global climate change is an international issue, and the atmosphere must be treated globally. But the impacts and the will to act and adjust will occur regionally.

Changnon, S. A., 1992: Where does weather modification fit within the atmospheric sciences? *Journal of Weather Modification*, 24:118-121.

No abstract.

Changnon, S. A., A. M. Carleton, D. J. Travis, H. D. Orville, W. H. Lambright, W. L. Woodley, J. Augustine, and R. Scott, 1992: Precipitation-Cloud Changes and Impacts Program (PreCCIP). Part 1: Overview, special study reports and project publications. Annual Report, NOAA Cooperative Agreement NA90AAH0A175. Illinois State Water Survey, Champaign, IL, 15 pp. + appendices (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Changnon, S. A., and colleagues, 1992: Precipitation-Cloud Changes and Impacts Program (PreCCIP), 1989-1991 selected reprint collection. Illinois State Water Survey, Champaign, IL.

No abstract.

Changnon, S. A., and R. R. Czys, 1992: Results from the 1989 cloud seeding experiment in Illinois. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 74-79.

No abstract.

Changnon, S. A., 1991: Cloud and precipitation development related to the St. Louis precipitation anomaly. SWS Contract Report 532, NOAA Cooperative Agreements NA90AAH0A175 and NA27RA017301. Illinois State Water Survey, Champaign, IL, 28 pp.

No abstract.

Changnon, S. A., 1991: The dilemma of climatic and hydrologic forecasting for the Great Lakes. Proceedings, Symposium of the Great Lakes Water Level Forecasting and Statistics, Windsor, Ontario, May 16-17, 1991. Great Lakes Commission and NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 13-25.

No abstract.

Changnon, S. A., R. R. Czys, S. E. Hollinger, F. A. Huff, K. E. Kunkel, M. S. Petersen, R. W. Scott, D. W. Staggs, and N. E. Westcott, 1991: Analysis and planning for Precipitation Augmentation for Crops Experiment. Annual Report, NOAA Cooperative Agreement NA90AAHOA175. Illinois State Water Survey, Champaign, IL, 122 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Changnon, S. A., R. R. Czys, R. W. Scott, and N. E. Westcott, 1991: Illinois precipitation research: A focus on cloud and precipitation modification. *Bulletin of the American Meteorological Society*, 72:587-604.

At the heart of the 40-year atmospheric research endeavors of the Illinois State Water Survey have been studies to understand precipitation processes in order to learn how precipitation is modified purposefully and accidentally, and to measure the physical and socioeconomic consequences of cloud and precipitation modification. Major field and laboratory activities of past years are briefly treated as a basis for describing the key findings of the past ten years. Recent studies of inadvertent and purposeful cloud and rain modification and their effects are emphasized, including a 1989 field project conducted in Illinois and key findings from an ongoing exploratory experiment addressing cloud and rain modification. Results are encouraging for the use of dynamic seeding on summer cumuliform clouds of the Midwest.

Typical in-cloud results at -10°C reveal multiple updrafts that tend to be filled with large amounts of supercooled drizzle and raindrops. Natural ice production is vigorous, and initial concentrations are larger than expected from ice nuclei. However, natural ice production is not so vigorous as to preclude opportunities for seeding. Radar-based studies of such clouds reveal that their echo cores usually can be identified prior to desired seeding times, which is significant for the evaluation of their behavior. Cell characteristics show considerable variance under different types of meteorological conditions. Analysis of cell mergers reveals that under conditions of weak vertical shear, mid-level intercell flow at 4 km occurs as the reflectivity bridge between cells rapidly intensifies. The degree of intensification of single-echo cores after they merge is strongly related to the age and vigor of the cores before they join. Hence, cloud growth may be enhanced if seeding can encourage echo cores to merge at critical times. Forecasting research has developed a technique for objectively distinguishing between operational seeding and nonoperational days and for objectively predicting maximum cloud-top height and seeding suitability. An accuracy rate of up to 60% in predicting maximum echo-top height using four categories has been achieved and suggests its use as a covariate in future experimentation. Impact studies illustrate that sizable summer rain increases would be necessary to produce economically beneficial outcomes for Corn Belt agriculture. Increases of ≥25% in July rainfall across certain high-production crop districts of the Corn Belt would produce economic effects realized nationally.

Changnon, S. A., R. T. Shealy, and R. W. Scott, 1991: Precipitation changes in fall, winter, and spring caused by St. Louis. *Journal of Applied Meteorology*, 30:126-134.

Analysis of precipitation events in the St. Louis area, based on pre-event low-level wind flow, was pursued to ascertain the presence of urban effects on fall, winter, and spring precipitation. Data from a circular, dense raingauge network were used to define quadrant (NW, NE, SE, SW) average precipitation. Winds before each event (443 events in 1971-75) were used to define the urban plume and identify which quadrant was "downwind" of the city. Results for fall revealed a 17% increase in precipitation downwind of St. Louis and a 13% increase in events with their peak rainfall occurring downwind; both outcomes were statistically significant at the 1% level. The downwind enhancement was greatest when pre-event winds were from the SE, and when average precipitation in the quadrant with the maximum value was either light (<5.1 mm) or quite heavy (>17.9 mm). The fall results agree well with earlier findings for summer rainfall that revealed a 25% increase due to enhancement in isolated airmass showers and during heavier, well-organized convective systems. Winter precipitation indicated little precipitation change downwind of St. Louis. However, when SW pre-event winds existed (a flow often associated with convection), there was a statistically significant downwind increase in winter precipitation; but when pre-event winds were from SE or NW (flows frequently associated with stratiform precipitation), downwind decreases occurred. The number of spring precipitation conditions that maximized downwind of St. Louis was significantly greater than expected by chance particularly in light (<5.1 mm) events, but the total spring rainfall downwind increased only 4%. There was no suggestion of decreased precipitation in spring or fall. The urban influences to enhance precipitation appeared to be related to precipitation conditions with convective processes, and urban influences in more stratiform precipitation situations were negligible.

Changnon, S. A., 1990: Great Lakes waters: Too little or too much? In: *Supplying Water and Saving the Environment for Six Billion People*, EE Division/ASCE. American Society of Civil Engineers, New York, 41-49.

Water supplies in the Great Lakes Basin, the world's largest fresh water supply, are more than adequate to meet current and projected needs. However, supplies could become a problem if the climate changes or water quality seriously degrades. The principal water quantity problem of the Great Lakes is the fluctuations in lake levels, providing too much or too little water. Society around the lakes has become extremely sensitive to these aberrations around average levels, one of the major lessons learned in recent years. Recent basin-wide problems like water quality, fluctuating levels, and acid rain reveal a need for new policies and institutional approaches to the management of the Great Lakes. Lake-level forecasts are not sufficiently accurate or long-term to allow for wise management decisions. Continuing degradation of water quality or a major climatic change during the next few decades could seriously reduce net basin supplies and create serious water supply problems.

Changnon, S. A., 1990: Impacts and some lessons taught by the 1988 drought. Planning for water shortages. Proceedings, Irrigation and Drainage Division, 1989 Meeting of the ASCE, St. Louis, MO, October 15-16, 1990. American Society of Civil Engineers, New York, 263-270.

No abstract.

Changnon, S. A., R. R. Czys, S. E. Hollinger, F. A. Huff, M. S. Petersen, R. W. Scott, and N. E. Westcott, 1990: Analysis and planning for Precipitation Augmentation for Crops Experiment. Final Report, NOAA Cooperative Agreement NA89RAH0986. Illinois State Water Survey, Champaign, IL, 110 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Changnon, S. A., and S. E. Hollinger, 1990: Crop yield results from simulated rain applications to agricultural plots in Illinois. *Journal of Weather Modification*, 22:58-62.

Ten different levels of rainfall were applied (during 1987, 1988, and 1989) to agricultural plots in central Illinois to discern effects on corn and soybean yields. Increases in rainfall during a hot dry summer (June-August 1988) revealed sizable yield gains. For one inch of added rainfall, the yields increased 10 bu/acre for corn and 4 bu/acre for soybeans. In a summer of near average rain (1989), the increases were less, about 5 bu/acre for corn and 3 bu/acre for soybeans. When summer rainfall exceeded 14 inches, yields of both crops were decreased. The various rainfall tests revealed that rain increases done only on days when natural rainfall was $\leq$0.1 inch provided no detectable yield increases, whereas a 40% increase on all rain days (the largest increase tested) produced the greatest crop yield increase (up to the 14-inch optimum). Corn yields reacted very favorably to added rains on days with $\geq$1.0 inch of rain.

Changnon, S. A., and W. H. Lambright, 1990: Response. *Bulletin of the American Meteorological Society*, 71:1758-1759.

No abstract.

Changnon, S. A., S. E. Hollinger, and P. Garcia, 1989: Analyzing the effects of additional rainfall on corn and soybean yields. Preprints, 6th Conference on Applied Climatology, Charleston, SC, March 7-10, 1989. American Meteorological Society, Boston, MA, J41-J45.

No abstract.

Changnon, S. A., 1988: Climate-based representations of summer rainfall in Illinois. *Journal of Climate*, 1:1041-1046.

Historical (1901-1985) summer (June-August) rainfall data in central Illinois were used to construct three typical rain conditions: one representing the typical dry summer (based on the driest 20% of the summers of the past 85 years), a typical wet summer (from the 20% wettest), and the near-average summer rainfall conditions (the 20% nearest the long-term average). Monthly rain totals for each type were established first, then daily rain frequencies were used to define all individual rain day amounts, and historical rain-day amounts by date were used to assign rain days to dates throughout the three types of summers. In-day conditions relating to rainfall rates, time of rain, and durations were constructed for each day of rain. The resulting three summer rainfall conditions are being used to guide applications of water onto agricultural test plots (protected from natural rains) to measure crop yield effects from weather modification but the approach and system could serve other applications like effects of climate change.

Changnon, S. A., R. R. Czys, S. E. Hollinger, F. A. Huff, J. Nespor, R. W. Scott, and N. E. Westcott, 1988: The Precipitation Augmentation for Crops Experiment. Phase II. Final Report, NOAA Cooperative Agreement NA87RAH07077. Illinois State Water Survey, Champaign, IL, 82 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Changnon, S. A., and S. Hollinger, 1988: Use of unique field facilities to simulate effects of enhanced rainfall on crop production. *Journal of Weather Modification*, 20:60-66.

In the spring of 1987, recently constructed "rain shelters" became available in which field experiments of rain effects on crops could be conducted. Some shelters were designed to be moved over the test plot area during a rain event to exclude natural rain. When there was no precipitation falling, the shelters could be moved off the plots so the plants experienced the same weather as other crops in the region. An overhead sprinkler irrigation system was installed in the shelters so the time, amount, and quality of water applied to each plot could be controlled. This system allowed for the establishment of an experimental design to begin to test the validity of the crop-weather model results in an actual field situation. This paper addresses the 1987 field experiment, the facility, the rain models used, and the yield results.

Changnon, S. A., F. A. Huff, and C.-F. Hsu, 1988: Relations between precipitation and shallow groundwater in Illinois. *Journal of Climate*, 1:1239-1250.

The statistical relationships between monthly precipitation (P) and shallow groundwater levels (GW) in 20 wells scattered across Illinois with data for 1960-84 were defined using autoregressive integrated moving average (ARIMA) modeling. A lag of one month between P to GW was the strongest temporal relationship found across Illinois, followed by no (0) lag in the northern two-thirds of Illinois where mollisols predominate, and a lag of two months in the alfisols of southern Illinois. Spatial comparison of the 20 P-GW correlations with several physical conditions (aquifer types, soils, and physiography) revealed that the parent soil materials of outwash alluvium, glacial till, thick loess (≥2.1 m), and thin loess (>2.1) best defined regional relationships for drought assessment.

Equations developed from ARIMA using 1960-79 data for each region were used to estimate GW levels during the 1980-81 drought, and estimates averaged between 25 to 45 cm of actual levels. These estimates are considered adequate to allow a useful assessment of drought onset, severity, and termination in other parts of the state. The techniques and equations should be transferrable to regions of comparable soils and climate.

Changnon, S. A., D. Brunkow, R. R. Czys, A. Durgunoglu, P. Garcia, S. E. Hollinger, F. A. Huff, H. T. Ochs, R. W. Scott, and N. E. Westcott, 1987: Precipitation Augmentation for Crops Experiment: Phase II. Exploratory research, year 1. Final Report, NOAA Grant NA86RAH05060, Contract Report 430. Illinois State Water Survey, Champaign, IL, 195 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Changnon, S. A., and F. A. Huff, 1987: Design of the 1986 Illinois weather modification experiment. *Journal of Weather Modification*, 19:77-81.

A summary of the design aspects of the 1986 PACE field project is presented. A review of the experimental background, overall objectives, the 1986 objectives, and an assessment of the 1986 field effort and design is provided. In general, the design proved satisfactory, although a few modest adjustments were needed to overcome certain unforeseen sampling problems.

Changnon, S. A., and W. H. Lambright, 1987: The rise and fall of federal weather modification policy. *Journal of Weather Modification*, 19:1-12.

Three hundred million dollars in federal funds have been expended since 1960 to conduct research and to develop weather modification capabilities. This has resulted in techniques to operationally eliminate fogs, to reduce or enhance stratus clouds, and to increase snowfall and rainfall during certain conditions. But, the annual research and development funding has been halved since 1978, and the general public, many scientists, and most government decision makers now believe, rightly or wrongly, that major scientific uncertainties and policy problems exist in the field. Rather than serving as spurs to heightened federal efforts, these beliefs have had a dampening effect. Support for the field is decreasing and weather modification research and development is in trouble.

Changnon, S. A., 1986: A perspective on weather modification evaluation. *Journal of Weather Modification*, 18:1-7.

Evaluation of outcomes of weather modification has been a necessity and an evolving process. Early efforts were largely based on statistical techniques of surface weather variables, but over the past 20 years, use of physical processes assessment has grown. Great progress has been made in learning how to effectively use physical and statistical approaches for the assessment of weather modification, both operational and experimental efforts.

Changnon, S. A., 1986: Illinois Weather Modification Program: PACE. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 315-319.

No abstract.

Changnon, S. A., B. Ackerman, A. Durgunoglu, R. Gabriel, A. Gagin, P. Garcia, C.-F. Hsu, F. A. Huff, S. Kidder, H. V. Knapp, E. A. Mueller, H. T. Ochs, M. Pinar, and D. Rosenfeld, 1986: Precipitation Augmentation for Crops Experiment: Pre-experimental phase studies. Final Report, NOAA Cooperative Agreement NA85RAH05060. Illinois State Water Survey, Champaign, IL, 319 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Changnon, S. A., 1985: Progress on PACE. Spring Meeting, Weather Modification Association, Monterey, CA, 6 pp.

No abstract.

Changnon, S. A., 1985: The evaluation of weather modification. Proceedings, International Conference of WMA-ANALFA, Clermont-Ferrand, France, 10 pp.

No abstract.

Changnon, S. A., 1985: The weather and climate of Illinois. *Illinois Research*, 27:3-5.

No abstract.

Changnon, S. A., 1979: An assessment of the socio-economic and environmental aspects of weather modification. *World Meteorological Organization Report*, No. 13, Precipitation Enhancement Project, Geneva, Switzerland, 122-135.

No abstract.

Changnon, S. A., and F. A. Huff, 1979: Review of societal, environmental, and legal aspects of precipitation modification in Illinois. Report, NOAA Contract 03-78-B01-89. Illinois State Water Survey, Champaign, IL, 79 pp.

No abstract.

Chou, H.-Y., 1991: Doppler radar analysis of the 17 July 1989 squall line in North Dakota. M.S. thesis, Department of Meteorology, South Dakota School of Mines & Technology, Rapid City, SD, 88 pp.

No abstract.

Cleveland, H. (Chairman, The Weather Modification Advisory Board), 1978: *The Management of Weather Resources*. Vol. 1. Proposals for a national policy and program. Supt. of Doc; US-GPO, Washington, DC (003-018-00090-3), 229 pp.

No abstract.

Cotton, W. R., E. E. Hindman, G. J. Tripoli, and P. A. Walsh, 1983: Numerical simulation and observational analysis of the dynamic response of towering cumuli to massive seeding. Final Report, NOAA Grant NA81RAH00001. Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 365 pp.

No abstract.

Czys, R. R., and R. W. Scott, 1993: A simple objective method used to forecast convective activity during the 1989 PACE cloud seeding experiment. *Journal of Applied Meteorology*, 32 (accepted).

A simple objective procedure used exploratively to forecast the occurrence, height, and coalescence activity of summertime convective clouds in Illinois during the cloud seeding trials of the 1989 Precipitation Augmentation for Crops Experiment is described. The method used the temperature of the convective condensation level (T_{CCL}) and potential buoyancy (PB) at 500 mb, easily determined from morning National Weather Service sounding data, to forecast afternoon convection. Maximum echo top heights were found to group according to T_{CCL} and PB. The physical basis of T_{CCL} and PB to implicitly represent a period of time for coalescence to produce supercooled drizzle and rain drops is discussed. The technique performed well at forecasting the occurrence and height of afternoon convective clouds. Aircraft measurements of supercooled rain drop concentrations showed that a discriminator function, dependent only on T_{CCL} and PB, gave a good indication of the presence or absence of supercooled drizzle and rain drops in the updrafts of clouds at the -10°C seeding level. Median concentrations of supercooled drizzle and rain drops ($N_{D>300}$) in updraft regions at the -10°C level were found to be best approximated by a third-order polynomial dependent on T_{CCL} and PB, presenting a possible physical link between cloud scale environment and in-cloud conditions.

Czys, R. R., 1992: Temperature effect on the coalescence of precipitation-size drops in free fall. Proceedings, 11th International Conference on Clouds and Precipitation, Montreal, Canada, August 17-21, 1992. International Commission on Clouds and Precipitation, International Association of Meteorology and Atmospheric Physics, Innsbruck, Austria, 1-4.

No abstract.

Czys, R. R., S. A. Changnon, M. S. Petersen, R. W. Scott, and N. E. Westcott, 1992: Initial results from the 1989 cloud seeding experiment in Illinois. *Journal of Weather Modification*, 24:13-18.

Some early results from the 1989 cloud seeding experiment conducted in Illinois are reported in this paper. This exploratory field project was designed to achieve four primary objectives: (1) to obtain data on the largest possible sample of clouds (treated and natural); (2) to test some of the early physical steps of the dynamic seeding hypothesis; (3) to provide data for the development of analytical tools for discerning seeding effects; and (4) to improve basic knowledge about natural cloud and precipitation processes in the Midwest. The treatment randomization was based on "floating" experimental units, initially defined by a single cumulus congestus. Analysis of predictor variables revealed significant differences between the AgI and sand treated clouds at the time of treatment in many aspects that might govern future cloud growth. A Seedability Index composed of criteria physically consistent with the dynamic seeding hypothesis is described which was developed as an initial approach to addressing the problem of the bad draw revealed by the predictor variable analysis. The temporal series of the empirically-defined Seedability Index revealed that seedable conditions did not remain constant over the course of the field experiment and that even the seedable conditions for pairs of experimental units obtained on the same day were not always comparable. These findings illustrate the large inherent natural variability which has come into play in other cloud seeding experiments, and has frustrated efforts to randomly select two populations of clouds having sufficient similarity in individual characteristics to allow valid comparisons.

Czys, R. R., and M. S. Petersen, 1992: A roughness-detection technique for objectively classifying drops and graupel in 2-D image records. *Journal of Atmospheric and Oceanic Technology*, 9:242-257.

The development and evaluation of a new computerized technique for classifying drops and graupel in two-dimensional (2D)-image records is described. The method is unique because images are classified as drops or graupel on the basis of their exterior roughness rather than shape. The technique involves using the method of least squares to fit a fourth-order polynomial to the outside curvature of each half of large, symmetric, circular images. Formulations for determining variance and polynomial coefficients are reviewed. Roughness criteria determined using 2D-C and 2D-P cloud data in a quadtree analysis of maximum variance of the polynomial approximations and image diameters are illustrated. A method for determining the radius of "center-out" images is also reviewed. Size distributions formed by combining 2D-C and 2D-P data for either drops or graupel are illustrated with error bars based on Poisson statistics. Two different methods of calculating water content based on size-distribution information for particles with diameters greater than 150 μm are demonstrated. An independent evaluation of the objective classification technique using 2D-C and 2D-P cloud data shows that the polynomial classification of images as drops or graupel performed sufficiently well to give a population of size-distribution parameters and water contents that were generally not statistically different from those obtained by human classification.

Czys, R. R., and M. S. Petersen, 1992: Observations of first ice in Illinois cumulus. Proceedings, 11th International Conference on Clouds and Precipitation, Montreal, Canada, August 17-21, 1992. International Commission on Clouds and Precipitation, International Association of Meteorology and Atmospheric Physics, Innsbruck, Austria, 264-267.

No abstract.

Czys, R. R., 1991: A preliminary appraisal of the natural structure and seedability of updrafts in Midwestern cumulus at the -10°C level. *Journal of Weather Modification*, 23:1-16.

The properties of 40 updrafts in 11 warm-based Midwestern cumulus congestus are characterized on the basis of aircraft data collected at the -10°C level during the 1986 Precipitation Augmentation for Crops Experiment field program. Typically, clouds in this sample were found to be composed of multiple updrafts, with one updraft encountered on average for every 1.5 km of cloud penetrated. Mean updraft velocities ranged from 1 to 12 m s^{-1}, with a sample average of 4.2 m s^{-1}.

All updrafts contained at least some supercooled liquid water content in the size range of cloud droplets (D < 50 μm). Cloud droplet liquid water content was low, typically 0.3 g m^{-3}, and bimodal cloud droplet size distributions were occasionally observed. Most updrafts contained supercooled drizzle and raindrops. The mass of supercooled drizzle and raindrops was often as large as or larger than the mass of supercooled cloud droplets, indicating an efficient coalescence process.

Submillimeter-size graupel was the apparent dominant first ice form, often occurring in concentrations that exceeded those conventionally expected from ice nuclei by factors from 10 to 100. Images of vapor-grown ice crystals were not often identified in the records from 2D optical array probes. Thus it is likely that the very first ice initiated from the freezing of supercooled drizzle and raindrops. Aircraft instrumentation available to the 1986 field program was not adequate to detect ice smaller than approximately 150 μm diameter. Secondary ice production (SIP) by Hallett-Mossop rime-splintering could not be verified on the basis of available information.

Natural updraft buoyancies were often close to neutral, and the amount of loading by the condensate was found to have deciding influence on net buoyancy. The results of calculations suggest that buoyancy enhancements are feasible by seeding, particularly for clouds with substantial water loads and moderate updrafts. However, discerning seeding effects will be complicated by large variations in initial conditions for seeding.

Czys, R. R., and M. S. Petersen, 1991: A least-squares polynomial technique for discriminating between drops and graupel in 2D image records. Preprints, 7th Symposium on Meteorological Instrumentation and Observations, New Orleans, LA, January 13-18, 1991. American Meteorological Society, Boston, MA, J51-J55.

No abstract.

Czys, R. R., 1990: Observed versus diagnosed ice production rates in warm-based Midwestern cumuli. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 25-29.

No abstract.

Czys, R. R., 1989: Physical models used in the Precipitation Augmentation for Crops Experiment. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO Report No. 12, WMO/TD-No. 269, 221-224.

No abstract.

Czys, R. R., 1989: The visualization of cloud droplet spectra. *Journal of Atmospheric and Oceanic Technology*, 6:182-185.

This paper draws attention to the use of readily available wire cage graphics for inspecting cloud droplet spectra measured using a Forward Light-Scattering Spectrometer Probe. The high resolution cloud droplet spectra from two different clouds are presented to illustrate the clarity with which microphysical processes can be visualized.

Czys, R. R., 1988: A new mechanism for ice initiation on warm-based Midwestern cumuli. Preprints, 10th International Cloud Physics Conference, IAMAP/IUGG, Bad Homberg, F.R.G., August 15-20, 1988. *Annalen der Meteorologie*, No. 25, ISBN 3-88148-240-7, I:25-27.

No abstract.

Czys, R. R., 1988: Ice initiation by collision-freezing in warm-based cumuli. *Journal of Applied Meteorology*, 28:1098-1104.

The mechanical shock of collision between supercooled water drops is explored as a mechanism for the origin of ice in the warm-based cumuli of the central United States. The results of laboratory experiments, using groups of 3-mm diameter hemispherical drops supported on a petroleum substrate and cooled to either -10° or -15°C, are presented to demonstrate that supercooled drops can be caused to freeze mechanically. Cavitation is examined as a mechanism closely associated with ice nucleation in supercooled water. Pressure differences extrapolated from the Weber number for collisions between precipitation-size collector drops and a wide size range of smaller drops were found to exceed the criteria for cavitation and hence, freezing. This finding suggests that collision-freezing may occur in clouds and is worthy of further attention.

Czys, R. R., 1988: Microphysical characteristics of warm-based cumuli: Observations at -10°C. Preprints, 10th International Cloud Physics Conference, IAMAP/IUGG, Bad Homberg, F.R.G., August 15-20, 1988. *Annalen der Meteorologie*, No. 25, ISBN 3-88148-240-7, I:64-66.

No abstract.

Czys, R. R., and H. T. Ochs III, 1988: The influence of charge on the coalescence of water drops in free fall. *Journal of the Atmospheric Sciences*, 45:3161-3168.

The influence of charge on coalescence was determined in the laboratory for isolated pairs of 340 and 190 μm water drops falling freely at terminal velocity. A microcomputer-controlled apparatus was used to produce collisions. Drop charges were independently controlled and collisions occurred in a humidified chamber at laboratory temperature and pressure. Two cameras were used to record the interactions from orthogonal directions and the photographs used to determine the impact angle for each collision. A single charge-independent critical impact angle of 43° ±1° was observed that distinguished an inner collision cross section for coalescence from an outer annular cross section for noncoalescence. Collisions occurring for impact angles less than the critical value *always* resulted in coalescence

regardless of charge. Collisions having impact angles greater than the critical value resulted in either bounce, temporary coalescence, or coalescence depending on charge. A satellite drop was produced with temporary coalescence at the intermediate charges of this experiment. Electrohydrodynamic theory in plane geometry applied to the conditions for deformable spheres gave an electric field strength between the approaching drop surfaces sufficient to cause a surface instability that may aid in drop coalescence.

Czys, R. R., 1987: Microphysical observations from PACE-86: Characteristics near -10°C. Preprints, 11th Conference on Weather Modification, Edmonton, Alberta, Canada, October 6-8, 1987. American Meteorological Society, Boston, MA, 72-75.

No abstract.

Czys, R. R., and S. Weaver, 1987: Microphysical observations from PACE-86: Feeder cloud input/rain output. Preprints, 11th Conference on Weather Modification, Edmonton, Alberta, Canada, October 6-8, 1987. American Meteorological Society, Boston, MA, 106-109.

No abstract.

DeGrand, J. Q., A. M. Carleton, and P. J. Lamb, 1990: A mid-season climatology of jet condensation trails from high resolution satellite data. Proceedings, 7th Conference on Atmospheric Radiation, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 309-311.

No abstract.

DeMott, P. J., 1992: Quantifying ice nucleation by cloud seeding aerosols for use in conceptual and numerical cloud models. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 148-155.

No abstract.

DeMott, P. J., D. C. Rogers, and L. O. Grant, 1992: Concerning primary ice nuclei concentrations and water supersaturations in the atmosphere. Proceedings, 11th International Conference on Clouds and Precipitation, Montreal, Canada, August 17-21, 1992. International Commission on Clouds and Precipitation, International Association of Meteorology and Atmospheric Physics, Innsbruck, Austria, 284-287.

No abstract.

Demoz, B. B., J. A. Warburton, and R. H. Stone, 1991: The influence of riming on the oxygen isotopic composition of ice-phase precipitation. *Atmospheric Research*, 26:463-488.

The oxygen isotopic composition of freshly fallen snow has been measured simultaneously with ice-crystal photography at a high altitude station in the central Sierra Nevada. These and other meso- and microscale cloud measurements have been used to study the short-term $\delta^{18}O$ variations of ice-phase precipitation from winter storms. In this study, snow samples collected from six storm events in 1985 were used.

The results show that: (1) the degree of riming and the $\delta^{18}O$ value of the ice particles correlate positively for six of the six storms sampled, except at times of strong convective activity; (2) temperatures of ice phase initiation do not agree with the isotopically derived "temperatures" of the precipitation reaching the ground, as a result of riming; hence, the amount and location of supercooled liquid water in the clouds are considered to be strong determining factors influencing the $\delta^{18}O$ values; and (3) no obvious correlations were observed between precipitation rate and $\delta^{18}O$ or between the maximum precipitation intensity and the range of the $\delta^{18}O$ values of the snowfall.

Dennis, A. S., P. L. Smith, and J. R. Miller, Jr., 1991: Comments on "Further exploratory evaluations of Grossversuch IV using hailpad data: Analysis of hail patterns and stratification by storm type for seeding effect." *Journal of Applied Meteorology*, 30:901-902.

No abstract.

Detwiler, A. G., P. L. Smith, and J. L. Stith, 1992: Observations of microphysical evolution in a high plains thunderstorm. Proceedings, 11th International Conference on Clouds and Precipitation, Montreal, Canada, August 17-21, 1992. International Commission on Clouds and Precipitation, International Association of Meteorology and Atmospheric Physics, Innsbruck, Austria, 260-263.

No abstract.

Detwiler, A. G., J. H. Helsdon, Jr., and D. J. Musil, 1990: Evolution of a band of severe storms. Preprints, 16th Conference on Severe Local Storms, Kananaskis Provincial Park, Alberta, Canada, October 22-26, 1990. American Meteorological Society, Boston, MA, 705-709.

No abstract.

Detwiler, A. G., P. L. Smith, and D. J. Musil, 1990: T-28 participation in the 1989 North Dakota Thunderstorm Project. Report SDSMT/IAS/-R-90/05. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 29 pp. + appendices.

No abstract.

Detwiler, A. G., and P. L. Smith, 1988: T-28 participation in the 1987 field season of the North Dakota Federal/State Cooperative Weather Modification Program. Report SDSMT/IAS/R-88/02 to Desert Research Institute. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 46 pp.

No abstract.

Doneaud, A. A., A. Makarau, and L. R. Johnson, 1988: A modified ATI technique for nowcasting convective rain volumes over areas. *Journal of Applied Meteorology*, 27:491-502.

Digital radar data from the North Dakota Cloud Modification Project (NDCMP)—the 1981 and 1982 summer experiments—are used to further investigate the relationship between convective rain volumes and area-time-integrals (ATI). The ATI technique provides a means of estimating total rain volumes using areas covered by rain events (for reflectivities ≥25 dBZ) integrated over the cluster duration.

The purpose of this investigation is twofold: (a) to estimate ATIs only for the growth portion of a convective storm (while the rain volume is computed using the entire life history of the convective event); and (b) to nowcast the total rain volume of a convective system at the stage of its maximum development. For the aforementioned purpose, the ATIs were computed using the maximum echo area ≥25 dBZ (ATIA), the maximum reflectivity (ATIR), and the maximum echo height (ARIH) as the end of the growth portion of the convective event.

A simple linear regression analysis demonstrated that correlations between total rain volume (TVR) or the maximum rain volume (MVR) versus the ATIA were the strongest. In a log-log plot, the correlation coefficient and the standard error of estimates of total rain volume versus ATIA were 0.98 and 0.23 for the summer 1982 data, and 0.96 and 0.24 for the summer 1981 data, respectively. In percentage terms, the corresponding range of variation of the rain volume for a given ATIA lies between 70% and -41% (1982 data) and between 74% and -44% (1981 data). This is comparable to the uncertainties which typically occur in rain volume estimates obtained from radar data employing Z-R conversion followed by space and time integration. This demonstrates that the total rain volume of a storm can be nowcasted at its maximum stage of development (max ATIA).

The scatter in the rain volume and in the maximum volumetric rain rate estimates is somewhat smaller if a multiple linear regression instead of a simple linear regression is considered, but the improvement is of little significance. The tests with independent data confirmed the consistency of the results for the region considered.

Doneaud, A. A., J. R. Miller, Jr., and A. Makarau, 1986: A modified ATI technique for possible satellite applications. Preprints, 23rd Conference on Radar Meteorology and Conference on Cloud Physics, Snowmass, CO, September 22-26, 1986. American Meteorological Society, Boston, MA, Vol. 3, JP27-JP32.

No abstract.

Doneaud, A. A., S. Ionescu-Niscov, and J. R. Miller, Jr., 1984: Convective rain rates and their evolution during storms in a semiarid climate. *Monthly Weather Review*, 112:1602-1612.

Rain rates and their evolution during summertime convective storms were analyzed for the semiarid climate of the northern High Plains. Radar data from a total of 750 radar echo clusters from the 1980 and 1981 summer cloud seeding operations of the North Dakota Cloud Modification Project (NDCMP) were used. The analysis suggests that the average rain rate $\overline{R}$ among storms is, in a first approximation, independent of the total rain volume if the entire storm duration is considered in the averaging process. This average rain rate depends primarily on the reflectivity threshold considered in calculating the area coverage integrated over the lifetime of the storm, the area-time integral (ATI). For the 25 dBZ reflectivity threshold used in the ATI computations, $\overline{R}$ was 4.0 mm h^{-1}, with a standard deviation of 1.55 mm h^{-1} being ~20% higher for wet season conditions.

The evolution of rain rates during storms was analyzed by dividing each storm lifetime into 10 min, 1, 2, and 4 h, and growing and decaying periods. A 10-min time increment was used in computing the parameters for all time intervals. A storm cluster reached its maximum growth after an average of 56% of its lifetime. The average rain rate for the growing period exceeded that for the decaying period by about 10%. As the time interval used in the computations approached the storm lifetime, the scatter of the average rain rates was reduced, thus increasing the accuracy of rainfall estimates using the area-time integral. The value of $\overline{R}$ remained independent of the total rain volume when the growing or decaying periods of storms were considered separately. The total rain volume was also well correlated with the maximum single-scan rain volume. These findings suggest the possibility of estimating total storm rain volume at its maximum stage of development.

It is hoped that improvements in rainfall estimation over areas using satellite data may result from further studies, since the precipitating part of a cloud picture can be more accurately defined for the growing period of a cloud's history.

Doneaud, A. A., S. Ionescu-Niscov, D. L. Priegnitz, and P. L. Smith, 1984: The area-time integral as an indicator for convective rain volumes. *Journal of Climate and Applied Meteorology*, 23:555-561.

Digital radar data are used to investigate further a simple technique for estimating rainfall amounts on the basis of area coverage information. The basis of the technique is the existence of a strong correlation between a measure of the rain area coverage and duration called the area-time integral (ATI) and the rain volume. This strong correlation is again demonstrated using echo cluster data from the North Dakota Cloud Modification Project 5-cm radars.

Integration on a scan-by-scan basis proved to be superior for determining ATI values to the hour-by-hour integration used previously. A 25 dB(z) reflectivity threshold was found suitable for the ATI calculation. The correlation coefficient on log-log plots of cluster rain volume versus ATI is approximately 0.98, indicating a power-law relationship between the variables. The exponent of that relationship is just a little higher than one, which indicates that the cluster average rainfall rate is almost independent of the storm size and duration.

A test of the relationship derived from one set of data (1980) against an independent set (1981) showed it to be consistent. Using the 1980 relationship to estimate the 1981 cluster rain volume for a given ATI, the uncertainty of the rain volume estimates was found to be -31%, +46%.

Doneaud, A. A., S. Ionescu-Niscov, and J. R. Miller, Jr., 1983: The evolution of the average rain rate during storms in a semi-arid climate. Preprints, 21st Conference on Radar Meteorology, Edmonton, Alberta, Canada, September 19-23, 1983. American Meteorological Society, Boston, MA, 15-20.

No abstract.

Doneaud, A. A., S. Ionescu-Niscov, D. L. Priegnitz, and P. L. Smith, 1983: The area-time integral as an indicator for convective rain volumes. Preprints, 21st Conference on Radar Meteorology, Edmonton, Alberta, Canada, September 19-23, 1983. American Meteorological Society, Boston, MA, 675-680.

No abstract.

Durgunoglu, A., H. V. Knapp, and S. A. Changnon, 1988: PACE watershed model (PWM): Vol. 2, Weather Modification Simulations. SWS Contract Report 439 to NOAA. Illinois State Water Survey, Champaign, IL, 55 pp.

No abstract.

Elliott, R. D., and D. A. Griffith, 1984: Final report on modeling and radar/rawinsonde analysis for North Dakota. NAWC Report SLWM-84-1. North American Weather Consultants, Salt Lake City, UT, 73 pp.

No abstract.

Feng, D., and W. G. Finnegan, 1989: An efficient, fast-functioning nucleating agent—AgI·AgCl-4NaCl. *Journal of Weather Modification*, 21:41-45.

A composite ice nucleus aerosol, AgICl-4NaCl, has been generated and characterized for nucleation efficiencies, rates of ice crystal formation, and mechanisms of nucleation, under water saturation and transient supersaturation conditions. The addition of NaCl to the highly efficient contact nucleus, $AgI_{0.8}Cl_{0.2}$, changed the nucleation mechanism to condensation-freezing at water saturation and increased the rates of ice crystal formation dramatically, while retaining the high efficiency of the AgICl nucleus aerosol. Under transient supersaturation conditions, this new aerosol demonstrated improved ice nucleation efficiencies at $T > -12°C$, and even faster ice crystal formation rates, suggesting a change of nucleation mechanism to forced condensation-freezing. This ice nucleation aerosol should be advantageous for use in weather modification field programs under conditions where low cloud droplet concentrations suggest the use of a condensation-freezing nucleant.

Finnegan, W. G., and R. L. Pitter, 1991: Chemical reactions in growing snowflakes. Poster presentation, Annual Meeting of the AAAS, Washington, DC, February 14-19, 1991. American Association for the Advancement of Science, Washington, DC.

No abstract.

Finnegan, W. G., and R. L. Pitter, 1991: Comments on "The persistence of seeding effects in a winter orographic cloud seeded with silver iodide burned in acetone." *Journal of Applied Meteorology*, 30:903-904.

The article by Deshler and Reynolds (1990) contains errors and misconceptions concerning the chemistry, generation, characterization, and functioning mechanisms of silver iodide-containing ice nucleus aerosols. These errors may be due in part either to the authors not understanding the processes of ice nucleation and ice crystal formation, which are critical aspects of cold cloud modification, or to their careless use of jargon. In this Comment, only the errors in Deshler and Reynolds (1990) relevant to ice formation are discussed.

Finnegan, W. G., R. L. Pitter, and L. G. Young, 1991: Preliminary study of coupled oxidation-reduction reactions of included ions in growing ice crystals. *Atmospheric Environment*, 25A:2531-2534.

Cloud chamber studies have demonstrated coupled oxidation-reduction reactions of included ions in free-falling ice crystals growing in a supercooled liquid water cloud. These reactions are hypothesized to occur as a consequence of preferential ion separations which take place at the interface between growing ice and the liquid layer at the growing crystal surfaces, followed by electron transfers to establish system neutrality. Oxidations of sulfide ion to sulfate ion and of halide ions to higher valence species have been documented. Reductions of silver ion to metallic silver and of sulfate ion to lower valence species have also been documented in systems of appropriate ion compositions. Similar reactions have been reported to occur during the freezing of bulk dilute solutions of ammonium and/or halide salts.

Finnegan, W. G., and R. L. Pitter, 1990: Ice crystal breeding: A primary nucleation mechanism. Nucleation Symposium, Bethlehem, PA, June 18-20, 1990. American Chemical Society, Washington, DC, 114.

No abstract.

Finnegan, W. G., and R. L. Pitter, 1990: Ice phase induced chemical reactions. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 473-474.

No abstract.

Finnegan, W. G., and R. L. Pitter, 1989: Another role for CCN in clouds. Preprints, Symposium on the Role of Clouds in Atmospheric Chemistry and Global Climate, Anaheim, CA, January 30-February 3, 1989. American Meteorological Society, Boston, MA, 104-105.

No abstract.

Finnegan, W. G., R. L. Pitter, and L. G. Young, 1989: Experimental study of coupled oxidation-reduction reactions of soluble ionic aerosol constituents in growing ice crystals. Annual Meeting, AAAR, Sparks, NV, October 9-13, 1989. American Association for Aerosol Research, Washington, DC, 142.

No abstract.

Finnegan, W. G., R. L. Pitter, and L. G. Young, 1989: Reduction-oxidation (REDOX) reactions in growing ice crystals. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, II:655-658.

No abstract.

Finnegan, W. G., and R. L. Pitter, 1988: A postulate of electric multipoles in growing ice crystals: Their role in formation of ice crystal aggregates. *Atmospheric Research*, 22:235-250.

This paper describes the basis of the postulate of electric multipoles in growing ice crystals. The postulate was initially developed to describe the orientation of aggregated ice crystals, for the purpose of learning about rate-determining forces involved in the initiation of ice crystal aggregation. A series of laboratory experiments were undertaken to test the postulate. A 6.7-m^3 controlled-temperature chamber was used to investigate the aggregation of growing ice crystals. The results show that small changes in dissolved salts are important in the orientation of initial ice crystal aggregates. We interpret these results to strongly support our hypothesis of electric multipoles in growing ice crystals.

Finnegan, W. G., and R. L. Pitter, 1988: Rapid ice nucleation: Laboratory and field studies of the phenomenon and its importance. Proceedings, 12th International Conference on Atmospheric Aerosols and Nucleation, Vienna, Austria, August 22-27, 1988. *Atmospheric Aerosols and Nucleation*, P. E. Wagner and G. Vali (eds.), Springer-Verlag, Berlin, Germany, 693-696.

The ice phase plays an important role in the formation of precipitation in cold continental clouds. Nucleation of the ice phase is one of the less understood processes in clouds. Knowledge of ice nucleation in clouds is limited by poor information concerning where, how, and how fast ice nucleation occurs.

Artificial ice nucleation, using silver iodide (AgI) and AgI-containing aerosol particles, has been studied in laboratory cloud chambers and used for atmospheric experimentation. These aerosols produce ice crystals by processes described as contact freezing, condensation freezing, immersion freezing, and deposition nucleation. AgI functions by contact freezing in cloud chambers at temperatures from -6 to -16°C.

One of the difficulties of contact freezing for cloud glaciation is the slow rate of interaction between aerosol particles and supercooled water drops. This is not greatly speeded by considering scavenging of nucleus aerosols by drops at temperatures above 0°C. Rapid cloud glaciation in nature indicates that there is a rapid ice nucleation mechanism which can occur. Our recent studies focused on this rapid ice nucleation mechanism.

Finnegan, W. G., and R. L. Pitter, 1988: Rapid ice nucleation by acetone-silver iodide generator aerosols. *Journal of Weather Modification*, 20:51-53.

A field test conducted on 10 January 1987 confirmed a postulate that rapid ice nucleation occurs on wet silver iodide aerosols at temperatures below -6°C. The postulate was developed from laboratory tests and is consistent with results from winter orographic cloud seeding programs which have used ground generators sited at mountain tops and along ridges, where they are located within supercooled water clouds during their operation.

Finnegan, W. G., and R. L. Pitter, 1987: Rapid ice nucleation by acetone-silver iodide generator aerosols and implications to winter orographic storm seeding strategies. Preprints, 11th Conference on Weather Modification, Edmonton, Alberta, Canada, October 6-8, 1987. American Meteorological Society, Boston, MA, 9-10.

No abstract.

Finnegan, W. G., and R. L. Pitter, 1986: Study of the initial aggregation of ice crystals. Preprints, Conference on Cloud Physics, Snowmass, CO, September 22-26, 1986. American Meteorological Society, Boston, MA, Vol. 2, 110-112.

No abstract.

Finnegan, W. G., 1984: Characterization of Loshe generator and NEI TB-1 pyrotechnic aerosols in the CSU isothermal cloud chamber. Report to the North Dakota Weather Modification Board. Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 19 pp.

No abstract.

Finnegan, W. G., D. Feng, and L. O. Grant, 1984: Composite AgI·AgCl ice nuclei efficient, fast-functioning aerosols for weather modification experimentation. Extended Abstracts, 9th Conference on Weather Modification, Park City, UT, May 21-23, 1984. American Meteorological Society, Boston, MA, 3-4.

No abstract.

Fletcher, J. A., 1986: NOAA perspectives and planned and inadvertent weather modification. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 307-311.

No abstract.

Flueck, J. A., and D. W. Reynolds, 1986: A forecast experiment on the prediction of cloud conditions suitable for treatment in the Sierra Nevadas. Proceedings, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 13-17.

No abstract.

Flueck, J. A., M. E. Solak, R. B. Allan, and T. S. Karacostas, 1986: An exploratory analysis of the National Hail Suppression Program in Greece. Proceedings, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 124-127.

No abstract.

Flueck, J. A., M. E. Solak, and T. S. Karacostas, 1986: Results of an exploratory experiment within the Greek National Hail Suppression Program. *Journal of Weather Modification*, 18:57-63.

During the summers of 1984 and 1985, a multi-area operational hail suppression program was conducted in northern and central Greece, sponsored by the Greek National Agricultural Insurance Institute. This operational program included a small exploratory randomized cross-over seeding experiment embedded within one of the three operational project areas. This article summarizes the experiment's design, the network hailpad data, and the initial analyses and results. Substantial reductions (e.g., 30% to 75%) in the area of coverage, hailstone size, and concentration are apparent in the two summers' data, and the combined two-season sample provides correspondingly strong inferential two-tailed P-value support (e.g., .08 to .02) for evidence of treatment effects.

Flueck, J. A., W. L. Woodley, A. Barnston, and T. J. Brown, 1986: A further assessment of treatment effects in the Florida Area Cumulus Experiment through guided linear modeling. *Journal of Climate and Applied Meteorology*, 25:546-564.

The Florida Area Cumulus Experiment (FACE) was a two-stage program dedicated to assessing the potential of "dynamic seeding" for enhancing convective rainfall in a fixed target area. FACE-1 (1970-76) was an exploratory cloud seeding experiment that produced substantial indications of a positive treatment effect on rain at the ground, and FACE-2 (1978-80) was a confirmatory experiment that did not confirm the treatment effect results of FACE-1.

This article presents some new analyses of both the FACE-1 and FACE-2 data in an effort to better understand the role of meteorological and treatment factors on rainfall in the days selected for experimentation in Florida. The analyses rely upon a guided exploratory linear modeling of the natural target area rainfall and the potential treatment effects. In particular, a conceptual model of natural Florida rainfall is utilized to guide the construction of the exploratory linear model. After the form of the model is selected, it is fitted to both the FACE-1 and the FACE-2 data sets in an attempt to reassess the effects of treatment.

Two approaches are taken to assess the treatment effects in FACE-1 and in FACE-2: cross-comparison and cross-validation. Both techniques suggest a positive treatment effect in each stage of FACE (i.e., 30%-45% in FACE-1 and 10%-15% in FACE-2). However, the conventional 0.05 unadjusted statistical level of support is only present in the FACE-1 data. The question of whether FACE-1 results were different from FACE-2 is unresolved. These results continue to emphasize the need to better account for the natural convective precipitation processes in south Florida prior to conducting a cloud seeding project.

Flueck, J. A., and W. L. Woodley, 1985: A guided linear model "sweep out" method for both exploration and confirmation of treatment effects with application to the FACE project. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 311-316.

No abstract.

Frisch, A. S., B. W. Orr, and B. E. Martner, 1992: Doppler radar observations of the development of a boundary-layer nocturnal jet. *Monthly Weather Review*, 120:3-16.

A single Doppler radar obtained detailed clear-air measurements of the development of a strong boundary-layer nocturnal jet in North Dakota during the summer of 1989. The evolution of the jet was monitored by the radar with a high degree of vertical and temporal resolution using a repetitive sequence of four different elevation scans. A new variation of the velocity-azimuth display (VAD) analysis technique provided vertical profiles of the mean wind components and several turbulence terms. Boundary-layer wind speeds began to increase in the late afternoon, well before sunset, as surface cooling began. Wind speeds accelerated faster after sunset and eventually produced a jet that exceeded 23 m s^{-1} at about 0.5 km AGL. The wind veered with height and time and followed the expected inertial oscillation pattern. Measured shear stresses, vertical fluxes of momentum, and velocity variances, which were initially large, decreased sharply after the surface began to cool. The directly measured vertical velocities were significantly downward during the late afternoon and upward at night.

Fuhs, M. J., 1986: North Dakota hail suppression analysis using crop-hail insurance data. M.S. thesis, Department of Meteorology, South Dakota School of Mines & Technology, Rapid City, SD, 53 pp. + appendices.

Except in 1955-1957 and 1960, operational cloud seeding programs have been conducted in North Dakota every year since 1951. Seeding from aircraft started in 1961 and weather radar was added in the mid-1960s to increase the lead time in treating hailstorms. North Dakota has the longest-running hail mitigation program in the world using aircraft.

The analysis used for this project involves crop hail insurance data from the Crop Hail Insurance Actuarial Association (CHIAA). Historical trend analysis using weighted loss/cost (WLC) values is examined for non-seeded and seeded years both in target and control areas. The overall trend suggests long-term hail reductions of 23% and 7% in seeded areas using mean and median values, respectively, from the Double Ratio. The Mann-Whitley U rank test gives a level of significance of 0.02 that WLC values are lower during the seeded years compared to the non-seeded years when all target counties are compared with eastern Montana control counties. Sub-target areas generally have levels of significance above 0.10 when compared with adjacent control areas. Scatter plot analysis generally shows lower hail losses for the seeded years. A cumulative double mass analysis gives a hail loss reduction of about 22% for North Dakota target counties when compared with eastern Montana.

The North Dakota Cloud Modification Project appears to be paying for itself in apparent hail reduction success alone. A benefit to cost ratio of 3.7:1 exists when all crop savings are evaluated for North Dakota target counties. If the project is also successful in its rain enhancement objectives, greater benefit to cost ratios may result.

Fukuta, N., and C. Redder, 1988: Development of superior equations of ice crystal growth microphysics for modeling and analysis. Final Report to Utah Department of Natural Resources, Division of Water Resources. University of Utah, Salt Lake City, UT, 112 pp.

No abstract.

Gagin, A., D. Rosenfeld, W. L. Woodley, and R. E. López, 1986: Results of seeding for dynamic effects on rain-cell properties in FACE-2. *Journal of Climate and Applied Meteorology*, 25:3-13.

Volume scan radar studies incorporating the use of an elaborate method of defining and tracking convective rain cells through their lifetime have been used to:

(a) Explore and verify, in quantitative terms, the basic tenet of the technique of cloud seeding aimed at producing dynamic effects. This technique relates increases in the depth of convective cells, assumed to occur due to this type of seeding, to corresponding increases in the treated cells' rainfall intensity, area and duration of precipitation, and consequently, to the total yield of rainfall volume.

(b) Employ the data gathered on the gross properties of rainfall of convective cells, namely their heights, intensities, precipitation areas and their durations and total rain volume, to estimate the effect of seeding, if any, on their properties.

These studies suggest that seeding convective cells for dynamic effects affected the preceding properties of these cells in a manner that resulted in increases in their total rainfall and that the positive changes in these properties could be predicted from the changes in maximum cell height following seeding.

The effect of seeding appears to be strongest for cells treated early in their life cycle with a substantial amount of AgI (i.e., more than 600 g). Seeding effects of 22% increases in cell heights and over 100% increases in cell rain volume are indicated under such seeding conditions. The significance levels of these results are found to be 2.1% and 0.6%, respectively.

The positive effects produced by seeding on the AgI treated cells may have resulted in a compensating negative effect on the smaller untreated clouds forming in the vicinity of these treated cells.

Garcia, P., S. A. Changnon, and M. Pinar, 1990: Economic effects of precipitation enhancement in the Corn Belt. *Journal of Applied Meteorology*, 29:63-75.

Policy formulation in weather modification requires an understanding of the economic effects from altered weather. The focus of this study is to provide insight into the beneficiaries of a functioning weather modification technology when applied at various spatial and temporal levels. An econometric model which links the corn/soybean production to U.S. cattle, hog, and poultry sectors is used to determine the effects of precipitation enhancement in the U.S. Corn Belt, a humid climatic region. A regional supply formulation permits assessment of weather modification on production, prices, revenues to producers, and savings in consumers expenditures on meat. The results provide insight into the distribution of economic effects, emphasize the importance of careful planning in the use of weather modification technology, and provide useful information on the roles of local, state, and federal governments in the support of weather modification.

Garcia, P., S. E. Offutt, M. Pinar, and S. A. Changnon, 1987: Corn yield behavior: Effects of technological advance and weather conditions. *Journal of Climate and Applied Meteorology*, 26:1092-1102.

This study explores the relationships between U.S. corn yields (level and stability), advances in technology, and weather. Evaluations at the farm, sub-state, and national levels reveal no evidence of yield plateaus, and absolute, but not relative, yield variability increased over time. When yield behavior is adjusted for weather, variances are more likely to be equal between early and late periods. Results suggest that technology has not been the only determinant of changing yield risk, and emphasize the importance of weather conditions in assessing these effects.

Garcia, P., S. E. Offutt, and M. Pinar, 1986: Technological advance, weather, and the potential economic benefits of weather modification. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 285-289.

No abstract.

Garcia, P., S. E. Offutt, and M. Pinar, 1985: Methodological considerations for assessing the potential benefits of weather modification in Illinois agriculture. Preprints, 17th Conference on Agricultural and Forest Meteorology and 7th Conference on Biometeorology and Aerobiology, Scottsdale, AZ, May 21-24, 1985. American Meteorological Society, Boston, MA, Vol. 1, 169-172.

No abstract.

Grant, L. O., and R. M. Rauber, 1988: Radar observations of wintertime mountain clouds over Colorado and Utah. *Journal of Weather Modification*, 20:37-43.

Ludlam (1955) postulated that seedable clouds for initiating snowfall are the extensive, shallow orographic clouds. He referred to these as "extensive low clouds." He specifically excluded clouds that contain persistent vertical motions not associated with localities where the airstream flows over mountains. The orographic, randomized Climax, Colorado, cloud seeding experiment conducted during the 1960s followed the seeding hypothesis for orographic clouds as proposed by Ludlam. This paper presents the results of recent radar observations of the characteristics of differing types of clouds that form over the mountains of Colorado and Utah.

Cloud radar echo observations show that deep, stable and deep, convective cloud systems in the interior areas of the western United States during winter generally extend to elevations higher than the 50 Kpa pressure level where temperatures during winter are sufficiently cold to permit efficient ice nucleation processes to occur. Shallow, orographically forced clouds, on the other hand, almost always occur in their entirety at elevations below the 50 Kpa level where wintertime temperatures are variable with respect to temperatures at which natural ice nucleation can be either efficient or inefficient.

Grant, L. O., and R. M. Rauber, 1986: Weather modification related characteristics of Colorado and Utah orographic clouds. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 254-259.

No abstract.

Grant, L. O., and R. M. Rauber, 1984: Hypothesis evaluation and development for seeding continental wintertime mountain cloud systems. Extended Abstracts, 9th Conference on Weather Modification, Park City, UT, May 21-23, 1984. American Meteorological Society, Boston, MA, 33-34.

No abstract.

Griffith, D. A., G. W. Wilkerson, and W. J. Hauze, 1992: Sulfur hexafluoride tracer results from a winter orographic research program. Poster session. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 166.

No abstract.

Griffith, D. A., G. W. Wilkerson, W. J. Hauze, and D. A. Risch, 1992: Observations of ground-released sulfur hexafluoride tracer gas plumes in two Utah winter storms. *Journal of Weather Modification*, 24:49-65.

Research was conducted for a two-month period over the Wasatch Plateau of central Utah during the winter of 1990-91. A portion of this research was devoted to tracking sulfur hexafluoride (SF_6) released from various ground-based locations during winter storms. A NOAA King Air research aircraft was the primary mode of tracking the SF_6. Seven flights were conducted under IFR conditions when SF_6 was released from a foothill or valley location. SF_6 was detected on six of these flights. Information on SF_6 plume widths, concentrations, vertical extent, and estimated numbers of ice crystals that would be possible if a silver iodide generator had been operated from the SF_6 release site are provided for two of these flights.

Griffith, D. A., G. W. Wilkerson, and D. A. Risch, 1990: Airborne observations of a summertime, ground-based tracer gas release. *Journal of Weather Modification*, 22:43-48.

Two research aircraft were equipped with real-time sulfur hexafluoride analyzers in support of the North Dakota/NOAA 1987 summertime weather modification research program. Sulfur hexafluoride (SF_6) was released from a ground location and the plume was detected by both aircraft on several downwind transects. The SF_6 plume was tracked to near the base of a developing thunderstorm by one of the research aircraft. Calculations were made of what the concentration of silver iodide (AgI) seeding material would have been had a seeding generator been operated concurrently with the SF_6 release. These calculations utilized the SF_6 release rate, an assumed AgI release rate, and the observed SF_6 concentrations.

Griffith, D. A., H. R. Swart, and G. W. Wilkerson, 1988: Transport and diffusion in complex terrain as depicted by winter tracer programs. Preprints, 8th Symposium on Turbulence and Diffusion, San Diego, CA, April 25-29, 1988. American Meteorological Society, Boston, MA, 384-387.

No abstract.

Griffith, D. A., H. R. Swart, and G. W. Wilkerson, 1988: Transport and dispersion in complex terrain as depicted by winter tracer programs. Preprints, 81st Annual Air Pollution Control Association (APCA) Meeting, Dallas, TX, June 20-24, 1988, Paper no. 88-49.3.

No abstract.

Griffith, D. A., R. L. Benner, and J. L. Stith, 1986: In-cloud plume tracking in North Dakota. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 248-252.

No abstract.

Griffith, D. A., 1985: Utilization of sulfur hexafluoride gas as a tracer in a summer cloud seeding experiment. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 255-260.

No abstract.

Griffith, D. A., 1984: Selected analyses of a Utah/NOAA cooperative research program conducted in Utah during the 1982-83 winter season. Extended Abstracts, 9th Conference on Weather Modification, Park City, UT, May 21-23, 1984. American Meteorological Society, Boston, MA, 85-86.

No abstract.

Hall, W. D., D. Matthews, and A. Super, 1990: Orographic production of supercooled liquid water and precipitation over the Mogollon Rim of Arizona. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 754-757.

No abstract.

Heimbach, J. A., Jr., and A. B. Super, 1992: Targeting of AgI in a Utah orographic storm. Proceedings, Irrigation and Drainage Division, Water Forum '92, Baltimore, MD, August 2-6, 1992. American Institute of Civil Engineers (ASCE), New York, NY, 553-558.

No abstract.

Heimbach, J. A., Jr., and A. B. Super, 1992: The number of experimental units required to achieve statistical significance with different seeding responses in a winter orographic experiment. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 132-135.

No abstract.

Heimbach, J. A., Jr., 1991: Interim data inventory for 1991 flight operations in support of Utah/NOAA Cooperative Atmospheric Modification Research Program. Department of Natural Resources, State of Utah, Salt Lake City, UT, 59 pp.

No abstract.

Helsdon, J. H., Jr., 1990: Analysis of a high positive flash frequency severe storm (June 28, 1989) from the North Dakota Thunderstorm Project. Preprints, 16th Conference on Severe Local Storms, Kananaskis Provincial Park, Alberta, Canada, October 22-26, 1990. American Meteorological Society, Boston, MA, 744-747.

No abstract.

Henderson, T. J., 1986: PACE 1986—A summary report of activities conducted by Atmospherics Incorporated during July 1, 1986, through August 31, 1986. Atmospherics Inc., Fresno, CA, 33 pp.

No abstract.

Henderson, T. J., 1985: Supercooled liquid water concentrations in winter orographic clouds from ground-based ice accretion measurements. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 189-194.

No abstract.

Hill, G. E., 1982: Evaluation of the Utah operational weather modification program. Final Report, NOAA Contract NA81RAC00023. Atmospheric Water Resources Series UWRL/A-82/02, Utah Water Research Laboratory, Utah State University, Logan, UT, 291 pp.

No abstract.

Hirsch, J. H., 1990: North Dakota Thunderstorm Project—1989 Field Program Data Inventory. Bulletin 89-5. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 133 pp.

No abstract.

Hjelmfelt, M. R., H.-Y. Chou, R. D. Farley, and D. L. Priegnitz, 1992: Organization and development of a squall line in North Dakota as revealed by Doppler radar and numerical simulations. Preprints, 5th Conference on Mesoscale Processes, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 221-226.

No abstract.

Hollinger, S. E., and S. A. Changnon, 1992: Studies of effects of increased rainfall in crop production. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 80-83.

No abstract.

Hollinger, S. E., and S. A. Changnon, 1991: Response of corn yield components to simulated precipitation augmentation. Preprints, 20th Conference on Agricultural and Forest Meteorology, Salt Lake City, UT, September 10-13, 1991. American Meteorological Society, Boston, MA, 17-20.

No abstract.

Hollinger, S. E., and S. A. Changnon, 1991: Response of corn yield components to simulated precipitation augmentation. *Journal of Weather Modification*, 23:45-48.

Mobile rain shelters were used to protect corn (Zea Mays L.) from all natural rainfall during the summers of 1987, 1988, 1989 while providing water to the crop through an overhead sprinkler system mounted in the rain shelters. Water was applied to the crop to simulate typical dry, normal, and wet summers in central Illinois. Final yields were measured at harvest along with the various yield components (number of kernel rows/ear, number of kernels/row, total number of kernels/ear, kernel mass) that determine final yield. Yields were increased in each of the typical summers by increased rainfall. The greatest benefit of the increased rainfall was realized at pollination and the two weeks following pollination as expressed by an increase in the number of kernels/fertile ear. Neither the number of kernel rows/fertile ear nor the final mass of the kernels were affected by the rainfall treatments. In addition to larger fertile ears, some yield increase was realized by a reduction in the number of barren plants in the plant population under higher rainfall treatments.

Hsu, C.-F., 1985: Selected techniques for assessing weather modification: Texas hail suppression case. *Journal of Weather Modification*, 17:18-22.

An operational hail suppression project in the Texas Panhandle areas in 1970-1976 was evaluated using a variety of graphical display methods and statistical techniques. When using a historical target-control approach, the findings indicate a significant 48% reduction of hail insurance loss/cost values in the two-county target area during the seeding period. The results were compared with a hail-suppression project in Kansas, which showed comparable reduction in the target area. The exploratory techniques are shown to be useful in deciding about further use of more elaborate statistical techniques.

Hsu, C.-F., and F. A. Huff, 1985: Assessment of problems, successes, and failures in past weather modification projects. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 649-653.

No abstract.

Hsu, C.-F., F. A. Huff, and S. A. Changnon, 1985: Assessment of statistical-physical techniques for evaluating operational weather modification projects. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 327-332.

No abstract.

Huff, F. A., 1990: Time distributions of heavy rainstorms in Illinois. Circular 173. Illinois State Water Survey, Champaign-Urbana, IL, 18 pp.

No abstract.

Huff, F. A., 1987: Summary of several radar echo studies for weather modification in Illinois. *Journal of Weather Modification*, 19:10.

No abstract.

Huggins, A. W., 1992: Mapping supercooled liquid water with a mobile radiometer. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 102-107.

No abstract.

Huggins, A. W., 1990: Investigations of winter mountain storms in Utah during the 1989 Utah/NOAA field program. Final Report to Utah Division of Water Resources, subcontract under NOAA FY 89 Cooperative Agreement. Atmospheric Sciences Center, Desert Research Institute, Reno, NV, 98 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Huggins, A. W., 1990: Investigations of winter mountain storms in Utah during the 1987 Utah/NOAA field program. Final Report to Utah Division of Water Resources, subcontract under NOAA FY 87 Cooperative Agreement. Atmospheric Sciences Center, Desert Research Institute, Reno, NV, 212 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Huggins, A. W., R. J. Meitín, and R. F. Reinking, 1990: Comparison of radiometric measurements of cloud liquid water near a mountain crest and over a downwind valley. Proceedings, 5th Conference on Mountain Meteorology, Boulder, CO, June 25-29, 1990. American Meteorological Society, Boston, MA, 135-142.

No abstract.

Huggins, A. W., and K. Sassen, 1990: A high altitude ground-based cloud seeding experiment conducted in southern Utah. *Journal of Weather Modification*, 22:18-29.

A wintertime ground-based cloud seeding experiment conducted as part of the 1989 Utah/NOAA cooperative weather modification program is described. The results from one experiment on 3 February 1989 are presented. Meteorological conditions led to the development of orographic clouds over the Tushar Mountains of southern Utah which appeared to be nearly ideal for seeding operations. Radiometrically measured liquid water was abundant in the vicinity of seeding generators and the water appeared to be sufficiently supercooled to enable nucleation by silver iodide.

The experiment entailed pulsed releases of silver iodide from high altitude generators located on upwind ridges of the Tushar Mountains. A K_a-band radar, aspirated PMS 2D-C probe, and manual microphysics observations were used to monitor precipitation 10-13 km downwind of the seeding generators. Snow samples were also collected periodically and analyzed for silver content. The overall results were disconcerting in that two estimated periods of effect showed no enhanced silver content, and no clear microphysical or radar seeding signatures due to large background variability produced by a propagating mesoscale cloud feature, and natural snow characteristics which resembled the expected characteristics due to seeding. A third period of effect had apparent microphysical and radar signatures, but also lacked the presence of silver in the snow. Targeting of the single downwind ground target apparently failed in this case due to inadequate wind documentation in the cloud layer, remote-generator malfunction, or fallout of the seeded plume upwind of the target.

Huggins, A. W., A. B. Long, and B. A. Campistron, 1989: The impact of mesoscale precipitation bands on liquid water and precipitation efficiency in a winter storm in Utah. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, 55-58.

No abstract.

Huston, M. W., 1991: One- and two-dimensional model results compared with observations from a North Dakota cloud. M.S. thesis, Department of Meteorology, South Dakota School of Mines & Technology, Rapid City, SD, 97 pp.

No abstract.

Huston, M. W., A. G. Detwiler, F. J. Kopp, and J. L. Stith, 1991: Observations and model simulations of transport and precipitation development in a seeded cumulus congestus cloud. *Journal of Applied Meteorology*, 30:1389-1406.

Observations made by three instrumented aircraft, a Doppler radar, and other data sources were used to follow the initiation and development of precipitation in a small cumulus congestus cloud. The cloud was seeded at its base using an airborne silver iodide solution burner. Sulfur hexafluoride tracer gas was released along with the seeding material. Analyzers on two instrumented aircraft detected the tracer gas during subsequent cloud penetrations as it was carried up into the cloud along with the seeding agent. Ice developed initially in the upper regions of the cloud near the -10°C level ~15 min after the commencement of seeding. This is consistent with primary nucleation by the seeding agent. The cloud developed millimeter-size graupel within the following few minutes. A radar echo approaching 40 dBZ subsequently developed. The echo was observed to descend through the cloud as the cloud dissipated.

One-dimensional, steady-state and two-dimensional, time-dependent bulk water models were used to simulate this cloud. The one-dimensional model produced realistic values for updraft speeds allowing credible estimates of time required for transport from cloud base to upper regions of the cloud. The development of precipitation in the two-dimensional simulation resembled that in the observed cloud. Precipitation developed through riming of snow to graupel. In both the observed and simulated clouds, precipitation development was limited by cloud lifetime. Both clouds collapsed at a time when they were still generating ample supercooled water in their updrafts. Total precipitation on the ground from the seeded cloud simulations was ~5 times the radar estimated rainfall total of 0.5 mm from the observed seeded cloud. This occurred despite the fact that the simulated cloud went through an accelerated life cycle compared to the observed cloud. A comparison between simulations with a natural ice process and with cloud base release of silver iodide shows that seeding accelerated precipitation formation in the model cloud leading to a fourfold increase in total precipitation for the seeded cases compared to the natural one.

Johnson, H. L., 1986: The effectiveness of cloud seeding in North Dakota: 1976-1982. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 137-138.

No abstract.

Johnson, H. L., 1985: An evaluation of the North Dakota Cloud Modification Project: 1976-1982. Final Report to the North Dakota Weather Modification Board. Oklahoma Climatological Survey, Norman, OK, 35 pp.

No abstract.

Johnson, H. L., and M. P. Foster, 1985: A statistical study of the North Dakota Cloud Modification Project. Final Report to the North Dakota Weather Modification Board. Oklahoma Climatological Survey, Norman, OK, 58 pp.

No abstract.

Johnson, H. L., 1983: An evaluation of the 1981 North Dakota Cloud Modification Project. Final Report to the North Dakota Weather Modification Board. Oklahoma Climatological Survey, Norman, OK, 92 pp.

No abstract.

Johnson, J. E., R. C. Coon, and J. W. Enz, 1989: Economic benefits of crop hail reduction efforts in North Dakota. Agricultural Economics Report No. 247, Agricultural Experiment Station, North Dakota State University, Fargo, ND, 26 pp.

No abstract.

Johnson, L. R., and P. L. Smith, 1990: Estimation of convective rain volumes utilizing the area-time-integral technique. Preprints, 8th Conference on Hydrometeorology, Kananaskis Provincial Park, Alberta, Canada, October 22-26, 1990. American Meteorological Society, Boston, MA, 165-168.

No abstract.

Jung, J. A., 1990: Preliminary field experiments of Snomax™ on cumulus mediocris clouds to artificially induce the production of ice particles. *Journal of Weather Modification*, 22:153-157.

Snowmax™ Snow Inducer, *Pseudomonas syringae*, has undergone preliminary field studies to determine its ability to produce ice particles in cumulus-type clouds. Initial results show the production of ice particles at concentrations of 100's/liter within 8 minutes after seeding with Snowmax™ at temperatures near -5°C.

Kennedy, P. C., N. E. Westcott, and R. W. Scott, 1990: Single Doppler radar observations of a mini-tornado. Preprints, 16th Conference on Severe Local Storms, Kananaskis Provincial Park, Alberta, Canada, October 22-26, 1990. American Meteorological Society, Boston, MA, 209-212.

No abstract.

Kidder, S. Q., and H. T. Ochs III, 1987: A low-cost system for the acquisition and display of digital GOES satellite images. *Bulletin of the American Meteorological Society*, 68:1251-1253.

Using new technology, an inexpensive, high quality system for the display of digital GOES images has been developed, which is suitable for use at remote field sites. The digital data are acquired at high speed (up to 10,000 baud) over ordinary telephone lines. The system allows the display of satellite images from either the viewpoint of the satellite or remapped into an azimuthal-equidistant map projection, which allows direct, undistorted comparison with radar displays. The images can be enhanced with several built-in algorithms, and images at several resolutions up to the limits of the GOES satellite can be displayed. Images processed with this system have proved useful for both forecasting and operational decision making in a meteorological field experiment.

Kim, K., B. Gardiner, and J. Hallett, 1986: Raindrop formation in convective clouds: A comparative study. Preprints, Conference on Cloud Physics, Snowmass, CO, September 22-26, 1986. American Meteorological Society, Boston, MA, Vol. 2, 60-63.

No abstract.

Klimowski, B. A., and J. D. Marwitz, 1992: Developing flow structure of a severe squall line. Preprints, 5th Conference on Mesoscale Processes, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 227-232.

No abstract.

Klimowski, B. A., and J. D. Marwitz, 1990: Single Doppler analyses of a severe squall line and gust front. Preprints, 16th Conference on Severe Local Storms, Kananaskis Provincial Park, Alberta, Canada, October 22-26, 1990. American Meteorological Society, Boston, MA, 252-255.

No abstract.

Knapp, H. V., A. Durgunoglu, and S. A. Changnon, 1988: Effects of added summer rainfall on the hydrologic cycle of Midwestern watersheds. *Journal of Weather Modification*, 20:67-74.

The effects of added summer rainfall on agricultural areas in Illinois and the Midwest were investigated by using a quasi-distributed-parameter watershed model. Increases in summer convective rainfall during July-August were simulated and used in the model to describe the changes in soil moisture, crop water use, shallow ground water, and streamflow conditions which could potentially result from precipitation augmentation practices. Two periods, representing very dry and very wet conditions, were used in the simulations with 10% to 25% precipitation increases. Results suggest that the greatest proportion of additional summer rainfall eventually percolates into ground water, and that less than 25% of the precipitation increase is used by the crops. Simulated increases in summer rainfall offer limited utility in reducing crop water stress because the rainfall events do not always coincide with the period of greatest crop water need. Methods, such as irrigation, which provide additional water at a specified time and amount can produce significant benefits to the plants.

Knight, C. A., and L. J. Miller, 1990: First 5-cm radar echoes at low dBZ values in convective clouds. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 716-721.

No abstract.

Kopp, F. J., and H. D. Orville, 1990: The use of a cloud model to predict convective and stratiform clouds and precipitation. Preprints, 16th Conference on Severe Local Storms, Kananaskis Provincial Park, Alberta, Canada, October 22-26, 1990. American Meteorological Society, Boston, MA, 322-327.

No abstract.

Kopp, F. J., H. D. Orville, J. A. Jung, and R. T. McNider, 1990: A parameterization of radiation heating at the surface in a numerical cloud model. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, J81-J84.

No abstract.

Kopp, F. J., 1988: A preliminary numerical experiment in simulating the dispersion of SF_6. *Journal of Weather Modification*, 20:75-81.

A numerical simulation of an SF_6 tracer experiment conducted on July 19, 1985, in North Dakota has been made. Both SF_6 and AgI seeding are simulated in the model, although not concurrently. Only one seeding agent is simulated in a particular run of the model. The numerical experiments show that the SF_6 and AgI will disperse in a similar fashion initially but, as the AgI is activated inside the cloud, there will be some differences. The development of detectable ice and precipitation as a result of AgI seeding will likely diverge somewhat from the SF_6 dispersion.

Kunkel, K. E., S. E. Hollinger, and F. Kogan, 1991: Soil moisture/evaporation/precipitation feedback. A case study of the 1988 drought. Proceedings, 10th Conference on Biometeorology and Aerobiology (Special Session on Hydrometeorology), Salt Lake City, UT, September 10-13, 1991. American Meteorological Society, Boston, MA, J42-J45.

No abstract.

Lamb, D., D. Mitchell, and R. Blumenstein, 1986: Snow chemistry in relation to precipitation growth forms. Preprints, Conference on Cloud Physics, Snowmass, CO, September 22-26, 1986. American Meteorological Society, Boston, MA, Vol. 2, 77-80.

No abstract.

Lamb, D., and R. L. Pitter, 1985: Examination of selection mechanisms operating during precipitation formation. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, I:41-44.

No abstract.

Liao, L., and K. Sassen, 1992: Theoretical investigation of the relationship between ice mass content and K_a-band radar reflectivity factor. Proceedings, 11th International Conference on Clouds and Precipitation, Montreal, Canada, August 17-21, 1992. International Commission on Clouds and Precipitation, International Association of Meteorology and Atmospheric Physics, Innsbruck, Austria, 1005-1008.

No abstract.

Liao, L., and K. Sassen, 1991: K_a-band radar studies of winter storms from the 1991 Utah/NOAA Cooperative Weather Modification Program. Final Report, Utah subcontract 91-2017 under NOAA Cooperative Agreement NA89RAH09090. Department of Meteorology, University of Utah, Salt Lake City, UT, 62 pp.

No abstract.

Long, A. B., B. A. Campistron, and A. W. Huggins, 1990: Investigations of a winter mountain storm in Utah. Part I: Synoptic analyses, mesoscale kinematics, and water release rates. *Journal of the Atmospheric Sciences*, 47:1302-1322.

A winter storm passing across the north-south-oriented Tushar Mountains in southwest Utah is investigated in this multipart paper. This Part I describes the evolving synoptic pattern, mesoscale kinematics, and calculated water release rates (condensation or deposition) in clouds over the western upslope part of the mountains. Horizontal mesoscale kinematic variables come from direct application of Volume Velocity Processing to single C-band Doppler radar data. Water release rates are computed from updrafts derived from the radar data and from the vertical gradient of saturation mixing ratio obtained from soundings.

In Stage I of the storm, altostratus was present on the leading side of a long-wave trough. Weak updrafts occurred only at the higher altitudes within the clouds where there was convergence and large-scale synoptically forced lift. Downdrafts as great as -0.6 m s^{-1} occurred in the lower parts of

the cloud where there was divergence. The downdrafts were induced in part by sublimation cooling of solid (ice) precipitation falling from the altostratus. Only virga was observed and the radar echoes did not reach the surface.

Stage II was initially dominated by passage of a short-wave aloft. Drier air associated with the short-wave led to complete evaporation of the altostratus of Stage I. The lower parts of the cloud (<4.5 km MSL) eventually redeveloped into altocumulus.

Later in Stage II, the wind veered more perpendicular to the mountains. Simultaneously, convergence developed in the lower 900-1200 m of the atmosphere, and mesoscale updrafts of 0.1-0.2 m s^{-1} were calculated. Maxima in the water release rate were associated with the updrafts.

During Stage III, a passing cold front influenced the kinematics and cloud and precipitation. From prior to frontal passage to a few hours afterward, the wind beneath the frontal surface veered from southwesterly to northerly. There was strong convergence at low altitudes just upwind of the Tushar Mountains. It was accompanied by strong, deep mesoscale updrafts extending from near the ground up through the frontal surface and by water release maxima.

The storm changed character after the wind at low altitudes had veered to northerly and had become parallel to the Tushar Mountains. Convergence maxima continued to be present beneath the frontal surface but weaker. They preceded by ~0.5 h maxima in the convergence above the frontal surface. Associated with these paired convergence features were updraft maxima located above the frontal surface. Water release rates were generally lower than earlier in Stage III. The decrease was greatest at low altitudes beneath the frontal surface where the wind had veered to northerly, where there was little uplift by the Tushar Mountains, and where updrafts were weak. Above the frontal surface, the decrease in water release rate was not as great inasmuch as lift by the frontal surface was still occurring.

The storm dissipated in Stage IV. The axis of the longwave trough passed through the area, winds at higher altitudes beneath the frontal surface veered more northerly, and there was substantial drying at all altitudes above and below the frontal surface. The winds beneath the frontal surface were divergent, indicative of subsidence, and mesoscale downdrafts were present.

Long, A. B., 1988: On the precipitation efficiency of a winter mountain storm in Utah. Preprints, 11th Conference on Weather Modification, Edmonton, Alberta, Canada, October 6-8, 1987. American Meteorological Society, Boston, MA, 64-67.

No abstract.

Long, A. B., 1987: 1987 Field Operations Report—Utah/NOAA Cooperative Weather Modification Research Program. For Utah Department of Natural Resources, Division of Water Resources. Atmospheric Sciences Center, Desert Research Institute, Reno, NV, 133 pp.

No abstract.

Long, A. B., 1987: 1986 Field Operations and Analysis Plan—Utah/NOAA Cooperative Weather Modification Research Program. For Utah Department of Natural Resources, Division of Water Resources. Atmospheric Sciences Center, Desert Research Institute, Reno, NV, 78 pp.

No abstract.

Long, A. B., 1986: Investigations of winter mountain storms in Utah. Final Report, Utah Division of Water Resources, NOAA Cooperative Agreements NA84RAD05125, NA85RAH05031, NA86RAH06052. Atmospheric Sciences Center, Desert Research Institute, Reno, NV, 350 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Long, A. B., 1986: Mesoscale air motions and supercooled liquid water development in winter clouds in a mountainous region. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 192-197.

No abstract.

Long, A. B., K. Sassen, J. Snider, and N. Fukuta, 1986: Remote sensing investigation of the mesoscale kinematics and the microphysics of a winter mountain storm. Preprints, 23rd Conference on Radar Meteorology and Conference on Cloud Physics, Snowmass, CO, September 22-26, 1986. American Meteorological Society, Boston, MA, Vol. 3, J237-J240.

No abstract.

Long, A. B., N. Fukuta, L. O. Grant, T. J. Henderson, R. A. Kropfli, W. R. Moninger, C. K. Mueller, R. M. Rauber, K. Sassen, J. B. Snider, H. R. Swart, T. Uttal, P. A. Walsh, J. W. Wilson, and R. W. Winther, 1985: Joint remote-sensing, radar, and surface microphysical investigations of winter orographic clouds in central Utah, USA. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 175-180.

No abstract.

Long, A. B., 1984: Physical investigations of winter orographic clouds in Utah. Final Report, Utah Division of Water Resources, NOAA Cooperative Agreement NA82RAD05125. Atmospheric Sciences Center, Desert Research Institute, Reno, NV, 286 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Long, A. B., and P. A. Walsh, 1984: Radiometric detection and measurement of liquid water in wintertime orographic clouds. Extended Abstracts, 9th Conference on Weather Modification, Park City, UT, May 21-23, 1984. American Meteorological Society, Boston, MA, 55-56.

No abstract.

López, R. E., R. F. Reinking, J. Hallett, and D. Rosenfeld, 1985: 5-cm radar echoes and their microphysical significance in Florida cumuli. *Journal of Geophysical Research*, 90(D6):10,667-10,673.

Aircraft microphysical and 5-cm radar data from the second Florida Area Cumulus Experiment (FACE-2) have been interrelated to study the development of precipitation in Florida cumuli. Both sets of data demonstrate the importance of the generation of large drops not only at temperatures warmer than freezing but also at altitudes where drops become supercooled. The radar data and, to a limited extent, the microphysical data support the suggestion that a considerable number of Florida cumuli reach very substantial supercoolings, to -10°C or -20°C for example, before producing drops large enough to

generate a first echo. The existence of high updraft speeds, as detected by both the aircraft platform and the radar, implies short transit times of the droplets upward through the clouds and adds credibility to these observations. The radar data further indicate that if a cloud can grow above the -10°C level before generating an echo, then it will probably grow to much greater final altitudes than one that generates a first echo at temperature levels warmer than freezing. This may result from updrafts that rise free of the load of precipitation-size drops in transit to the higher altitudes and then are enhanced owing to the release of latent heat of fusion derived from the larger amounts of supercooled liquid water transported to the higher altitudes, where a high rate of heat input from accelerated freezing is relatively more effective in maintaining convection.

López, R. E., R. F. Reinking, J. Hallett, and J. Jordan, 1982: 5-cm radar echoes and their microphysical significance in Florida cumuli. Preprints, Conference on Cloud Physics, Chicago, IL, November 15-18, 1982. American Meteorological Society, Boston, MA, 183-186.

No abstract.

Martner, B. E., J. D. Marwitz, and R. A. Kropfli, 1992: Radar observations of transport and diffusion in clouds and precipitation using TRACIR. *Journal of Atmospheric and Oceanic Technology*, 9:226-241.

A remote-sensing technique called TRACIR (tracking air with circular-polarization radar) was developed recently for studying air-parcel trajectories in clouds. The technique uses a dual-circular-polarization radar to detect microwave chaff fibers that serve as tracers of the air motion. The radar is able to detect the chaff inside clouds and precipitation by measuring the circular-depolarization ratio, which is much higher for chaff than for hydrometeors. Chaff concentrations are also estimated by the technique, thus permitting turbulent diffusion in clouds to be examined. Demonstrations of TRACIR's capabilities are presented for three cases in which chaff was used to simulate the movement of cloud-seeding nuclei in clouds and precipitation. In two cases involving airborne chaff releases, the gradual drift and diffusion of chaff in a stratiform cloud are contrasted with its abrupt transport and dispersion in a convective cloud. In the third case study, the technique successfully detected a plume of chaff released from the ground in a snowstorm. In each case, the radar data provided three-dimensional visualizations of the extent of the chaff region and maps of the chaff concentration with excellent spatial and temporal resolution.

Martner, B. E., 1990: Radar observations of transport and diffusion of chaff in a stratus cloud. Preprints, 9th Symposium on Turbulence and Diffusion, Roskilde, Denmark, April 30-May 3, 1990. American Meteorological Society, Boston, MA, 115-118.

No abstract.

Martner, B. E., and J. D. Marwitz, 1990: Transport and diffusion of chaff in a convective cloud. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 722-729.

No abstract.

Meitín, R. J., R. A. Brown, and J. G. Meitín, 1991: Comparison of airborne dual-Doppler and airborne/ground-based dual-Doppler analyses of North Dakota thunderstorms. Preprints, 25th International Conference on Radar Meteorology, Paris, France, June 24-28, 1991. American Meteorological Society, Boston, MA, 474-477.

No abstract.

Meitín, R. J., and R. A. Brown, 1990: A dual-Doppler analysis of North Dakota thunderstorms using airborne and ground-based radars. Preprints, 16th Conference on Severe Local Storms, Kananaskis Provincial Park, Alberta, Canada, October 22-26, 1990. American Meteorological Society, Boston, MA, 225-230.

No abstract.

Meitín, R. J., and R. F. Reinking, 1989: A Doppler radar analysis of a winter mountain storm. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:93-96.

No abstract.

Meitín, R. J., and R. F. Reinking, 1989: A preliminary radar analysis of a winter mountain storm. Preprints, 24th Conference on Radar Meteorology, Tallahassee, FL, March 27-31, 1989. American Meteorological Society, Boston, MA, 490-493.

No abstract.

Miller, J. R., Jr., and M. J. Fuhs, 1986: Results of hail suppression efforts in North Dakota as shown by crop hail insurance data. *Journal of Weather Modification*, 19:45-49.

No abstract.

Miller, J. R., Jr., and M. J. Fuhs, 1986: Results of hail suppression efforts in North Dakota as shown by crop hail insurance data. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 27-30.

No abstract.

Miller, J. R., Jr., R. L. Rose, and T. C. Jameson, 1986: Transfer of weather modification technology to the North Dakota Cloud Modification Project. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 27-30.

No abstract.

Miller, J. R., Jr., and P. L. Smith, 1986: Some characteristics of radar first echoes in the High Plains. *Journal of Weather Modification*, 18:95-101.

Radar first echoes identified in northeast Colorado and southwestern North Dakota convective clouds are examined. The first-echo temperatures in Colorado appear related to thermodynamic energy in the sounding rather than to seeding effects, when compared to earlier South Dakota studies. Mean first-echo temperatures in North Dakota are related to model-predicted maximum updraft speeds. New echoes developing near existing radar echoes have lower temperatures than ones developing far away from existing echoes. These results suggest that cloud dynamics play an important role in the temperature and height of first-echo formation. About one-third of the first-echo temperatures are higher than -5°C, which suggests that collision-coalescence rain processes may be important in High Plains clouds.

Miller, J. R., Jr., 1984: Seeding results favor small clouds in China, South Dakota, and Yugoslavia. *Journal of Weather Modification*, 16:27-29.

A comparison of four cloud seeding projects on three continents indicates that smaller clouds may give much greater percentage increases in rainfall than do larger ones in weather modification efforts. Project Cloud Catcher, a randomized single-cloud project in South Dakota 1969-1970, is compared here to a randomized two-area project in Fugian province, China, 1975, 1977, 1981. Also compared are rainfall results from two non-randomized, hail suppression efforts in South Dakota, 1972-1976, and in Serbia, Yugoslavia, 1970-1979.

Miller, J. R., Jr., S. Ionescu-Niscov, D. L. Priegnitz, A. A. Doneaud, J. H. Hirsch, and P. L. Smith, 1983: Development of physical evaluation techniques for the North Dakota Cloud Modification Project. *Journal of Weather Modification*, 15:34-39.

This paper is a summary progress report on the development of physical evaluation techniques aimed at assessing the effects of ice phase cloud seeding on summertime convective storms in North Dakota. The use of digitized 5-cm radar data, rawinsonde data, and one-dimensional cloud model results are discussed in this techniques development effort. These preliminary results suggest favorable tendencies toward successful rainfall enhancement. Various biases are presented and suggestions for further research are made.

Mitchell, D. L., 1991: Evolution of snow-size spectra in cyclonic storms. Part II: Deviations from the exponential form. *Journal of the Atmospheric Sciences*, 48:1885-1889.

Using a form of the stochastic collection equation, conservation equations for the first and second moments of the mass were parameterized to yield a height-dependent one-dimensional snow growth model for unrimed stratiform snowfall. Snow-size distributions were represented by the form $N(D) = N_0 D^{\nu} \exp(-\lambda D)$, and solutions for λ and N_0 were obtained. The spectral parameter ν allows the concentration of the smaller ice particles to deviate from the exponential form and controls the degree of subexponential or superexponential behavior. The sub- and superexponential spectra analyzed in this study had ν values of 1 and -1, respectively.

A number of simple analytical relationships was developed that describes various properties of size distributions, regardless of the particle type involved. A method was developed for obtaining the three parameters of the size distribution used in the model from measured size distributions. In addition, an expression was derived to relate the two λ of an exponentially parameterized and a nonexponentially parameterized size distribution.

The effect of sub- and superexponential spectra on the evolution of snow-size spectra by vapor diffusion and aggregation was examined using a steady-state, fixed snowfall rate profile. Diffusional growth rates of individual ice crystals (no aggregates) were relatively low when the size distribution was constrained to be superexponential in form. This resulted in steeper spectra (smaller crystal sizes) and higher ice-crystal number concentrations. The diffusional growth rate of individual ice crystals for subexponential spectra was relatively high. Subexponential spectra were characterized by broader distributions and lower ice crystal number concentrations. Aggregation was the only growth process that substantially increased ice particle sizes for superexponential spectra, while both vapor diffusion (in the upper cloud) and aggregation (in the mid-to-lower cloud) contributed substantially to size increases for subexponential spectra.

An expression for the aggregation efficiency was formulated. The primary factors governing aggregation appear to be the aggregation efficiency, the ice particle number concentration, and the mean diameter. The expression may be useful in larger numerical cloud models. Mean aggregation rate constants were determined for sub- and superexponential spectra, and for exponential spectra. The mean aggregation rate constant for superexponential spectra was approximately 50% greater than for subexponential spectra.

Finally, it was found that the degree of subexponential behavior predicted when $\nu = 1$ was consistent with that observed in various levels in stratiform clouds. However, better measurements are needed to substantiate this finding.

Mitchell, D. L., and R. D. Borys, 1991: A field instrument for examining in-cloud scavenging mechanisms by snow. Proceedings, 5th International Conference on Precipitation Scavenging and Atmosphere-Surface Exchange Processes, [*Award-Winning Poster*], Richland, WA, July 15-19, 1991. Electric Power Research Institute, U.S. Department of Energy, U.S. Environmental Protection Agency, NOAA, Washington, DC.

No abstract.

Mitchell, D. L., 1990: Evolution of snow-size spectra predicted by the growth processes of diffusion, aggregation and riming. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 270-277.

No abstract.

Mitchell, D. L., 1990: Modeling of microphysical and radiative properties of cirrus clouds. Preprints, 7th Conference on Atmospheric Radiation, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, J96-J101.

No abstract.

Mitchell, D. L., R. Zhang, and R. L. Pitter, 1990: Mass-dimensional relationships for ice particles and the influence of riming on snowfall rates. *Journal of Applied Meteorology*, 29:153-163.

The masses, dimensions, and habits of over 2800 natural ice particles precipitating from orographic winter storms in the central Sierra Nevada were obtained using photomicrographs. Ice particles that could be unambiguously classified were used to generate empirical expressions relating snow particle masses and dimensions. Many of the ice particle types had not been investigated previously. The influence of riming and aggregation on ice particle masses was examined. When possible, comparisons are made between these results and those of other experimental observations. By incorporating these mass-dimensional relationships into an expression for the ice mass content in a snowstorm, it was possible to estimate the mass fraction of the fresh snowpack resulting from accreted supercooled cloud water. The results from two storms analyzed suggest that about 30% to 40% of the deposited snow is composed of accreted cloud water during moderately riming snowfall.

Mitchell, D. L., and R. D. Borys, 1989: The effect of cloud and seeding on snow-size spectra and cloud droplet removal. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:217-220.

No abstract.

Musil, D. J., P. L. Smith, and N. E. Westcott, 1990: Armored aircraft observations of a severe hailstorm in Illinois. Preprints, 16th Conference on Severe Local Storms, Kananaskis Provincial Park, Alberta, Canada, October 22-26, 1990. American Meteorological Society, Boston, MA, 485-488.

No abstract.

Nagamoto, C. T., F. Parungo, R. Reinking, R. Pueschel, and T. Gerish, 1983: Acid clouds and precipitation in eastern Colorado. *Atmospheric Environment*, 17:1073-1082.

Rain and snow samples were collected at the eastern foothills of the Rocky Mountains and analyzed for chemical composition. Many precipitation samples had pH values considerably more acidic than the 5.6 value of pure water containing only an equilibrium amount of atmospheric CO_2. Clear and considerable dependencies of the acidity on seasonal synoptic scale weather patterns are demonstrated. Cloud water samples, collected by aircraft over eastern Colorado, also showed low pH values. The acidity of clouds was greatest near the city of Denver.

Nagamoto, C., F. Parungo, and J. Hallett, 1982: Analysis of silver in individual ice particles after cloud seeding. Extended Abstracts, Conference on Cloud Physics, Chicago, IL, November 15-18, 1982. American Meteorological Society, Boston, MA, 378-380.

No abstract.

Nair, U. S., 1991: Modeling and observational study of the June 28, 1989, case from the North Dakota Thunderstorm Project. M.S. thesis, Department of Meteorology, South Dakota School of Mines & Technology, Rapid City, SD, 153 pp.

No abstract.

Ochs, H. T., III, and S. Q. Kidder, 1989: A forecasting/nowcasting system for remote field locations. *Journal of Atmospheric and Oceanic Technology*, 6:218-221.

Vast quantities of frequently updated weather data for both forecasting and nowcasting are generally required in meteorological field programs. The continuing synthesis of this data to suit specific operations is best accomplished using computers. Recent advances in telecommunications and computer hardware have allowed improved assimilation and presentation of weather data to remote field sites at significantly reduced costs. This paper describes a forecasting/nowcasting system designed and assembled to support a weather modification field project in Illinois. With minor modifications, this system can be located anywhere that has access to electrical power and standard telephone lines. The use of new technology with on-site computer capabilities allows rapid generation of products specifically tailored to meet the requirements of individual field projects, both for forecasting the operations and nowcasting during operations.

Offutt, S. E., P. Garcia, and M. Pinar, 1985: Potential benefits to agriculture of augmenting precipitation. *Journal of Weather Modification*, 17:23-29.

This paper discusses ongoing research intended to develop a clearer understanding of the impact of weather modification on a portion of the agricultural sector of the U.S. economy, the feed-livestock complex. The research framework models the interactive effects of the changing weather, technology, government policies, and demand on market prices. Supply and demand relations may be estimated and solved within the context of a simultaneous equation econometric model. Within the model, crop yield response relations must be estimated at an appropriate level of geographical aggregation to ensure uniform measurement of weather modification effects. An econometric technique, based on the use of binary variables, is proposed as a means for selecting geographical aggregates. The transmission of the "weather effect" to the agricultural sector is accomplished in the supply-demand model. Benefits accruing to various market participants may then be identified under alternative scenarios of weather modification.

Orr, B. W., 1990: Boundary-layer momentum budgets as determined from a single-scanning Doppler radar. M.S. thesis, Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 116 pp.

The Velocity Azimuth Display (VAD) technique is extended to third-order turbulent velocity statistics. By applying this extended VAD technique to a single-scanning Doppler radar, a solution for the horizontal turbulent momentum flux budget is obtained. All terms excluding the buoyancy, pressure, and eddy dissipation terms can be solved for directly. High-resolution measurements of the momentum flux budget can then be studied in both space and time. Specifically, the third-order turbulent transport term can be examined.

Three data sets characterized by hot, clear summertime planetary boundary layers (PBL) are analyzed using this extended VAD technique. These data show turbulent transport to be very significant throughout the day and night. Daytime values were observed to be of the same order or slightly larger than shear production. At night, shear production dominated but turbulent transport was still of significant magnitude. Other notable features were the high degree of variability in all turbulent quantities in both space and time. The large contribution from turbulent transport and the high degree of nonstationarity in the turbulence field are in contrast to most other field measurements. Brief explanations are given for these differences. Comparisons with computer modeling studies are also made which agree more closely with the radar analysis than did the field studies.

Orville, H. D., 1992: A review of theoretical developments in weather modification in the past twenty years. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 35-41.

No abstract.

Orville, H. D., and N. C. Knight, 1992: An example of a research experience for undergraduates. *Bulletin of the American Meteorological Society*, 73:161-167.

This paper illustrates the planning and conduct of a Research Experience for Undergraduates (REU) project associated with the 1989 North Dakota Thunderstorm Project held in June/July of that year near Bismarck, North Dakota. This was a National Science Foundation/REU site award and required students from more than one school to participate. Ten students from seven schools were selected. They operated instruments on research aircraft, ran atmospheric sounding equipment, intercepted hailstorms and tested hailstone sensors, and coordinated Doppler radar data acquisition.

Orville, H. D., F. J. Kopp, U. S. Nair, J. L. Stith, and R. Rhinehart, 1990: On the origin of ice in strong convective cells. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 16-20.

No abstract.

Orville, H. D., W. R. Cotton, L. G. Davis, D. B. Johnson, and R. M. Rauber, 1986: A program of federal/state/local cooperative weather modification research: Design considerations. Part I: Hypothesis, description, and assessment. Final Report, NOAA Contract NA83RAC00088, L. O. Grant (ed.). Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 36 pp. + appendices (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Parungo, F. P., 1983: Comments on "Measurements of cloud nuclei in the effluents from launches of liquid- and solid-fueled rockets." *Journal of Climate and Applied Meteorology*, 22(8):1472-1473.

No abstract.

Parungo, F. P., and H. K. Weickmann, 1983: Ice crystal growth at (-8 ±2)°C. *Journal de Recherches Atmospheriques*, 17(2):139-156.

In investigations made on (1) snow crystals collected at ground level, (2) hydrometeors replicated in clouds, and (3) ice crystals produced in the laboratory, two major particle forms were observed at (-8 ±2)°C: non-crystalline frozen droplets and their conglomerates formed at water saturation; hexagonal thick plates or columns formed at ice supersaturation. The observations are explained as a consequence of the existence of a quasi-liquid layer on the ice surface. The thickness of the layer decreases with decreasing temperature and humidity. At (-8 ±2)°C and water saturation, the ice crystal surface may be fully covered with this liquid-like layer, thus preventing crystalline growth by conversion of vapor-to-ice. Instead, isometric growth takes place in two steps, first vapor to quasi-liquid layer, then quasi-liquid layer to ice. Frozen droplets are produced. Because of the quasi-liquid layer on their surface, the frozen droplets cohere easily on contact to form conglomerates or graupel. However, when the humidity decreases to ice saturation, the quasi-liquid layer disappears and vapor deposition growth becomes the main process to produce hexagonal crystals.

Parungo, F. P., and G. Langer, 1982: Comments on "Properties of pyrotechnic nucleants used in Grossversuch IV." *Journal of Applied Meteorology*, 21:1582-1583.

No abstract.

Parungo, F. P., and C. Nagamoto, 1982: Case study of hydrometeors in Florida cumuli. Preprints, Conference on Cloud Physics, Chicago, IL, November 15-18, 1982. American Meteorological Society, Boston, MA, 366-369.

No abstract.

Parungo, F. P., C. Nagamoto, I. Nolt, M. Dias, and E. Nickerson, 1982: Chemical analysis of cloud water collected over Hawaii. *Journal of Geophysical Research*, 87(C11):8805-8810.

Two types of cloud water collectors were developed, and the devices were used to collect samples around the Hawaiian Islands. The chemical analyses of cloud water showed that Na^+, Cl^-, and $SO_4^=$ ion concentrations were approximately 10^{-4} m; NH_4^+, NO_3^-, and Ca^{++} were 1 order of magnitude lower. The pH values were in the range of 4-5 regardless of sampling locations. The high acidity of cloud water over Hawaii may originate in the ocean or from long-range transport of anthropogenic pollution, in addition to local pollution, if present.

Petersen, M. S., K. E. Kunkel, and P. J. Lamb, 1991: Implementation of a semi-physical model for examining solar radiation in the Midwest. Preprints, 7th Conference on Applied Climatology, Salt Lake City, UT, September 10-13, 1991. American Meteorological Society, Boston, MA, 81-86.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1992: Mechanism of ice crystal habit formation and change. Proceedings, 11th International Conference on Clouds and Precipitation, Montreal, Canada, August 17-21, 1992. International Commission on Clouds and Precipitation, International Association of Meteorology and Atmospheric Physics, Innsbruck, Austria, 79-80.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1991: A mechanism for ice crystal symmetry and for processes of ice crystal growth and interaction. Poster presentation, Annual Meeting of the AAAS, Washington, DC, February 14-19, 1991. American Association for the Advancement of Science, Washington, DC.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1991: Implications of the separation of ions in growing ice crystals. Abstracts, IAMAP Symposia, Vienna, Austria, August 11-24, 1991. International Union of Geodesy and Geophysics, Brussels, Belgium.

No abstract.

Pitter, R. L., and R. Zhang, 1991: Numerical simulation of the scavenging rates of ice crystals of various microphysical characteristics. *Advances in Atmospheric Science*, 8:175-200.

Numerical models of trajectories of small aerosol spheres relative to oblate spheroids were used to determine ice crystal scavenging efficiencies. The models included the effects of aerodynamic flow about the ice particle, gravity, aerosol particle inertia, and drag and electrostatic effects. Two electric configurations of the ice particle were investigated in detail. The first applied a net charge to the ice particle, of magnitude equal to the mean thunderstorm charge distribution, while the second applied a charge distribution, with no net charge, to the ice particle to model the electric multipole charge distribution. The results show that growing ice crystals with electric multipoles are better scavengers than single ice crystals with net thunderstorm charges, especially in the Greenfield gap (0.1 to 1.0 μm), and that larger single crystals are better scavengers than smaller single crystals. The results also show that the low density ice crystals are more effective scavengers with net charges than they are with charge distribution.

Pitter, R. L., and W. G. Finnegan, 1990: An experimental study of effects of soluble salt impurities on ice crystal processes during growth. *Atmospheric Research*, 25:71-88.

Experimental investigations of phenomena associated with the growth and interaction of ice crystals during free-fall in supercooled liquid water clouds are presented. This report focuses on the effects that included inorganic salts have on the microphysical processes. Dilute aqueous solutions of inorganic salts of typical concentrations and chemical composition of atmospheric cloud and precipitation water were used to form supercooled liquid water clouds in a cloud chamber. Subsequent nucleation of ice produced a cloud of rapidly growing ice crystals which simulated atmospheric ice crystal initial growth and interaction. The investigations found that the salt composition affected: (1) ice crystal morphology; (2) orientation of aggregate junctions; and (3) probability of secondary ice formation occurring during an experiment. The results were reproducible and were not as strongly affected by other experimental variabilities as by the chemical composition of the aqueous solution. A conceptual model, based upon the observed freezing potential (the Workman and Reynolds effect) which results from freezing of dilute aqueous solutions is advanced, which explains the observed phenomena.

Pitter, R. L., and W. G. Finnegan, 1990: Ice crystal breeding. *Journal of Weather Modification*, 22:63-68.

When ice crystals rapidly grow and aggregate in the Desert Research Institute (DRI) cloud chamber, they frequently produce new ice crystals without the presence of ice forming nuclei. Ammonium salts, initially present in the cloud water and later detected in the ice crystals, enhanced this phenomenon. The continual ice crystal production was observed at temperatures from -4°C to 30°C, although it occurred more frequently when the ice crystals were long needles or dendrites—highly non-spherical. Ice multiplication and secondary ice formation are commonly used in the meteorological literature to describe the phenomenon. The chemical literature (crystal growth) predates the meteorological literature and describes a similar process that occurs in systems of crystals growing in solution. The chemical literature calls the phenomenon crystal breeding. This paper describes the similarity between the systems and advances of two postulated mechanisms, both of which are consistent with our observations of ice crystal breeding and other observations of crystal breeding in solution.

Pitter, R. L., and W. G. Finnegan, 1990: The effect of solute impurities on morphology of diffusion-grown ice crystals. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 471-472.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1990: The retention of ice crystal structure and habit during diffusional growth. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 93-96.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1989: Development of heterogeneous nucleation theory for application in weather modification. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:131-132.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1989: Ice crystal morphology: What makes snowflakes different, or alike. Preprints, Symposium on the Role of Clouds in Atmospheric Chemistry and Global Climate, Anaheim, CA, January 30-February 3, 1989. American Meteorological Society, Boston, MA, 108-109.

No abstract.

Pitter, R. L., W. G. Finnegan, and L. G. Young, 1989: Electrochemical oxidation-reduction reactions in growing ice crystals: Freezing induced chemical reactions. Proceedings, International Conference on Global and Regional Environmental Atmospheric Chemistry, Beijing, China, May, 466-469.

No abstract.

Pitter, R. L., and R. Zhang, 1989: Effect of internal charge distribution in ice crystals on scavenging of aerosol particles. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, II:643-646.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1988: Field observations of ice crystal formation in clouds at warm temperatures. *Journal of Weather Modification*, 20:54-59.

A field study of the effect of treating a shear line convective cloud with a 20% aqueous solution of ammonium carbonate is described. The results indicate that the presence of certain soluble salts in growing ice crystals may be sufficient to initiate ice crystal multiplication in clouds at temperatures of -4° to -5°C, as measured by a Rosemount instrument, or -3°C, as measured by a reverse flow thermometer. The field results are consistent with laboratory experiments conducted in the Desert Research Institute's cloud chamber, where ice multiplication was observed at temperatures as warm as -4°C. In the cloud chamber experiments, ice multiplication only occurred when crystals were growing rapidly and aggregating. Aggregation was more readily observed when certain soluble salts were added to the water which formed the supercooled cloud. A postulate is advanced as an explanation of the ice multiplication observed in the laboratory and field studies.

Pitter, R. L., and W. G. Finnegan, 1988: Ice electronucleation: Laboratory and field evidence in support of a new mechanism of ice nucleation. *Atmospheric Aerosols and Nucleation*, P. E. Wagner and G. Vali (eds.), Springer-Verlag, Vienna, 713-716.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1988: Studies of cloud microchemical physics. Preprints, 10th International Cloud Physics Conference, IAMAP/IUGG, Bad Homberg, F.R.G., August 15-20, 1988. *Annalen der Meteorologie*, No. 25, ISBN 3-88148-240-7, I:243-245.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1987: Observations of spontaneous ice formation in a cloud chamber: A new process of atmospheric ice multiplication. Preprints, 11th Conference on Weather Modification, Edmonton, Alberta, Canada, October 6-8, 1987. American Meteorological Society, Boston, MA, 52-55.

No abstract.

Pitter, R. L., and W. G. Finnegan, 1986: Effect of the size distribution of falling snow on aerosol particle scavenging. Preprints, Conference on Cloud Physics, Snowmass, CO, September 22-26, 1986. American Meteorological Society, Boston, MA, Vol. 2, 71-74.

No abstract.

Politovich, M., and R. F. Reinking, 1987: Characteristics of updrafts in central Illinois cumuli. Preprints, 11th Conference on Weather Modification, Edmonton, Alberta, Canada, October 6-8, 1987. American Meteorological Society, Boston, MA, 68-71.

No abstract.

Price, P. E., R. D. Farley, J. H. Hirsch, and H. D. Orville, 1986: Microphysical model comparisons of seeded and non-seeded North Dakota clouds. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 27-30.

No abstract.

Price, P. E., 1985: Microphysical model comparisons of seeded and non-seeded North Dakota clouds. M.S. thesis, Department of Meteorology, South Dakota School of Mines & Technology, Rapid City, SD, 70 pp.

A two-dimensional time-dependent cloud model has been used to simulate both the silver iodide and dry ice seeding at cloud top of a rapidly developing convective North Dakota cloud. The two seeding methods produce similar results and both methods are effective in reducing the surface hail accumulations, as well as rainfall accumulations at later times. The seeding results in the earlier generation and fallout of the hail field. The melting hail is the major source of rain.

The model contains bulk water microphysics and a new process is added which involves the conversion of rimed snow into graupel/hail. The inclusion of this riming process reduces the differences between the natural and seeded simulations. The development of large snow and hail fields in the natural simulation is reduced in the riming process. The evolution of the hail field in the natural simulation approaches that of the seeded cases. The accumulated hail and rain at the surface are again reduced by both seeding methods, but by a smaller amount because the rain and hail which reach the surface in the natural simulation are reduced by the inclusion of the riming process.

Priegnitz, D. L., 1991: The interactive radar analysis software (IRAS) package. Preprints, 7th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, New Orleans, LA, January 14-18, 1991. American Meteorological Society, Boston, MA, 173-176.

No abstract.

Priegnitz, D. L., 1990: *Interactive Radar Analysis Software (IRAS).* User's Guide, Version 1.0, 14 February 1990. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 73 pp.

No abstract.

Rauber, R. M., and L. O. Grant, 1985: Supercooled liquid water structure of a shallow orographic cloud system in southern Utah. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 385-390.

No abstract.

Redder, C. R., 1988: Development of empirical equations of ice crystal growth microphysics for modeling and analysis. M.S. thesis, Department of Meteorology, University of Utah, Salt Lake City, UT, 112 pp.

Experimental data on ice crystal growth measured during recent investigations in a supercooled cloud tunnel that suspended ice crystals for time periods up to 30 min at the University of Utah have been analyzed. These experimental investigations previously generated unique data sets of mass, dimensions,

and fall velocity as a function of time under different temperatures and removed some obstacles caused by the lack of proper experimental data that have hindered cloud microphysical research.

The analysis in this thesis was set out to fulfill at least the following four goals using the data sets from the previous experiments. First, some specific features of microphysical theories have been verified with the experimental data. Second, time-dependent equations of mass, dimensions, and fall velocity applicable to different regimes of growth have been developed by considering the measured data and the functional styles of theories and not by merely obtaining a set of best fitting polynomials. Third, an empirical equation was derived by similar means to express the aerodynamic behavior of the falling ice crystal with the relationship among the Reynolds number, the Best number, and the axial ratio. Finally, a set of simplified parameterized equations has been generated that is experimentally consistent and suitable for cloud modeling and analysis.

The empirical equations generated in this thesis based on the specific functional style of the theory have the advantage over the best fit polynomial equations, which have little support from physics and chemistry of the ice crystal growth and are valid only within the range of experimental data.

Redder, C., and N. Fukuta, 1988: Empirical equations of ice crystal growth microphysics for modeling and analysis. Preprints, 10th International Cloud Physics Conference, IAMAP/IUGG, Bad Homburg, F.R.G., August 15-20, 1988. *Annalen der Meteorologie*, No. 25, IBSN 3-88148-240-7, I:12-14.

No abstract.

Reinking, R. F., R. J. Meitín, F. Kopp, H. D. Orville, and J. L. Stith, 1992: Fields of motion and transport within a sheared thunderstorm. *Atmospheric Research*, 28:197-226.

The fields of motion within a small, strongly sheared High Plains thunderstorm are examined using measurements of reflectivity and velocity from an airborne Doppler radar and other in situ measurements. The measurements are complemented by a high resolution two-dimensional numerical simulation of the storm. Implications for predicting storm characteristics, delivery and effectiveness of seeding material, and precipitation efficiency are examined. The numerical model run was made in the forecasting mode 5 h before initial storm development and 7 h before the observations of the mature stage. The main features of the simulated storm structure and motions are very similar to those measured, except that the model produced a vertically and temporally compressed storm. The characteristics of the measured and the modeled storm, in combination, are consistent with other theories and observations that precipitation efficiency is low and a large portion of the processed water substance is transported out through the anvil in thunderstorms that develop in an environment with strong wind speed shears in the vertical. The measurements and the model reveal a quasi-steady-state organization during the mature stage. Although the storm formed in response to surface heating, the simulation and the radar measurements in combination indicate that the relative importance of inflow directly from the surface was diminished during the mature stage and completely cut off during the dissipation stage. Despite the modest size and intensity of this storm, the actual circulation within it was highly three dimensional, and this, of course, could not be directly simulated by the two-dimensional model. Mature-stage inflows between about 3 and 6 km above ground level from a south-flank feeder cell field contributed significantly to the main updraft. Effective delivery of cloud seeding material to a storm like this would be influenced by the three-dimensionality and the relative importance of surface feeding in relation to inflows from levels above the surface. Such features would have to be determined in real time, and state-of-the-art technologies offer the means to do this.

Reinking, R. F., R. J. Meitín, F. Kopp, and H. D. Orville, 1991: Fields of motion and transport within a sheared thunderstorm. Preprints, 2nd International Meeting on Agriculture and Weather Modification, Zamora, Spain, March 12-15, 1991. Ministry of Agriculture, Fisheries, and Nutrition, ISBN 84-87469-15-9-DL:LE-321-1991, Zamora, Spain, 59-66.

No abstract.

Reinking, R. F., J. L. Stith, and R. J. Meitín, 1990: Airborne Doppler radar and *in situ* studies of the transport of ozone and other constituents in feeder cells and anvils. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 698-705.

No abstract.

Reinking, R. F., and R. J. Meitín, 1989: Advances and challenges in obtaining physical evidence for weather modification potentials and effects. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:7-10.

No abstract.

Reinking, R. F., and R. J. Meitín, 1989: Recent progress and needs in obtaining physical evidence for weather modification potentials and effects. *Journal of Weather Modification*, 21:85-93.

Statistical and numerical modeling approaches to assess the effects of cloud seeding require the interactive input of, and understanding derived from, measurements that provide direct evidence of natural and altered development of precipitation. A brief review of recent progress in obtaining physical evidence to evaluate and verify potentials for and effects of precipitation enhancement and hail suppression is presented. Recent findings from the National Oceanic and Atmospheric Administration's Federal/State Cooperative Program in Weather Modification Research are emphasized, but other related results are included. In the context of many significant new advances toward proving hypotheses by direct measurement, a number of remaining needs for measurements and corresponding technologies are identified.

Reinking, R. F., 1988: Perspectives for research in wet chemistry and unintentional cloud modification from the discipline of purposeful cloud modification. *Boundary-Layer Meteorology*, 41:381-405.

Fundamental goals and scientific problems facing researchers in purposeful cloud modification and applicable to air quality pertaining to unintentional cloud modification are defined. These encompass experimental design and verification, transport and dispersion, aerosol and hydrometeor evolution and removal, and the interactive nature of chemical, microphysical, dynamical, and other cloud processes on micro- to mesoscales. Some recent advances in purposeful weather modification are reviewed and parallels are drawn to wet chemistry and unintentional cloud modification. Gains to be made in further cross-fertilization of the disciplines are suggested.

Reinking, R. F., 1987: Chemical-microphysical-dynamical interactions: Parallels in purposeful and unintentional cloud modification. International Conference on Energy Transformations and Interactions with Small-Scale Atmospheric Processes, March 2-6, 1987. Ecole Polytechnique Federal, Lausanne, Switzerland, 15 pp.

No abstract.

Reinking, R. F., and J. F. Boatman, 1987: Upslope precipitation events. Chapter 19, *Mesoscale Meteorology and Forecasting*, P. Ray (ed.). American Meteorological Society, Boston, MA, 437-471.

Plains on the lee side of mountain ranges in the middle latitudes commonly receive their winter precipitation from circulations that are counter to the climatologically prevailing westerlies; moisture-bearing easterly currents are driven up the slopes of the lee-side plains, toward the mountains, by synoptic circulations. "Upslope storms" have been so named under the presumption that advection over the generally rising terrain induces lifting, cloudiness, and precipitation. This term is inexact; the lifting from low to high plains is more subtle than lifting by mountain ranges, and must be considered relative to superimposed lifting over frontal surfaces or by cyclonic convergence. "Upslope," by popular usage, nonetheless suffices to categorize the cloud systems described in this chapter.

Two extremely different driving circulations determine the characteristics of upslope events: the fully developed extratropical cyclone and the shallow arctic anticyclone. Mesoscale forecasting is made difficult by a number of variable and often contradictory factors that include blocking or cyclogenesis induced by the mountain range, depth and vorticity of the synoptic circulations, overriding countercurrents, oceanic or regional sources of moisture, degree and irregularities of topographic lifting, and dynamic and thermodynamic support for various microphysical precipitation-forming processes. Observational studies of the dynamical and microphysical events and processes that cause winter upslope cloudiness and precipitation are reviewed, with the focus on upslope precipitation in the rain shadow of the Rocky Mountains, where the full range of interactive processes and scales comes into play.

Reinking, R. F., 1986: On the communication and practical value of research results. Proceedings, 12th Annual Meeting of the North American Interstate Weather Modification Council, Austin, TX, May 3-5, 1986. Office of the NAIWMC, Mesilla Park, NM, 71-78.

No abstract.

Reinking, R. F., 1986: Research for managing the quantity and quality of precipitation: Perspectives for scientists and policy makers. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 298-303.

No abstract.

Reinking, R. F., and D. A. Griffith, 1986: Recent findings from the State of Utah (session leaders' summary). In: *Physics of Winter Orographic Precipitation and its Modification: Summary of Workshop Presentations*, A. B. Super (ed.), Bureau of Reclamation, P.O. Box 25007, Denver, CO, 35-44.

No abstract.

Reinking, R. F., W. H. Hooke, and W. T. Brennan, 1986: Water, water (but not everywhere). *NOAA*, 16:10-12.

It is in NOAA's interests to define, through basic research, the realities of cloud seeding and, in so doing, to learn more about the water budget of clouds and their precipitation efficiency. An effort of this sort, addressing the atmospheric portion of the hydrologic cycle, not only could permit more productive cloud seeding—the goal of the weather modification operators and users—but also better water management through more accurate quantitative precipitation forecasting, improved runoff prediction, better river flow forecasting, and improvements in other predictive areas in which

NOAA elements have responsibilities. The NOAA Federal-State Cooperative Program in Weather Modification Research is described in light of impending national challenges to water supply and NOAA's responsibilities in water resources management.

Reinking, R. F., 1985: An overview of the NOAA Federal-State Cooperative Program in Weather Modification Research. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 643-648.

No abstract.

Reinking, R. F., and J. F. Boatman, 1984: Upslope precipitation events. Intensive Course on Mesoscale Meteorology and Forecasting, Boulder, CO, June 8-20, 1984. American Meteorological Society, Boston, MA, Section 19, 30 pp.

No abstract.

Riebsame, W. E., S. A. Changnon, and T. R. Karl, 1991: *Drought and Natural Resources Management in the United States. Impacts and Implications of the 1987-89 Drought.* Westview Press, Boulder, CO, 174 pp.

The 1987-89 drought was a signal event in the evolving interrelationships among climate, natural resources management, technology, and society in the United States. Over half of the country experienced severe to extreme drought by midsummer of 1988. Losses upward to $39 billion illustrate the continuing, perhaps growing, vulnerability of many natural resources and economic sectors to drought and other climate fluctuations in the U.S. Despite decades of crop breeding, water system development, and other improvements in climate-sensitive technologies like cloud seeding, the drought demonstrated that the simple lack of "normal" rainfall still provokes serious disruptions in agriculture, water supply, transportation, environmental quality, and other areas. It can affect the health and well-being of millions of people and evoke billions of dollars in government aid. The drought did evoke some successful responses, and lessons from past droughts were profitably applied in some cases. No rapid adoption of weather modification occurred, a condition different than in past major droughts of 1950-1985. Indeed, the successful responses in 1988-89 indicate a greater potential for reducing drought impacts than was observed, especially during the height of the drought in 1988. By diagnosing this case, and placing it in the context of the evolving relationship between climate and society, we seek to point the way toward improved drought management in the future, as well as to better illuminate the path to reduced overall climate vulnerability.

Rodi, A. R., and J. A. Flueck, 1986: A study of aggregate in-cloud seeding effects in winter convective clouds in the High Sierra. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 280-282.

No abstract.

Rogers, D. C., R. M. Rauber, and L. O. Grant, 1986: Studies of wintertime storms over the Tushar Mountains of Utah. Final Report to Utah Division of Water Resources, subcontract under NOAA FY 85 Cooperative Agreement. Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 50 pp.

No abstract.

Rogers, R., K. Sassen, and G. Dodd, 1988: Comparison of satellite data with surface-based remote sensing equipment in Utah winter orographic storms. Preprints, 10th International Cloud Physics Conference, IAMAP/IUGG, Bad Homberg, F.R.G., August 15-20, 1988. *Annalen der Meteorologie*, No. 25, ISBN 3-88148-240-7, II:659-661.

No abstract.

Rose, R. L., J. L. Stith, D. A. Griffith, and P. L. Smith, 1987: Atmospheric resource development and research in North Dakota. First International Meeting on Agriculture and Weather Modification, Leon, Spain. University of Leon, Leon, Spain, 263-273.

No abstract.

Rose, R. L., and T. C. Jameson, 1986: Evaluation studies of long-term hail damage reduction programs in North Dakota. *Journal of Weather Modification*, 18:17-20.

An exploratory look at a long-term seeding program, which is operating in one of the most severe hail prone regions of the United States, has been conducted. Using hail insurance data, a historical and target-control analysis attempt has been completed. The changes in loss cost averages are impressive, but due to the nature of the variability in hail losses as recorded by insurance data, are not solely convincing. Subsequent testing by the Mann-Whitney U test shows the disparity of loss equalized between the target and the east and west control. The north control, seemingly consistent in its history of loss over the past third of a century, presents an opportunity for further study. One can only consider the possibility that the target may be experiencing a climatological increase in hail loss and the seeding may be having a far greater effect than measured, or the climatology is providing what many think and believe is a seeding effect. Regardless of the possibilities, it is certain that only detailed physical studies conducted through well-designed field experiments and supported analyses will unlock the answers to understanding the questions of hail damage reduction seeding.

Rose, R. L., T. C. Jameson, and H. L. Johnson, 1986: Assessment of operational hail damage reduction programs in North Dakota. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 133-136.

No abstract.

Sassen, K., and H. Zhao, 1992: Polarization lidar liquid cloud detection algorithm for winter mountain storms. Preprints, 16th International Laser Radar Conference, Cambridge, MA, July 20-24, 1992. NASA Conference Publication 3158, NASA Langley Research Center, Hampton, VA, 357-359.

No abstract.

Sassen, K., H. Zhao, and G. C. Dodd, 1992: Simulated polarization diversity lidar returns from water and precipitating mixed phase clouds. *Applied Optics*, 31(15):2914-2923.

The dependence of polarization lidar returns on basic microphysical and thermodynamic variables is assessed by using a cloud model to simulate the growth of water and mixed (water and ice) phase clouds. Cloud contents that evolve with height in updrafts are converted, by using Mie theory, into cloud droplet single and double backscattering, and attenuation coefficients. The lidar equation includes forward multiple scattering attenuation corrections based on diffraction theory for droplets and ice crystals, whose relative scattering contributions are treated empirically. Lidar depolarization is

computed from droplet and crystal single scattering and an analytical treatment of droplet double scattering. Water cloud results reveal the expected increases in linear depolarization ratios (δ) with increasing lidar field of view and distance to cloud, but also show that depolarization is a function of cloud liquid water content, which depends primarily on temperature. Ice crystals modulate mixed-phase cloud liquid water contents through water vapor competition effects, thereby affecting multiple scattering δ values as functions of updraft velocity, temperature, and crystal size and concentration. Although the minimum δ at cloud base increases with increasing ice content, the peak measurable δ in the cloud decreases. Comparison with field data demonstrate that this modeling approach is a valuable supplement to cloud measurements.

Sassen, K., 1991: The lidar depolarization technique for cloud and aerosol research. Preprints, 71st Annual Meeting of the American Meteorological Society, New Orleans, LA, January 14-18, 1991. American Meteorological Society, Boston, MA, 448-451.

No abstract.

Sassen, K., 1991: The polarization lidar technique for cloud research: A review and current assessment. *Bulletin of the American Meteorological Society*, 72:1848-1866.

The development of the polarization lidar field over the past two decades is reviewed, and the current cloud research capabilities and limitations are evaluated. Relying on fundamental scattering principles governing the interaction of polarized laser light with distinctly shaped hydrometers, this remote sensing technique has contributed to our knowledge of the composition and structure of a variety of cloud types. For example, polarization lidar is a key component of current climate research programs to characterize the properties of cirrus clouds, and is an integral part of multiple remote sensor studies of mixed-phase cloud systems, such as winter mountain storms. Although unambiguous cloud phase discrimination and the identification of some ice particle types and orientations are demonstrated capabilities, recent theoretical approaches involving ice crystal ray-tracing and cloud microphysical model simulations are promising to increase the utility of the technique. New results simulating the single and multiple scattering properties of precipitating mixed-phase clouds are given for illustration of such methods.

Sassen, K., A. W. Huggins, A. B. Long, J. B. Snider, and R. J. Meitín, 1990: Investigations of a winter mountain storm in Utah. Part II: Mesoscale structure, supercooled liquid water development, and precipitation processes. *Journal of the Atmospheric Sciences*, 47:1323-1350.

A comprehensive analysis of a deep winter storm system during its passage over the Tushar Mountains of southwestern Utah is reported. The case study, drawn from the 1985 Utah/NOAA cooperative weather modification experiment, is divided into descriptions of the synoptic and kinematic properties in Part I, and storm structure and composition here in Part II. In future parts of this series, the turbulence structure and indicated cloud seeding potential will be evaluated. The analysis presented here in Part II focuses on multiple remote sensor and surface microphysical observations collected from a midbarrier (2.57 km MSL) field site. The collocated remote sensors were a dual-channel microwave radiometer, a polarization lidar, and a K_a-band Doppler radar. These data are supplemented by upwind, valley-based C-band Doppler radar observations, which provided a considerably larger-scale view of the storm.

In general, storm properties above the barrier were either dominated by barrier-level orographic clouds or propagating mesoscale cloud systems. The orographic cloud component consisted of weakly (-3° to -10°C) supercooled liquid water (SLW) clouds in the form of an extended barrier-wide cap cloud that contained localized SLW concentrations. The spatial SLW distribution was linked to topographical features surrounding the midbarrier site, such as abrupt terrain rises and nearby ridges. This orographic cloud contributed to precipitation primarily through the riming of particles sedimenting from aloft, and

also to some extent through an ice multiplication process involving graupel growth. In contrast, mesoscale precipitation bands associated with a slowly moving cold front generated much more significant amounts of snowfall. These precipitation bands periodically disrupted the shallow orographic SLW clouds. Mesoscale vertical circulations appear to have been particularly important in SLW and precipitation production along the leading edges of the bands. Since the SLW clouds during the latter part of the storm were based at the frontal boundary, SLW and precipitation gradually diminished as the barrier became submerged under the cold front.

Based on a winter storm conceptual model, we conclude that low-level orographic SLW clouds, when decoupled from the overlying ice cloud layers of the storm, are generally inefficient producers of precipitation due to the typically warm temperatures at these altitudes in our region.

Sassen, K., 1989: Supercooled liquid cloud distribution over complex mountainous terrain. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:51-54.

No abstract.

Sassen, K., M. T. Davies, and L. Liao, 1989: Remote sensing observations of seeded winter storms from the 1989 Utah/NOAA Cooperative Weather Modification Program. Final Report to Utah Division of Water Resources. University of Utah, Salt Lake City, UT, 35 pp.

No abstract.

Sassen, K., G. Dodd, and L. Liao, 1988: Polarization lidar and K_a-band radar studies of winter storms from the 1987 Utah/NOAA Cooperative Weather Modification Program. Final Report to Utah Division of Water Resources. University of Utah, Salt Lake City, UT, 27 pp.

No abstract.

Sassen, K., and M. Griffin, 1988: Mesoscale and microscale structure of cirrus clouds. Three case studies. Preprints, 10th International Cloud Physics Conference, IAMAP/IUGG, Bad Homberg, F.R.G., August 15-20, 1988. *Annalen der Meteorologie*, No. 25, ISBN 3-88148-240-7, II:473-475.

No abstract.

Sassen, K., 1986: Lidar and supporting observations of winter storms from the 1985 Utah/NOAA Cooperative Weather Modification Program. Final Report to Utah Division of Water Resources, subcontract under NOAA Cooperative Agreement NA85RAH05031. Department of Meteorology, University of Utah, Salt Lake City, UT, 73 pp.

No abstract.

Sassen, K., R. M. Rauber, and J. B. Snider, 1986: Multiple remote sensor observations of supercooled liquid water in a winter storm at Beaver, Utah. *Journal of Climate and Applied Meteorology*, 25:825-834.

The temporal and spatial distribution of cloud liquid water in a winter storm from the 1983 Utah/NOAA Cooperative Weather Modification Program is characterized using remote sensing observations. The remote sensors, located at a mountain-base site near Beaver, Utah, consisted of a dual-channel microwave radiometer operated in an azimuthal scanning mode, and a polarization lidar and K_u-band radar both operated in the vertically pointing mode. The cloud system was associated with the passage of a weak cold front and produced only light snowfall across the barrier network of precipitation gages. Although the amounts of supercooled water detected radiometrically varied considerably during the storm, liquid water depths were consistently enhanced in the direction of the barrier. The spatial distribution of liquid water was observed to undergo a transition from a primarily orographic distribution to a more area-wide pattern immediately behind the front, and then became convective as the storm dissipated. A new method of analysis applied to the scanning microwave radiometer measurement appears promising for relating liquid water concentrations with the local topography. It is suggested that the near real-time availability of the measurements could lead to improvements in cloud seeding strategies.

Sassen, K., 1985: High elevation polarization lidar observations of orographic liquid water in the Tushar Mountains, Utah, USA. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 417-420.

No abstract.

Sassen, K., 1985: Supercooled liquid water in winter storms: A preliminary climatology from remote sensing observations. *Journal of Weather Modification*, 17:30-35.

Drawing from a remote sensing data base obtained from winter storm research programs in Colorado and Utah, the occurrence of supercooled liquid water over mountain barriers is examined. Combined polarization lidar and dual-channel microwave radiometer data reveal that liquid water was nearly always present in the storms studied. Moreover, the highest frequency of occurrence and liquid water amounts were most often associated with relatively warm cloud base temperatures and K_u-band radar reflectivity factors between 0 and -10 dBZ at the liquid cloud base position. A preliminary climatology of supercooled liquid water in southern Utah reveals a bimodal distribution of liquid cloud base heights, representing convective clouds (~3.0 km MSL) and generally prefrontal stratiform clouds (~4.5 km MSL). Although the liquid water associated with the efficient natural generation of precipitation may not always be detected by any single probe, the conditions which could be expected to yield a favorable seeding response can be indentified through joint remote sensing observations.

Sassen, K., 1983: Polarization lidar and other remote sensing measurements from the 1983 orographic cloud seeding program at Beaver, Utah. Final Report to Utah Division of Water Resources, subcontract under NOAA Cooperative Agreement NA82RAD050125. Department of Meteorology, University of Utah, Salt Lake City, UT, 51 pp.

No abstract.

Schaffner, L. W., J. E. Johnson, H. G. Vruegdenhil, and J. W. Enz, 1983: Economic effects of added growing season rainfall on North Dakota agriculture. Agricultural Economics Report No. 172, Agricultural Experiment Station, North Dakota State University, Fargo, North Dakota, 19 pp.

No abstract.

Scott, R. W., and R. R. Czys, 1992: Objective forecasting of some individual cloud characteristics in the 1989 Illinois cloud seeding experiment. *Journal of Weather Modification*, 24:1-12.

A simple objective procedure used exploratively to forecast the occurrence, height, and coalescence activity of summertime convective clouds in Illinois during the cloud seeding trials of the 1989 Precipitation Augmentation for Crops Experiment is described. The method used the temperature of the convective condensation level (T_{CCL}) and potential buoyancy (PB) at 500 mb, easily determined from morning National Weather Service sounding data, to forecast afternoon convection. Categories of maximum echo top heights were found to arrange according to T_{CCL} and PB. The physical basis of T_{CCL} and PB to implicitly represent a period of time for coalescence to produce supercooled drizzle and rain drops is discussed. The technique performed well at forecasting the occurrence and height of afternoon convective clouds, and the accuracy of the occurrence forecast improved if precipitable water was used as an additional criteria. Aircraft measurements of supercooled rain drop concentrations showed that a discriminator function, dependent only on T_{CCL} and PB, gave a good indication of the presence or absence of supercooled drizzle and rain drops in the updrafts of clouds at the -10°C seeding level. Median concentrations of supercooled drizzle and rain drops ($N_{D > 300}$) in updraft regions at the -10°C level were found to be best approximated by a third order polynomial dependent on T_{CCL} and PB, presenting a possible physical link between cloud scale environment and in-cloud conditions.

Scott, R. W., and R. R. Czys, 1990: An objective process to forecast convective precipitation and seedability of clouds in the Midwestern United States. XV General Assembly, April 23-27, 1990. European Geophysical Society, Copenhagen, Denmark.

No abstract.

Scott, R. W., and R. R. Czys, 1990: Convection intensity and seeding suitability forecasts in a dynamic seeding experiment in Illinois. 12th Conference on Weather Analysis Forecasting, Monterey, CA, October 2-6, 1989. American Meteorological Society, Boston, MA, 107-110.

No abstract.

Scott, R. W., 1989: Forecasting convection intensities in Illinois from rawinsonde signatures. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:221-224.

No abstract.

Scott, R. W., and F. A. Huff, 1987: Forecasting with a contemporary forecasting/nowcasting system in a randomized dynamic seeding experiment. Proceedings, XIX General Assembly of the International Union of Geodesy and Geophysics, August 9-22, 1987, Vancouver, British Columbia, Canada, Vol. 3, 852.

No abstract.

Secretary of Commerce, 1979: *National Weather Modification Policies and Programs*. A report to the President and the Congress. Supt. of Doc., US-GPO, Washington, DC (003-017-00470-8), 93 pp.

No abstract.

Shang, R., 1989: A numerical study of aerosol scavenging by ice crystals. M.S. thesis, Department of Atmospheric Physics, University of Nevada, Reno, NV, 93 pp.

Two theoretical models are presented which allow computing the efficiency with which aerosol particles are collected by simple ice crystal plates. The present models incorporate gravitational, inertial, diffusive, and electrostatic effects. The effect of an internal charge distribution, due to differential incorporation of ionic substances into ice crystal lattice, on aerosol scavenging is also investigated. Some calculations were performed using a low density for ice particles, to simulate scavenging

efficiency considerably affected by such an internal charge distribution for aerosol particles $0.1 \leq r \leq 1.0$ m. The present results imply that growing ice crystals containing dilute concentrations of ionizable salts may exhibit higher collision efficiencies. The present theoretical results reconcile the previously widely diverging results of snow crystal scavenging reported by many researchers. This study suggests that as aggregates form and grow, the internal charge distribution effect diminishes, while the net charge effect increases.

Smith, P. L., Z. Liu, and J. Joss, 1993: A study of sampling-variability effects in raindrop-size observations. *Journal of Applied Meteorology*, 32 (accepted).

Because of the randomness associated with sampling from a population of raindrops, the data contain some undetermined mixture of sampling variability and real physical variations in the precipitation. This study begins with a Monte-Carlo simulation of the sampling process and then evaluates the resulting estimates of the characteristics of the underlying drop population. The characteristics considered include the liquid water concentration and the reflectivity factor; the maximum particle size in each sample is also determined. The results show that skewness in the sampling distributions when the samples are small (which is the usual case in practice) produces a propensity to underestimate all of the characteristic quantities. In particular, the distribution of the sample maximum drop sizes suggests that it may be futile to try to infer an upper truncation point for the size distribution on the basis of the maximum observed particle size.

Resulting paired values, e.g., of Z and W, for repeated sampling were plotted on the usual type of log-log scatter plots. This yielded quite plausible-looking "Z-R" and "Z-W" relationships even though the parent drop population (and hence the actual values of the quantities) were unchanging; the "relationships" arose entirely from the sampling variability. Moreover, the sample points are shown to be necessarily displaced from the point corresponding to the actual population values if the sample size is small. Consequently, any assessment of the "accuracy" of a Z-R relationship based on drop-size data should include some consideration of the numbers of drops involved in the samples making up the scatter plot. These findings shed a new perspective on the reasons for some of the variability appearing in the wide range of Z-R relationships reported in the literature.

Smith, P. L., 1992: Hail suppression activity around the world. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 28-34.

No abstract.

Smith, P. L., A. G. Detwiler, J. H. Helsdon, M. R. Hjelmfelt, L. R. Johnson, F. J. Kopp, H. D. Orville, D. L. Priegnitz, and J. P. Searles, 1992: Continuing analysis of data for the North Dakota Thunderstorm Project. Report SDSMT/IAS/R-92/01 to North Dakota Atmospheric Resources Board, subcontract under NOAA Cooperative Agreement NA90AAH0176. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 167 pp.

No abstract.

Smith, P. L., L. R. Johnson, D. L. Priegnitz, and P. W. Mielke, Jr., 1992: A target-control analysis of wheat yield data for the North Dakota cloud modification project region. *Journal of Weather Modification*, 24:98-105.

A combined historical/target-control analysis of annual wheat yield data for western North Dakota provides indications of possible seeding effects in the target areas of the North Dakota Cloud Modification Project (NDCMP). The basic analysis procedure comparing post-1975 seeded-period data with pre-1961 non-seeded data gives an estimated yield increase of about 6%, relative to the control area, during the NDCMP operational period. However, the statistical (P-value) indications of the significance of the difference are somewhat equivocal. The historical increase in yields due to improvements in agricultural technology apparently contributes to this difficulty, but an attempt to resolve the issue by redefining the historical reference period to reduce the time gap was unsuccessful.

Smith, P. L., H. D. Orville, B. A. Boe, and J. L. Stith, 1992: A status report on weather modification research in the Dakotas. *Atmospheric Research*, 28:271-298.

An overview of the status of weather modification research in North Dakota and South Dakota (USA) is presented. The operational North Dakota Cloud Modification Project has, since 1976, been seeding summer convective clouds for the dual objectives of hail suppression and rainfall enhancement. Research being carried out as part of a Federal/State cooperative program, in coordination with the operational activities, has included physical and statistical evaluation studies as well as numerical cloud modeling investigations. The statistical analyses provide some indications that the intended seeding effects are being obtained. The physical studies involve aircraft and radar observations and emphasize tracer experiments to study the transport and dispersion of seeding agents and the activation of ice nuclei. The modeling studies simulate the experiments and aid in investigation of the processes involved and the effects of seeding. The 1989 North Dakota Thunderstorm Project, a major field study emphasizing physical and numerical modeling studies, is described briefly.

Smith, P. L., Z. Liu, and J. Joss., 1991: Apparent Z-R relationships arising from sampling variability in raindrop size observations. Preprints, 25th International Conference on Radar Meteorology, Paris, France, June 24-28, 1991. American Meteorological Society, Boston, MA, 760-763.

No abstract.

Smith, P. L., H. D. Orville, and B. A. Boe, 1991: An overview of the 1989 North Dakota Thunderstorm Project. Preprints, 2nd Yugoslav Conference on Weather Modification, Mavrovo, Yugoslavia, April 2-4, 1991. Republic Hydrometeorology Institute of SR, Macedonia, Skopje, Yugoslavia, I:16-24.

No abstract.

Smith, P. L., H. D. Orville, B. A. Boe, and J. L. Stith, 1991: Weather modification in the Dakotas. Preprints, 2nd International Meeting on Agriculture and Weather Modification, Zamora, Spain, March 12-15, 1991. Ministry of Agriculture, Fisheries, and Nutrition, ISBN 84-87469-15-9-DL:LE-321-1991, Zamora, Spain, 71-82.

No abstract.

Smith, P. L., A. G. Detwiler, J. H. Hirsch, L. R. Johnson, F. J. Kopp, J. R. Miller, Jr., H. D. Orville, and D. L. Priegnitz, 1990: Development of evaluation techniques for operational convective cloud modification projects: 1988-89 studies. Report SDSMT/IAS/R-90/01. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 31 pp. + appendices.

No abstract.

Smith, P. L., and Z. Liu, 1990: Some statistics of sampling from exponential particle size distributions. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 367-370.

No abstract.

Smith, P. L., M. W. Huston, and L. R. Johnson, 1989: Development of evaluation techniques for operational convective cloud modification projects: 1987-88 studies. Report SDSMT/IAS/R-89/03. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 43 pp.

No abstract.

Smith, P. L., L. R. Johnson, and F. J. Kopp, 1989: Development of evaluation techniques for operational convective cloud modification projects: 1986-1987 studies. Report SDSMT/IAS/R-89/02. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 33 pp.

No abstract.

Smith, P. L., H. D. Orville, J. L. Stith, B. A. Boe, D. A. Griffith, M. K. Politovich, and R. F. Reinking, 1989: Evaluation studies of the North Dakota Cloud Modification Project. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:371-376.

No abstract.

Smith, P. L., J. R. Miller, and P. W. Mielke, Jr., 1987: An exploratory study of crop-hail insurance data for evidence of seeding effects in North Dakota. Report SDSMT/IAS/R-87/01 to North Dakota Resource Board. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 21 pp.

No abstract.

Smith, P. L., J. R. Miller, Jr., R. L. Rose, and P. W. Mielke, Jr., 1987: An exploratory study of North Dakota crop-hail insurance data for evidence of seeding effects. Preprints, 11th Conference on Weather Modification, Edmonton, Alberta, Canada, October 6-8, 1987. American Meteorological Society, Boston, MA, 86-89.

No abstract.

Smith, P. L., J. R. Miller, Jr., and J. H. Hirsch, 1986: Dynamic versus microphysical effects of seeding: Some cloud model and radar observations. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 27-30.

No abstract.

Smith, P. L., A. A. Doneaud, J. H. Hirsch, J. R. Miller, Jr., and P. E. Price, 1985: Development of evaluation techniques for operational convective cloud modification projects: 1984-1985 studies. Report SDSMT/IAS/R-85/05. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, 34 pp.

No abstract.

Smith, P. L., J. R. Miller, Jr., A. A. Doneaud, J. H. Hirsch, D. L. Priegnitz, P. E. Price, K. J. Tyler, and H. D. Orville, 1985: Research to develop evaluation techniques for operational convective cloud modification projects. Report SDSMT/IAS/R1-85/02. Institute of Atmospheric Sciences, South Dakota School of Mines & Technology, Rapid City, SD, January 1985, 99 pp.

No abstract.

Smith, P. L., J. R. Miller, Jr., H. D. Orville, J. H. Hirsch, A. A. Doneaud, and D. L. Priegnitz, 1985: Research for physical evaluation of the North Dakota Cloud Modification Project. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 209-214.

No abstract.

Smith, P. L., J. R. Miller, Jr., D. L. Priegnitz, and A. A. Doneaud, 1984: Some radar observations associated with an operational convective cloud modification project. Preprints, 22nd Conference on Radar Meteorology, Zurich, Switzerland, September 10-13, 1984. American Meteorological Society, Boston, MA, 151-155.

No abstract.

Smith, P. L., J. R. Miller, Jr., D. L. Priegnitz, J. H. Hirsch, and A. A. Doneaud, 1984: Physical evaluation studies of the North Dakota Cloud Modification Project. Extended Abstracts, 9th Conference on Weather Modification, Park City, UT, May 21-23, 1984. American Meteorological Society, Boston, MA, 98-99.

No abstract.

Snider, J. B., T. Uttal, and R. A. Kropfli, 1986: Remote sensor observations of winter orographic storms in southwestern Utah. NOAA Technical Memorandum ERL WPL-139, NOAA Environmental Research Laboratories, Boulder, CO, 99 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Solak, M., and R. B. Allan, 1987: Detection of low altitude supercooled liquid water in Utah. Report to Utah Division of Water Resources, subcontract under NOAA FY 87 Cooperative Agreement. Atmospherics, Inc., Fresno, CA, 52 pp.

No abstract.

Solak, M. E., and R. B. Allan, 1986: The detection of supercooled liquid water—additional analysis of ground-based ice accretion measurements. Addendum to Final Report to Utah Division of Water Resources. Atmospherics Inc., Fresno, CA, 50 pp.

No abstract.

Sonka, S., and W. Easterling, 1985: Assessing the economic benefits of planned weather modification. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 41-44.

No abstract.

Stith, J. L., 1992: New techniques for studying the microphysical effects of cloud seeding. Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 156-160.

No abstract.

Stith, J. L., 1992: Observations of cloud-top entrainment in cumuli. *Journal of the Atmospheric Sciences*, 49:1334-1347.

Sulfur hexafluoride tracer gas was released during single aircraft passes just above growing convective turrets to study its entrainment into the clouds as they grew through the release altitude. The tracer was sampled in situ from a second research aircraft that carried a real-time sulfur hexafluoride analyzer. The results from three experiments are presented. They were done with clouds ranging in size from a vigorous convective turret to a small cumulus.

The observations suggest that during the early stages of entrainment, the tracer remained mostly out of the cloud and was carried alongside the upper cloud regions by the circulation present there. In each experiment, concentrated tracer was first found on the edges of the turrets. Later, the tracer mixed into the central portions of the turrets where it had diluted considerably and mixed through most of the turret. The observations are consistent with the hypothesis that cloud-top entrainment occurs through a vortex-like circulation that brings air from above the cloud into the central region of the cloud. The results are compared to some recent conceptual and numerical models of entrainment.

Stith, J. L., D. A. Burrows, and P. J. DeMott, 1992: Initiation of ice in clouds: Comparisons of numerical model results with observations. Proceedings, 11th International Conference on Clouds and Precipitation, Montreal, Canada, August 17-21, 1992. International Commission on Clouds and Precipitation, International Association of Meteorology and Atmospheric Physics, Innsbruck, Austria, 196-199.

No abstract.

Stith, J. L., 1990: Observations of cloud top entrainment using gaseous tracer techniques. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 532-535.

No abstract.

Stith, J. L., A. G. Detwiler, R. F. Reinking, and P. L. Smith, 1990: Investigating transport, mixing, and the formation of ice in cumuli with gaseous tracer techniques. *Atmospheric Research*, 25:195-216.

Applications of tracer techniques using insoluble sulfur hexafluoride (SF_6) to studies of transport, mixing, and the activation of silver iodide (AgI) aerosols in cumuli are presented. One cumulus was treated with SF_6 and aerosol near the cloud top (-13.5°C), in a region of little vertical transport. Up to 24% of the potential nuclei produced measurable ice particles 7 min after treatment, in accord with the results of recent laboratory measurements of activation of this aerosol by contact nucleation. A second cumulus was treated at the cloud base with SF_6 and the aerosol. The materials were transported to and mixed through the upper regions of the cloud. Ice particles evidently formed near the cloud top (estimated cloud top temperature -13°C). Only low concentrations of natural ice were found in untreated regions of the cloud. In the treated regions, the ice particle concentrations in the cold, upper part of the cloud and in downdrafts at lower levels were consistent with the concentrations of AgI nuclei estimated from the tracer measurements. At lower levels of the cloud, the materials were not so well mixed, the most concentrated regions being found on the upshear side of the cloud and dilute regions downshear. Mid- and upper-level ice concentrations were greatest in downdrafts on the downshear side, suggesting that the downdraft was important in transporting the ice to lower levels of the cloud.

Stith, J. L., and M. K. Politovich, 1989: Observations of the effects of entrainment and mixing on the droplet size spectra in a small cumulus. *Journal of the Atmospheric Sciences*, 46:908-919.

Sulfur hexafluoride was released at the base of a small, nonprecipitating, warm cumulus to study cloud mixing and entrainment processes. The tracer gas traveled to the top of the cloud where, during a 2.5 min period, it had mixed to produce a dilute mixture containing 30%, 19%, and 51% of air from the original tracer region, an adjacent region of the same cloud, and the environment surrounding the cloud, respectively. The droplet size distributions measured at the top of the cloud represented a mixture of larger droplets that had been growing from the base and smaller, recently activated droplets. The observations suggest that the source region for the small droplets was near cloud top. The large droplet concentration was conserved during the mixing process. These observations are compared with predictions from some recent models for cloud entrainment and droplet evolution.

Stith, J. L., M. Politovich, R. Reinking, A. Detwiler, and P. Smith, 1988: Investigating mixing and the activation of ice with gaseous tracer aerosols. Preprints, 10th International Cloud Physics Conference, IAMAP/IUGG, Bad Homberg, F.R.G., August 15-20, 1988. *Annalen der Meteorologie*, No. 25, ISBN 3-88148-240-7, II:588-590.

No abstract.

Stith, J. L., and R. L. Benner, 1987: Applications of fast response SF_6 analyzers to *in situ* cloud studies. *Journal of Atmospheric and Oceanic Technology*, 4:599-612.

The airborne applications of two recently developed analyzers for sulfur hexafluoride (SF_6) to investigations of cloud top mixing and cloud seeding are described. The analyzers were developed by AeroVironment (AV) and by Washington State University (WSU). Both analyzers were capable of detecting cumulus-scale plume features. The more elaborate flow control mechanism in the AV analyzer was helpful in reducing the effects of altitude on the instrument response, while the faster response and lower baseline noise level of the WSU analyzer were necessary to detect many plume features.

A midcloud injection of SF_6 was followed as it mixed through the tops of a small cumulus cloud. The tracer plume was first detected upshear, then mixed through the cloud top region as the cloud top began to collapse.

A plume of AgI cloud seeding agent mixed with SF_6 was used to investigate the activation and growth of ice particles in a stratocumulus cloud which was overseeded. The SF_6 tracer and ice particle plumes remained collocated during the 45-min sampling period, except for one region of ice particles which had begun to separate from the SF_6 26 min after the cloud was treated. The growth of ice was limited by water vapor diffusion into the seeding plume. The measured tracer concentrations were used to estimate the fraction of the seeding nuclei which had activated and grown to detectable sizes. A maximum fraction of 54% was observed 17.5 min after seeding.

Several other applications for SF_6 tracer applications are recommended.

Stith, J. L., D. A. Griffith, R. L. Rose, J. A. Flueck, J. R. Miller, Jr., and P. L. Smith, 1986: Aircraft observations of transport and diffusion in cumulus clouds. *Journal of Climate and Applied Meteorology*, 25:1959-1970.

A gaseous tracer, sulfur hexafluoride, was used to follow the path of two different AgI cloud seeding aerosols in cumulus clouds. The materials were released at cloud base or midlevels. Plumes sampled at midlevels were found to be relatively narrow and embedded within updrafts or downdrafts; relatively high concentrations of the tracer were observed in some downdrafts. Plumes with diameters comparable to the cloud diameters were found in the upper 20% of the clouds. These observations suggest only limited dispersion of the plumes in the clouds, with greater mixing occurring at cloud top. Similar behavior of the in-cloud plume is observed in results from a two-dimensional, numerical cloud model used to simulate the introduction of seeding materials into convective clouds. Observations of the ice crystal production rates are consistent with the results of recent laboratory findings concerning the properties of the seeding agents. The usefulness of this tracer technique in studying transport, diffusion, and ice activation in cumulus clouds is discussed.

Stith, J. L., 1985: Following the path of cloud seeding agents in cumulus clouds with a gaseous tracer. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 247-250.

No abstract.

Stith, J. L., 1983: Limitations to dynamic seeding of North Dakota summer clouds. *Journal of Weather Modification*, 15(1):28-33.

During the summer of 1981, cumulus clouds in North Dakota were unlikely candidates for dynamic seeding. Ice particle concentrations were well below 100/liter in feeder-type clouds associated with seeded convective storms. Comparisons of aircraft measurements and the output from a one-dimensional steady-state cloud model were also made.

Stone, R. H., and J. A. Warburton, 1989: The dispersion of silver iodide in mountainous target areas of the western United States. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:167-169.

No abstract.

Stone, R. H., 1986: Targeting effectiveness in a shallow orographic cloud seeding experiment. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 34-38.

No abstract.

Summers, P. C., 1986: State-federal cooperative research in weather modification. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 330-331.

No abstract.

Super, A., and A. W. Huggins, 1992: Investigations of the targeting of ground-released silver iodide in Utah. Part I: Ground observations of silver-in-snow and ice nuclei. *Journal of Weather Modification*, 24:19-34.

During the winter of 1989-90, the Utah Division of Water Resources, the National Oceanic and Atmospheric Administration, and the Bureau of Reclamation cooperated in a limited sampling project to investigate the transport and dispersion of silver iodide (AgI) cloud-seeding aerosol over two target areas in the mountains of Utah. Seeding was done using the ground-based AgI generator network of the Utah operational cloud seeding program. Transport and dispersion over the Wasatch Range and Wasatch Plateau were evaluated using a silver-in-snow sampling technique and the real-time detection of AgI aerosol or sulfur hexafluoride gas.

This report contains an extensive review of past silver-in-snow results from several different regions as a basis for comparison with the current study. The 1989-90 Utah results indicated that a low percentage (<15%) of bulk snow samples from 10 mountain target area locations had silver (Ag) concentrations above background values for periods when seeding had been conducted. Consistently poor targeting and/or low seeding generator output could explain the general lack of detectable Ag in the two Utah target areas.

Seeding generator output also forms the basis for estimates of average ice particle masses required to achieve the greater than 11% snowfall increase reported from statistical analyses of the Utah operational program. These estimates are based on very optimistic assumptions (perfect targeting, 100% nucleation, 100% fallout, etc.). They indicate that snowfall enhancements of 10% or greater are unlikely with the current AgI seeding rates of 6 grams per hour used in Utah.

Real-time detection of ground-released AgI showed that seeding material was routinely transported up a particular canyon when releases were made near the bottom of the canyon. Concentrations of AgI at the up-canyon observation site (adjusted for nucleation activity at -10°C) were, however, estimated to average only about one ice nucleus per liter. This relatively low concentration of active AgI nuclei offers a partial explanation of the observed low percentage of silver-in-snow above background at sampling sites above the canyons where AgI was released.

Super, A., and A. W. Huggins, 1992: Investigations of the targeting of ground-released silver iodide in Utah. Part II: Aircraft observations. *Journal of Weather Modification*, 24:35-48.

As part of a cooperative research program between the Utah Division of Water Resources, the National Oceanic and Atmospheric Administration, and the Bureau of Reclamation, a series of aircraft missions was flown to track silver iodide plumes in the Utah operational cloud seeding program. Both valley floor and canyon mouth generator sites were tested using releases of sulfur hexafluoride tracer gas and silver iodide. Optically tracked Airsondes provided supporting wind and stability data. Five missions were flown under atmospheric conditions that either simulated, or were the beginning of, the prefrontal phase of typical Utah winter storms. The silver iodide and tracer gas were confined to the lower atmosphere during four flights and were not transported over the intended mountain barriers. The plumes did cross the Wasatch Plateau during part of the fifth sampling mission. Ice nucleus concentrations were estimated from the tracer gas measurements of the fifth mission for typical supercooled liquid water temperatures. These estimates indicated that limited ice crystal concentrations would be formed with the generators and seeding agent currently used in Utah.

Swart, H., R. Benner, and D. A. Griffith, 1987: Study of the transport of cloud seeding material by releases of SF_6 and sampling with sequential samplers and a continuous tracer analyzer. Preprints, 11th Conference on Weather Modification and 7th Conference on Hydrometeorology, Edmonton, Alberta, Canada, October 6-8, 1987. American Meteorological Society, Boston, MA, 23-25.

No abstract.

Swart, H. R., R. L. Benner, and D. A. Griffith, 1986: Analysis of data collected during the 1985 NOAA/Utah cooperative research field program, Vol. I. NAWC Report WM 86-2 to Utah Division of Water Resources. North American Weather Consultants, Salt Lake City, UT, 186 pp.

No abstract.

Swart, H. R., and R. L. Benner, 1985: Study of the feasibility of using tracer gases to simulate ground releases of AgI. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 251-254.

No abstract.

Tyler, K. J., J. H. Helsdon, Jr., and H. D. Orville, 1984: Model comparisons of seeded versus non-seeded clouds in the North Dakota weather modification project. Extended Abstracts, 9th Conference on Weather Modification, Park City, UT, May 21-23, 1984. American Meteorological Society, Boston, MA, 112-113.

No abstract.

Uttal, T., J. B. Snider, R. A. Kropfli, and B. W. Orr, 1990: A remote sensing method of measuring atmospheric vapor fluxes: Application to winter mountain storms. *Journal of Applied Meteorology*, 29:22-34.

Vapor fluxes are calculated across a mountain barrier during two wintertime storms using a passive microwave radiometer and a Doppler radar. The vapor flux fields are shown to have complicated structures that are not detectable by conventional rawinsonde techniques. The vapor-flux fields show several major pulses which are compared to episodes of supercooled liquid water, riming, precipitation, and synoptic weather patterns. It appears from this data that the presence of an enhanced vapor in the flux field is a necessary condition for precipitation, but not a sufficient condition. It is suggested that detailed measurements of the vapor flux field are imperative to the improved local forecasting of precipitation.

Uttal, T., R. A. Kropfli, and J. B. Snider, 1986: Measurements of vapor flux, liquid water contents, precipitation rates, and riming in a Utah mountain cloud system. Preprints, 23rd Conference on Radar Meteorology and Conference on Cloud Physics, Snowmass, CO, September 22-26, 1986. American Meteorological Society, Boston, MA, Vol. 3, J233-J236.

No abstract.

Uttal, T., J. B. Snider, and R. A. Kropfli, 1986: Determinations of vapor flux using K_a-band Doppler radar and dual-channel microwave radiometer. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 229-233.

No abstract.

Walkinshaw, H., 1985: Report on the economic and social impacts of long-term federal and state-supported weather modification projects in the United States. North Dakota Atmospheric Resource Board, Bismark, ND, 109 pp.

No abstract.

Walsh, P. A., 1985: K_a-band radar observations of wintertime Sierra Nevada clouds. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 181-184.

No abstract.

Walsh, P. A., R. F. Reinking, and J. B. Cunning, 1982: Graupel characteristics in relation to the dynamics of Florida cumuli. Preprints, Conference on Cloud Physics, Chicago, IL, November 15-18, 1982. American Meteorological Society, Boston, MA, 362-366.

No abstract.

Warburton, J. A., 1992: Atmospheric (weather) modification in the decade of the 80s. What is new for the 90s? Preprints, Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, January 5-10, 1992. American Meteorological Society, Boston, MA, 5-11.

No abstract.

Warburton, J. A., and colleagues, 1991: Natural and augmented snowfall growth processes and their interactions with the natural and modified aerosol. Final Report, NOAA Cooperative Agreement NA89AARAH0987. Atmospheric Sciences Center, Desert Research Institute, Reno, NV, 52 pp. + appendices (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Warburton, J. A., and R. L. Smith, 1991: Mobile dual-channel scanning microwave radiometer. Final Report, NOAA Grant NA90AAH0A430. Atmospheric Sciences Center, Desert Research Institute, Reno, NV, 12 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Warburton, J. A., R. H. Stone, and L. G. Young, 1991: Assessment of seeding effects by chemical methods. Preprints, 2nd International Meeting on Agriculture and Weather Modification, Zamora, Spain, March 12-15, 1991. Ministry of Agriculture, Fisheries, and Nutrition, ISBN 84-87469-15-9-DL: LE-321-1991, Zamora, Spain, 41-44.

No abstract.

Warburton, J. A., and M. A. Wetzel, 1991: The liquid water and ice content in winter storms in relation to precipitation augmentation potential. Preprints, 2nd International Meeting on Agriculture and Weather Modification, Zamora, Spain, March 12-15, 1991. Ministry of Agriculture, Fisheries, and Nutrition, ISBN 84-87469-15-9-DL:LE-321-1991, Zamora, Spain, 37-40.

No abstract.

Warburton, J. A., and colleagues, 1990: Evaluation of Sierra Nevada seeding effects on snowfall processes and distribution. Final Report, NOAA Cooperative Agreement NA88RAHO8126. Atmospheric Sciences Center, Desert Research Institute, Reno, NV, 59 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Warburton, J. A., and R. H. Stone, 1990: The chemistry of snow in the central Sierra Nevada: A study of snowfall over a 20-year period, 1966-1985. I. Changes in pH. *Atmospheric Research*, 25:377-384.

Fresh snowfall precipitation has been collected at 14 sites in the central Sierra Nevada during the winter seasons from 1966 to 1985. The pH of these 1,398 individual snow samples has been measured throughout this 20-year period. The results indicate that there has been a small increase in acidity of 0.02 pH units per year in this region over this 20-year period. The pH has changed from approximately 5.6 in 1966 to 5.2 in 1985.

In the period from 1972 to 1974, the pH changed more dramatically from 5.2 to 4.6, but returned to 5.4 again in 1975-76. The cause of such an increase in acidity in this period is not known, but it was coincidental with the world energy crisis when larger quantities of high lead and sulfur content fossil fuels were in use in the United States.

Warburton, J. A., R. H. Stone, and B. B. Demoz, 1989: A conceptual model for determining seeded/non-seeded ratios in weather modification experiments based on stable oxygen isotopic ratios and snow chemistry. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:187-190.

No abstract.

Warburton, J. A., R. H. Stone, and L. Young, 1989: A new scientific method employing ice-nucleating and non-ice-nucleating aerosols simultaneously for assessing the effects of cloud seeding on precipitation. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:191-194.

No abstract.

Warburton, J. A., 1986: Weather modification research in Nevada. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, Arlington, VA, May 27-30, 1986. American Meteorological Society, Boston, MA, 320-322.

No abstract.

Warburton, J. A., and T. P. DeFelice, 1986: Oxygen isotopic composition of Central Sierra Nevada precipitation. I. Identification of ice-phase water capture regions in winter storms. *Atmospheric Research*, 20:11-22.

Measurements of the stable isotopic ratios of oxygen and simultaneously observed ice crystal structure in freshly fallen snow have been used to estimate the weighted mean altitudes of ice-phase precipitation formation in winter clouds over the Central Sierra Nevada.

Observations of dominant, diffusionally grown ice-crystal habits were used to estimate relatively narrow ranges of temperatures of initial formation of the precipitation particles using the Nakaya (1954) ice-crystal classification techniques. The mean oxygen isotope ratio $^{18}O/^{16}O$ for each snow sample, together with local upper air soundings, were used to estimate ranges of temperature-altitude within the clouds where the precipitating particles had captured their ice-phase water. For this initial study, snow samples were collected each 5 to 10 minutes during three snowfall periods on 27 January, 26 February, and 28 February 1983.

For the 27 January case, the ice formation mechanism was predominantly vapor deposition and hence the narrow range of temperatures determined by the ice-crystal habits was directly relatable to the mean $\delta^{18}O$ value.

The 26 and 28 February cases were more complicated because the solid-phase precipitation was formed by vapor deposition and by freezing of drops and droplets (which occurs without isotopic fractionation). In these cases, the oxygen isotopic composition of the snow reaching the ground was representative of solid phase precipitation which had formed at warmer temperatures than those corresponding to the primary ice-crystal habits alone. There was no apparent relationship between ^{18}O values and surface temperature at the sample site.

If the relationships between $^{18}O/^{16}O$ and temperature-altitude are established for this geographic region for winter snowfall conditions, this crystal habit-isotopic composition technique can provide knowledge about the regions of the clouds in which the ice-phase precipitation is forming over the Central Sierra Nevada.

Warburton, J. A., R. D. Elliott, W. G. Finnegan, B. Lamb, R. T. McNider, and J. W. Telford, 1986: A program of federal/state/local cooperative weather modification research: Design considerations. Part II: Transport and dispersion of seeding materials. Final Report, NOAA Contract NA3RAC00088, L. O. Grant (ed.). Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 80 pp. (available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161).

No abstract.

Warburton, J. A., and T. P. DeFelice, 1985: Stable isotopic composition of snow as an indicator of cloud seedability. *Journal of Weather Modification*, 17:36-37.

The stable oxygen isotopic composition has been measured in three sets of snow samples collected sequentially at a remote mountain station during winter storms. Replication techniques were used in conjunction with the sequential sampling to provide information on ice crystal habits and degree of riming in the snowfall. The results indicate stable isotope measurements combined with ice crystal replication techniques can be successfully used to estimate the weighted mean elevations of ice phase water captured by precipitating cloud particulates.

Warburton, J. A., and R. F. Reinking, 1985: The Nevada/NOAA Cooperative Weather Modification Project. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Symposium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, 245-246.

No abstract.

Warburton, J. A., L. G. Young, M. S. Owens, and R. H. Stone, 1985: The capture of ice nucleating and non-ice nucleating aerosols by ice phase precipitation. *Journal de Recherches Atmospheriques*, 19:249-255.

Chemical analyses of snow collected from five winter seasons in the Sierra Nevada show that there is a positive correlation between the silver concentration and the snow water mass containing the silver which originates from AgI ice-nucleating aerosol sources in the region. When the same snow is analyzed for its indium content for those occasions when non-ice nucleating indium sesquioxide (In_2O_3) is released as aerosols, at the same rates and at the same locations as the AgI, the indium oxide is found to be removed at lesser rates than the silver iodide. In addition, the indium concentration and the mass of snow containing it do not appear to be positively correlated, but rather constant or slightly negatively correlated. It is considered that the differences in capture and removal of the two aerosol types are due to their different physical nucleating properties.

Warburton, J. A., 1984: The seeding of cold clouds—the optimization problem. Extended Abstracts, 9th Conference on Weather Modification, Park City, UT, May 21-23, 1984. American Meteorological Society, Boston, MA, 1-2.

No abstract.

Warburton, J. A., and T. P. DeFelice, 1984: Stable isotopic composition of snow as an indicator of cloud seedability. Extended Abstracts, 9th Conference on Weather Modification, Park City, UT, May 21-23, 1984. American Meteorological Society, Boston, MA, 63-64.

No abstract.

Westcott, N. E., 1991: The bridging and growth of aggregating echo cores. Preprints, 25th International Conference on Radar Meteorology, Paris, France, June 24-28, 1991. American Meteorological Society, Boston, MA, 424-427.

No abstract.

Westcott, N. E., 1990: Radar results of the 1986 Exploratory Field Program relating to the design and evaluation of PACE. *Journal of Weather Modification*, 22:1-17.

The initial phase of the Precipitation Augmentation for Crops Experiment (PACE), directed at enhancing rainfall, was conducted in Illinois during the summer of 1986. This first experiment resulted in a limited sample (19 clouds and 3 experimental units), but one sufficient to provide information pertinent to the design and evaluation of future efforts.

In particular, it was determined that differences in meteorological conditions may mask any seeding signature present, requiring that the experimental units be stratified or normalized. It was found that for these clouds, the height of the echo at first detection and the age of the echo at treatment (AgI or placebo) have an important bearing on the expected growth of the echo. Additionally, the area and reflectivity of the echo at 6 km at the time of treatment seem to be related to the maximum size attained by the echo cores. That is, the larger the echo at treatment, the larger the echo can be expected to grow.

However, the growth of the echo core in terms of reflectivity, height, and area appeared to slow as the echo cores matured. This suggests that explosive growth sometimes expected from cloud seeding may not be the rule in this area of the country and that a comparison of before and after treatment growth rates may not be a good evaluation tool. Rather, the post-treatment growth, with the experimental units stratified by the age of the echo at treatment and by the height of formation may be more useful in discriminating seeding effects.

Radar-derived predictor variables were examined to assess echo behavior based on the ambient weather conditions, and response variables were developed which may be useful in detecting potential seeding effects. Inferences were made with regard to stratification of the data, experimental unit definition, and cloud behavior. This work emphasized, as others have found, the need for predictor variables and a large sample.

Westcott, N. E., 1989: Differential reflectivity (ZDR) measurements. Preprints, 24th Conference on Radar Meteorology, Tallahassee, FL, March 27-31, 1989. American Meteorological Society, Boston, MA, 388-390.

No abstract.

Westcott, N. E., 1989: Growth habits of seeded and non-seeded radar echoes from the 1986 Precipitation Augmentation for Crops (PACE) field program. Preprints, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:7-10.

No abstract.

Westcott, N. E., 1989: Influence of mesoscale winds on the turbulent structure of the urban boundary layer over St. Louis. *Boundary-Layer Meteorology*, 48:283-292.

Two fair weather afternoons have been examined, where the urban boundary layer over St. Louis, though exhibiting similar thermal characteristics, had a markedly different kinematic structure. The turbulent nature of the boundary layer was examined through analysis of double theodolite wind profiles at an urban and at a rural site on each day. On 14 July 1975, the winds increased with height above the inversion at both sites and on the following day, the winds decreased above the boundary layer in the same region. While the mean wind speed in the lowest 0.8 km AgI was similar on both days, the turbulence characteristics of the urban boundary-layer winds were distinctly different on these two afternoons. This was evidenced by the variance of the wind and is in agreement with simultaneous aircraft measurements reported by Hildebrand and Ackerman (1984). A similar difference in turbulence was not found over the rural site. It is suggested that the enhanced turbulence at the urban site on 14 July is likely associated with the wind profile immediately above the boundary layer, where the downward flux of high momentum air from above the inversion may have resulted in stronger mechanical mixing within the boundary layer.

Westcott, N. E., and S. A. Changnon, 1989: Properties of echoes at first detection resulting in multicelled storms. Preprints, International Symposium on Hydrological Applications of Weather Radar. University of Salford, Salford, England, 8 pp.

No abstract.

Westcott, N., and P. Kennedy, 1989: Cell development and merger in an Illinois thunderstorm observed by Doppler radar. *Journal of the Atmospheric Sciences*, 46:117-131.

A reflectivity and triple-Doppler radar study of the development of several cells and their successive union within a nonsevere thunderstorm is presented. Two characteristic separations were found between the newly formed cells and the parent thunderstorm, with the closer cells forming in response to the collapse of an active cell and the more distant cells forming in a previously existing storm-modified area characterized by mesoscale convergence and rain-cooled air. The manner in which these cells evolved appeared to be partially related to differences in the environment in which they formed. As suggested by Peterson, the cells that formed closer to the main storm resembled the "weakly evolving" cells of Foote and Frank. The updraft of the "weakly evolving" cell analyzed here merged with the updraft in a cell in the main storm as one cell was decreasing in intensity and the other was increasing.

Later in the life cycle of the storm, two cells which initially formed further away from the main storm appeared more like classical "strongly evolving" cells. While the vertical air velocity analyses of these cells were incomplete, a trend toward the maintenance of a discrete cell updraft was noted. The ways in which the reflectivity cores of these two cells became merged with the main storm differed. In one case, the development of a new cell between two existing cells produced the merger; in the second case, differential cell motion played an important role. Additionally, periods of significant intercell flow at 4 km coincided with the times when the midlevel reflectivity bond linking the cell cores showed a rapid intensification. It is proposed that the intercell flow is a result of radial outflow observed at heights above the maximum updraft level in the actively growing echoes. The strengthening of the reflectivity bridge may have been the result of both particle transfer and environmental modification brought about by this radial outflow.

Westcott, N., 1988: Local environmental conditions influencing the growth and internal structure of non-severe thunderstorms. Preprints, 10th International Cloud Physics Conference, IAMAP/IUGG, Bad Homberg, F.R.G., August 15-20, 1988. *Annalen der Meteorologie*, No. 25, ISBN 3-88148-240-7, II:632-634.

No abstract.

Westcott, N., 1987: Preliminary radar analysis of the 1986 Precipitation Augmentation for Crops Experiment (PACE) field program. Preprints, 11th Conference on Weather Modification, Edmonton, Alberta, Canada, October 6-8, 1987. American Meteorological Society, Boston, MA, 76-78.

No abstract.

Westcott, N., and B. Ackerman, 1985: Convective storm characteristics in the Midwest pertinent to the weather modification effort. Proceedings, 4th WMO Scientific Conference on Weather Modification, A Joint WMO/IAMAP Sympoium, Honolulu, HI, August 12-14, 1985. World Meteorological Organization, Geneva, WMO/TD-No. 53, II:433-436.

No abstract.

Williams, M. C., and R. D. Elliott, 1985: Weather modification. In: *Facets of Hydrology*, J. C. Rodda (ed.). John Wiley, New York, II:99-129.

No abstract.

Woodley, W. L., 1986: Final report on contract with Illinois State Water Survey to provide scientific support for the Precipitation Augmentation for Crops Experiment of 1986. Woodley Weather Consultants, Boulder, CO, 35 pp.

No abstract.

Zhang, R., and R. L. Pitter, 1991: Effect of internal charge distribution in ice crystals on scavenging of aerosol particles. *Precipitation Scavenging and Atmosphere-Surface Exchange*, S. E. Schwartz and W. G. N. Slinn, Coordinators, Hemisphere Publishing Corp., Washington, D.C., 97-106.

Two theoretical models are presented which allow computing the efficiency with which aerosol particles of radii $0.05 \leq r \leq 10.0$ μm are collected by simple ice crystal plates of radii $147.0 \leq r \leq 404.0$ μm. The effect of an internal charge distribution due to differential incorporation of ionic substances into ice crystal lattice is investigated. It is shown that the capture efficiency of an ice crystal is considerably affected by such an internal charge distribution in the aerosol size range $0.05 \leq r \leq 1.0$ μm. The results suggest that growing ice crystals containing dilute concentrations of ionizable salts exhibit a higher collision efficiency for small aerosol particles. The present theoretical results are found to agree satisfactorily with field observations presently available.

Zhang, R., D. L. Mitchell, S. Chai, and R. L. Pitter, 1990: Ground-based ice particle observations for analysis of Sierra winter orographic storms. Preprints, Conference on Cloud Physics, San Francisco, CA, July 23-27, 1990. American Meteorological Society, Boston, MA, 377-378.

No abstract.

Zhang, R., R. L. Pitter, and D. L. Mitchell, 1989: Ground-based snowflake observations for analysis of orographic winter storms. Proceedings, 5th WMO Scientific Conference on Weather Modification and Applied Cloud Physics, Beijing, China, May 8-12, 1989. World Meteorological Organization, Geneva, WMO/TD-No. 269, I:47-49.

No abstract.

Zhang, S., 1991: Two-dimensional model transport simulation in clouds compared with observations. M.S. thesis, Department of Meteorology, South Dakota School of Mines & Technology, Rapid City, SD, 75 pp.

No abstract.

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