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conference summary

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AMS special regional weather modification conference: augmentation of winter orographic precipitation in the western United States, 11–13 November 1975, Burlingame, Calif.

1. Introduction

The purpose of the conference was to assist the development of successful weather modification research programs and their applications to operations in the western United States, with specific focus on the proposed Sierra Nevada Project in relation to previously conducted projects in the West. This conference, the first such regional weather modification conference of the American Meteorological Society and the first to include the three cosponsors—the U.S. Department of the Interior, Bureau of Reclamation; the state of California, Department of Water Resources; and the Weather Modification Association—was very well attended by well-prepared and dynamic participants.

There seemed to be no doubt that the participants were successful in achieving the three stated goals of the conference, namely: 1) to bring together and summarize the most recent authoritative information on winter orographic precipitation augmentation and to define the knowns and the unknowns; 2) to encourage a broad discussion of the basis for augmenting orographic precipitation and for resolving the associated problems within a practical framework of scientific, engineering, social, political, and economic constraints; and 3) to provide information and ideas for planning experimental programs in winter orographic precipitation modification in the western United States.

The conference originated in the mutual interests of the Bureau of Reclamation and the California Department of Water Resources in gathering up-to-date scientific, technical, and social data relevant to the planning, design, and evaluation of a proposed cloud-seeding experiment in the American River Basin. The experiment, which would attempt to determine the feasibility of augmenting the water supplies for the California Central Valley Project and the Sacramento–San Joaquin Delta, was requested by the Bureau's Regional Director in Sacramento and is being designed under the Bureau's Project Skywater. Although the state of California had decided not to participate in the proposed experiment, the Department of Water Resources has maintained an active interest in the information provided during the conference.

The conference was opened with a reflection on the 29th anniversary of cloud seeding given in the form of a delightful and provocative review by Thomas J. Henderson. Tom described the original "Schaefer experiment" of 13 November 1946 and the first application of the principles to a long-range program on 2 February 1948 in the Bishop Cups area of the Sierra Nevada. Tom related a story of a discussion he recently had with a young lady in India who questioned him about the origins of cloud seeding. When Tom described the change of supercooled water drops to ice crystals that Schaefer produced by sprinkling dry ice pellets into a cold box, she said, "Isn't that remarkable." Tom responded, "Yes, the transition to ice certainly is." She said, "No, not the change to ice, but that Vincent Schaefer recognized the significance of his discovery."

2. Session 1

The first session of the conference dealt with the scientific credibility and rationale for seeding winter orographic storms for precipitation enhancement, the definition of the state of the art, and its application to the Sierra Nevada. Fourteen winter orographic precipitation augmentation projects conducted in the western United States during the past two decades were described. The session produced a consensus that modest increases in precipitation have been demonstrated by a few long-term seeding projects (notably, the King's River Project) in the Sierra Nevada. However, the fact that these increases have remained apparently constant over the years in spite of improved generators, radars, and other hardware led to the question of overall precipitation potential. Have these projects, for instance, already reached the natural limit for precipitation increases due to seeding, or do substantial increases remain to be achieved through a much more advanced technology of weather modification, as seems to be suggested by the North American Weather Consultants "Twelve Basin Study"? The question was not really answered but it did lead to a consensus that much more information is needed about the physical characteristics of these storms than is presently available in order to be able to calculate the natural limit to their precipitation enhancement.

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There is a host of physical problems whose solutions are fundamental to achieving a technology that can be reliably transferred from one location in the Sierra Nevada to another location only a few hundred miles away. There was some optimism that the work on an approach using multiparameter seedability criteria designed to separate the effects of convection, cloud top temperature, wind, etc., might assist the transfer of present precipitation modification technology to new areas. This approach, now being applied to experiments in Colorado, seems to be successfully defining basic similarities in cloud seedability criteria that may be applicable to the Sierra Nevada.

Cloud and precipitation mechanisms in the Sierra Nevada are acknowledged to be more complex than those in winter storms over the Climax area of the Rocky Mountains. The Sierra Nevada storms and also those in the San Juan Mountains of Colorado are warmer, lower, and wetter than their Climax counterparts and contain a much greater frequency of shallow, stratocumulus convective systems. There is a particularly wide variation in intensity, depth, and horizontal scale among the imbedded, prefrontal cumuliform towers in the mesoscale bands that have their origin over the Pacific. Since the tops of the convective towers in the Sierra Nevada vary considerably in height within a single storm, quantitative estimates of cloud top temperature are much more difficult to achieve than for the more layered type of orographic cloud found over Climax, where cloud top temperatures were found to be well represented by the temperature at 500 mb. It was repeatedly emphasized by the Climax researchers and others that a critical parameter to index is the coldest cloud temperature and not the specific 500 mb temperature that was found useful at Climax. The importance of this point has become clear in the analysis of the data for the San Juan Project, where the 500 mb temperature has been found to be not uniquely related to the cloud top temperature.

The physical mechanisms responsible for the demonstrated precipitation increases in the Sierra Nevada are not yet well understood. There have been no studies that show the physical relationship of ice crystals produced in the tops of orographically induced convective cells to natural ice nuclei, to artificial ice nuclei, to cloud top temperature, or to resulting precipitation. Ice formed from artificial nuclei inserted at cloud base may have an entirely different effect than ice formed from natural ice nuclei near the top of the cell. Is a convective cloud model designed for isolated cells representative of orographically induced or intensified cells imbedded in an intervening cloud of ice crystals? What is the natural variability in the Sierra Nevada of the intensity, depth, and horizontal scale of the orographically convective elements? What is the resulting effect of this variability on precipitation and its implications toward overall seeding effectiveness?

Although evidence was acknowledged to be lacking, it was suggested that the principal effect of seeding bands or cells from below with high-intensity nuclei generators such as pyrotechnics is an enhancement of convective intensity, which would produce subcloud convergence and cause the convective unit to process more water than would normally have been the case. The question was raised as to what extent the cloud between the band behaves like a more characteristic layered orographic cloud and whether some precipitation from this region of the cloud would be lost due to artificially induced intensity of the convective regions and the resulting increased low-level convergence. Although the analysis of the Santa Barbara 2 Project indicated that there was no effect on between-band precipitation, it was noted that the between-band component in the Sierra Nevada occurs at colder temperatures and is a larger fraction of the total precipitation at higher elevations.

An emphasis on performing physical studies and improving numerical models was recommended, with the focus to extend to the total storm system from the Pacific to the Sierra Nevada and beyond, before the implementation of a seeding experiment.

Perhaps the most important point of the session was that precipitation anomalies due to seeding have been demonstrated and that these provide a starting point for useful future investigation. The fundamental question is no longer *whether* orographic precipitation can be altered, but rather when, where, how, and how much it can be altered. A basic management decision, which was not brought out in the discussions but which has important implications for the future, is: What is the next step? We are at a branch point where the next step can emphasize the transfer to other areas of the technology responsible for the small demonstrated increases and an associated search for better understanding of the relevant precipitation processes, or it can emphasize achieving a more thorough evaluation of precipitation potential and a much more advanced technology, which might, or might not, result in substantial increases in the precipitation enhancement from seeding.

3. Session 2

The second session focussed upon the design, control, and evaluation of seeding winter orographic storms in the Sierra Nevada.

Some old contentions were revived in the discussion of the relative importance of the physical and statistical aspects of weather modification experiments and the extent to which they are separable. It eventually became apparent that a misunderstanding was emanating from two different approaches to the subject. From the viewpoint of one group, the physical considerations of an experiment include the monitoring of relevant physical data, and the statistical considerations include determining the type of statistical analysis to be used to arrive at the conclusions of the experiment. From this viewpoint, no adequate analysis can be done without adequate physical monitoring. From the viewpoint of the second group, physical considerations are those experimental efforts employed to test the hypotheses about the step-by-step physical processes linking seeding or nonseeding with a final observable result, and the statistical considerations include an analysis of the relationship of the final observable result as a function of seeding or nonseeding and other defined criteria. From this viewpoint, the experiment can be approached in either a physical or a statistical way, but most scientists would seem to prefer an experiment in which various physical hypotheses were formulated and announced before its start and were tested by methods similarly specified in advance.

The most sophisticated attempts to incorporate interactive physical hypotheses into an overall hypothesis concerning the effect of specified initial conditions on resulting precipitation have been made in the form of numerical cloud models. However, as was concluded in Session 1, no currently available model can predict the effects of seeding and specific meteorological conditions on precipitation with sufficient accuracy to provide a reliable physical formulation for the experimental design. It is even possible that the physics is too complex to allow the construction of a model that can make these predictions to the accuracy required. Either conclusion weighs heavily against the persuasive power desired of the so-called "physical experiment." Nevertheless, the models do help forge links in the chain of events from the initial modification to the final output of precipitation at the ground and, therefore, can assist in the formulation and clarification of specific hypotheses to be tested in an experiment. It was also concluded that models can *assist* the evaluation of seeding experiments by providing predictors and the daily operation of seeding experiments by providing seed/no-seed forecasts. Thus the models, based upon physical theories and hypotheses, are of more assistance to the overall statistical experiment than in providing strong persuasive power to arguments based upon the physical elements of the experiment.

This led to the question as to the extent to which and the reliability with which the weather modification technology under consideration is transferable to new locations. The general judgment was that transferability is presently more of an art than a science and that in each case a new application of the art must be subjected to a scientific test before definitive conclusions may be drawn. As in any art, the probability of a successful transfer is greater if the differences in the new situation from the old ones are minimized. The ability to adapt to each new situation is assisted by knowledge, good judgment, and experience. Thus both the scientist and the practitioner have much to gain by an orderly progression from the simple to the more complex and by having checkpoints of definitive observation and evaluation on the way.

The Climax Experiment seems to have been the simplest version of orographic seeding. Efforts like the San Juan Project and the Central Sierra Research Experiment (CENSARE) introduced complexities both in the types of storms and in the targeting of seeding materials. Much intensive postanalysis has assisted in sorting the problems and in identifying positive effects of the seeding. Intensive postanalysis of CENSARE has resulted in the identification of storm and terrain characteristics that tend to complicate the systematic transfer of technology from one location in the Sierra Nevada to another.

Three uncertainties were identified as the source of most of the problems in evaluating orographic seeding projects, and perhaps most other weather modification projects as well. These are the uncertainties associated with quantitative precipitation prediction, with precipitation measurement, and with the transport and diffusion of the seeding material. The uncertainty in precipitation prediction results principally from the present inadequate description of natural cloud processes, the present inability to incorporate this physics into accurate cloud models, and the present difficulty in acquiring meteorological measurements aloft.

There is no consensus on whether statistical storm units should be 6 or 24 h, or something between or beyond. Data were presented to indicate the statistical problems resulting from poor short-range predictions, but no evidence was presented on how to improve the predictions. There was information presented that described the large uncertainties with measuring precipitation in the mountainous terrain and even data that suggested systematic errors as large as 100% on currently installed snow gages. These uncertainties alone led some statisticians to suggest that a careful preanalysis be made prior to any project to determine the expected time required to detect and verify a given magnitude increase in precipitation due to seeding.

While some participants felt that weather modification might best be served by a concentrated attack on reducing the above-mentioned uncertainties, many others felt that a direct move to a comprehensive weather modification project would be of more value. There was general agreement that any such project should be designed to provide information to answer specific questions and to better understand the local physical processes and that it should be a mixture of observational studies, laboratory tests, field trials, modeling, randomized experiments, and operational projects.

Also, all generally agreed that designing a good experiment would be a very difficult task and perfection should not be expected. Both natural and economic restrictions exist that are insurmountable and require compromise. Not all variables can be measured, full spatial replication is impossible, time units are seldom independent, equipment is frequently unreliable and inaccurate, the actual distribution and lifetime of seeding materials can not be precisely known. Nevertheless, it was felt that a strong effort should be made to design the best experiment possible.

Most participants felt that in addition to improved prediction and measurement, future efforts should include directions toward improved situation recognition (through radar, satellites, meteorological forecasts, etc.), faster response to the situation, and more accurate and cost-effective delivery of the seeding materials.

4. Session 3

Session 3 dealt with the anticipated environmental, social, and economic impacts of the new Sierra Nevada Project. This well-attended session produced a wide range of perspectives. Although the social and economic areas were perhaps not sufficiently emphasized, realizing that it is upon these two grounds that any proposed project must be justified, it was remarked that the program had more balance than any weather modification conference in the past eight years.

The Natural Resources Defense Council and the Sierra Club urged full assessment of environmental and socioeconomic impacts before a massive commitment to cloud seeding is made. This assessment, it was urged, should go beyond the particular project being proposed to include the impact of the full-scale application of the technology growing out of the experimental program. It should also include an exploration of alternatives to cloud seeding such as improved water conservation and more efficient water use. Both of these latter items are being intensively studied by the Department of Water Resources, state of California, as was learned in a luncheon speech by the Department's Deputy Director.

Opinions were expressed in the discussion session that a full assessment of cloud seeding should also include an evaluation of the relative environmental impact and economic costs of alternative ways of generating power and increasing water supply. For instance, the difference in hydroelectric power in California between a wet year and a dry year is 50×10^9 kW h, or the equivalent of five nuclear- or fossil-fueled power plants. If it were determined that cloud seeding could supply the need of, say, one of these power plants, then the assessment should consider the total costs of alternative ways of supplying California with 10×10^9 kW h of energy per year. Added to this should be the value of additional water, especially in a dry year, to agriculture and livestock.

There was general agreement that the time and effort to gather some of the desired environmental data may equal or exceed the time and effort to gather the physical data more directly relevant to the proposed experiment. Also, it appeared that much of the relevant environmental data may be collectable only in the context of an all-inclusive experiment, much in the way it was done in the San Juan Project. Many scientists expressed the opinion that *environmental views should derive from the same level of competence and proof as expected of the views of physical science researchers, and that the costs to society of postponing an experiment should be compared to its expected socio-economic impacts.*

Two "fallacies" were presented that are commonly encountered in discussions of environmental impact. The first is that "the large natural variation in the weather renders innocuous the small induced increases in precipitation." The second fallacy is that "ecological effects can be predicted from short term experiments or studies." Some scientists, however, felt that the implications of these fallacies were superfluous for the following reasons: Regarding the first, it has not been demonstrated that small increases in precipitation lead to ecological changes, as data adequate to show such changes are difficult to obtain. Although ecological changes are expected to accompany large variations in precipitation, the determinations of the "desirability" or "undesirability" of such changes is a value judgment. Some felt that if seeding increases precipitation enough to indicate an economic benefit, then it might have an ecological impact as well.

Regarding the second, the ecological evaluation suggested would, in most cases, be prohibitively expensive and take many times the years now required to determine even the more immediate effects of seeding. Even natural climate change could be a complicating factor in such an evaluation. Though it is probably true that short-term experiments can not provide all the answers to the effects of cloud seeding, some argued that the long-term risks suggested by short-term experiments are acceptable if a significant economic benefit is expected.

Ecological studies in the San Juan Project determined that a snow depth of 70 cm forced elk to a lower elevation. Avalanche studies showed that heavy avalanche years are not necessarily heavy snow years. Progress in forecasting avalanche conditions was reported, and note was made that the economic effect of an avalanche is large. Ecological studies in the Medicine Bow Mountains have found that two species of plants and one species of trout have very high tolerances to silver iodide.

Economic analysis tools were considered useful for producing estimates for policy decisions, even though predictions of economic models were acknowledged to be as fallible as models for rainmaking. The principles, but not the details, of the Stanford Research Institute technology assessment for Colorado snowpack appear to be generally transferable to the Sierra Nevada. Advocated changes included having an oversight committee to bring in outside expertise, to reevaluate the basic premises, and to accelerate dissemination of the findings and having a broadened technology assessment context with longer time horizons.

Preliminary assessment of social effects of a Sierra Project indicated that public knowledge about the project is considerably less in evidence than was true in South Dakota prior to completion of the planning stage of the project. Of those people interviewed who favored a water program (40%), most (35%) preferred building more reservoirs to cloud seeding, and only a few (4%) preferred cloud seeding. Twenty percent would strongly oppose cloud seeding. Opinions were not correlated with information level.

Two crucial sets of information seem to be lacking in studies to date. The first concerns the "facts of life" in the power balance of interests for and against the proposed project. There seems to have been no careful, systematic analysis of this subject even though the conflicts must be settled in some fashion before the project is begun. The second is that real, hard-headed empirical data on socio-economic impacts are not available.

Since the primary purpose of the conference was to assist the consideration of how best to meet the growing need for water in the state of California, a much broadened context of research was suggested for the future. To what extent, for instance, should the American taxpayer help Californians live in a "desert"? It is relevant that the state produces via 85% of its water some 25% of the table food in this country. What gains can be achieved by improved conservation in water use? And what are the long-term consequences of no increase of water in California? Are the consequences really bad?

Thus future investigations might examine the proposed Sierra Nevada Project in the light of alternative national policies, e.g., population growth and redistribution, energy sources, food production, pollution problems, and vulnerability to natural hazards. Also of relevance are alternative state policies regarding the concern about becoming more dependent on federally produced water and the future determination of the cost of water.

Overall, it was clear that an early involvement of all talents in the proposed weather modification project would be advantageous to all concerned. The exploration of ways to achieve this involvement was not a subject of this conference.

5. General comments

Presentations were made without breaks each morning and afternoon. During or between the presentations the audience delivered their written questions or comments to one of the two session summarizers, who were seated at a table in the back of the room. At the end of each morning and afternoon session, discussions were initiated with an organized review of the questions and comments by the summarizers. The use of summarizers helped focus the discussion on the more significant issues. A large number of speakers were accommodated, yet the timing was almost precise as chairpersons had to close the discussions only once—at the end of the session. No speaker had to follow a lengthy discussion or a coffee break. There were few distractions. The lack of scheduled breaks seemed to assist the continuity of the sessions and eliminated the requirement of calling the session together more than once. The use of only single sessions kept the group more cohesive and reduced anxiety and travel in and out of sessions. The summary session provided a final focus to the conference and maintained the interest of the participants to the end.

Participants seemed to like the convenience of being within 7 min of a major airport combined with the quieter virtues of a suburban area and a hotel-side park. While the days were intense, the evenings after 5:00 p.m. were entirely open. Some participants chose to use this opportunity to go into the big city, while others chose to dine at one of the several excellent restaurants within a mile of the hotel. The final session closed at 4:00 p.m., and participants were thus able to be on their airplanes by 4:30 p.m.