AUSTRALIAN CLOUD SEEDING RESEARCH SYMPOSIUM

7-9 MAY 2007

Bureau of Meteorology
Melbourne, Australia

Australian Government
Bureau of Meteorology

snowy hydro Limited
renewable energy

CSIRO

Hydro Tasmania
the renewable energy business

State Government Victoria
Department of Sustainability and Environment

SYDNEY CATCHMENT AUTHORITY

Scientific Committee

Dr Neville Smith (Chair), Chief Scientist, Bureau of Meteorology
Dr Greg Ayers, Chief, CSIRO Marine & Atmospheric Research
Mr John Denholm, Snowy Hydro Limited
Dr Tom Keenan, Bureau of Meteorology Research Centre
Prof. Mike Manton, Monash University
Mr Alex Nazarov, Hydro Tasmania
Prof. Roger Stone, University of Southern Queensland

Local Organising Committee

Mr Andrew Hollis, Bureau of Meteorology Research Centre
Ms Val Jemmeson, Bureau of Meteorology Research Centre
Ms Meryl Wiseman, Bureau of Meteorology Research Centre

Sponsors

Snowy Hydro Ltd

Hydro Tasmania

Sydney Catchment Authority

Department of Sustainability & Environment (Victoria)

Bureau of Meteorology

CSIRO

CONTENTS

PROGRAM

Monday 7 May: Invited Talks

08:30	Registration	
09:00	**Opening Ceremony** • **Geoff Love** (Director of Meteorology) • **Mr John Forrest MP** (Federal Member for Mallee) • **Sharon Howes** (Snowy Hydro) • **Alex Nazarov** (Hydro Tasmania)	
Session 1: Overview of Cloud Seeding Research - CHAIR: Arlen W. Huggins		
09:30	Cloud Seeding in Australia – the first forty years	**Warren King** Chief Technology Officer, Cap-XX; formerly CSIRO
10:00	US National Research Council - Review of Weather Modification	**Roelof Bruintjes** National Center for Atmospheric Research, USA
10:30-11:00	Morning Break	
11:00	WMO Guidance on Cloud Seeding	**Deon Terblanche** Chair, WMO Expert Team on Weather Modification; and South African Weather Service
11:30	The Israeli experience of Cloud Seeding and its Ramifications	**Daniel Rosenfeld** The Hebrew University of Jerusalem
12:00	Examination of Anomalies in the results of Australian Cloud Seeding experiments	**Keith Bigg** CSIRO (retired)
12:30-13:30	Lunch	
Session 2: Scientific Basis and Challenges - CHAIR: Deon Terblanche		
13:30	Modelling and Related Requirements in Cloud Seeding	**Roelof Bruintjes** National Center for Atmospheric Research, USA
14:00	Cloud Seeding for Snowfall Enhancement - Concepts, Evidence of Effects and New Evaluation Techniques	**Arlen W. Huggins** Desert Research Institute, Reno, Nevada, USA
14:30	Challenges in Hygroscopic Seeding of Convective Clouds	**Daniel Rosenfeld** The Hebrew University of Jerusalem
15:00	Evaluation of the impacts of Cloud Seeding	**Michael Manton** Monash University
15:30– 16:00	Afternoon Break	
Session 3: Practical Applications of Cloud Seeding - CHAIR: Daniel Rosenfeld • Scientific methodology • Technical approach • Practical aspects • Validation		
16:00	Japan Weather Modification Research	**Masataka Murakami** Japan Meteorological Agency
16:30	Snowy Precipitation Enhancement Research Project	**Loredana Warren** Snowy Hydro
16:50	A Brief Discussion of Cloud Seeding Operations in Tasmania	**Alex Nazarov** Hydro Tasmania
17:15	Discussion	
19:30	**SYMPOSIUM DINNER (Savoy Hotel) – included in Registration**	

Tuesday 8 May: Invited Talks and Round Table Discussion

Session 3: (Cont.) Practical Applications of Cloud Seeding - CHAIR: Roelof Bruintjes		
09:00	Harvesting the clouds (VIDEO CONFERENCE)	**George W. Bomar** Texas State Meteorologist, USA
09:30	South Africa	**Deon Terblanche** South African Weather Service
10:00	The Nevada State Weather Modification Program	**Arlen W. Huggins** Desert Research Institute, Reno, Nevada, USA
10:30–10:45	Discussion	
10:40-11:30	Morning Break	
Session 4: User Perspectives -		
11:30- 12:45	Round-Table Discussion on User Issues	
12:45- 14:00	Lunch	

Tuesday 8 May: Restricted Workshops

<u>Scientific Workshop Session</u>

- Break-out groups ~ 15
  All groups address the same issue
- Focus on scientific and technical aspects
- Overarching aim of determining path forward

~60 minutes in break-out,
20 minutes for report

14:00: The Scientific and Technical Basis • What is known and agreed • What is known but not agreed • What is unknown (gaps)		
15:30- 16:00	Afternoon Break	
16:00 Required Research • List of scientific questions • Technical and Observational needs (objectives) • Need research on impacts (socio, economic, ..)		
17:30- 18:00	Additional Plenary Discussion	

Wednesday 9 May: Workshop and Planning

09:00	The Way Forward • Possible research frameworks • Coordination options • Available mechanisms	
10:30- 11:00	Morning Break	
11:00	Consolidation, Conclusions • Report • Actions	
13:00	Close	

Australian Government Bureau of Meteorology · snowy hydro renewable energy · Sydney Catchment Authority · Hydro Tasmania · State Government Victoria Department of Sustainability and Environment · CSIRO

INTRODUCTION

The availability and use of water are key issues for Australia. Significant parts of south-eastern and south-western Australia are experiencing ongoing rainfall deficits, and drought is impacting on agricultural production, some of our industries and the viability of some farming enterprises. Major river systems are currently receiving record low inflows and many cities and towns are experiencing urban water shortages.

Within this context, it is timely to examine the potential benefits and, as appropriate, mechanisms for support of cloud seeding research, one technique proposed for ameliorating water shortages.

The Bureau of Meteorology is convening this conference and workshop to discuss existing and planned research activities, including those being conducted in other parts of the world. Cloud seeding experiments were first performed in Australia in 1947, and subsequently a number of experimental programs were carried out. Over the intervening period, there has been considerable debate and, on occasions controversy over the efficacy of the approach with a number of reviews conducted to assess the scientific basis. This meeting provides an opportunity to revisit the scientific basis and methods for testing the effectiveness of various cloud seeding approaches, taking account of technological advances and changed circumstances.

Mr John Forrest MP (Federal Member for Mallee) has been active in encouraging cloud seeding research in Australia and this Symposium is in part a response to that advocacy and the associated public interest.

We are fortunate to have a number of valued international contributors, who are giving keynote presentations including Roelof Bruintjes (NCAR, USA), Arlen W. Huggins (Desert Research Institute, USA), Masataka Murakami (Japan Meteorological Agency), Daniel Rosenfeld (Hebrew University of Jerusalem), and Deon Terblanche (South African Weather Service). A video conference presentation from George W. Bomar (Texas State Meteorologist, USA) is also part of the program. The Symposium will include participants and presentations from researchers in Australia who will lead a workshop examining the potential for enhanced research and mechanisms that might be used to support such an effort. We are grateful for these expert contributions and to all the participants' contributions to the debate and discussions.

The level of interest in this topic is attested to by the strength of support and sponsorship the Symposium has attracted. The Bureau has been assisted by major sponsorship from Snowy Hydro Ltd and Hydro Tasmania. The Sydney Catchment Authority, Victorian Department of Sustainability and Infrastructure and CSIRO are also valued contributors. I would also like to thank the members of the Scientific Organising Committee and Local Organising Committee for the valuable contributions to the organisation of the meeting and assuring its success.

N.R. Smith

Chief Scientist, Bureau of Meteorology

May 2007

Cloud Seeding in Australia – the First Forty Years

Warren King

Chief Technology Officer, Cap-XX; formerly CSIRO

A surprising amount of the background science, and many of the early experiments in cloud seeding were conducted in Australia between 1947 and 1987. This talk will give an introduction to the physical principles behind cloud seeding, the basic concepts in measuring seeding effects on rainfall, the experiments conducted by CSIRO, and the circumstances leading to CSIRO's decision to cease active experimentation.

The earliest experiments were conducted on individual cumulus clouds using either dry ice or silver iodide as the seeding material, with some success, but it was also recognized that successful experiments on individual cumulus clouds would need to be replicated in wide areas over extensive time periods for cloud seeding to have serious economic impact. This led to several wide-area experiments being conducted in the Snowy Mountains, Warragamba in the Blue Mountains, the New England region and South Australia from 1955 to 1963. Together, these experiments suggested that cloud seeding could be successful, but it was by no means convincing because of the variability of results and because of a suggestion that the measured seeding effects decreased with successive years of seeding. A major experiment in Tasmania was designed to overcome this possible persistence effect by seeding in alternate years, and the results of this experiment, and a follow-up one showed that increases in rainfall could result from seeding in both autumn and winter, and that the increases were of economic benefit.

Success in Tasmania led to the design of an experiment in Western Victoria aimed at increasing rainfall in a prime wheat-growing area. Preliminary work was modeled on, and contributed to, the World Meteorological Organization's Precipitation Enhancement project (PEP). In both the Western Victoria and the WMO experiments, three conditions were required to be satisfied before the experiment would proceed: (i) There had to be physical evidence that there would be a reasonable number of opportunities in which clouds deemed suitable for seeding would occur (ii) rainfall records in the area had to be of sufficient quality to enable statistical simulations of the seeding to be performed and these simulations had to show it was possible to detect the nominated seeding effects in a period of five years and (iii) the economic benefits of seeding had to exceed the cost.

Preliminary work in Western Victoria showed that all three of these conditions appeared to be satisfied, but the experiment was abandoned after just two years because instrumented aircraft measurements showed that the number of seeding opportunities was far fewer and of shorter duration than had been expected, leading to an inability to detect increases in the proposed five-year time frame and to consequent reduced economic benefit. A further study looking at general characteristics of many areas of Australia showed that it was unlikely that economic benefits would be demonstrated in a reasonable time frame other than in the orographic uplift areas of the Snowy Mountains and Tasmania. This led to the decision by CSIRO to abandon cloud seeding as a field for scientific exploration in 1984.

Weather Modification: Seeding is not *just* believing

Roelof Bruintjes

National Center for Atmospheric Research, USA

Water is the basic sustenance of all life on earth and recent reports by the United Nations project that approximately one third of the world population will live under severe water stresses by the middle of this century. This has motivated politicians and water managers to explore precipitation enhancement via cloud seeding as one alternative to augment water resources. In addition, there is now ample evidence that human activities, such as the emission of industrial air pollution and other anthropogenic activities can alter atmospheric processes on scales ranging from local precipitation patterns to global climate. Documentation of anthropogenic effects on the weather strengthens the physical basis for deliberate attempts to alter the weather.

Operational weather modification programs, which primarily involve cloud-seeding activities aimed at enhancing precipitation or mitigating hail fall, exist in more than 37 countries (more than 150 projects), and there were at least 66 operational programs being conducted in 11 states across the United States. Many of these programs operate without any scientific quantitative assessment or evaluation of the seeding experiments. Although there is strong evidence that cloud seeding could enhance precipitation under certain conditions in certain areas, there is also strong evidence that current technologies of cloud seeding to enhance precipitation will not work in other atmospheric conditions and areas. There is even evidence that in some situations glaciogenic seeding may reduce precipitation. There are actually some examples of ongoing operational cloud seeding programs in areas where it was previously found through scientific experimentation that seeding would not work.

The potential for increases in rainfall using cloud seeding is strongly dependent on the natural aerosols, microphysics and dynamics of the clouds that are being seeded. Microphysics means the size and concentration of water droplets and ice particles inside clouds. Dynamics means the forces affecting air motions in and around clouds. The microphysics are in turn dependent on background aerosol levels, because it is the aerosol particles that attract water vapor to form cloud droplets, and in cold clouds, ice particles. Furthermore, the types and concentrations of aerosol particles can be influenced by trace gases (i.e., air pollution). Given these dependencies, the microphysics of clouds and seeding effects can differ significantly from one geographical region to another, and even during and between seasons in the same region. In some instances, clouds may not be suitable for seeding, or the frequency of occurrence of suitable clouds may be too low to warrant the investment in a cloud seeding program. Both factors need to be evaluated and preliminary studies should be conducted on atmospheric aerosols and pollution levels and on the microphysics and dynamics of naturally forming clouds, prior to commencing a larger seeding experiment. In many operational programs these studies have never been done. If the targeted measurements and additional data show sufficient evidence for clouds to be positively affected by cloud seeding, the cloud seeding technique(s) should then be evaluated using a randomization procedure to statistically demonstrate that the seeding method works, and to quantify any possible increases. This approach is similar, for example, to what is commonly done in medical trials with a new drug.

The dilemma as highlighted in the 2003 report of the National Research Council (NRC) of the National Academy of Sciences report is that while little funding is available for physical measurements and understanding; others are willing to spend funds to apply these technologies even if they do not know if it will have an effect in their region. We know that human activities can affect the weather, and we know that seeding will cause changes to a cloud. However, in many instances we still are unable to translate these induced changes into verifiable changes in rainfall, hail fall, and snowfall on the ground, or to employ methods that produce scientifically credible, repeatable changes in precipitation. Among the factors that have contributed to the difficulty to verify seeding effects are such uncertainties as the natural variability of precipitation, associated background aerosol and microphysical characteristics of the atmosphere and clouds, inadequate understanding of the interactions between the microphysics and dynamics in clouds, inadequate targeting of seeding material, the inability to measure these variables with the required accuracy or resolution, and the detection of a small induced effect under these conditions.

The reasons that quantitative scientific proof is scanty are many and include the lack of scientifically demonstrable success in modification experiments, extravagant claims, attendant unrealistic expectations (i.e., pressure from agencies to meet short-term operational needs rather than to achieve long-term scientific understanding and assessment), growing environmental concerns, and economic and legal factors. This does not challenge the scientific basis of weather modification concepts. Rather it is the absence of adequate understanding of critical atmospheric processes that, in turn, lead to a failure in producing predictable, repeatable, detectable, and verifiable results.

Despite the lack of scientific proof, our scientific understanding has progressed on many fronts in the last twenty years. For instance, recent experiments using hygroscopic seeding particles in water and ice (mixed-phase) clouds have shown encouraging results, with precipitation increases attributed to increasing the lifetime of the rain-producing systems. There are strong suggestions of positive seeding effects in winter orographic cloud systems (i.e., cloud systems occurring over mountainous terrain). Satellite imagery has underlined the role of high concentrations of aerosols in influencing clouds, rain, and lightning, thus drawing the issues of intentional and inadvertent weather modification closer together. Changing levels of background aerosols associated with inadvertent weather modification in a region can influence or change the potential for deliberate weather modification and render previous cloud seeding results not applicable anymore. This and other recent work has highlighted critical questions about the microphysical processes leading to precipitation, the transport and dispersion of seeding material in the cloud volume, the effects of seeding on the dynamical growth of clouds, and the logistics of translating storm-scale effects into an area-wide precipitation effect. Questions such as the transferability of seeding techniques or whether seeding in one location can “steal” rain from other locations can only be addressed through sustained research of the underlying science combined with carefully crafted hypotheses and physical and statistical experiments.

In addition, significant and exciting advances in observational, computational, and statistical technologies have occurred over the past two to three decades. These include the capabilities to (1) detect and quantify relevant variables on temporal and spatial scales not previously possible; (2) acquire, store, and process vast quantities of data; and (3) account for sources of uncertainty and incorporate complex spatial and temporal relationships. Computer power has enabled the development of models that range in scale from a single cloud to the global atmosphere including enhanced detail of the physical processes. However, because of lack of funding, few of these tools have been applied in any collective and concerted fashion to resolve critical uncertainties in weather modification activities.

Capitalizing on these advances and especially new remote and *in situ* observational tools (e.g., polarimetric radars and lidars, radars and satellites, microwave radiometers, new cell-tracking software, and new airborne in-situ instrumentation, etc.) added to existing or new experiments could yield substantial new insights and provide for the first time the capability to simultaneously provide the necessary physical and statistical basis for the efficacy of cloud seeding experiments to enhance precipitation or mitigate hail. A coordinated sustained scientific effort will be needed to answer some of the questions raised in the previous paragraphs. Some especially promising possibilities to include these new advances where substantial further progress may occur include:

- Hygroscopic seeding to enhance rainfall. The small-scale experiments and larger-scale coordinated field efforts proposed by the WMO report on the workshop on hygroscopic seeding could form a starting point for such efforts.
- Orographic cloud seeding to enhance precipitation. A randomized program that includes strong modeling and observational components, employing advanced computational and observational tools could substantially enhance our understanding of seeding effects and winter orographic precipitation.
- Studies of specific seeding effects. This may include studies such as those of the initial droplet broadening and subsequent formation of drizzle and rain associated with natural, hygroscopic seeding and anthropogenic sources of particles.
- Improving cloud model treatment of cloud and precipitation physics. Special focus is needed on modeling cloud microphysical processes.

The basic science that will be learned in pursuing questions related to weather modification undoubtedly will lead to knowledge and capabilities in many other and in some cases unexpected areas.

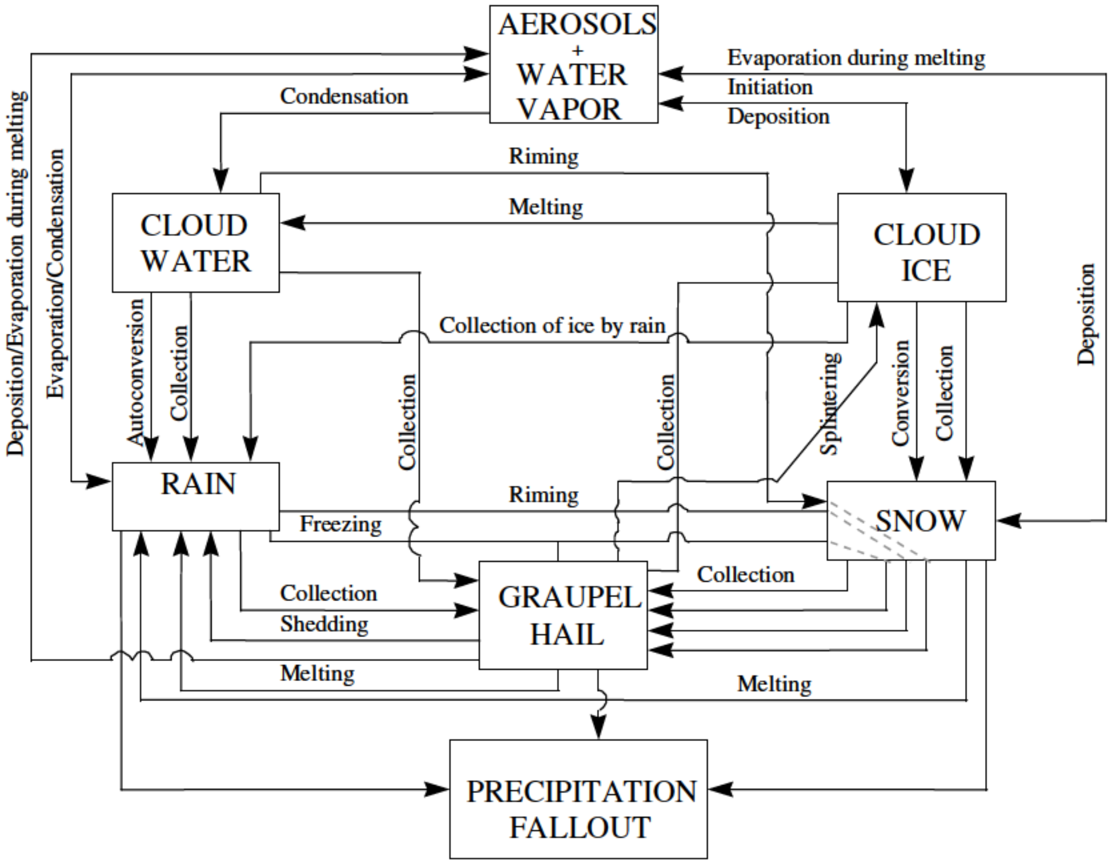

Figure 1: Various pathways by which water vapor and aerosols are transformed into various types of cloud particles and precipitation. Some paths may be more efficient than others in producing precipitation and both intentional and inadvertent weather modification changes these paths. Adapted from Houze (1993, p. 96).

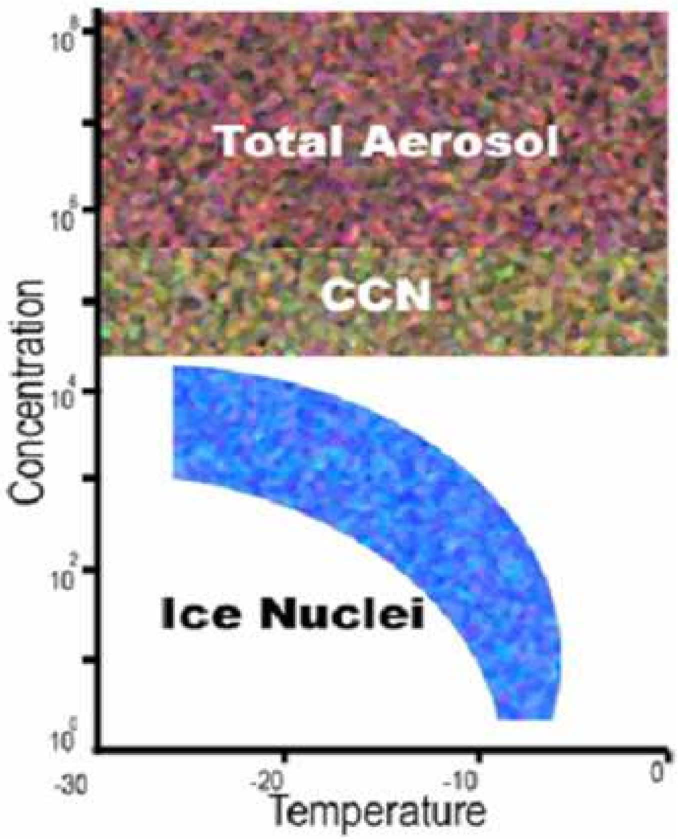

Figure 2: Total aerosol, cloud condensation nuclei (CCN), and ice nuclei (IN) concentrations as a function of temperature. In order to enhance precipitation the concept of seeding is to seed with appropriate CCN or IN to make precipitation develop more efficiently.

The opposite effects of pollution aerosols on convective and orographic precipitation

Daniel Rosenfeld

Institute of Earth Sciences, The Hebrew University of Jerusalem

Australian scientists pioneered the research of cloud-aerosol interactions, and established already in the 1960's that particulate air pollution adds large concentrations of small cloud condensation nuclei (CCN), which induce a larger concentration of smaller cloud drops. They have further shown that the process of drop coalescence into raindrops is slowed considerably when cloud drops are smaller (Squires, 1958, Warner et al, 1968). At the same time, it was shown that cloud seeding can accelerate the conversion rate of cloud drops into precipitation particles (Wegener, 1911; Bowen, 1952). These two facts are well established by now in the world scientific community.

However, the two main questions that remained at least partially unanswered until today are:

1. To what extent accelerating (slowing) the conversion rate of cloud drops into precipitation particles results in enhancement (suppression) of precipitation amounts on the ground?
2. If there are effects on precipitation amounts, do they occur at a meaningful scale from climatological, hydrological and economical points of view?

A "negative cloud seeding" by air pollution emanating by cities and industrial developments has been practiced far more extensively than intended cloud seeding. Small anthropogenic aerosols of air pollution serve as efficient CCN that suppress precipitation. Because “negative cloud seeding” by air pollution is practiced much more extensively around the world than intended cloud seeding, there are many more opportunities to study the sensitivity of precipitation to proper cloud seeding by studying the susceptibility to air pollution than the limited amount of advertent seeding experiments.

The extent of the impacts of air pollution on reducing cloud drop size became readily visible with the application of meteorological satellites that can retrieve cloud properties. This effect was first seen in 1987 conspicuously in the form of ship tracks and suppressed drizzle in polluted maritime stratocumulus (Coakley et al., 1987). It was then found to occur also well inland due to smoke from forest fires and anthropogenic air pollution (Rosenfeld and Lensky, 1998). The launching of the Tropical Rainfall Measuring Mission (TRMM) satellite allowed measuring of both cloud drop size and precipitation forming processes inside the cloud, and to link directly the changes in cloud drop size to suppression or enhancement of precipitation. TRMM observations showed that smoke from forest fires completely shut off precipitation from tropical clouds in Indonesia (Rosenfeld, 1999) and in the Amazon (Rosenfeld and Woodley, 2003), and that urban and rural air pollution did the same to clouds over India (Rosenfeld et al., 2002). TRMM observations have shown also conspicuous pollution tracks over Australia, where the pollution suppressed the formation of rain and snow precipitation along the Great Dividing Ranges of the Victorian Alps and Snowy Mountains (Rosenfeld, 2000). Simulations of pollution dispersion at the time of these observations done by CSIRO showed that the satellite retrieved pollution tracks coincided with pollution tracks emanating from major population centers in Victoria and South Australia (Rosenfeld et al., 2006). Similar satellite retrieved pollution tracks were found to be dominant features over all the moderately and densely populated regions of the world (Ramanathan et al., 2001). Hence, the advent of satellite technology underlined the potentially great importance of negative and proper cloud seeding on precipitation and water resources.

The next obvious question is the impact on surface precipitation. Slowing the conversion rate of cloud water to precipitation would result in a net decrease of precipitation if clouds live a shorter time than necessary for the completion of their precipitation process. Such are orographic clouds, i.e., clouds that form anew in air that ascends while crossing a topographic barrier and forced to evaporate with the descending air on the downwind slope. These clouds are of great importance, because they are responsible for much of the added precipitation over mountain ranges, which are a major source of water in semi arid areas, as is the case with the Victorian Alps and the Snowy Mountains in Australia. The acceleration (slowing) of the conversion cloud water to precipitation by "negative cloud seeding" (air pollution) of orographic clouds should be manifested as increase (decrease) in the orographic precipitation enhancement factor, i.e., the ratio between mountain to upwind lowland precipitation amounts. Following this realization, the trends of orographic enhancement factors during the last century in a large number of mountain ranges were found to be decreasing downwind of populated areas (Givati and Rosenfeld, 2004 and 2005; Jirak and Cotton, 2006; Griffith et al., 2005), whereas no precipitation reduction noted in the few remaining pristine regions (Givati and Rosenfeld, 2005). Aircraft measurements of aerosols cloud properties made in California (Rosenfeld, 2006b) and mountaintop measurements made in China (Rosenfeld et al., 2007) directly linked the suppressed precipitation to the sub-micron pollution aerosols. Furthermore, it was possible to decompose the positive effect of cloud seeding from the negative effects of air pollution that have been taking place over the upper Galilee hills in northern Israel (Rosenfeld and Givati, 2006). Therefore, quantification of the decreasing trend of orographic precipitation due to air pollution has become an excellent indicator to the susceptibility of the clouds to precipitation enhancement by cloud seeding.

The impact of aerosols on the rainfall amounts from deep convective clouds has added complications. If we are to learn on the susceptibility of convective clouds to rain enhancement by hygroscopic seeding, we should observe their behavior when the opposite is done to the clouds while being polluted with large concentrations of small CCN. Polluting (hygroscopic seeding) of clouds developing in relatively dry atmosphere can decrease (enhance) surface precipitation (Khain et al., 2001), but in warm base clouds in moist atmosphere the opposite can occur (Khain et al., 2005). The initially delayed (accelerated) rainfall causes subsequent invigoration (weakening) of the cloud system later on, with respective enhancement (suppression) of precipitation (Rosenfeld, 2006a).

The hygroscopic seeding agent of choice for convective clouds has been, recently, hygroscopic flares (Mather et al., 1997). But recent experimenting and modeling of hygroscopic flares performance have found that they were far from an optimal seeding method. A new seeding methodology has been recently developed that is more potent to produce embryos of raindrops by more than a factor of 100 compared to the hygroscopic flares. This methodology is based on salt powder milled to the optimal particle size that is calculated by cloud seeding simulations (Segal et al., 2004).

In summary, air pollution and cloud seeding are the two opposite sides of the same coin and therefore inseparable when we consider our impacts on precipitation and water resources.

References:

Bowen, E.G., A new method of stimulating convective clouds to produce rain and hail, *Q. J. Roy. Meteor. Soc.,* **78**, 37–45, 1952.

Coakley, J.A. Jr., R.L. Bernstein, and P.A. Durkee, Effects of ship-track effluents on cloud reflectivity, *Science,* **255**, 423–430, 1987.

Givati, A., and D. Rosenfeld, Quantifying precipitation suppression due to air pollution, *J. Appl. Meteor.,* **43**, 1038–1056, 2004.

Givati, A. and D. Rosenfeld, Separation between Cloud-Seeding and Air-Pollution Effects. *J. Appl. Meteor.*, **44**, 1298- 1315, 2005.

Griffith, D. A., M. E. Solak, and D. P. Yorty, Is air pollution impacting winter orographic precipitation in Utah? *Weather modification association. J. Wea. Modif.,* **37**, 14–20, 2005.

Jirak, I.L., W.R. Cotton, Effect of Air Pollution on Precipitation along the Front Range of the Rocky Mountains, *J. Appl. Meteor. Climate.* **45**, 236-246, 2006

Khain, A.P., D. Rosenfeld, and A. Pokrovsky, Simulating convective clouds with sustained supercooled liquid water down to -37.5ºC using a spectral microphysics model, *Geophys. Res. Lett*., **28**, 3887-3890, 2001.

Khain, A., **D. Rosenfeld** and A. Pokrovsky, Aerosol impact on the dynamics and microphysics of convective clouds. *Q. J. Roy. Meteor. Soc.,* **131**, 1-25, 2005.

Mather, G.K., D.E. Terblanche, F.E. Steffens, and L. Fletcher, Results of the South African cloud seeding experiments using hygroscopic flares, *J. Appl. Meteorol.,* **36**, 1433–1447, 1997.

Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld, 2001: Aerosols, Climate and the Hydrological Cycle. *Science*, 294, 2119-2124.

Rosenfeld, D., TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall, *Geophys. Res. Lett.,* **26**, 3105–3108, 1999.

Rosenfeld, D., Suppression of rain and snow by urban and industrial air pollution, *Science,* **287**, 1793-1796, 2000.

Rosenfeld D., 2006a: Aerosol-Cloud Interactions Control of Earth Radiation and Latent Heat Release. *Space Science Reviews*. Springer, 9p. 6 December 2006. DOI: 10.1007/s11214-006-9053-6.
http://dx.doi.org/10.1007/s11214-006-9053-6

Rosenfeld D., 2006b: Aerosols Suppressing Precipitation in the Sierra Nevada: Results of the 2006 Winter Field Campaign. Presented at the Third Climate Change Research Conference, California Energy Commission, Sacramento, California, 13-15 September 2006. Presentation available at:
http://www.climatechange.ca.gov/events/2006_conference/presentations/2006-09-14/2006-09-14_ROSENFELD.PDF

Rosenfeld, D., J. Dai, X. Yu, Z. Yao, X. Xu, X. Yang, C. Du, 2007: Inverse relations between amounts of air pollution and orographic precipitation. *Science*, **315**, 9 March 2007, 1396-1398.

Rosenfeld D., A. Givati, Evidence of orographic precipitation suppression by air pollution induced aerosols in the western U.S. *J. Appl. Meteor. and Climat.,* **45**, 893-911, 2006.

Rosenfeld, D., R. Lahav, A. Khain, and M. Pinsky, The role of sea spray in cleansing air pollution over ocean via cloud processes, *Science,* **297**, 1667-1670, 2002.

Rosenfeld D., and I.M. Lensky, Satellite-based insights into precipitation formation processes in continental and maritime convective clouds, *Bull. Amer. Meteor. Soc*., **79**, 2457–2476, 1998.

Rosenfeld D., I. M. Lensky, J. Peterson, A. Gingis, Potential impacts of air pollution aerosols on precipitation in Australia. *Clean Air and Environmental Quality*, **40**, No.2. 43-49, 2006a.

Rosenfeld D. and W. L. Woodley, 2003: Closing the 50-year circle: From cloud seeding to space and back to climate change through precipitation physics. Chapter 6 of "Cloud Systems, Hurricanes, and the Tropical Rainfall Measuring Mission (TRMM)" edited by Drs. Wei-Kuo Tao and Robert Adler, 234pp., p. 59-80, *Meteorological Monographs*, **51**, AMS.

Segal Y., A. Khain, M. Pinsky and D. Rosenfeld, 2004:. Effects of hygroscopic seeding on raindrop formation as seen from simulations using a 2000-bin spectral cloud parcel model. *Atmospheric Research* **71**, 3–34.

Squires, P., The microstructure and colloidal stability of warm clouds. I. The relation between structure and stability, *Tellus,* **10**, 256-271, 1958.

Warner, J., A reduction of rain associated with smoke from sugar-cane fires — An inadvertent weather modification, *J. App. Meteor.,* **7**, 247–251, 1968.

Wegener, A., *Thermodynamik der Atmosphäre,* J. A. Barth, Leipzig, 1911.

Examination of Anomalies in the results of Australian Cloud Seeding experiments

Keith Bigg

CSIRO Radiophysics and Cloud Physics Divisions, 1948-1985

Six randomised cloud seeding experiments lasting at least three years were conducted by CSIRO between 1955 and 1983, three in conjunction with other authorities. There were two basic designs. The first used a seeded target and an unseeded control area or areas and the second two nearby areas in which one or the other was seeded ("crossover" design). The seeding hypothesis was that silver iodide smoke introduced into deep clouds with top temperatures of about -10^{o} C or colder would produce sufficient ice crystals to induce precipitation to reach the ground within about 30 minutes and there would be no further effect on precipitation a few hours after seeding ceased. The hypothesis together with wind profiles predicted where seeding should take place in order to affect the target area. Some of the anomalous results are listed below.

1. All three target-control experiments were apparently successful, while all three crossover experiments were not.
2. Pluviographs placed in the Snowy Mountains target area found no evidence consistent with the seeding hypothesis. The statistical analysis estimated a 19% increase significant at the 3% level. As a result of this discrepancy the result was deemed to be inconclusive.
3. Ice nucleus concentrations increased during seeding periods and diminished very slowly in the year following the end of seeding, suggesting that there were after-effects of seeding.
4. There was a strong anti-correlation between annual estimates of precipitation increase and annual hours of seeding in the Snowy Mountains and first Tasmanian experiments.
5. The first four experiments showed a tendency towards worse results in each successive year of seeding.
6. If the New England experiment is analysed on a "seeded days only" basis the overall gain is 22% while the experimental design analysis showed only a 4% gain. Only half the difference could be explained by unseeded rain falling in seeded periods.
7. The first Tasmanian experiment was designed on a year-on, year-off basis on the assumption that the above anomalies were due to persistent after-effects of seeding. Seeding either began, or effectively began, in autumn of the seeded years. Apparent rainfall changes in autumn, winter and spring were +22%, +16% and -4% respectively, consistent with the possibility of a cumulative after-effect of seeding on the target area.

Assuming that the observed slow exponential decrease in ice nuclei following seeding is reflected in rainfall and that the effects of seeding are proportional to the amount of silver iodide used, a “cumulative seeding index” (CSI) can be constructed for each day of an experiment. Plots of CSI v. T/C rainfall help to explain the above anomalies.

After-effects of cloud seeding cause target areas to become effectively seeded in unseeded periods, leading to underestimates of precipitation changes. This explains why crossover experiments where both areas were seeded gave a worse result that those using unseeded control areas.

Evaluation therefore faces a choice between a statistical method embodying an incorrect assumption that gives misleading results and a procedure using comparison with lengthy unseeded periods where rigorous confidence levels are not readily obtained. Total precipitation in at least one year of an experiment rather than just that in seeded periods has to be compared with that in at least 5 unseeded years in a wide area surrounding the target. If seeding has been effective, the target area should show increases relative to surrounding areas. Results of four Tasmanian seeding sequences using this method showed consistently higher target precipitation than surrounding areas. Comparison of basic statistical parameters of target precipitation in seeded and unseeded periods of the same length suggested that the increases were significant. Downwind (east coast) precipitation fell within the range of expectation except in the case of a dry ice experiment. Mainland experiments showed consistently greater gains downwind than in the target areas.

We have to rethink how seeding experiments should be designed to minimize the persistent effects of seeding in their evaluation, and also consider how to make use of these after-effects.

Cloud Seeding for Snowfall Enhancement: Concepts, Evidence of Effects and New Evaluation Techniques

Arlen W. Huggins

Associate Research Scientist, Desert Research Institute, Reno, NV

This short paper reviews the basic concepts of winter orographic cloud seeding, or cloud seeding for snowfall enhancement over mountainous terrain. A conceptual model for orographic cloud seeding that has evolved over the past several decades is presented. The steps in the model are illustrated by examples from past well-designed experiments in the western U. S. Results from detailed ground-based and airborne measurements taken during these experiments are briefly described to show how steps in the cloud seeding chain-of-events (from the release, transport and dispersion of seeding material into clouds over an intended target, to microphysical changes brought about by artificial seeding aerosols in the cloud, to the development and fallout of precipitation in the seeding target area) have been verified. A combination of physical and statistical results from these same experiments form the basis upon which most operational wintertime programs are conducted.

The conceptual model for successful orographic cloud seeding includes successfully and reliably producing seeding material, having the seeding material be transported into a cloud region containing supercooled liquid water, having seeding material dispersed sufficiently to affect a significant cloud volume by the desired concentration of ice nuclei so a significant number of ice crystals can be formed, having seeding material reach the appropriate temperature level for substantial ice crystal formation and having ice crystals remain in a cloud environment suitable for growth long enough to enable them to fallout into the target area. Although these criteria are discussed primarily for seeding with silver iodide, some results using liquid propane as an ice nucleant are also presented.

All or portions of the cloud seeding chain-of-events have been documented by research studies in the Sierra Nevada of California, and in the Rocky Mountains of Montana, Colorado and Utah. Statistical evaluations of Montana experiments where the conceptual model was verified by physical measurements showed that seeding increased snowfall in the intended target, and that positive seeding effects were most prominent when the temperature near mountain-top level was -9^{o} C or colder. The partitioning of storms by temperature criteria indicated that ratios of target to control gauge precipitation were as high as 1.5, whereas the overall target-control ratio was generally about 1.15. Similar results were found in a Sierra Nevada project area.

Although the evidence of seeding effects in the examples being presented is strong, the examples of statistically significant results from randomized experiments are relatively few and there is still a need to conduct new randomized experiments, or to confirm the results from earlier experiments. New analysis techniques, particularly those combining physical measurements and the trace chemical analysis of snowfall, offer additional means of evaluating wintertime seeding projects and supporting the results of statistical studies.

Evaluation of the Impacts of Cloud Seeding

M.J. Manton

School of Mathematical Sciences, Monash University, Melbourne, Australia

Cloud seeding has been applied to the practical problem of enhancing precipitation at the ground since the late 1940s. Yet the USA National Research Council (NRC, 2003) reported a few years ago that “there is still no convincing scientific proof of the efficacy of intentional weather modification efforts”. The NRC concluded that the main reason for this deficiency of proof is a lack of focused research on the key scientific problems. This finding of the NRC highlights the fact that the evaluation of the impacts of cloud seeding is not straightforward.

Evaluation is difficult for three primary reasons. The first problem is that there is a mismatch between the scale of the required impact and the scale of the processes at which seeding acts. To be of practical value, cloud seeding generally needs to impact on the annual or at least seasonal rainfall over a substantial geographical area. On the other hand, seeding involves the introduction of minute particles with a view to influencing the microphysical processes associated with the formation of precipitation in clouds. The second problem is that the impact of cloud seeding is incremental, while rainfall is highly variable in space and time – especially in Australia where the El Nino – Southern Oscillation phenomenon is significant. Thus any increase in precipitation from seeding is generally small compared with the natural variations in rainfall. The third point is that evaluation is inherently expensive, and so substantial commitment is required if a cloud seeding experiment is to be evaluated properly.

Evaluation needs to occur at several levels in order to confirm that cloud seeding is both effective and efficient. The basic test for a practical process is whether it is cost effective. Because of the high cost of proper evaluation, it can be tempting to maximise the apparent benefit-to-cost ratio by minimising the cost of evaluation. This approach means that the evaluation is based on faith rather than science, and it means that the actual economic benefit is unknown. Thus, an economic evaluation is dependent upon the quality of the scientific evaluation, which has three components: statistical, physical and simulation. The statistical analysis determines whether the increase in precipitation can be detected and quantified. The physical evaluation consists of a set of measurements in the atmosphere and on the ground aimed at substantiating the hypotheses underlying the seeding method. An experimental result is further confirmed if it is possible to simulate the observed impact with a numerical weather prediction model, which has itself been independently evaluated on a range of weather events.

Because cloud seeding is routinely carried out in many countries and because evaluation is difficult, the World Meteorological Organization (WMO, 1978) established the Precipitation Enhancement Project (PEP) in the late 1970s to provide guidelines for its member countries on how to conduct a scientific cloud seeding experiment. In Australia guidelines focused on the application of cloud seeding to water management were prepared by Ryan and Sadler (1995), and the application of those guidelines (as well as the various WMO reports from PEP) remains as a test of the scientific credibility of any proposed cloud seeding project.

Two early cloud seeding experiments in Australia showed statistically significant impacts, and so it is worthwhile to consider the lessons learned from those projects when developing future cloud seeding activities. Smith et al. (1963) describe the cloud seeding project in the Snowy Mountains of south eastern Australia which provides a basis for the current project being carried out by Snowy Hydro Ltd (Warren, 2007), while a recent re-analysis of cloud seeding in Tasmania (Morrison et al., 2007) is based on the results of a continuing series of cloud seeding activities over more than forty years. The first experiment in Tasmania is described by Smith et al. (1979).

A key lesson from these Australian experiments is that statistical evaluation is critically dependent on the selection of control areas that can reliably estimate the rainfall in the target area on the time scale of the chosen experimental unit for seeding. In regions with large topographical variations and especially with highly-variable convective cloud, this selection can be difficult. Another major lesson is that a scientific measurement program needs to accompany the statistical evaluation of a cloud seeding project, in order to verify the basic seeding hypothesis and to support the statistical analysis. In addition to the scientific lessons from the past experiments, there is an important management lesson: the overall success of a project requires effective collaboration between all the groups involved in the project, especially between the people involved in the seeding operation and the users of the water from the rainfall.

Morrison et al. (2007) analyse the monthly rainfall data from Tasmania where seeding has occurred in 26 of the last 40 years. Although the seeding units have been much shorter than a month in Tasmania, the monthly rainfall record is more robust than the daily record. Moreover it is reasonable to expect a signal in the monthly rainfall if cloud seeding is to be economically viable. Such a long record provides an opportunity to investigate the robustness of the "ideal" evaluation, where a seeding effect is sought by comparing the rainfall in seeded months with that in unseeded months in the target area. However, it is found that the temporal variability of rainfall can lead to tantalising but incorrect inferences about the impact of seeding, even with a long time series. A conventional target-control double-ratio analysis is required to obtain a robust estimate of the impact of seeding. Further analysis of the spatial variation of the rainfall in seeded and unseeded months across the island provides support for the basic statistical evaluation. It does appear that the impacts of seeding can be detected at monthly time scales, although the basic experimental unit is as short as a day and the actual seeding time may be only a few hours over a month.

Because cloud seeding essentially provides incremental rainfall from naturally-precipitating systems, it is not an effective strategy in Australia during time of drought when there is an absence of rain and even cloud. On the other hand, cloud seeding may provide a mechanism for enhancing rainfall in times of normal and above-normal rainfall. Thus we have two cloud seeding experiments in Australia either underway in the Snowy Mountains or commencing in Queensland, as well as one operational activity in Tasmania. The two experiments provide an opportunity to use current science and technology to design and evaluate cloud seeding in both cold cloud (Snowy Mountains) and warm cloud (Queensland) conditions. There is the capability in Australia to improve on past efforts to estimate the natural rainfall, to collect observations of cloud processes, to conduct statistical analyses, and to estimate the economic benefit of cloud seeding.

References

Morrison, A., Siems, S.T., Manton, M.J. & Nazarov, A. (2007). Analysis of long-term cloud seeding operations over Tasmania. In preparation.

NRC (2003). "Critical Issues in Weather Modification Research". National Academy Press, 123pp.

Ryan, B.F. & Sadler, B.S. (1995). "Guidelines for the utilisation of cloud seeding as a tool for water management on Australia". *ARMCANZ Sub-committee on Water Resources Occasional Paper No. 2*, November 1995, 28pp.

Smith, E.J., Adderley, E.E. & Walsh, D.T. (1963). A cloud-seeding experiment in the Snowy Mountains, Australia. *J. Appl. Meteor.*, 2, 324-332.

Smith, E.J., Veitch, L.G., Shaw, D.E. & Miller, A.J. (1979). A cloud-seeding experiment in Tasmania. *J. Appl. Meteor.*, 18, 804-815.

Warren, L. (2007). Snowy Precipitation Enhancement Research Project. In this conference (pp 31-33).

WMO (1978) Precipitation Enhancement Project Report No. 9. PEP design document, Geneva, Switzerland.

JAPAN WEATHER MODIFICATION RESEARCH

Masataka Murakami*, Narihiro Orikasa*, Mizuho Hoshimoto*,
Kenichi Kusunoki*, Masumi Seki** and Akihiro Ikeda***

**Meteorological Research Institute, Tsukuba, Japan*
***Tone River Dams Integrated Control Office, Maebashi, Japan*
****Idea Co., LTD., Yokohama, Japan*

1. INTRODUCTION

In Kanto district, which includes Tokyo Metropolitan area, they have recently had a potential problem of water shortage due to an increase of the population and the water consumption by each person. For the last twenty years, they have had the problem of water shortage almost every two years. In the central and northern parts of Japan, where large portions of water resources rely on the snow-melted water from mountain areas, little snow in winter and subsequent little rainfall in Baiu season bring about a serious problem of water shortage.

Meteorological Research Institute (MRI), Japan Meteorological Agency and Tone River Dams Integrated Control Office, Ministry of Land, Infrastructure and Transport had been carrying out the orographic snow cloud modification projects from 1994 to 2002 in order to investigate the possibilities for snowpack augmentation by cloud seeding over the catchment area of Tone River dams, which are the main water supplies to Kanto district.

In this paper we present the microphysical structures in orographic snow clouds with high seedability, their appearance frequency in winter months and seeding effects on a basis of data obtained during IOPs in the past nine seasons. We also present the expected seeding effect on seasonal snowfall derived from numerical simulations.

2. OBSERVATION FACILITIES

Figure 1 shows the topography around observation area.

During phase I (1994 ~ 1997) of this project, microphysical structures of orographic snow clouds and their seedability were investigated by using hydrometeor videosonde (HYVIS), rawinsonde, microwave radiometers, Doppler radar and so on. Three dual frequency (23 GHz and 31 GHz) microwave radiometers were disposed at the windward foot (Shiozawa site), on the windward slope (Shimizu site) and leeward slope (catchment area of dams; Yagisawa-dam) of the Echigo Mountains to measure liquid water path in clouds during winter months (November through March). HYVIS and rawinsondes were launched at the foot of the Echigo Mts. during the IOPs.

During phase II (1997 ~ 2000), in addition to the observation facilities used in phase I, an instrumented aircraft (B200) was introduced to do small-scale cloud seeding with dry-ice pellets and in-situ measurements of inner structures of snow clouds before and after cloud seeding. The instrumented 4WD van equipped with 2D Grey probe, microwave radiometer, GPS and usual meteorological instruments was also introduced to investigate snow cloud modification by topography.

In phase III (2000 ~ 2003), another aircraft (C404) was introduced in order to carry out repeated, but still small-scale cloud seeding experiments.

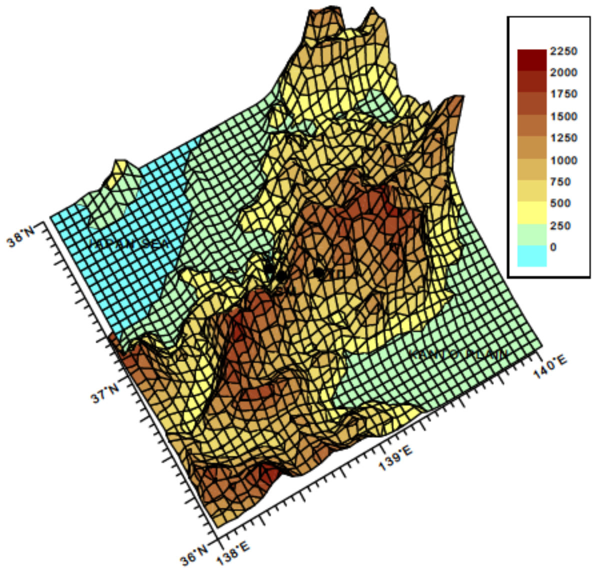

Fig.1 Topography around the observation area. Main instrument sites were Shiozawa (SO), Shimizu (SM) and Yagisawa-dam (YD).

Corresponding author address: Masataka Murakami, Meteorological Research Institute, Nagamine 1-1, Tsukuba, Ibaraki 305-0052, JAPAN
e-mail: mamuraka@mri-jma.go.jp

3. MICROPHYSICAL STRUCTURES IN SEEDABLE SNOW CLOUDS

Microphysical structures in orographic snow clouds were observed with the hydrometeor videosonde (HYVIS), which was developed by the cloud physics group of MRI (Murakami and Matsuo, 1990).

HYVIS observations showed that, in most of clouds with top temperatures between - 5 C and - 15 C, cloud water was not efficiently converted to precipitation water due to low concentrations of ice crystals (less than 1 particle/l) despite a sufficient amount of supercooled cloud water above the crest height of 2000 m in the clouds., suggesting the potential that cloud seeding causes an additional snowfall over the catchment area of dams which are located to the leeward slope of the mountains (Fig. 2a).

HYVIS observations also showed that graupel growth in coexistence with an abundant supercooled cloud water were frequently found above the crest height in snow clouds with top temperatures between - 15 C and - 25 C, suggesting that to overseed these clouds would change precipitation particle type from graupel to snowflake and shift the precipitation area downwind to the catchment area(Fig. 2b).

We call the former clouds "Type A" and the latter "Type B" for convenience sake although real clouds have characteristics of both types to some extent.

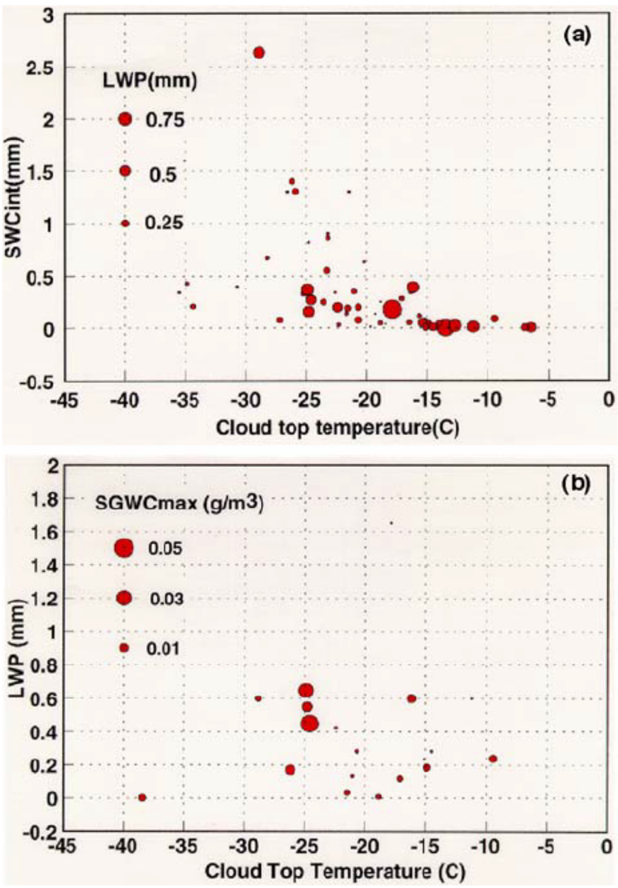

Fig.2 Vertically-integrated amount of cloud liquid water, indicated by the area of circles, as a function of cloud top temperature and vertically-integrated amount of graupel water above a height of 2 km (a) and maximum graupel water contents above the height of 2 km, indicated by the area of circles, as a function of cloud top temperature and vertically integrated amount of cloud liquid water (b).

4. APPEARANCE FREQUENCY OF SEEDABLE SNOW CLOUDS

A combination of cloud top temperatures derived from infrared imagery (0.05° × 0.05° pixel data) of Geostationary Meteorological Satellite and one-hour averaged liquid water path measured with ground-based microwave radiometers are used to investigate the frequency with which snow clouds with high seedability appear over the observation area during winter months.

Snow clouds of type A (B) are defined as ones having top temperatures between - 5 C and - 15 C (- 15 C and - 25 C), top height more than 2.5 km, cloud amount greater than 9/10 and one-hour averaged liquid water path more than 0.2mm. Appearance frequencies were high over the windward slope of the mountains. Snow clouds of type A frequently appeared in early and late winter (Nov., Dec., and Mar.) while snow clouds of type B frequently appeared in mid winter (Dec., Jan. and Feb.) although the appearance frequencies of snow clouds of

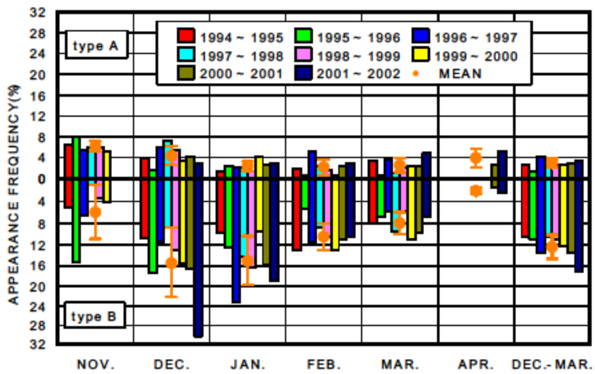

Fig.3 Appearance frequencies of snow clouds with high seedabilities on the windward slope of the Echigo Mountains.

types A and B varied from year to year. The sum of appearance frequencies for the both types of clouds reached 15~20 % of the time (Fig.3).

5. SMALL-SCALE SEEDING EXPERIMENTS WITH DRY-ICE PELLETS

Seeding experiments by an instrumented aircraft demonstrated that additional precipitation particles were produced in clouds with supercooled cloud droplets 20 ~ 30 min. after dry-ice pellet seeding. In coexistence with slight supercooled cloud water, ice crystals grew up to aggregates of several mm in size through vapor deposition for the first 10 min. and collision-coalescence for the next 10 ~ 20 min. (see Fig. 4). On the other hand, ice crystals grew up to heavily rimed snow particles of 1 ~ 2 mm in size in coexistence with supercooled cloud water of ~0.5gm^{-3}. Ice crystal concentrations in seeding curtains were initially more than 1000 particles/L and decreased to ~ 100 particles/L in 20 ~ 30 min. due to turbulent diffusion and aggregation. The width of seeding curtains increased from 200 m to 2 km for 30 min. Figures 5 shows radar reflectivity calculated from 2D images in seeding curtains and their surroundings as a function of the distance from mountain peak. The calculated radar reflectivity in seeding curtains increased by 3 ~ 5 dBZ as compared with their surroundings. Simultaneous radar observations confirmed the same amount of increase in dBZ in seeding curtains (Fig. 6).

Fig.4 2D-C images of ice crystals and snow particles taken 6, 11 and 26 min. after seeding.

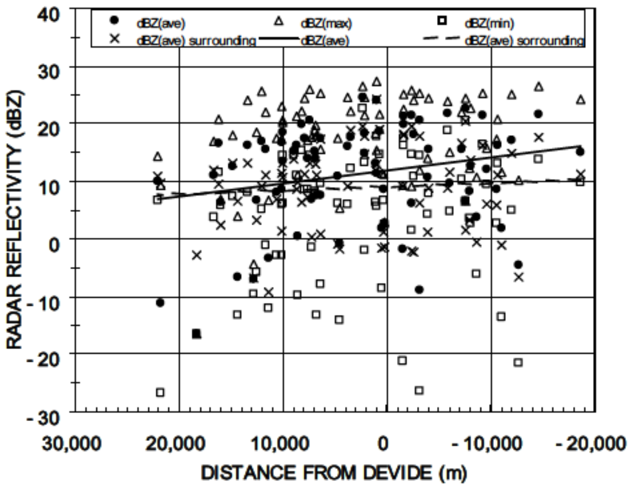

Fig. 5 Evolution of radar reflectivity calculated from 2D-C images in seeding curtains and their surroundings as a function of distance from mountain peak.

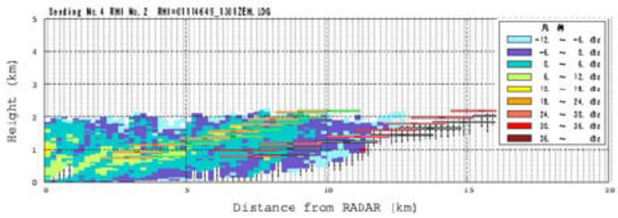

Fig. 6 RHI of Ka-band radar reflectivity and positions of seeding curtains estimated from aircraft measurements (horizontal bars).

6. RESULT OF NUMERICAL SEEDING EXPERIMENTS

Seeding effects on seasonal (from Dec. 1996 through Mar. 1997) snowfall were simulated by using the two-dimensional version of non-hydrostatic cloud model (Clark, 1977) with an improved microphysical parameterization (Murakami, 1990, Murakami et al., 1994). The model domain covers 600 km in horizontal and 15 km in vertical with resolutions of 3 and 0.3 km, respectively. The horizontal axis passes through the Yagisawa-dam and is roughly oriented northwest to southeast, including the Sea of Japan and the Central part of Japan Islands.

Cloud seeding with dry-ice pellets was simulated by the introduction of vertical seeding curtain with a prescribed ice crystal production rate. The initial and inflow boundary condition was taken from Global Analysis Data of Japan Meteorological Agency at 00, 06, 12 and 18Z

We determined the optimal seeding position (Fig. 7) and seeding rate (not shown) based on the result of 2D numerical seeding experiments under various

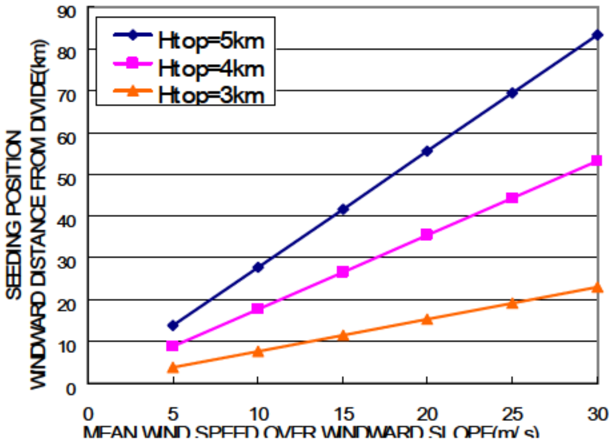

Fig. 7 Relation between optimal seeding position and mean wind speed over windward slope as a function of cloud top height.

derived from satellite IR data and 1-hr averaged liquid water path measured with ground-based microwave

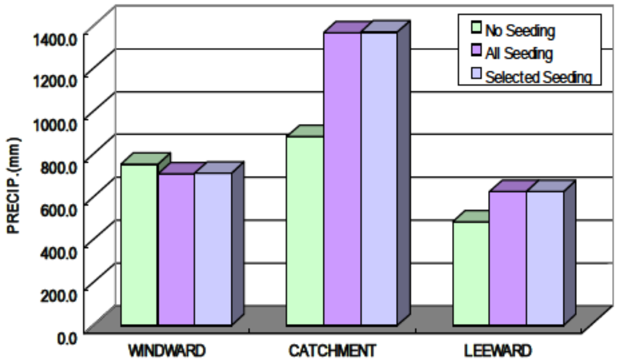

Fig. 8 Seeding effect on seasonal snowfall over the windward slope, catchment of dams and leeward slope.

meteorological conditions. The stronger the mean wind is, the more windward the optimal seeding position shifts. And the higher the cloud top, the more windward the optimal seeding position. Optimal seeding rate increases with increasing mean LWP. Usually optimal seeding rate is around 1,000 particles/m^3/sec. With mean concentration higher than 10 particles/L, seeding may not have any significant effect for clouds with mean LWP less than 0.3 mm. The model was run for 173 6-hr time periods from Dec. 1996 through Mar. 1997, when cloud formations and/or surface precipitation over the study area were expected under winter monsoon conditions. And the comparison of surface precipitation between unseeded and seeded cases was made. Over the catchment area of dams, cloud seeding causes an increase in surface precipitation by 30 ~ 40 % (Fig. 8).

7. CONCLUSIONS

In order to investigate the possibilities for snowpack augmentation by cloud seeding, research project on orographic snow cloud modification had been carried out in the central Japan from 1994 to 2003.

HYVIS observations showed the frequent occurrence of two types of snow clouds with high seedabilities. Of type A are snow clouds with top temperatures between - 5 C and - 15 C, which have few ice crystals and brought about no significant precipitation to the ground in spite of a sufficient amount of supercooled liquid water. Type B of snow clouds, which have top temperatures between - 15 C and - 25 C, produce graupel particles in coexistence with an abundant supercooled cloud water

Statistical evaluations based on cloud top temperatures radiometers indicated that snow clouds of type A appeared frequently in Nov., Dec. and Mar. while those of type B appeared in Dec., Jan. and Feb. The total appearance frequencies of the both types of snow clouds reached 15 ~ 20 % of the time in winter months.

Aircraft seeding experiments demonstrated that additional precipitation particles were produced in clouds with supercooled cloud droplets. Simultaneous radar observations confirmed that the reflectivity in seeding curtains increased by 3 ~ 5 dBZ as compared with their surroundings.

Numerical simulations showed that, with an opimal seeding method, seasonal snowfall over the catchment area could be augmented by 30 ~ 40 %.

MRI, in cooperation with 10 other research organizations, has launched the five-year research project (2006-2011) "Japanese Cloud Seeding Experiments for Precipitation Augmentation (JCSEPA)" to aim drought mitigation and water resources management. We will briefly introduce new approaches to weather modification research in JCSEPA.

REFERENCES

Clark, T. L. 1977. A small-scale dynamic model using a terrain-following coordinate transformation. *J. Comput. Phys.*, 24, 186-215.

Murakami, M. 1990. Numerical modeling of dynamical and microphysical evolution of an isolated convective cloud - The 19 July 1981 CCOPE cloud -. *J. Meteor. Soc. Japan*, 68, 107-128.

Murakami, M. and T. Matsuo. 1990. Development of hydrometeor videosonde. *J. Atmos. Oceanic Tech.*, 7, 613-620.

Murakami, M., T. Clark and W. Hall. 1994. Numerical simulations of convective snow clouds over the Sea of Japan. – 2-D simulations of mixed layer development and convective snow cloud formation. *J. Meteor. Soc. Japan*, 72, 43-62.

Snowy Precipitation Enhancement Research Project

Loredana Warren

Snowy Hydro Limited, New South Wales, Australia

Background

The terrain of the Snowy Mountains region of New South Wales and the prevailing meteorology during the winter months offers significant potential and an ideal location for a precipitation enhancement study. It is no surprise then, that one of the earliest Australian cloud seeding research programs was undertaken in the area over the period 1955 to 1959. The project was undertaken jointly by the CSIRO and the Snowy Mountains Hydro-electric Authority (the "Authority"). The results of the research were reported to be encouraging, but inconclusive. Further investigations were effectively abandoned for a number of years.

Research efforts resumed following a severe drought during late 1970s, prompting the Authority in 1985 to commission SIROMATH to undertake a feasibility study of the potential for winter cloud seeding. The SIROMATH researchers (Shaw & King, 1986) concluded that sufficient potential existed to justify the undertaking of a further cloud seeding experiment.

The Snowy Mountains Atmospheric Research Program ("SMARP", Warburton et al 1990) took place during the winters of 1988-1989, and was specifically designed to assess the physical and chemical characteristics of clouds and snowfall over the region. This research supported the findings of the SIROMATH investigation, determining that sufficient potential existed for winter time precipitation enhancement activities to be effective.

The Authority subsequently prepared a draft Environmental Impact Statement ("EIS", SMHEA, 1993) during 1993. The EIS described a proposal to undertake a six year cloud seeding trial over the catchments of the Snowy Mountains Scheme. The experimental design set out in the EIS prescribed a study area of approximately 2000km^2. A number of objections to the EIS were received from several key stakeholders, and the project did not proceed on that basis.

In 1997 the Authority revised the draft EIS to address the principal concerns that had been raised, which had the effect of reducing the target area to approximately 1000 km^2. The revised proposal was held over until corporatisation of the Authority, and was finally presented to the NSW government in November 2002.

This ultimately resulted in the passing of special enabling legislation, the *Snowy Mountains Cloud Seeding Trial Act 2004* (NSW) (the "Act") to allow a cloud seeding trial, the Snowy Precipitation Enhancement Research Project ("SPERP") to proceed.

The Snowy Precipitation Enhancement Research Project

The objectives of the SPERP are to determine the technical, economic and environmental feasibility of precipitation enhancement over the main range of the Snowy Mountains. The SPERP target area comprises approximately 1000 km^2 within the Kosciuszko National Park, including 320 km^2 of mountainous terrain above 1400m. This area incorporates the alpine catchments of the Snowy Mountains Hydro-Electric Scheme.

Traditional statistical analyses and an ultra-trace snow chemical technique will be used to evaluate the experiment at the end of the trial in 2009. Ultra-trace chemistry is also used to obtain a qualitative assessment of targeting and seeding effectiveness on an annual basis.

The project commenced in 2004, following proclamation of the Act.

The Act imposes a number of obligations on the SPERP including:

> Cloud seeding experiments must only be undertaken when precipitation is likely to fall as snow over the primary target area;
>
> Operations must be ground based;
>
> Silver iodide must be used as the seeding agent, and indium tri-oxide may be used as a tracer agent;
>
> The seeding agent is not to be discharged from within the Jagungal Wilderness Area; and
>
> The cloud seeding operations and their effect are monitored.

The project infrastructure was established and tested during 2004, while the experimental phase of the project commenced in the winter of 2005.

The key project infrastructure includes:

> Cooma control centre (project control and forecasting);
>
> Thirteen generator pairs (seeder and tracer) along the western side of the mountain range;
>
> Khancoban (upwind) rawinsonde launching site;
>
> Fifty weather sites (in the upwind, target and downwind areas) measuring varying surface meteorological parameters;
>
> Blue Calf remote sensing facility (including a radiometer, icing rate detector, 2D probe sensor and other meteorological parameters);
>
> Three icing rate detectors;
>
> Eleven snow sampling sites;
>
> Cooma clean room facility; and
>
> Khancoban maintenance and deployment facilities.

The SPERP implements a randomised experimental design, with a 2:1 seeding ratio. That is, for every six Experimental Units ("EU") of five hours duration, four are seeded (where the seeder and tracer burners are operated simultaneously) and two are un-seeded (where only the tracer burners are operated).

Stringent procedures have been developed and implemented to ensure that any personnel associated with the undertaking of SPERP cloud experiments do not have any knowledge of the seeding status at any time during the duration of the trial.

References

Shaw, D.E., & King, W.D. (1986). Report of a feasibility study to assess potential for a cloud seeding experiment over the catchment of the Snowy Mountains Scheme. Siromath Project No. SMC/N86/1.

Snowy Mountains Hydro Electric Authority (SMHEA). (1993) Snowy Precipitation Enhancement Project – Draft Environmental Impact Statement.

Warburton, J.A., & Meteorology Working Group. (1990). Snowy Mountains Atmospheric Research Program, (SMARP). Final report to Snowy Mountains Council.

A Brief Discussion of Cloud Seeding Operations in Tasmania

Alex Nazarov

Energy Market Operations, Hydro Tasmania

Background

More than forty years ago, the Tasmanian Hydro Electric Commission ("HEC", now Hydro Tasmania) was considering the merit of cloud seeding as a cost effective, non-structural means of augmenting inflows into the storages of the hydro-electric scheme. History shows that the HEC management of the day determined that there was sufficient justification to warrant further investigation. This resulted in three cloud seeding experiments over the Central Highlands of Tasmania being undertaken to assess the effect on catchment yields of key major storages of the scheme.

The first experiment was designed and conducted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Silver iodide dispensed from aircraft mounted burners was used as the seeding agent, and the results were considered to be encouraging. A second experiment designed by HEC with CSIRO scientific support was undertaken over a five year period commencing in 1979. The study was independently evaluated by CSIRO and SIROMATH, and as in the initial study, outcomes were shown to be positive.

Cloud seeding was suspended after the second experiment. Operational seeding commenced in 1988 following a severe drought and continued until 1991. This was followed by a further three year experiment that commenced in 1992 and used dry ice as the seeding agent. The results from this experiment were less convincing than those from the earlier research. The use of dry ice was abandoned in 1995.

An operational seeding program covering eight months of each year commenced in 1998, and continues to the present day.

Hydro Tasmania Cloud Seeding

Results of early cost: benefit analyses prompted Hydro Tasmania to regard cloud seeding as a cost effective means of enhancing system reliability.

There are key differences between operational seeding programs and randomised experiments. These differences relate principally to the suitability criteria. In an operational context there are different drivers: the objective of the program is to maximise the benefit side of the cost to benefit ratio. Consequently, many operational days do not satisfy the strict suitability criteria that would normally apply to a randomised experiment, and cannot easily be evaluated on that basis.

Our research efforts are now being directed on the use of physically based models to determine the effectiveness of marginally suitable operational events. This work is supported by an Australian Research Council Grant, and is being undertaken with research partners at Monash University.

Assessing the benefit of an incremental increase in storage position has proven to be a complex issue for cloud seeding programs all over the world. This presentation deals with some of the ambiguities in statistical analyses that pose issues in assessing the effectiveness of cloud seeding and in quantifying the incremental change in precipitation.

Harvesting the Clouds

George W. Bomar

Texas Department of Licensing & Regulation
Austin, Texas

The severe to extreme droughts so prevalent in Texas during the 1990s engendered among Texans a renewed appreciation for an adequate supply of fresh water. The prolonged dry spells also demonstrated just how vulnerable the state becomes when those supplies of fresh water dwindle to alarmingly low levels, as they were by the year 1995. With the state likely to double its population within the next 30 years, to as many as 35 million people, demands for sufficient fresh water to meet the needs of so many water consumers are certain to soar, particularly in times of deficit rainfall. Thus, with the dual threat of sustained population growth and inevitable droughts, those planning for Texas' future have had to search for new, innovative ways to ensure that the supply of fresh water keeps up with demand.

This accelerating demand for enough fresh water in arid and drought-stricken areas of Texas has focused renewed attention on alternative ways of conserving existing water resources and of procuring additional water by tapping into the abundant supply of moisture available in Earth's atmosphere. Action taken by the Texas Legislature in 1967 was a tacit acknowledgment that the use of cloud-seeding technology had earned a measure of acceptance within the water-management community of Texas. Subsequent actions of legislators, most notably in 1997 when State funds were appropriated for the first time to help construct rain-enhancement projects statewide, promoted the development, and refinement, of strategies to induce convective cloud systems to produce more rainwater.

Texas took a first step in developing and implementing viable weather modification technologies by linking up with the U. S. Bureau of Reclamation in 1973 to conduct *Project Skywater*. That multi-year research endeavor served as the foundation for subsequent scientific investigations, funded by both the Bureau and the National Oceanic & Atmospheric Administration (NOAA), performed during the 1980s and 1990s to corroborate and quantify the effects of timely seeding of young thunderstorms. Despite limited, and at times erratic, funding over the past 25 years, substantial progress has been made in pursuit of that goal. Evidence adduced from years of intensive research in Texas (1975-1980, 1984-89, 1995-1998, 2003-2005) has strongly suggested that researchers' efforts to explore, and appropriate, such a *non-structural* approach as weather modification for securing additional water supplies for a burgeoning population has been rewarded with more than a little success.

Project Skywater (1975-1980) helped researchers concentrate on multiple-cell convective cloud systems, which offer more promise for significant rainfall enhancement than do isolated cumulus congestus. Complementary research, as part of the Southwest Cooperative Program (1984-1989), consisted of randomized cloud-seeding experiments that led to the development of the first conceptual model that would serve as the foundation for widespread *operational* seeding in the two decades that followed. This research consisted of 213 convective cells (99 seeded, 114 not seeded) analyzed with radar data, with strong evidence suggesting the seeded (S) cells produced 2.63 times more radar-estimated rainfall than the non-seeded (NS) cells. This sizeable increase was due in part to seeded cells covering more area and having greater duration and larger rain volumes than adjacent cells not treated. Results for rain volume, area, duration, and merger were significant at the 5 percent level.

More recent research, as the Texas Experiment in Augmenting Rainfall through Cloud-seeding (TEXARC) Project (1995-1998), led to the conclusion that cloud microphysical structure is strongly dependent on the cloud-base temperature (CBT). Seeding increased cloud buoyancy and further invigorated the updrafts, while the cloud is still in a position to use the enhanced energy to support the growth of large precipitation particles. Results emphasized the importance of when and where the various microphysical processes take place within the cloud, and when and where the seeding takes place that is intended to alter these processes. They also highlighted the need to seed to produce glaciation within the vigorous supercooled updraft region of the cloud, where large artificially-nucleated precipitation-sized particles can be grown most efficiently. This can only be accomplished with careful placement of the nucleant either in the updraft directly near cloud top or in the strong inflow region at cloud base in well-developed convective cloud systems.

Armed with this knowledge of convective cloud behavior and how that behavior could be altered to prolong cloud life and yield additional rainfall, an assortment of *water conservation districts* organized into “weather modification associations” to plan, and implement, strategies for systematically seeding convective cloud towers during the growing season (April-October). These districts were instrumental in persuading the State of Texas to join them in investing funds to build, and maintain, cloud seeding projects. Public funds were used to procure capital assets, such as aircraft outfitted for seeding and C-band weather radar systems. Each cloud-seeding “target” area encompassed some 4 to 6 million acres. After four projects were organized in 1997, the number of seeding programs grew to as many as 12 by the year 2000. Today, some 29 million acres of Texas, or roughly a sixth of the state’s land area, are within cloud seeding “target” areas.

The end result of the collaborative efforts of state and local officials to orchestrate a well-designed, coordinated weather modification endeavor for the state has fostered a virtually ideal environment for continued research and development of appropriate cloud-seeding technologies. At the moment, the Texas legislature is deliberating on a proposal to establish a long-term weather modification research grant program to involve researchers from both public and private sectors of the state.

The Nevada State Cloud Seeding Program

Arlen W. Huggins

Associate Research Scientist, Desert Research Institute, Reno, NV

The Nevada State Cloud Seeding Program is a wintertime project designed to augment snowfall in selected mountainous regions of Nevada and California to increase the snowpack, the resultant spring runoff and the water supplies of municipalities, agricultural regions, recreational lakes, and environmentally threatened terminal lakes in the state of Nevada. The Program evolved from cloud seeding research studies conducted by the Desert Research Institute since the 1960s in the Lake Tahoe Basin and other areas of the Sierra Nevada. Currently the basins of Lake Tahoe, the Truckee River, the Carson River, the Walker River, the Upper Humboldt River (Ruby Mountains), the South Fork of the Owyhee River (Tuscarora Mountains), and the Reese River (Toiyabe Mountains) are seeded each year during the period from November through April. Ground-based and aircraft seeding techniques are currently in use.

Past research conducted mainly through projects funded by the U. S. Bureau of Reclamation (USBR) and National Oceanic and Atmospheric Administration (NOAA) resolved many of the issues, including environmental ones, related to the design of the Nevada Program. Physical and modeling studies helped explain the transport and dispersion of seeding material into clouds that form over the complex terrain of the Sierra Nevada. Detailed physical studies using remote sensing techniques, aircraft and standard meteorological instrumentation quantified the temporal and spatial characteristics of clouds that were suitable for treatment by various clouds seeding techniques. Laboratory and *in situ* measurements of the ice-forming capabilities of seeding materials led to the development of the current silver iodide compound used by the project. Many years of experimentation with methods of producing large numbers of ice nuclei (up to 7×10^{12} nuclei per second) from silver iodide solutions has led to the development of a reliable ground-based and remotely controlled seeding generator that is the primary method now used to seed clouds in the Nevada Program.

The Nevada Program is funded almost entirely by the state of Nevada. Although past statistical evaluations in the 1970s showed evidence of positive effects in some storm categories, the project is based mainly on the results of smaller-scale physical studies conducted in the 1980s and 1990s, and these evaluations continue as funding becomes available from non-state sources. Estimates of augmented water from seeding, based on increases documented in research experiments, have varied from 20,000 to 80,000 acre-feet over each of the last ten years. The most recent evaluations in 2004 and 2005 included atmospheric and hydrologic modeling, trace chemical studies to validate targeting effectiveness and remote sensing and aircraft measurements to validate the modeling results and to document the frequency of optimum cloud seeding conditions in one of the more remote target regions.

THE SOUTH AFRICAN EXPERIENCE IN RAINFALL ENHANCEMENT RESEARCH

Deon E. Terblanche
South African Weather Service, Private Bag X097, Pretoria, 0001, South Africa

1. RATIONALE OF THE STUDIES

Chronic water shortages in the economic and industrial heartland of South Africa, arising from excessive demand on limited water resources, prompted research into weather modification as a potential means of augmenting rainfall, river flow and reservoir storage.

Summertime convective storms provide a significant fraction of the rainfall over South Africa's interior. These storms, that generally have continental microphysical characteristics, have been the focus of rainfall enhancement research in South Africa.

Figure 1. Aircraft dispensing hygroscopic seeding material, resulting in a visible trail of water droplets.

A systematic approach was followed in South African in the development and testing of the hygroscopic flare seeding technology. Field experiments took place during period 1990 to 2000 and these were followed by benefit-cost analysis as well as identification of potential environmental impacts related to future large-scale operational application of the technology. This work was conducted in two phases under the banner of the South African National Precipitation Research and Rainfall Enhancement Programme (NPRP-SAREP).

The long-term commitment and leadership of the funding organizations in South Africa played a major role in the progress made, providing a stable working environment in which innovation and a multidisciplinary team effort could thrive.

The overall approach of NPRP-SAREP encompassed the following:

- Adapting and refining intervention strategies and cloud seeding techniques in accordance with the continuously evolving understanding of cloud and precipitation processes emerging from ongoing process studies;
- Subjecting refined seeding techniques to rigorous field testing and randomised experimentation, with numerical modeling support where appropriate, in order to quantitatively assess cloud-based responses to seeding;
- Investigating potential enhancement of area rainfall and associated economic, water-resource, agricultural and environmental costs and benefits.

In achieving the goals the available infrastructure of radars, instrumented aircraft, data acquisition and handling facilities, laboratories for hardware and software development, calibration facilities, statistical techniques and computational facilities were optimally used and adapted where necessary for:

- Improving the understanding of natural cloud and precipitation processes;
- Taking the above into account, developing the concept of the hygroscopic flare seeding methodology;
- Conducting a randomised cloud seeding experiment supported by microphysical and cloud modeling studies;
- Testing the requirements and logistics of possible operational applications through semi-operational pilot applications of the technology with specific reference to cloud climatology studies, benefit cost analyses and potential environmental impacts.

2. RESULTS

After 5 seasons of randomized experimentation, a database of 127 storms, 62 seeded and 65 control storms had been built up. The quartile analysis of these two groups is shown in Figure 2. In addition, results showed that the mean rain mass at the lowest scan for the seeded storms was significantly larger than for the controls, particularly from 40 minutes to 50 minutes after the seeding decision. The means of the total radar-estimated rain mass between 10 minutes and 60 minutes after the seeding decision were 1812 kilotons for the seeded storms and 1231 kilotons for the non-seeded storms. This gave an estimated seeding effect of 47%. Some inadvertent bias was, however, evident in the pre-seeding mean rain mass being lower in non-seeded than in seeded storms. Compensation for this bias resulted in an estimated seeding effect of 24%.

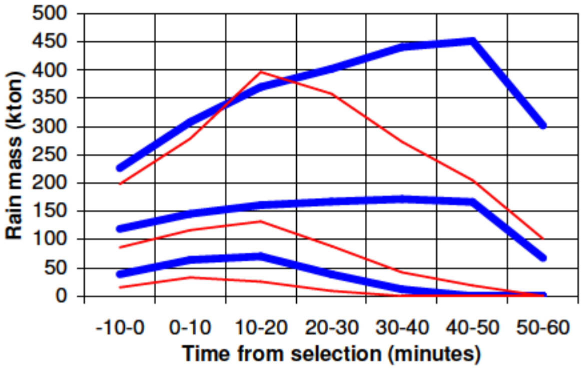

Figure 2. Quartile analysis of the NPRP randomized experiment – 62 seeded and 65 controls. *(Thick blue lines represent the seeded group, thin red lines the control group)*

Semi-operational cloud seeding in Limpopo (formerly Northern) Province had its origin in a request from the provincial government to the NPRP funding agencies and research team to undertake cloud seeding in an effort to alleviate a crippling drought in the province. In acceding to the request to seed as many storms as possible in an effort to meaningfully enhance rain over the target area, the decision was also taken to continue to treat individual convective storms as experimental units and to record detailed radar observations for each (Terblanche, Steffens, Fletcher, Mittermaier and Parsons, 2000). This approach and associated data collection was done with a view to facilitate development of scientific verification techniques, knowing that successful verification on the basis of rainfall or stream flow measurement would be unlikely in the short term, given the large natural spatial and temporal variability of these quantities.

The general approach to semi-operational seeding in Limpopo Province (NPRP-SAREP) was thus to define the target area and maintain a database of radar-observed storm track characteristics of all storms within the target area. Within logistical and funding constraints, as many as possible of these storms were seeded as early as possible in their lifetime. Approaches to analysis and interpretation of data, however, differed between the NPRP and SAREP phases.

The results of the quartile analysis on radar-derived rain mass of the 37 paired seeded and non-seeded cases are shown in Figure 3 (Terblanche, Mittermaier, Burger, de Waal and Ncipha, 2005). It is clear that the storms that were selected for SAREP were considerably larger than those in the NPRP.

For the 100-minute interval from time of origin, the ratio between accumulated arithmetic mean rain mass for the seeded and control storms was 2.08, indicating an average increase in rain mass of 108% or just more than a doubling.

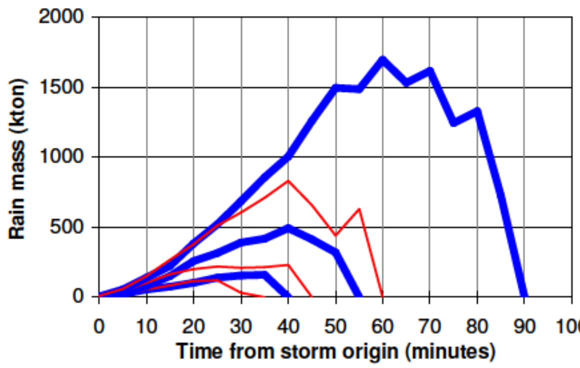

Figure 3. As in Figure 2 but quartile analysis of radar estimated rain mass of 37 paired storms observed under SAREP during 1997 – 2000.

Cloud climatology studies undertaken by 24-h radar observations in the Polokwane-Tzaneen target area during the 2000/2001 season revealed that approximately 290 potentially seedable clouds out of a total of more than 2000 may be expected in a season, and that at least 75 of these would have to be successfully seeded in order to achieve a 7-10% increase in rainfall over the target area.

3. CONCLUSION

The main outcome of the NPRP-SAREP was a new approach to rainfall enhancement that holds considerable promise as a viable technology for integrated water resource management schemes in areas with suitable rainfall formation processes. Mather et al. (1997), Terblanche et al. (2001) and Terblanche et al (2005) describe the development of the NPRP-SAREP and the results obtained during the program. It is believed that considerable insights can be gained by governments, funding agencies and scientists alike from the stepwise approach followed by the NPRP-SAREP. Without stable, long-term support, the relevant expertise, as well as a sound and systematic scientific approach, such programs will not succeed.

REFERENCES

WMO (2006) http://www.wmo.ch/web/arep/wmp/wmp_homepage.shtml

Mather GK, Terblanche DE, Steffens FE, and Fletcher L (1997) Results of the South African cloud-seeding experiments using hygroscopic flares. *J. Appl. Meteor.* **36** 1433-1447.

Terblanche DE, Steffens FE, Fletcher L, Mittermaier MP and Parsons R (2000) Toward the operational application of hygroscopic flares for rainfall enhancement in South Africa. *J. Appl. Meteor.* **39** 1811-1821.

Terblanche DE, Mittermaier MP, Burger RP, de Waal KPJ and Ncipha XG (2005) The South African Rainfall Enhancement Programme: 1997-2001. *Water SA*, **31**(3), 1-8.