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Light at the End of the Tunnel – April 2011

Weather Modification Association

Promoting research, development and understanding of
weather modification for beneficial uses

THE JOURNAL OF WEATHER MODIFICATION

COVER PHOTO: The “Once in a Lifetime” photo was taken by University of North Dakota (UND) Atmospheric Sciences Chief Research Pilot Wayne Schindler on April 22, 2011 in southern Oklahoma from the UND Cessna Citation Research Aircraft. The Citation was being flown in support of the NASA-sponsored Mid-latitude Continental Convective Clouds Experiment.

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THE JOURNAL OF WEATHER MODIFICATION – WEATHER MODIFICATION ASSOCIATION

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THE WEATHER MODIFICATION ASSOCIATION

The Weather Modification Association was organized in 1950 to develop a better understanding of weather modification among program sponsors, the operators and members of the scientific community. In 1966, the first suggestion for a professional journal was proposed and Volume 1, No. 1, of the Journal of Weather Modification was published in March 1969. This historic publication now includes 44 volumes (45 issues).

Originally called the Weather Control Research Association, the name of the organization was changed to the Weather Modification Association in 1967. During its 60-year history, the Association has:

- Pressed for sound research programs at state and federal levels.
- Promoted a better understanding of weather modification for beneficial use.
- Acted as a disseminating agent for literature.
- Provided extensive testimony before many federal, state and local committees and agencies in regard to all aspects of weather modification research and operations.
- Assumed an active role in the promotion of policy statements concerning all aspects of weather modification.
- Developed active positions on ethics, minimum standards for operations, and a strong certification program for operators and managers.
- Published the Journal of Weather Modification, the only professional journal in the world totally dedicated to the operational, societal, economic, environmental, legal and scientific aspects of weather modification.

The Journal is published annually and papers are always welcome for consideration in either the reviewed or non-reviewed sections. A nominal charge of $60 per black-white page is made for each page ($130 per color page) published in the final double-column format of the Journal. This fee is charged for all papers, foreign and domestic.

Additional information on the individual classes of membership can be found in the Articles of Incorporation found at http://www.weathermodification.org.

Applications for membership on a calendar year basis, as well as additional information, can be obtained by writing to WMA at the permanent address of the Association:

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PO Box 845
Riverton, Utah 84065 USA
Phone: 801-598-4392
E-mail: wmaexecsec@gmail.com
Web: http://www.weathermodification.org

President's Message

The past year has been a busy one for the WMA. We discovered in May 2011 that the WMA had lost its non-profit corporate status with the State of Utah in 2006. A Salt Lake City attorney was retained to help re-establish our corporate status with the State. In our discussion with this attorney we also explored whether the WMA had been registered with the IRS. Our records indicated an application had been filed in 1986 but no record of the IRS ever recognizing the WMA as confirmed by this attorney. The membership approved some new Articles of Incorporation which were short and generic in nature as recommended by the attorney. We then filed the appropriate paperwork with the State of Utah and were granted non-profit corporate status in August 2011. We then filed an application with the IRS to become a 501 C6 non-profit corporation. Discussions with IRS personnel indicated the WMA had been granted a 501 C3 status in 1986 but this status expired in 2006 when we lost our non-profit status with the State of Utah. Approval of this application was received in January 2012 but backdated to our Utah incorporation date in August, 2011. Discussions with our attorney and a requirement of the IRS were that the WMA adopt Bylaws that specify how the corporation operates (the WMA had previously never had any Bylaws, just Articles of Incorporation). Draft Bylaws were prepared by our attorney and modified to better represent the WMA's specific interests. Draft Bylaws were approved by the Board of Directors and submitted to the membership for comments. The draft Bylaws were then revised and re-submitted to the membership for a vote. These Bylaws were accepted by the membership in March 2012.

Other achievements included:

- The approval of a revised Capabilities Statement thanks to the efforts of the Standards and Ethics Committee.
- Development of some Frequently Asked Questions and Answers (FAQs) regarding precipitation enhancement thanks to the work of the Publications Committee.
- Ongoing improvements were made to the WMA web site which included adding a list of past officers, posting the FAQs, providing a list of all WMA Journal articles dating back to 1969, and development of a separate Las Vegas meeting web site. Thanks go to Stephanie Beall for all her hard work as WMA's web site manager.
- Development of a WMA Facebook page. Thanks go to Duncan Axisa and Stephanie Beall our co-hosts of this web site.

We have experienced some personnel changes in a couple of key areas: Executive Secretary/Treasurer and WMA Journal Editor. After 34 years of outstanding service to the WMA as its Executive Secretary/Treasurer, Hilda Duckering informed the WMA at the 2011 Park City annual meeting of her desire to retire. She agreed to serve one more year and to cross train with a replacement to be selected by the WMA membership. Two replacement candidates were considered; Amber Blount with SOAR and Laurie Capece with NAWC. Laurie Capece was selected through a vote of the membership. Laurie and Hilda have successfully worked together since the Park City meeting in order for Laurie to get up to speed on the duties associated with this very important position. For all that know and love Hilda, even though small in stature, her "shoes" will be difficult to fill. Thank you Hilda for your unwavering dedication to the WMA you have been a good example for us all! You have been the stable "rock" that others have turned to for advice and counsel as numerous previous WMA officers fully recognize and appreciate.

Andy Detwiler served as the Editor of the WMA Journal of Weather of Weather Modification from 2005 to 2011. He, like Hilda, informed the WMA membership of his desire to step down from this position in 2011. Again, high commendation goes to Andy for his fine work in nurturing and developing the Journal of Weather Modification into the fine Journal that it is today. Thanks Andy for all your hard work as Editor as well as Connie Crandall who served as your able assistant! Fortunately Dr. David Delene of the University of North Dakota stepped forward to become the new Editor following the Park City meeting. Welcome aboard, David!

The WMA is dependent on the involvement of its members to carry out the goals of the Association. Many WMA members have served as officers or committee members during this past year. Speaking for the Association, your involvement and support has been greatly appreciated. I issue a special charge to the in-coming members of the Board of Directors of the Association. You will fulfill increasingly important roles as granted in the newly approved Bylaws of the Association. You are our elected representatives; do your jobs well!

Unfortunately a number of former WMA members passed during the year including: Charles Chappell, William Finnegan, Nancy Knight, Harold Orville, Pierre St. Amand and Barbara Welles. Each contributed to the weather modification field; they will be missed.

I believe the future of the WMA is bright. There will be increasing interest in the type of weather modification activities that the WMA supports. This increased interest will be driven by increasing demands on fresh water supplies around the world: the need to increase municipal water supplies due to rising populations, the desire for clean energy sources (e.g. hydropower), concerns about having adequate irrigation water supplies and reducing crop damage due to hail.

Don Griffith
WMA President 2011-2012

Editor's Message

The past year has been very busy with Wanda Seyler and I learning all the details involved in publishing a journal. We would like to thank our predecessors, Connie Crandall (Editorial Assistant) and Andrew Detwiler (Editor), for all their help getting us going and their hard work over the years putting together the Journal of Weather Modification. As we have found out, there is a lot of time involved in getting the Journal put together. The Journal is late in getting published this year but there are several good articles that you hopefully will enjoy reading. Thanks to all the authors for submitting their manuscripts and all the reviewers for taking the time to provide feedback on science articles. The Journal depends largely on Weather Modification Association (WMA) members to serve as reviewer and your time is greatly appreciated.

An important improvement to the Journal's publishing process is to start using an online Web-based software tool kit. Using Web-based software will make the handling of the review process less time consuming and speed up the article publication process. The latest version of the Public Knowledge Project software has been setup on the WMA website and will be used for all future articles. This software provides editorial functions (accepting submission, sending out review, sending emails) and handles publication of articles online. Science papers for 1979 and 1980 are currently available online and accessible by creating a fee account. The WMA board is currently discussing my proposal to put additional articles online. One critical issue under discussion is when an article should appear online. I have proposed that articles be published online as soon as they have been accepted. The idea is that immediate open access makes research freely available to the public which supports a greater global exchange of knowledge. Having immediate open access would hopefully result in more articles being submitted to the Journal and an increase in funds from page charges. The drawback to immediate publication online is that it may reduce library subscriptions of the Journal. Hence, a delay of between one and five years for the online version of articles may be appropriate.

We have moved to a print-as-you-need publication model for the Journal. This results in lower printing cost because fewer copies are printed since only the number currently needed is printed. Additional copies can easily be printer at a later date if they are needed. Another improvement that we are looking into is having a DOI number for each article to make the Journal more visible and hopefully lead to more submissions.

I believe the future of the Journal is bright. There will be increasing interest in the type of research and activities that the Journal reports on. Increasing demands on fresh water supplies around the world will drive research to furthering our understanding of the precipitation process. Increasing populations and the desire for more hydropower will lead to more operational programs. With the adaption of the latest technologies, the Journal is well positioned to report the ever changing field of Weather Modification.

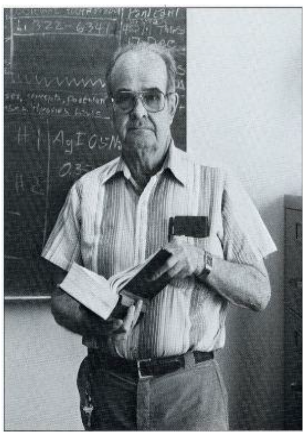
Dr. David J. Delene
Journal of Weather Modification Editor 2011-2012

In Memoriam
William G. Finnegan
(1923 – 2011)

The fields of chemistry and weather modification lost a truly dedicated and innovative scientist this past year. William (Bill) Finnegan died in Reno, Nevada, on September 16, 2011 at the age of 87. Bill had retired from the Desert Research Institute (DRI) in 1994, was granted Research Professor Emeritus status, and then came to work at DRI every day that he was able to until late 2010. Until his last year with us he continued to park in our lower parking lot and climb the 80 steps to his office level to “get some daily exercise”. The flow of ideas from Bill never slowed after his third retirement and he continued to talk (and/or argue) science with anyone who had a spare minute. He continued to pursue his research with an idea for the next generation of non-silver-containing ice nucleants with his friend and collaborator Lee Ates at Concho Cartridge in San Angelo, Texas.

Much of the personal information below was provided by John Lewis, taken from many of his conversations with Bill during his last years at DRI.

Bill was born in Dollar Bay on the Upper Peninsula of Michigan. He grew up in the Upper Peninsula during the Great Depression and recollected the enjoyment he experienced taking a small wagon around the area and picking up pieces of scrap copper from the mines and selling it for a little cash. He used that money to buy fishing gear and had wonderful experiences fishing on the shores of Lake Superior. His mother would make him a Cornish pastie (meat and vegetables wrapped in dough covering, something like an apple turnover) and that would be his meal for the day while fishing. Bill’s father was a Chief Petty Officer in the Navy and was at sea much of the time. Bill’s father was killed on one of the ships in Pearl Harbor during the Japanese attack on December 7, 1941. As such, he was exempt from military service during WWII. At the time of his father’s death, Bill’s mother and family resided in San Diego, California. Bill finished high school in San Diego (probably 1942) and decided on a career in chemistry as the result of his outstanding performance in the high school chemistry class. He was accepted into Cal-Berkeley and majored in chemistry. Cal-Berkeley at the time was among the top few schools in chemistry with world-renowned professors (Nobel laureates among them and also Joel Hildebrand). One of the stories he told me led me to believe he was an exceptional student. He took quantum mechanics in the physics department (the top physics school at that time) and received the top grade among a class of mostly physics students. The professor called him into his office at the end of the course and discussed his outstanding performance; but then added, “Bill, I know you received the top grade in this class, but you’re a chemistry major. Therefore I must give you a B”. Bill accepted the decision without complaint.



Bill at DRI (mid 1990’s) with his beloved handbook of Chemistry and Physics.

During his senior year at Berkeley he heard a seminar from an Ohio State University Professor (Albert Henne) who was a world authority in Freon gases that were used in refrigeration and had many patents. Bill was impressed and asked if he might be considered for grad school under this professor at OSU. It was during the war and Bill couldn't get into OSU immediately after graduation (related to issues about the war). So, he worked for a camera company in New York (maybe Kodak) for a year, and then started his studies at OSU under Professor Henne. In record time he graduated with the PhD in organic chemistry in 1949. Upon graduation Henne told him: "You're one of the frontrunners, Bill, but don't go into teaching, you're a researcher". Bill told me this professor had three rankings for chemists: literature searchers, follower uppers, and frontrunners.

With the help of his professor, Bill obtained a post-doc position in chemistry at Caltech. After his post doc, he took a job in 1950 with the Navy at China Lake Naval Ordinance Test Station (NOTS), later the Naval Weapons Center (NWC) near Ridgecrest in southern California. There he worked in ordinance and was the recipient of several patents. He rose to the maximum grade of a research chemist. After about 1958 and through the remainder of his career at China Lake he conducted basic and applied research on the generation and characterization of artificial ice nucleants. This was the focus of his research for the remainder of his career. Some of his first work related to artificial ice nucleants can be found in reports from the Yellowstone Field Research Expeditions (YRFE) in 1965-67 (see picture below). Collaborations with Pierre St.- Amand and other researchers at China Lake resulted in dozens of papers on ice nucleation, pyrotechnic production of ice nucleants and delivery systems. Much of this groundbreaking work on pyrotechnics was published in a seven part series of articles in the second and third volumes of the Journal of Weather Modification. In all, Bill was coauthor on 10 articles in these two volumes. Also at China Lake, Bill began to study the ice nucleating properties of complexes of silver iodide; research he then continued in his second career at Colorado State.

Bill (left) with Vince Schaefer at the YFRE in February 1965. Photo contributed by Ward Hindman

Dr. Edward (Ward) Hindman collaborated with Bill both at NWC and at CSU. He first met Bill at one of Schaefer's Yellowstone experiments and recalls Bill was a cigar smoker at the time and witnessed the tests of some of his pyrotechnic flares that produced ice-forming nuclei. Ward recalls crossing paths with Bill on several occasions, and he eventually ended up at NWC where Bill advised him on flying a glider. Bill also flew gliders and had built his own. One study that Bill led in 1977 was to determine the ice-forming capacity of the ground clouds produced by the solid rocket motors of the developing Space Transportation System (the Space Shuttle). Ward went to CSU shortly after Bill did and kept in touch after Bill left for DRI. He recalls, "… Bill was never far away. I could phone his DRI office almost any time for an insightful and thorough discussion. My last visit with Bill was in Reno in late December 2006 (see photo below) where he was as unrepentant and audacious as ever in discussing his science. Unfortunately, he no longer drank Scotch but had given up smoking. His motto: plan, characterize and, ultimately, understand!"

Retired Professor Lew Grant recalls first meeting Bill at a weather modification conference and was impressed with his work. This was research with F. K. Odencratz, W. S. McEuwan and Pierre St. Amandin the 1966-1968 period, involving the chemical and physical properties of industrial particles. This work also included investigations of the mechanisms for multiplication of atmospheric ice crystals and the apparent charge distribution on laboratory crystals. Lew and others thought it was great that they were able to get him come to CSU in 1978. At CSU he worked with another chemist, Mike Corrin. Lew indicates that the two were a good combination for the work in nucleation; they connected on the chemistry, which the program was weak in at that time. Mike provided solid academics and Bill provided hands on laboratory research, innovative ideas, and invaluable contributions working with graduate students. Lew notes "Bill had a one track commitment to his area of research. This included research to help understand the basics of the nucleation processes, improving and testing weather modification devices, and involving and encouraging the students that he was working with. And, perhaps most important of all, he was a friend to many of us at CSU."

Bill with Ward Hindman in Reno in December 2006. Photo contributed by Ward Hindman

Dr. Paul DeMott recalls Bill's influence on his career, and the careers of many other CSU graduate students. Paul notes that Bill's research focus at CSU was to bring his special perspective, shaped by a career in chemistry and a legacy of research in the development of pyrotechnic ice nuclei generators, toward the understanding of how ice nucleating aerosols work, and how to potentially engineer these to benefit weather modification. In the process he also became interested in the influence of aerosol chemistry on ice crystal processes following nucleation, an interest he continued at DRI. Paul stated, "I think I could paraphrase Bill's mantra to be that conventional approaches were the bane of discovery. He challenged all around him to abandon classical approaches in their search for new knowledge, and in that regard he was an inspiration to me, more so than he ever knew. His approach was to use chemical kinetics, and analysis of the rates of formation of new ice crystals, as they depend on cloud droplet concentrations and/or water supersaturation, to discern how ice crystals formed in a cloud setting, whether that be in the laboratory or in the atmosphere. He beat the drum hard that the weather modification community needed to consider the possible mechanisms by which ice crystals formed, as much as considering the numbers of ice nuclei generated on the basis of mass of material consumed. Also, Bill was fond of pointing out that when a solution or propellant mix containing silver iodide or silver iodate was combusted, the product was not necessarily silver iodide alone, but reflected the chemical products of the mix.

Bill, looking a bit skeptical, wearing his Thunderbird award at the WMA meeting in Reno in 2002

This information was shown to affect how the nucleant acted to form ice crystals, and was used to engineer ice nuclei with specific properties; for example, to possess the highest efficiency possible and/or to act via a certain ice nucleation mode such as condensation freezing. This research was showcased at the AMS Weather Modification Conference in Park City, Utah, in 1984 and in publications during this time. Bill was proud of this work and some of us were the beneficiaries of his basic ideas and promotion. That these things were taken to heart, to some extent at least, is still reflected in the seeding agents applied in current cloud and precipitation modification projects. Also while at CSU, Bill improved facilities, initiating addition of measuring systems and automation aspects that made possible some unique experiments using the CSU continuous expansion cloud chamber during the mid- to late 1980s."

The following thoughts from Paul about Bill were also common among the many of us who got to know his more personal side. Paul notes that "the time at CSU was a heady time for me to be a graduate student, an understudy/disciple of someone who loved to think and explore and was never discouraged by a result he did not yet understand. We ran hundreds of experiments with endless alterations based on an almost daily assessment of new results discussed in a smoky room over morning coffee and donuts, or during one of multiple weekly lunches at restaurants that reflected Bill's love of ethnic cuisine. There was burrito day, Greek day, Chinese food day, etc... Bill ultimately gave up smoking in favor of his health, but I will forever see him bantering with the group of us gathered each morning, that cigarette bobbing in his mouth. I think most important to know is that Bill was a generous man when it came to sharing knowledge, humor, encouragement, or anything. He hosted dinners at his home that made me aware that, not only was cooking and food a hobby, but he was a plants person as well, specializing in indoor succulents and orchids, I believe. Overall, I will remember Bill for his personality as a restless thinker, wandering the halls in search of a good conversation or someone to bounce an idea off of, and a scientist who made significant contributions to the fields of ice nucleation, ice crystal formation, and weather modification."

With weather modification studies on the decline at CSU, Bill was invited to DRI to continue work in weather modification. He arrived there in 1985 and worked on issues related to ice crystal characteristics and growth processes, the effects of salt impurities on ice growth processes, charge separation on ice crystals and further work on artificial ice nucleants. He always thought that there was a better chemical for cloud seeding than what was currently being used. He shared his knowledge freely, as is evidenced by the many parenthetical remarks, "(from W. Finnegan, private communication)", regarding the cloud seeding formulation chosen by a project. He certainly had a lot of those "private communications". There are few people who have had as many significant impacts on the field of weather modification in a career that spanned six decades. We all were privileged to have known Bill and will certainly miss him.

Remembrances of Bill Finnegan were contributed by colleagues at DRI (John Lewis, Steven Chai, Randy Borys and Arlen Huggins), former Colorado State colleagues (Paul DeMott, Lewis Grant, and Bob Rilling) and former China Lake and CSU colleague and friend Ward Hindman.

In Memoriam
Dr. Harold “Harry” Orville
(1932 - 2011)

Dr. Harold “Harry” Orville, 79, Distinguished Professor Emeritus of Atmospheric Sciences at the South Dakota School of Mines and Technology, died 6 June 2011 at a Rapid City nursing home. Over a long and distinguished career he contributed much to the science of weather modification and the use of numerical cloud models in support of weather modification research. Harry was a long-time member of the WMA and received its Schaefer, Thunderbird and International awards (the only WMA member to hold all three).

Harry was born 23 January 1932 in Baltimore, MD to Capt. Howard and Lillian Orville. He grew up in Arlington, VA, graduating from high school in 1950. He received a degree in political science from the University of Virginia in 1954, along with a commission in the U.S. Army, and married Laura Milster the same year. In his senior year he gave a speech in speech class on the newly developing field of weather modification by cloud seeding. In those days Harry’s father chaired President Eisenhower’s Committee on Weather Control. Harry, now following in his father’s footsteps, served as a Signal Corps meteorologist at Ft. Huachuca, AZ, and was honorably discharged in 1956 as a 1st Lieutenant. He subsequently received his M.S. degree in meteorology from Florida State University and his PhD from the University of Arizona in 1965.

In February 1965 Dr. Orville came with his family to the Black Hills to join Dr. Richard Schleusener, Dr. Arnett Dennis and other colleagues at the Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology. His main activity was developing numerical cloud models as a major component of the Institute’s weather modification research program, being carried out under what came to be known as the Bureau of Reclamation “Skywater” program. His PhD research involving cloud photogrammetry led him into cloud physics, and Harry and his students and colleagues were careful to include cloud microphysics as well as dynamics in their models. They developed microphysical parameterization schemes to represent the generation, growth and interactions of different classes of cloud and precipitation particles. As computer capabilities advanced, these schemes became more complicated and sophisticated and the models moved from clouds containing only liquid particles (cloud droplets and raindrops) to incorporate various forms if ice including cloud ice crystals, snow, graupel and hail. Furthermore, Harry always paid close attention to comparisons between the model simulations and corresponding observations.

Often the focus of the modeling work was on understanding and properly simulating basic physical processes, but as the capabilities improved it became possible to simulate effects of cloud seeding in the models as well. The first journal publication dealing with glaciogenic cloud seeding appeared in 1980, and many followed. Harry understood that models offer a unique capability to compare the behavior of the same cloud with and without the application of seeding treatments. He thus became an international leader in the application of numerical cloud modeling to the simulation of cloud seeding processes. Work expanded to cover seeding for precipitation enhancement from both summer convection and winter orographic storms, for hail suppression, and even for trying to enhance convection through widespread dispersal of carbon black dust. More recent years saw the addition of hygroscopic- seeding simulations (though some simulations of salt seeding had been carried out in the 1970s). In 1990 and 1996 he published important surveys of the role of numerical cloud modeling in weather modification research and operations.

Harry helped set up the Department of Meteorology (now the Department of Atmospheric Sciences) – the academic arm of the Institute – in 1966, became department head in 1974, and served for over twenty years in that position. He also served as interim vice president at SDSM&T in 1987 and 1993, and as acting director of IAS. Upon retiring from fulltime teaching in 1996, Orville was named a distinguished professor emeritus.

He successfully advocated for cloud seeding trials, sponsored by the West Dakota Water Development District and the City of Rapid City, to enhance reservoir levels in the Black Hills during 1989. He organized a local workshop with invited national speakers, spoke at council meetings, and participated in on-air call-in shows on the topic. In the early 1990's he conducted local research involving microwave radiometer measurements of the vapor flux over the Black Hills region and, in collaboration with Richard Farley and several students, simulated Black Hills spring storm cases to explore the potential enhancement due to seeding of these storms.

Dr. Orville and Nancy Knight collaborated on two NSF-sponsored Research Experiences for Undergraduates projects associated with major convective-storm field projects conducted in Bismarck, ND, in 1989 and 1993 to study potential for hail damage mitigation using cloud seeding. He helped organize a program development workshop for the Board on Atmospheric Sciences and Climate of the National Academies of Science in November 2000, to assess whether a new study of the scientific underpinnings of weather modification was needed. It led to a study that resulted in the National Research Council report on ***Critical Issues in Weather Modification Research***, issued in 2003.

Dr. Orville was a Fellow of the American Meteorological Society and in 1993 was awarded the Charles Franklin Brooks Award, the highest AMS award for service. He served the AMS in many capacities, including AMS councilor and member of the Executive Committee from 1983-1986, and Scientific and Technical Activities Commissioner from 1989-1996. In addition, he chaired the AMS Committee on Weather Modification on two different occasions and also served on the Committees on Cloud Physics and on Severe Local Storms. He was a member of the International Commission on Cloud Physics from 1971 to 1980, spent the academic year 1972-73 working with the NOAA Office of Environmental Modification (dealing with their weather modification programs), and spent a 1982 sabbatical in the Weather Modification Office at the World Meteorological Organization headquarters in Geneva. He later chaired the WMO Executive Council Panel of Experts/ Committee on Atmospheric Sciences Working Group on the Physics and Chemistry of Clouds and Weather Modification Research from 1991-1997. He chaired the organizing committees for WMO scientific conferences on weather modification in Italy (1994) and Thailand (1999), and was instrumental in initiating the series of International Cloud Modeling Workshops conducted under WMO auspices.

Harry had a lifelong interest in sports and athletics, including being a boxer in college. In 1965 he became the manager of Harney Little League teams, and was also active in the Boy

Scouts of America and served as PTA President. He was an avid golfer, becoming a member of the Hole in One Club in 1998, and initiated the annual South Dakota School of Mines and Community Golf Tournament (which has raised tens of thousands of dollars for scholarships). The seventh annual event took place on the day that Dr. Orville passed away. Survivors include his wife, Laura Orville, Rapid City; their golden retriever, “Breezy;” four children, six grandchildren, and three great grandchildren; and two brothers, of whom Richard Orville of Texas A&M University will be familiar to many WMA members. Memorials will be placed towards the Harold and Laura Orville Graduate Fellowship or to the South Dakota School of Mines and Community Golf Tournament through the SDSM&T Foundation.

In Memoriam
Nancy Knight
(1922 - 2011)

Nancy Chase Knight (1922-2011) was born in Boston. Although she attended Wellesley College, most of the knowledge gained during her 49-year career in the atmospheric sciences was accomplished through learning on the job. She took great pride in her lack of formal education.

Nancy's introduction to atmospheric science - and to her future husband, Charlie - resulted from an invitation to apply for a job at the then Department of Meteorology at the University of Washington. While there, Nancy worked for Project Husky, taking observations of the Arctic from encampments on the ice, and she eventually became assistant director. She and Charlie were married in Big Bend, Texas, in 1962, after which they moved to Colorado. They soon joined the National Center for Atmospheric Research (NCAR); there they learned that money was available through the U.S.-Japan Scientific Cooperation Committee to support scientists to make extended visits to Japan. Charlie welcomed the opportunity to visit the University of Hokkaido in Sapporo. While he worked on ice crystals, Nancy taught conversational English to faculty, people in the community, and children, and also helped professors write their papers in English.

By the time they returned to the United States in 1965, discussions of an American hail-modification research program were gaining momentum. A delegation of Americans visiting the Soviet Union had been led to believe that the Soviets had succeeded in suppressing hail; it was important to verify these results, and if valid, to replicate and even improve on their success. Even though there was little enthusiasm for the project, NCAR and the Knights became quickly involved in a series of hail experiments: Project Hailswath (1966), the North-east Colorado Hail Experiment (1969-70), and the National Hail Research Experiment (NHRE; 1971-76). With Charlie's interest in ice, hail was a natural topic to pursue.

Nancy's work evolved into hailstone collection and analysis, first with Charlie and then independently. She participated in many hail and hail suppression research projects into the 1990s, both chasing storms to collect hailstones in real- or near-real time and collecting hail from farmers and ranchers afterward. Once back in the laboratory, Nancy would slice the stones into thin-sections and take photographs in both natural and cross-polarized light to highlight the crystal structure. These studies took her not only to northeast Colorado, but also to South Dakota, Montana, Oklahoma, North Dakota, Alberta, Bulgaria, Italy, Switzerland, and South Africa. It was often a challenge, particularly overseas, to find a cold room appropriate for storing and analyzing the hailstones she collected; often Nancy shared space with vegetables, ice cream, and dead animals.

Copyright, University Corporation for Atmospheric Research

During the 1960s and 1970s, Nancy assisted Charlie on several studies of hail behavior as revealed from the stones collected; studies dealt with hail embryos, conical graupel, spongy hail, and the origin of hailstone lobes. Each of these papers represented analysis of hundreds of hailstones, from many different storms, necessary to make reasonable conclusions.

By the late 1970s, Nancy was writing some articles as lead author, building on the previous papers with Charlie as well as statistics on an ever larger collection of hailstones. She synthesized data from previously collected hailstones from many parts of the world in a climatology of hail embryos (1983). It shows some tantalizing relationships between embryo type (frozen drop vs. graupel) and hailstone size or cloud-base temperature (in an average sense). She nonetheless concluded, in the careful style which characterized the earlier papers, that firm generalizations are hard to come by and the only firm-but-important conclusion was that one hail-suppression strategy cannot be applied to all regions.

In the late 1980s, Nancy started working on cirrus ice crystals as well as hail. Her primary duty was to photograph samples collected from aircraft in a preserving material, an effort that took her to Wisconsin, Kansas, and the Pacific (TOGA COARE and CEPEX). She also collaborated with Harry Orville on two NSF-sponsored Research Experiences for Undergraduates projects associated with major convective-storm field projects conducted in Bismarck, ND, in 1989 and 1993 to study the potential for hail damage mitigation using cloud seeding.

Nancy was a mentor to many younger scientists and an inspiration to women at NCAR and elsewhere. She taught by example a healthy skepticism, and shared her passions with those she inspired. Nancy had many passions; she loved the sea and sailing before moving to inland Boulder. Her love of birds and the ocean led to the purchase of a second house in the prime birding territory of Padre Island, Texas. She loved small dogs, fine food, wine and Armagnac and was an outstanding cook. Nancy read voraciously and loved a good turn of phrase. She had a collection of stories and sayings, one of the most memorable being: “I change my mind often because I keep it clean that way.” Nancy would also lend her blue pencil to both Japanese and American scientists in need of editing help, something she kept up to the end of her career.

Her character is best painted in bright colors rather than pastels. She was certainly one of the most colorful figures in the weather modification field. Many participants in field projects will recall her “holding court” at a group dinner session after a long day in the field, recounting tales of her many adventures. When she was present, meals were often rapid-fire exchanges punctuated by gales of laughter when Nancy drove a point to its target. Those who knew Nancy can quickly summon up a story on her driving habits (sudden stops for an interesting bird; driving at speeds associated more with catching up with storms than with road conditions or speed limits and the resulting exchanges with the Highway Patrol) or her dislike of flying.

That she commanded respect is illustrated by a story Charlie tells. During NHRE, Ron Rinehart asked all the participants to estimate the height of their colleagues and compared the estimates to their actual height. Nancy’s estimated height was much greater than her actual height - a tribute to her stature in the eyes of her friends and colleagues.

Based on the BAMS obituary by Peggy Lemone and colleagues.

USING DYNAMICALLY DEFINED CONTROLS TO EVALUATE THE IMPACT OF AN IONIZATION TECHNOLOGY

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ABSTRACT. An additional field trial of an ionisation technology, called Atlant, was conducted in late 2010. Previous analysis of the data collected in field trials of the technology conducted in 2008 and 2009 used spatio-temporal statistical models to account for the impact of meteorological and topographic conditions not controllable by the randomised experimental design. In addition, a novel application of a random effect block bootstrap was developed for inference. These techniques are applied to the analysis of the 2010 Atlant field trial. In response to peer-review of previous trials, a new modelling approach is developed for this 2010 analysis, that uses dynamically defined upwind control areas to generate values of an instrumental variable that integrates the effects of meteorology and topography induced variation in rainfall. This allows a much simpler model specification and a clearer delineation between naturally occurring rainfall and any additional rainfall attributable to the operation of Atlant. Results using both the statistical methodology of previous trials and also by fitting this so-called "instrumental" model are consistent with those obtained in previous analyses, which had suggested a positive increases in rainfall of around nine percent relative to the predicted rainfall that would have occurred in the absence of Atlant operation.

1. INTRODUCTION

Ground-based ionisation as a means of weather modification was first investigated experimentally by Bernard Vonnegut (Vonnegut and Moore, 1959). Vonnegut carried out numerous experiments into the electrification of clouds, including the widespread releases of ions into the sub-cloud air using a high-voltage power supply that generates corona discharges from an extensive array of small diameter wires elevated above the ground and exposed to local winds and updrafts (Vonnegut et al. 1961, 1962a, 1962b).

Over the years a number of field experiments have been run using technologies derived from this technique (Moore et al. 1986; Kaufman and Ruiz-Columbié, 2005, 2009). Most recently a series of field trials of ground-based ionisation rainfall enhancement technology known as Atlant have been conducted in Australia (Beare et al. 2010; 2011). Further detailed information on the Atlant technology can be downloaded from the Australian Rain Technologies' website (ART, 2012).

Several mechanisms exist by which ions might influence the microphysical processes of precipitation formation at multiple stages through the process (e.g. Harrison and Carslaw, 2003 for an overview; Harrison 2000, Khain et al. 2004, Tinsley et al. 2000). In particular, there is evidence consistent with ions enhancing the coalescence efficiency of charged cloud droplets compared to the neutral case, which provides the basis for a possible hypothesis for how the Atlant system may function to affect rainfall. Initially, negative ions generated from a high-voltage corona discharge wire array become attached to particles in the atmosphere (especially soluble particles), which later act as cloud condensation nuclei (CCN). The ions are conveyed to the higher atmosphere by wind with the electric charges on these particles being transferred to cloud droplets. Finally the electrostatic forces on droplet interaction aids the coalescence of the cloud droplets, resulting in enhanced raindrop growth rate and ultimately increasing rainfall downwind from the Atlant ion emitter. However while previous studies provide this at least semi-plausible “chain of events” mechanisms by which ions generated by the Atlant may influence precipitation, they are yet to be verified observationally and at present there is no physical evidence to indicate that Atlant affects the microphysical properties of clouds. While a scientific program to investigate these mechanisms is highly desirable, this may prove to be a long-term and expensive operation, as the required airborne measurement technologies, remote sensing and modelling capabilities are not as yet sufficiently advanced to readily conduct such investigation. In part, the Atlant field trials have been conducted to establish whether such a major scientific undertaking would be warranted.

Previous analysis of the data collected in these field trials used spatio-temporal statistical models to account for the impact of meteorological and topographic conditions not controllable by the randomised experimental design. In addition, a novel application of a random effect block bootstrap was developed for inference (Chambers and Chandra, 2011). We applied these techniques to the 2010 Atlant field trial using methods similar to those used for the 2008 and 2009 Atlant field trials, see Beare et al. (2010; 2011). In addition, we develop a new modelling approach for the 2010 analysis. This approach uses dynamically defined upwind control areas to generate values of an instrumental variable that integrates the effects of meteorology and topography induced variation in rainfall. This allows a much simpler model specification and a clearer delineation between naturally occurring rainfall and additional rainfall induced by operation of Atlant. Results from fitting this so-called "instrumental" model are consistent with those obtained in previous analyses.

2. APPROACH TO EVALUATION OF THE 2010 TRIAL

The fundamental aspect of the methodology used in the evaluation of the 2008 and 2009 trials is the use of a statistical model to estimate the unobserved (or natural) rainfall that would have occurred in the target area had the Atlant system not been operating. The weather modification effect is then the difference between observed rainfall and the estimated natural rainfall. The target area, as in the 2009 trial, was defined to be the region defined by the union of two 60º downwind arcs extending out from the two Atlant sites used in the trial. The statistical model adopted for this purpose was itself rather complex, being a mixture of fixed effects, based on meteorological and orographic covariates, plus random spatial andtemporal affects to account for correlations in the data due to systematic but unmeasured influences that might be inadvertently attributed to the operating status of the system.

Peer review of the 2009 trial identified three issues that needed to be considered in the design and analysis of the 2010 trial. First, the ex-post development of the statistical model made statistical inference less reliable than indicated by the model fit diagnostics. Second, the complexity of the modelling approach, while not seen as undue, made it difficult to follow and interpret the results. Third, the absence of blocking in the randomised design used to determine day-to-day operation of the Atlant mechanisms was a potential source of inefficiency that should be considered in further trials. The last of these issues was the driving force in the design that was adopted for the 2010 trial.

3. DESIGN OF THE 2010 MOUNT LOFTY RANGES TRIAL

A primary aim of the 2010 Mount Lofty Ranges trial was to again test the hypothesis that operation of the Atlant systems in the assessment region lead to increased rainfall in the trial target area. The sites C2 and C3 used in the 2009 Mount Lofty Ranges Trial were again selected for the 2010 trial (Figure 1).

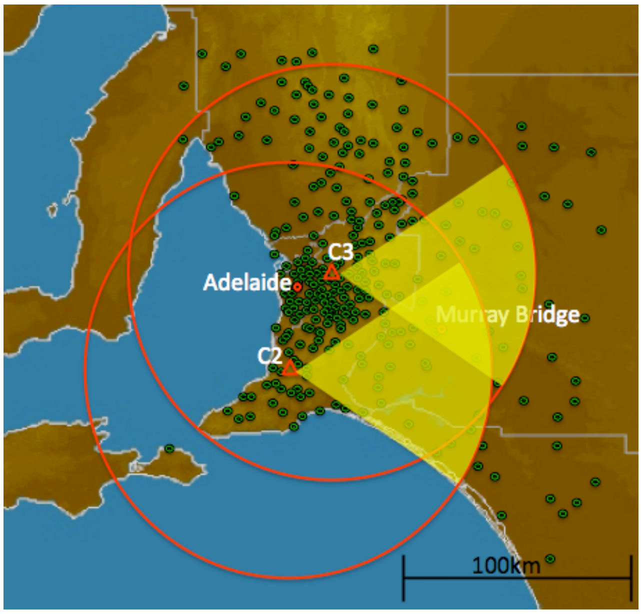

Figure 1. The location of the Atlant sites (∆) at C2 and C3. The rain gauges used in the trial are indicated by green dots. The circles centred on the Atlant sites have a radius of approx 90 km. Downwind target sectors (yellow) are shown for a westerly wind. The orientation of the sectors and degree of overlap is dependent on the direction of the wind.

Note that the C2 site was the only one used in the 2008 Mount Lofty Ranges Trial. The trial ran for 128 days subject to the operating protocol described below, commencing at 9 am 11 July 2010 and finishing at 9 am 14 December 2010, local time. During the trial, the Atlant ion generation sites were switched on and off at 9 am in accor dance with the specified switching regime. This was to coincide with the Bureau of Meteorology (BoM) reporting time for the rain gauges, and to reduce the chance that overlap of rainfall measurements diluted the results. An additional advantage was one of operational convenience, in that 9 am is approximately the start of a working day.

A 30-minute 'temporal buffer' was also added to the switch time, in recognition that there may be a delay, albeit of unknown length, between when the device is switched off or on and any effect on rainfall downwind of the device. Thus, with a nominal switch time at 9 am, the operating Atlant was turned off at 8.30 am and the ongoing Atlant was then turned on at 9 am.

The Atlant systems were operated according to a standard randomised block design. This plan was "blocked" by calendar time and propensity to rain, with rainfall propensity on a day determined by the BoM Poor Man's Ensemble (PME) rainfall model forecast in the assessment region on the day. A random number generator in Matlab was used to randomly allocate the one-day units leading to a random sequence of 64 days when each Atlant (either C2 or C3 depending on the site) is on, and 64 days when it is off. On each day, if the PME model 'chance of rainfall' showed that there was at least a 10 per cent chance of average rainfall greater than 1 mm within the assessment region (34°S-36°S, 138°E-140°E) for the morning of the day in question, then this day was deemed a 'suitable day' and operation commenced. If a day was deemed not suitable, then no operation took place until the next suitable day when the next consecutive randomised day schedule was followed. The PME model combines several Numerical Weather Prediction (NWP) models to produce rainfall forecasts using a technique known as "probability matched ensemble mean". Such a combination has been shown to provide a more accurate forecast than using a single model, and is considered to be BoM's most accurate small area rainfall model (Ebert, 2001). The PME model is updated at approximately 5 am each day. Of the 128 days of the trial, 117 were considered suitable according to this procedure. There were equipment malfunctions on 5 of these suitable days leading to a loss of operating hours. As a consequence, only data from the 112 suitable days when the Atlant mechanisms operated continuously for at least 12 hours each day (57 days when C2 was operated and 55 days when C3 was operated) were used in the trial analysis.

4. COMPARISON WITH 2009 MODELLING APPROACH

The same statistical methodology used in the 2009 trial was used with the 2010 trial data. This was done in order to ensure comparability with the model used to assess the 2009 trial and also to address the issue of ex-post model development that had been raised with respect to the analysis of the data collected for that trial. The model is for rainfall at individual gauges (hereafter termed gauge-level rainfall) in the target area each day, and controls for the influence of meteorological and orographic conditions on observed rainfall. Daily variation in atmospheric moisture is controlled using the proportion of upwind gauges (i.e. those gauges at least 90º away from directly downwind at either Atlant site) that reported rainfall on the day. There were substantial differences in meteorological conditions over the 2009 and 2010 trials. In particular, there was an increase in prevailing winds from the southwest. Average rainfall for the trial area was also much higher in 2010, with two days where average rainfall across the trial area exceeded 20 mm, with over 90 per cent of gauges reporting rainfall. There were a further 10 days when widespread heavy rain was recorded, defined as an average rainfall of 10 mm or more across the trial area, with over 85 per cent of gauges recording rain. Overall, the statistical model was able to explain 68 per cent of the gauge-by-day variation in observed rainfall for the gauges in the target area, which was similar to its performance in the 2009 trial.

A total of 4711 rain measurements were made over the 112 days of the trial when the Atlants were operational, and an average of 4.7 mm of rain was recorded at each downwind gauge that reported rainfall. The model estimated that 4.2 mm of this rain could be attributed to natural causes, leaving 0.5 mm of rainfall attributable to the operation of Atlant. This corresponded to an estimated rainfall enhancement effect of 11.5 per cent, with a bootstrap p-value of 0.04. This is of the same order of magnitude as the effect estimated for the 2009 trial. Figure 2 shows the random effect block bootstrap distribution of the estimated enhancement effect for 2010, based on 10,000 bootstrap replicates. This shows that a one-sided 95 per cent bootstrap confidence interval for the true enhancement effect excludes zero.

As with the model fitted to the data collected in the 2009 trial, there was asymmetry in the contribution of the two Atlant sites to this estimated enhancement effect. In 2009, the estimated effect was strongly associated with the operation of C3 rather than C2. However, in 2010 this asymmetry was reversed, with the estimated effect strongly associated with the operation of C2 rather than C3. No single clear reason could be identified for this switch. However, there is some evidence that it is partly the result of the change in meteorological conditions between 2009 and 2010.

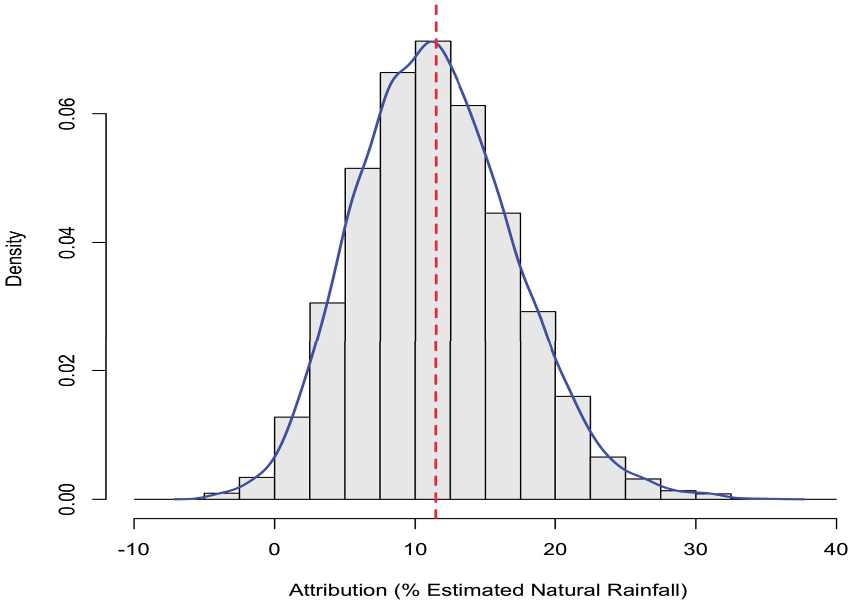

Figure 2. Random effect block bootstrap distribution of the estimated Atlant enhancement effect (Attribution) relative to estimated natural rainfall over the 112 operating days of the 2010 trial period. Vertical dashed line indicates the value of the estimated enhancement effect.

5. A SIMPLIFIED APPROACH TO MODELLING THE 2010 TRIAL DATA

The complexity of the model used to fit gauge-level rainfall in the presence of potential effects due to the operation of Atlant was raised in the peer review of the 2009 trial. In particular there was some concern about the fact that the model simultaneously accounted for both the day-to-day variation in natural rainfall at a gauge, as well as the potential Atlant effect.To address this issue of model complexity, a simpler instrumental variable model was developed for the 2010 trial data.

This model bases prediction of natural rainfall downwind purely on the relationship between upwind rainfall and the meteorological and orographic covariates. This predicted value is then used as a fixed effect in a much simpler second model for downwind rainfall that accounts for the operating status of the system and the spatial and temporal random effects.

5.1 Upwind model development

A key aspect of the instrumental modelling approach is the development of the instrumental variable, i.e. the variable that is used to indicate the expected amount of 'natural' rain at a gauge. This variable was defined by modelling the relationship between observed rainfall and meteorological and orographic covariates for upwind gauges. As noted earlier, these are gauges that are at least 90º away from directly downwind at either Atlant site on the day. Effectively, rainfall data from these gauges over the trial period were used to generate a 'modelled' control value for every downwind rainfall observation. Like the downwind target area, the upwind control area is dynamically defined, since a gauge can be downwind one day (when its rainfall is subject to Atlant influence, and so constitutes a potential target value) and be upwind the next day (when its rainfall is not subject to Atlant influence and hence serves as a control).

In order to develop the upwind model, two changes were made to improve the explanatory power of the meteorological and orographic covariates used in this model. The first involved modifying the wind direction variable used in the 2009 modelling exercise to further reduce its non-monotone behaviour.As measured, the difference between any two wind directions has two values with a singularity at 0 or 360 degrees. An initial attempt to transform wind directions was made for the 2009 trial analysis in order to address the first problem. However, the transformation was not monotone as can be seen in the left hand panels of Figure 3. Note that directions shown here are 'East Zeroed', i.e. due East is set to 0/360 degrees. An iterated logarithmic transformation was used to define the smooth monotone transformations shown in the right hand panel. Wind direction values defined by this modified transformation, denoted LSWD, were then used in the modelling process. A second issue related to the use of an indicator variable for days with heavy widespread rainfall. This indicator was necessary in order to stop rainfall values from such days dominating the modelling process. However, peer review of the 2009 trial analysis suggested that it should be possible to remove much of the need for this ad-hoc model adjustment by including the daily values of the three BOM stability indices into the model. There were three such indices: the Total Totals index (TT); the Lifted Index (LI); and the Precipitable Water index (PW). Values of these indices were available at 12 hourly intervals. An examination of the relationship between the values of these indices and daily gauge level rainfall indicated a strong relationship between Precipitable Water and gauge-level rainfall, but much weaker relationships between the other two indices and gauge level rainfall. In particular, values of Precipitable Water were generally good indicators for widespread rain events in 2010. However, none of these indices were able to identify two extreme rain events: 3 September, when average rainfall across the trial area was 32.9 mm with 287 out of 294 gauges reporting rain; and 7 December, when average rainfall across the trial area was 51.1 mm with 286 out of 294 gauges reporting rain. Consequently these two days were the only days allocated a separate mean effect (Heavy Rain Day) in a model that included three extra effects defined by these indices - the average of the two Precipitable Water readings (Precipitable Water) and the first and second principal components of the remaining four index values, denoted 1st PrinComp (TT&LI) and 2nd PrinComp (TT&LI) respectively.

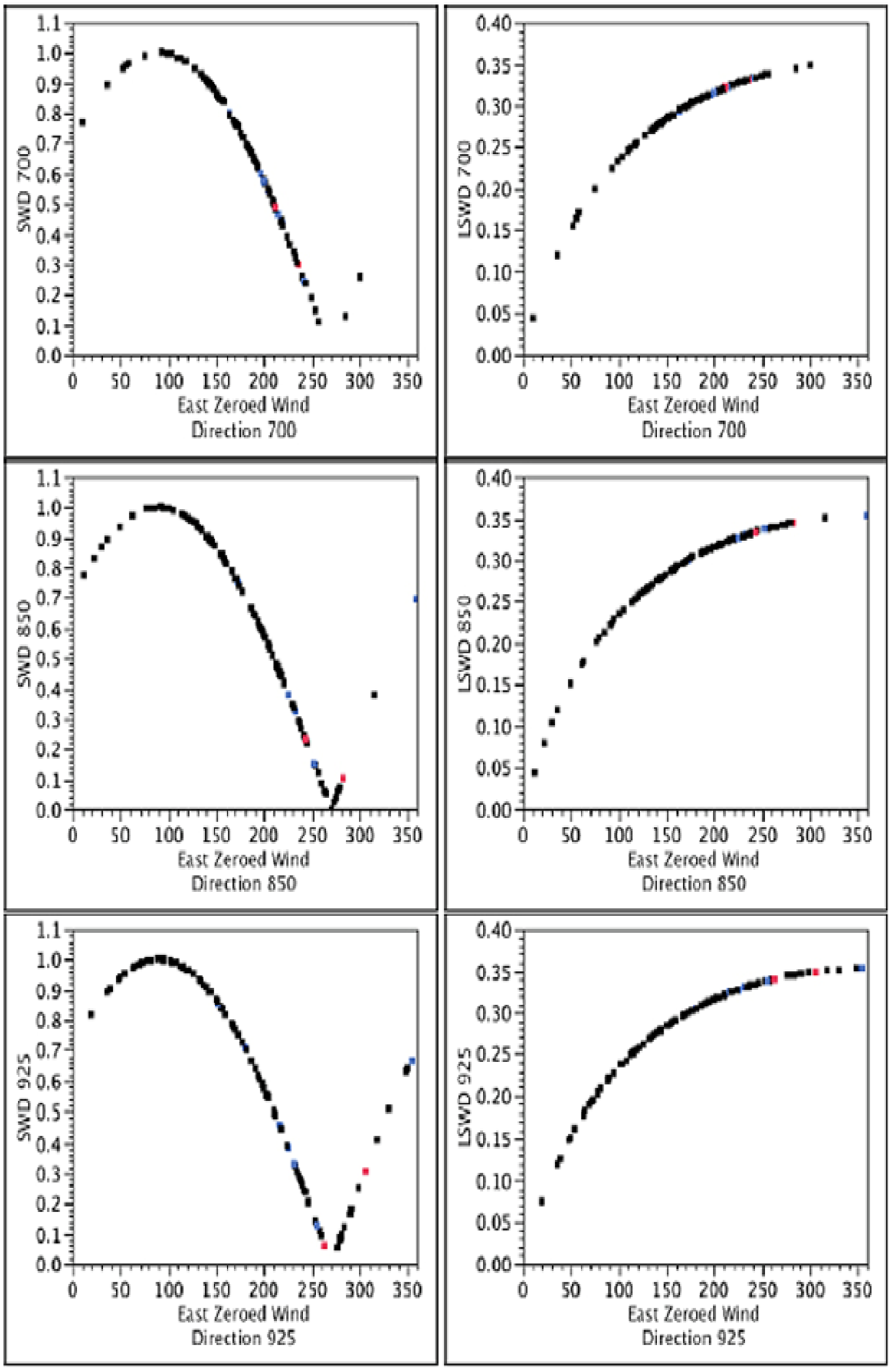

Figure 3. Transformation of wind direction data. Left panel is transformation used in 2009 trial analysis (denoted by SWD). Right panel is new transformation (denoted by LSWD). Rows correspond to different values of hPa.

Table 1 shows the fit of the regression model to the logarithm of upwind gauge level rainfall from 2010, based on the 4388 upwind rainfall readings over the trial period. The variable definitions are the same as in 2009, with the exception of the introduction of revised wind direction effects (denoted by LSWD - see Figure 3); the inclusion of daily range effects for Average Daily Temperature, Dew Point Temperature and Sea Level Pressure; and the use of average daily values of Precipitable Water and the first two principal components of daily values of the Total Totals and Lifted Index indices. The use of Precipitable Water in particular allowed the dropping of the Widespread Rain Day effect used in 2009. However, as we have already noted, there were still two days (3 September and 7 December) in 2010 when the rainfall was extreme. These days are allowed for via the inclusion of the zero-one effect Heavy Rain Day. Note that significant day-to-day and gauge-to-gauge differences in the rainfall data unexplained by the meteorological and orographic variables in the model were allowed for in model fitting by the inclusion of random gauge and day effects. Together, these effects account for approximately 55 per cent of the unexplained variability in the logarithms of the gauge level upwind rainfall data that was recorded.

Table 1. Upwind model parameter estimates for logarithm of rainfall in the 2010 trial. Statistically significant covariates are bolded.

Parameter	Estimate	SE	Significance
Intercept	0.4994	25.3697	0.9843
AugSept	0.1934	0.2768	0.4866
Heavy Rain Day	1.3670	0.7988	0.0910
Precipitable Water	0.1191	0.0290	**<.0001**
1st PrinComp (TT&LI)	-0.0165	0.0883	0.8518
2nd PrinComp (TT&LI)	0.1136	0.1095	0.3025
Wind Speed 700	-0.0212	0.0086	**0.0158**
Wind Speed 700 L1	-0.0036	0.0075	0.6341
Wind Speed 850	0.0156	0.0157	0.3230
Wind Speed 850 L1	0.0061	0.0141	0.6650
Wind Speed 925	0.0105	0.0142	0.4645
Wind Speed 925 L1	0.0041	0.0115	0.7203
LSWD 700	1.3414	3.5852	0.7092
LSWD 700 L1	2.3376	3.0528	0.4459
LSWD 850	2.5695	3.4882	0.4632
LSWD 850 L1	3.4868	2.4322	0.1550
LSWD 925	-4.4023	3.0688	0.1549
LSWD 925 L1	-4.3302	2.9794	0.1495
Average Daily Temp	-0.0478	0.0608	0.4340
Temp Range	0.0027	0.0423	0.9495
Dew Point Difference	-0.0220	0.0580	0.7054
Dew Point Range	0.0339	0.0492	0.4935
Sea Level Pressure	-0.0025	0.0243	0.9184
Pressure Range	0.0612	0.0333	**0.0693**
Elevation (100 m)	0.0618	0.0138	**<.0001**

Ideally, one would like to measure rainfall on the same day at matched control and target gauges, i.e. gauges that differ only in their exposure to the Atlant process. In this context, upwind gauges on any particular day satisfy the requirement that they are not exposed.

Unfortunately, an individual gauge cannot serve as a control for the entire period of the trial as it can be upwind of the Atlant sites on one day and downwind on another. However, given that the level of rainfall recorded when a gauge is upwind is determined independently of anything occurring downwind, it is possible to use the rainfall data measured when the gauge is upwind to construct an instrumental control variable that is independent of a gauge's location relative to the prevailing wind direction. This instrumental control variable is defined by the model fit shown in Table 1, since the predicted value of upwind rainfall generated by this model as a function of meteorological and fixed orographic effects is independent of any downwind influence. The fitted values generated by applying the model parameters in Table 1 to the meteorological and orographic conditions when a gauge is downwind can then used to calculate a prediction of natural rainfall at this gauge at that time. This instrumental prediction is by construction independent of any downwind conditions associated with the gauge's relative location to the Atlant devices and their operating statuses. As an aside, we also note that no attempt has been made to simplify the model in Table 1 using statistical methods of variable selection, since its main use is calculation of unbiased rainfall predictions independent of the operation of the Atlant mechanisms.

5.2 The instrumental variable downwind model

By construction, the instrumental control variable developed in the previous section provides a prediction of rainfall at a downwind location under similar meteorological and orographic conditions and therefore serves to replace the large number of meteorological and orographic covariates used in the 2010 version of the downwind model underpinning the results discussed in section 4. However, there is still the need to include effects in the instrumental variable-based downwind model associated with location of a gauge relative to steering wind direction and the location of the ion generation sites, since these are relevant to assessing the impact of Atlant operation on downwind rainfall. In this context we note that operating effects in the 2009 model specification included a distance interaction but not a crosswind interaction. However, the extent to which a gauge is crosswind as opposed to downwind when the systems are operating seems a relevant consideration, and so these interactions were included in the 2010 downwind model. In particular, the relative downwind locations (both for the day of measurement as well as the previous day) of a gauge were specified in terms of its distances from the two Atlant sites and its angles of orientation relative to the direction of the steering wind at these sites. The spatio-temporal random effects in the 2009 downwind model were also retained.

The fit of the downwind instrumental model for the 2010 gauge level data is shown in Table 2. Note that the instrumental variable Predicted LogRain in Table 2 is calculated as the fitted value generated by the upwind model fit defined by Table 1. Note that the model fit shown in Table 2 only includes the instrument and significant effects defined by operating status and gauge location relative to the Atlant locations C2 and C3. There are significant effects identified with respect to the operating status of the Atlants at C2 and C3 as well as interaction effects at C3 with respect to relative wind direction.The spatio-temporal random effects account for just under 50 percent of the unexplained variability in the model fit.

Based on this fitted model, the overall Atlant enhancement effect for 2010 is estimated at 10.0 percent with a standard error of 6.4 percent. The confidence bounds are shown in Table 3 and the bootstrap distribution of this estimated enhancement effect is shown in Figure 4. The estimated level of enhancement is significant at the 95 percent level.

Table 2. Parameter estimates for the instrumental model for logarithm of downwind rainfall in the 2010 trial. Statistically significant covariates are bolded.

Parameter	Estimate	SE	Significance
Intercept	-0.5132	0.1028	**<.0001**
Predicted LogRain	1.1482	0.0533	**<.0001**
C2 Distance	-0.1797	0.1091	0.0997
C2 Theta	0.0023	0.0004	**<.0001**
C3 Distance	-0.1208	0.1441	0.4017
C3 Theta	0.0002	0.0004	0.6772
C3 Theta L1	-0.0005	0.0003	0.1384
C3 Distance*C3 Theta	0.0053	0.0011	**<.0001**
C3 Distance*C3 Theta L1	0.0015	0.0005	**0.0063**
C2 Target	0.2651	0.1085	**0.0150**
C3 Target	0.5811	0.1448	**<.0001**
C3 Theta* C3 Target	-0.0100	0.0023	**<.0001**
C3 Theta L1* C3 Target	-0.0015	0.0007	**0.0350**

Table 3. The lower confidence bounds for the size of the Atlant enhancement effect (in %) from the instrumental model-based gauge-level analysis of the 2010 trial.

Confidence Level	Estimate
99 percent	**-2.4**
95 percent	**0.7**
90 percent	**2.4**
80 percent	**4.7**
70 percent	**6.4**
60 percent	**8**
50 percent	**9.6**

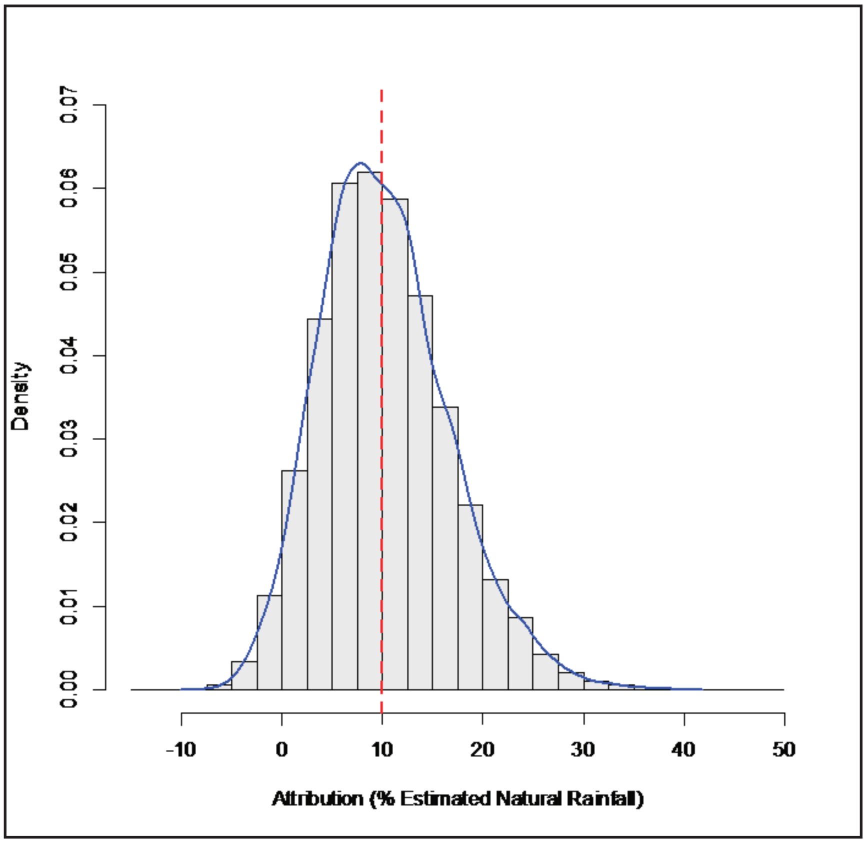

Figure 4. Random effect block bootstrap distribution of the estimated Atlant enhancement effect (Attribution) relative to estimated natural rainfall over the 112 operating days of the 2010 trial. Estimates are based on the instrumental model. The vertical dashed line shows the value of the estimated 2010 enhancement effect under this model

Overall, the instrumental model-based analysis of the 2010 trial led to very similar results in terms of the level of increased rainfall attributed to the operation of the ion generation system. The significance levels of the enhancement estimates are also quite similar. When compared to the approach developed for the 2009 trial, the instrumental model was able to isolate significant effects at both C2 and C3 in 2010, whereas the approach used in the 2009 trial (which only modelling the downwind rainfall data) was only able to identify a significant effect at C3 in 2009 and at C2 in 2010. However, the estimated enhancement levels under both approaches were of the same order of magnitude.

6. CONCLUSION

Australian Rain Technologies (ART) conducted a field trial of the Atlant ionisation technology in the Mount Lofty Ranges trial from July to December 2010, utilising the same installation sites as those used in the 2009 trial. The trial was conducted using a randomised cross-over design and the data collected in it were analysed using the same spatio-temporal statistical methodology that was developed for analysis of the 2009 trial.

Even though meteorological and rainfall conditions in 2010 varied considerably from 2009, and experimental conditions also varied, similar models and estimation methods to those used in the analysis of the 2009 Mount Lofty Ranges trial were used when analysing the 2010 trial. The analysis of the 2010 trial showed enhancement estimates consistent with those obtained in the analysis of the 2009 trial, of the order of 9 percent. It should be noted however that this analysis is purely statistical, and so interpretation of its results with respect to the efficacy of ionization as a means of planned weather modification are indicative. However, the repeated demonstration of a positive enhancement effect of the order of 9 percent, the plausible, though not well understood mechanisms of this effect, and the significant cost and environmental advantages of the technology if proven, warrant further research in this area.

Refinements to the analysis methodology used in 2009 were also investigated. These included redefining the variable used to measure wind direction in order to make it more monotone, inclusion of daily range data for temperature and pressure and the use of BOM stability indices to replace subjective assessment of widespread rain events. The main development however was the introduction of an instrumental model specification for the logarithm of gauge-level rainfall. The instrument itself was developed by modelling daily rainfall data from the trial gauges when they were upwind of the two ion generators. The values of the instrument were then used to replace the meteorological and orographic variables in the 'standard' model, leading to a more transparent model specification that focused solely on variables measuring daily variation in gauge characteristics (e.g. target/control status, distance, orientation etc.) downwind of the generators. Although this refined model did not lead to any significant change in the estimated level of enhancement, it did allow effects associated with the two sites to be compared with less noise due to between site differences in meteorological and orographic effects. Although not shown here, when applied to the 2009 data, the instrumental model indicated that effects at C2 compared with C3 were similar to those observed in 2010.

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SUMMARY OF A WEATHER MODIFICATION FEASIBILITY/DESIGN STUDY FOR WINTER SNOWPACK AUGMENTATION IN THE UPPER BOISE RIVER BASIN, IDAHO

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ABSTRACT. North American Weather Consultants (NAWC) performed a feasibility/preliminary design study of potential means of augmenting an existing operational winter cloud seeding program in the Upper Boise River Basin (UBRB) program in Idaho by extending the base project period of November through March by one month (April) and possibly adding remote generators and seeding aircraft to the existing lower elevation manual generator network. This study was performed for the Idaho Water Resources Board (IWRB). The IWRB noted that the upper Boise, including the North Middle and South Forks, and Mores Creek supplies 90% of the water for the lower Boise Basin. The UBRB ranges in elevation from approximately 915 m (3,000 feet) MSL at Lucky Peak Dam to crest elevations of approximately 2590 – 2700 m (8,500 to 9,500 feet) MSL between the Boise River and Big Wood River Basins. NAWC recommended that the intended target area for the UBRB program be defined as those regions in the basin that are above 1524 m (5,000 feet) MSL. The primary program goal would be to increase winter snowpack in the target area through operational cloud seeding. The resulting augmented spring and summer stream flow would be used in a number of ways including augmented hydroelectric power production and agricultural irrigation.

Average increases of 4.7% in April 1st snow water contents from cloud seeding were estimated through transference of the indicated results from the Climax I and II research programs. Simulations using empirically derived snowpack-stream flow relations yielded estimated average increases in March-July stream flow from three seeding modes totaling approximately 1.004×10^8 m^3 (81,425 acre-feet). The costs of the estimated increases in March-July stream flow range from \$0.003 to \$0.01 per cubic meter (\$3.29 to \$12.45 per acre-foot) of additional water in an average water year. A preliminary design for an augmented operational winter cloud seeding program is described.

1. INTRODUCTION

The Idaho Water Resource Board (IWRB) contracted with North American Weather Consultants (NAWC) of Sandy, Utah for the performance of a comprehensive study of the feasibility/design of applying modern cloud seeding methodologies for winter snowpack augmentation in a portion of the Upper Boise River Basin located in southwestern Idaho (Griffith and Yorty, 2009a). This paper presents the key elements, findings, conclusions and recommendations of that feasibility/design study. The study included a survey of relevant prior research and operational seeding programs, considerable analysis of program area-specific historical weather data, assessment of potential cloud seeding methods, plus evaluation techniques. Procedures and recommendations of the ASCE publication entitled “Standard Practice for the Design and Operation of Precipitation Enhancement Projects” were utilized where appropriate (ASCE, 2004).

An interesting aspect of the Upper Boise River Basin feasibility/design work is that NAWC had already conducted operational winter cloud seeding programs in this area. NAWC conducted five-month programs during the water years of 1992-1996, 2001-2005, and 2007-2009 (Griffith and Solak, 2002, Griffith, et al, 2009) and a three month program during the 2010 - 2011 water year (Griffith, et al, 2011). In recent seeded seasons, a network of approximately 20 manually operated, ground based silver iodide generators have been used in the conduct of this operational program. Therefore, the design of the program that is considered in this study is focused upon potential means of augmenting or enhancing this existing operational cloud seeding program.

A preliminary operational program design, including identification of permit and reporting requirements, was prepared. The study also included hydrologic estimates of the potential program yield in terms of additional runoff and the estimated costs associated with conduct of the program, based on different seeding modes.

The tasks specified by the IWRB in the performance of this feasibility/design study included:

- Review and Analysis of Climatology of the Target Area
- Review and Assessment of the Existing Program
- Evaluate Enhancements of the Existing Program
- Establish Criteria for Program Operation
- Development of Monitoring and Evaluation Methodology
- Development of Operational Suspension Criteria
- Preparation of a Final Report including an Executive Summary

Summaries of prior applicable research and operational programs and environmental and legal considerations were included in the final report. This information had been generated in the performance of similar feasibility/design studies conducted for the IWRB focused on the Eastern Snake River Basin in Idaho (Griffith, et al, 2010) and the Salt and Wyoming Ranges in southwestern Wyoming conducted for the Wyoming Water Development Commission (Griffith, et al, 2007).

2. PROGRAM GOALS AND SCOPE

The stated goal of the proposed seeding program is to increase winter snowpack in the target area to provide additional spring and summer stream flow and recharge of underground aquifers at a favorable benefit/cost ratio without the creation of any significant negative environmental impacts. Seeding operations are to be conducted on a non-randomized basis. Randomization is a technique often used in the conduct of research programs whereby approximately one-half of the potential seed cases are left unseeded to allow a comparison with the seeded cases (Hess, 1974). Evaluation procedures, based upon an historical target and control approach, were developed and incorporated in the program design. Limited investigational elements are included in the design, whereby measurements highly focused on a) identifying the presence of supercooled liquid water, the substance targeted by glaciogenic (ice forming) seeding methods and b) characterizing the vertical atmospheric structure via program specific rawinsonde (balloon) soundings are recommended for conduct on a phased rather than ongoing basis, to help maintain program cost effectiveness.

3. TARGET AREA

The Idaho Water Resources Board (IDWR) specified the area of interest to be the Upper Boise River Basin (UBRB). This area lies within portions of Boise, Camas and Elmore Counties. The IDWR noted that the upper Boise, including the North Middle and South Forks, and Mores Creek supplies 90% of the water for the lower Boise Basin. The UBRB ranges in elevation from approximately 915 m (3,000 feet) MSL at Lucky Peak Dam to crest elevations of approximately 2591 to 2744 m (8,500 to 9,500) feet MSL between the Boise River and Big Wood River Basins. NAWC recommended that the intended target area for the UBRB program be defined as those regions in the basin that are above 1524 m (5,000 feet) MSL since a high percentage of the runoff originates from regions above this elevation. This area is outlined in Figure 1.

Runoff from this target area benefits hydropower production, agriculture (both surface runoff and ground water recharge), municipalities (drinking water), as well as recreational interests. Approximately 70 - 80% of the annual precipitation in the target area accumulates during the October-April period, with area average snowpack water equivalent on April 1 of 64.5 cm (25.4 in).

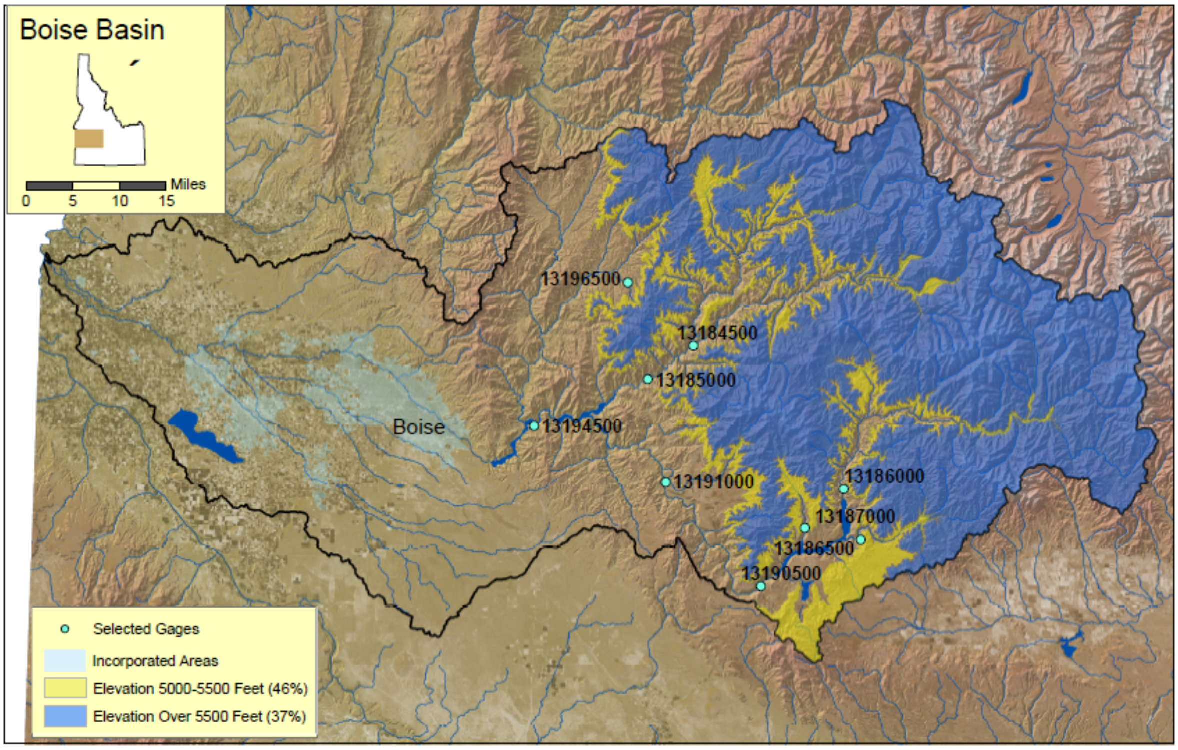

Figure 1. Proposed Target Area above 1524 meters (area includes those areas outlined in yellow and blue, black line outlines the Boise River Basin.)

4. REVIEW AND ANALYSIS OF THE CLIMATOLOGY OF THE TARGET AREA

The meteorological parameters of greatest interest in this feasibility study are: precipitation, surface and upper-level wind directions and velocities, temperatures at the surface and aloft, and the structure of the lower to mid-levels of the atmosphere. Information on these parameters during winter storm periods that impact the proposed target area is of primary interest. Two factors drive these considerations: 1) the likely presence of “seedable” conditions, and 2) the potential ability to target these seedable regions. Considerations involving the first factor (seedability) may be focused on the temperatures and winds within the storms. To be seedable, a portion of the cloud system needs to be colder than freezing. Also, the height of certain temperature levels such as the -5^0 C (23^0 F) are important for one of the primary seeding materials (silver iodide), since this is the warmest temperature at which silver iodide begins to be active as an ice or freezing nuclei. Another consideration is the speed and direction of the lower level winds. If winds are blowing up and over the mountain barrier and the cloud top temperatures are not too cold, then supercooled (colder than freezing) cloud droplets will likely be present in the storm clouds. It is the presence of these supercooled cloud droplets that determines whether there is any seeding potential within the clouds. Clouds that are naturally efficient in producing precipitation reaching the ground will contain few or no supercooled cloud droplets; inefficient clouds will have higher concentrations of supercooled cloud droplets. Targeting considerations are related to the likely transport and diffusion of seeding materials, which becomes a function of seeding mode (ground based, aerial), the lower level wind speed and direction, and lower level atmospheric stability. Information on these parameters of interest is provided in the following sections. This feasibility/design study was defined as a wintertime activity. We have therefore provided information for the October through April time frame.

4.1 Precipitation and Snow Water Content

Data on the natural precipitation in the target area provides useful information concerned with the different types of storms that impact this area. Such data also provide a baseline for estimation of the magnitude of precipitation increases that may be possible through cloud seeding. For example, if a potential target site receives an average 50 cm (20 inches) of precipitation during the winter months and if our analyses indicate that a 12% increase in precipitation is possible from cloud seeding, then the estimated increase in an average winter season at this site would be 6.0 cm (2.4 inches) of additional precipitation. This estimate may then be used to provide estimates of resultant increases in stream flow. Observations of precipitation in the higher elevation target area have primarily been made by the Natural Resources Conservation Service (formerly the Soil Conservation Service). These observations are of two basic types: 1) measurements of snow water content and 2) measurements of rainfall and melted snowfall.

Five NRCS sites located in the proposed target area were selected to provide monthly and seasonal data on precipitation and snow water content. Tables 1 and 2 provide these data.

Table 1. Average Monthly Precipitation at Five SNOTEL Sites (inches)

Site	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Oct.-Apr.	Water Year
Atlanta Sum.	2.5	6.3	6.5	6.8	4.9	5.9	2.9	35.8	44.2
Soldier R.S.	1.2	2.9	3.2	3.3	2.3	2.0	1.6	16.5	23.2
Mores Ck Sum.	2.2	6.8	6.9	7.7	5.7	4.8	3.1	37.2	45.7
Camas Ck Div	1.3	2.9	3.3	3.3	2.2	1.8	1.5	16.3	21.9
Trinity Mtn	2.6	8.3	8.7	8.5	7.0	5.2	3.3	43.6	52.7

Table 2. First of the Month Average Cumulative Snow Water Content at Five SNOTEL Sites (inches)

Site	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**
Atlanta Sum.	0.0	1.4	7.0	13.4	20.1	26.2	31.9	31.1
Soldier R.S.	0.0	0.3	2.3	5.8	9.2	12.0	10.0	0.0
Mores Ck Sum.	0.0	0.8	6.3	13.7	21.7	29.2	34.6	31.0
Camas Ck Div.	0.0	0.0	1.6	5.1	9.3	11.7	11.0	3.0
Trinity Mtn.	0.0	2.0	9.1	17.0	25.5	33.4	39.5	40.5

From Table 1 the October through April average precipitation produces approximately 80% of the annual average water year precipitation. From Table 2, the average April 1st snow water content is 64.5 cm (25.4 in).

4.2 Specialized (Storm Period-Specific) Climatological Information

A detailed analysis of storm periods affecting the target area was conducted for an eight-season period (water years 2001-2008) for the October-April season. Precipitation data from several SNOTEL sites were considered and six-hour time blocks were selected when precipitation was clearly occurring in the target area. Data were examined from three SNOTEL sites: Atlanta Summit, Soldier R.S., and Mores Creek Summit. The SNOTEL data ranged from hourly to six-hourly in resolution and were obtained from the Natural Resources Conservation Service (NRCS).

A total of 386, six-hour periods were selected for analysis, generally corresponding to precipitation at the SNOTEL sites averaging more than about 0.1” and generally with precipitation evident in the data for at least two of the sites. These six-hour periods were matched as closely as possible to Boise weather balloon soundings, which we believe provide a good representation of the target area.

These soundings were used to derive temperature and wind data at the 700-mb and 500-mb levels, which are at approximately 3050 m (10,000') and 5490 m (18,000') MSL. The soundings also provided moisture (dewpoint) values, and a general idea of low to mid-level atmospheric stability. Estimates of the -5^0 C isotherm height and cloud-top temperature were also obtained from these sounding profiles.

4.2.1 Storm Precipitation

Figure 2 provides the number of six-hour periods in the analysis (by month) for four different ranges of precipitation amounts in inches (0.10 - 0.19, 0.20 - 0.29, 0.30 - 0.39 and 0.40 or greater). The highest frequency is in the 0.20-0.29" range. This suggests that the precipitation rates are usually rather light, a common feature of winter storms in many of the mountainous areas of the Intermountain West.

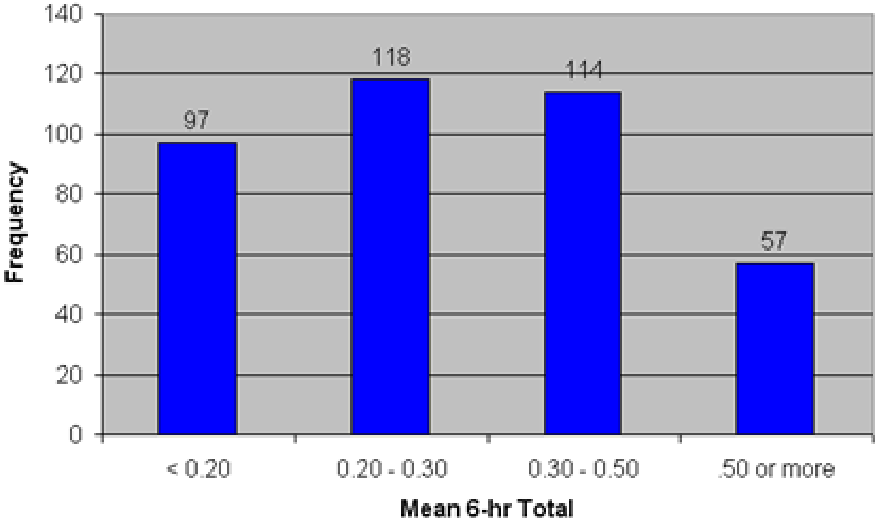

Figure 2. Frequency of 6-hour Storm Events by Precipitation Amount (inches)

4.2.2 700 mb Storm Winds

NAWC has utilized the 700 mb level as an index of important meteorological features regarding targeting of the seeding effects. First, the 700 mb wind is considered a good steering winds indicator, i.e., an approximation of the direction along which storm elements will move. NAWC has also used this level as guidance in the selection of ground -based generator sites. The 700 mb wind directions and speeds for the 6-hourly, eight-season sample-described above were used to generate wind roses that graphically display the average information for each of three potential seeding modes: 1) lower elevation, ground based generators, 2) higher elevation, remotely operated ground generators, and 3) airborne seeding. Discussions of these three seeding modes are provided in Sections 5.1 – 5.3. The wind roses provide the frequency of wind direction and speeds by 22.5^0 wind sectors. The velocities on these wind roses are plotted in knots. Figure 3 provides an example of one of these plots. This information is useful in the potential siting of ground generators and selecting aircraft seeding tracks.

4.2.3 700 mb Storm Temperatures

A plot of the average 700-mb temperatures during the six-hour precipitation periods by month was prepared (Figure 4). NAWC uses temperatures at this level in helping decide whether a specific storm period is considered seedable using ground-based silver iodide generators, since the 700-mb level is typically near the height of the target mountain barriers.

Seeding materials released from ground generators have been shown to rise to approximately 300-600 m (1000-2000 feet) above the mountain crest heights (Super, 1999). Silver iodide becomes an active ice nucleant at temperatures of about -4 to -5^{0} C. These factors indicate that the 700-mb temperature should be approximately -5^{0} C or colder in order for ground seeding to have an appreciable effect.

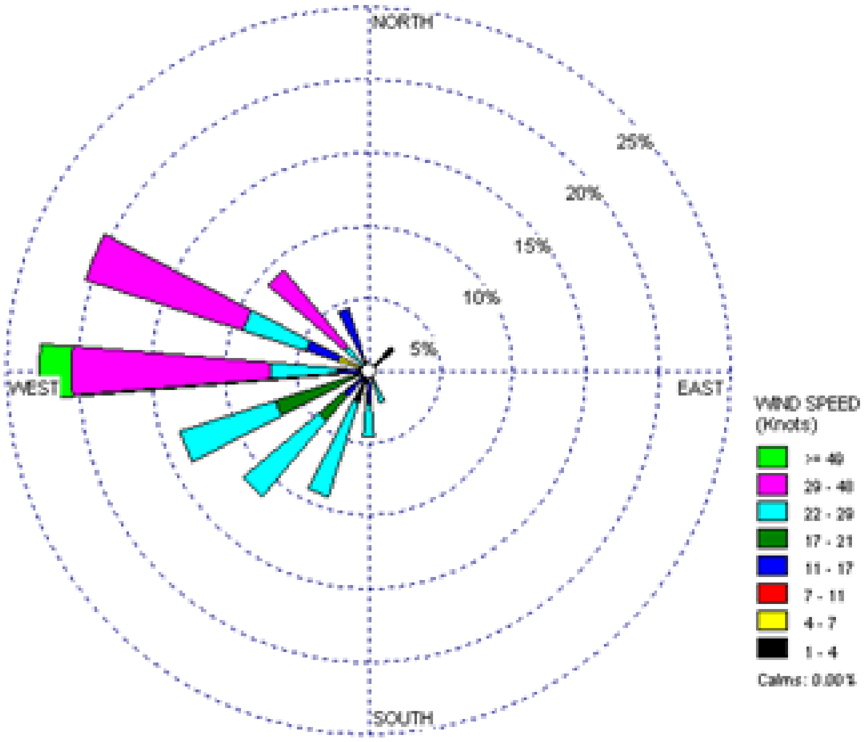

Figure 3 700-mb Storm Wind Rose for Ground-based Seedable Events

The seeding material must have the opportunity to form ice crystals upwind of the barrier, which can then grow into snowflakes and fall onto the barrier. Figure 4 indicates that 700-mb temperatures did, in general, average $–5^{0}$ C or colder during the precipitation events. The month of October was marginally warm on average.

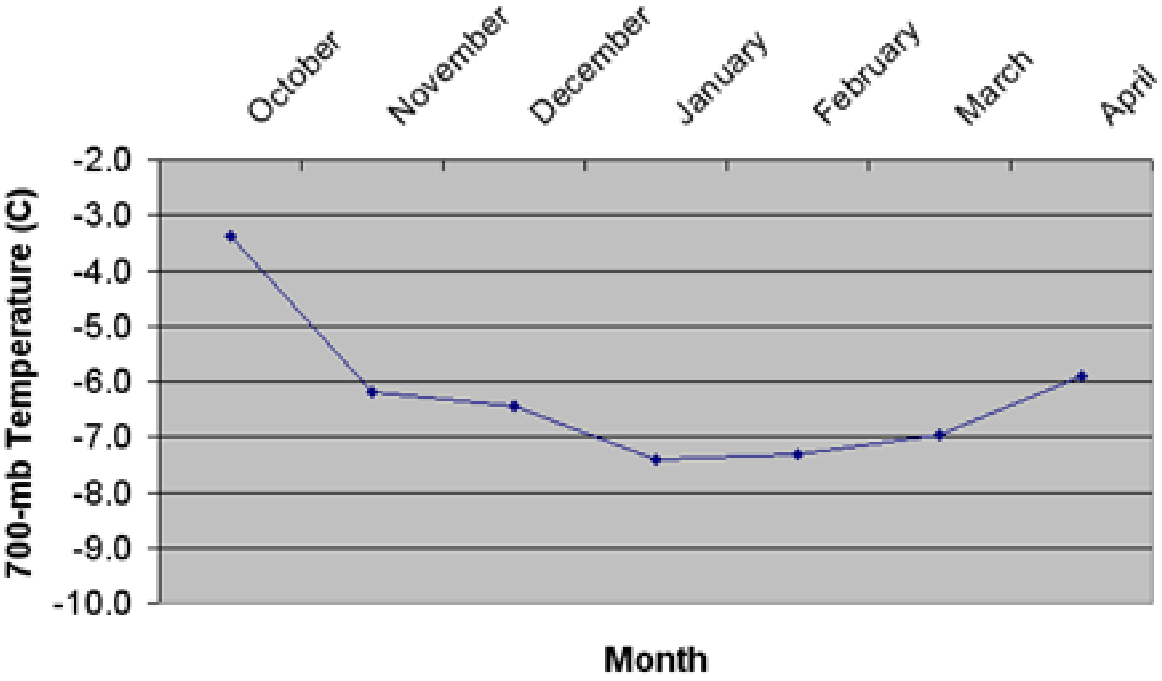

Figure 4. Mean 700-mb Temperature during Storm Periods by Month

4.2.4 <u>700 mb Storm Stability</u>

Another meteorological feature of special interest and importance when considering ground-based cloud seeding is the frequency of occurrence of low-level temperature inversions in the atmosphere that may restrict the vertical transport of seeding materials released from the ground into seedable cloud regions.

An analysis was performed to examine whether low-level stability might present a problem in seeding from ground generators in the UBRB. For this analysis, atmospheric stability (between the surface and 700 mb) was determined for the 386, six-hour precipitation events with concurrent Boise rawinsonde observations. Surface temperature, wind and dewpoint observations were also utilized in conjunction with the Boise sounding profiles to obtain better estimates of low-level stability issues and wind patterns.

Low-level stability (which could prevent seeding material from reaching the –5^0 C level over the target area) was classified into four categories: Well-mixed or <u>neutral</u> conditions (no stability problems evident), which should mean that silver iodide particles released near the surface should be transported over the mountain barriers by the storm winds), slightly stable, moderately stable, and very stable. These categories correspond roughly to situations where less than 2^0 C of surface heating or upper level cooling would be necessary to mix out the atmosphere (slightly stable), 2 - 4^0 C (moderately stable), and more than 4^0 C (very stable). Cases that were well mixed or slightly stable were considered suitable for lower elevation ground-based seeding, while more stable cases would require remotely operated high-elevation ground generators or aircraft seeding.

The more-stable situations are cases where lower elevation ground-based seeding would probably not be attempted due to stability considerations. Figure 5 is a plot of the frequency of "neutral" stability below 700 mb for the seedable periods. Seedable periods are defined as those storm events that have estimated cloud top temperatures between -5^0 and -25^0 C (refer to Section 5.4). As shown in the figure, the most favorable category of stability (neutral) averages about 28% of the seedable cases during the October - April (and November - April) period, and is only about 21% of all seedable cases when considering only the November - March period. This analysis suggests that low-level stability presents significant problems during the winter months. These are the months that have the highest average amounts of precipitation.

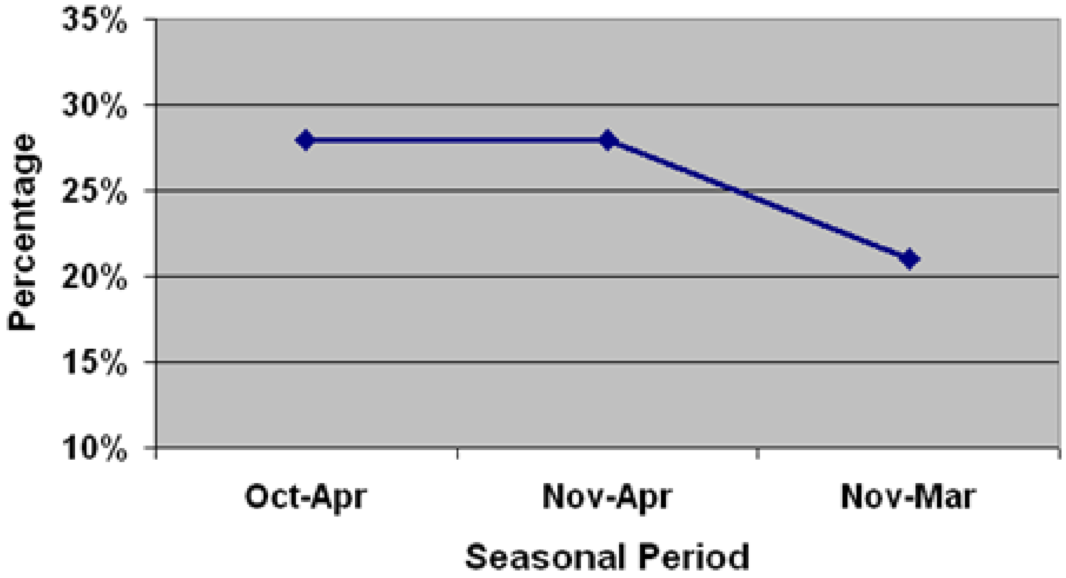

Figure 5. Percentage of Seedable Periods with a "Neutral" Stability Profile by Different Seasonal Time Periods

5. SEEDING PROGRAM RECOMMENDED DESIGN

5.1 <u>Conceptual Model</u>

The basic conceptual model upon which the UBRB cloud seeding program was based can be summarized as follows:

Some winter storms or portions of naturally occurring winter storms that pass over Idaho contain/produce supercooled cloud droplets. Some of these droplets are not converted to ice crystals as they pass over the mountainous areas of Idaho. The presence of supercooled cloud droplets over the crests of these mountain barriers indicates that these storms or portions of storms are inefficient in the production of precipitation. This inefficiency is attributed to the lack of sufficient natural ice nuclei (also called freezing nuclei) to covert these supercooled cloud droplets to ice crystals which, given the right conditions, could develop into snowflakes that would fall on the mountain barriers.

The deficit in natural ice nuclei occurs primarily in the range 0 to –15^0 C cloud temperatures. Introduction of silver iodide particles into cloud systems that contain supercooled cloud droplets in approximately the –5 to –15^0 C range will artificially nucleate some of the supercooled cloud droplets. The –5^0 C temperature is considered the nucleation threshold of silver iodide. At temperatures below approximately –15^0 C there are normally adequate numbers of natural ice nuclei to freeze the supercooled cloud droplets.

The artificially created ice crystals then have the potential to grow into snowflakes through vapor deposition and riming processes. If the ice crystals are generated in the rightgeographic locations, the artificially generated snowflakes will fall onto the targeted mountain barriers, resulting in increases in precipitation above what would have occurred naturally. Super and Heimbach, 2005, provide a more detailed discussion of the various microphysical processes pertaining to the conceptual model as summarized in the above text.

Research conducted in Utah and other Intermountain West locations (e.g., Super, 1999; Reynolds, 1988; Solak, et al, 1988 and 2005) has verified the presence of supercooled cloud droplets over or upwind of mountain barrier crests in a large number of winter storm periods. Research in a variety of locations has indicated the background concentrations of ice nuclei are low in the warmer portions of the atmosphere but increase exponentially at colder temperatures. Dennis, 1980, states "the concentration of active ice nuclei increases by about a factor of 10 for each temperature drop of 3.5 to 4^0 C. Prior research conducted in cloud chambers and in the atmosphere have demonstrated the ability of silver iodide nuclei to serve as ice nuclei in significant concentrations beginning near the –5^0 C level and increasing exponentially to the –2^0 to –25^0 C level (Garvey, 1975).

5.2 Operational Period and Selection and Siting of Equipment

An operational period of November through April was recommended based upon the precipitation and temperature climatologies of the area and the likelihood of generating positive seeding effects during this period. NAWC recommended silver iodide as the seeding agent to be used in the conduct of the enhanced UBRB program. The current program utilizes ground based, manually operated silver iodide generators. In terms of suggested enhancements, we recommend the potential addition of remotely operated, ground based generators and airborne seeding to the existing program if the perceived value of these additions exceeds the potential cost of such additions by a favorable margin as determined through a benefit/cost analysis.

5.3 Remotely Controlled, High Elevation Ground Based Silver Iodide Generators

Data presented in section 4 suggests that remotely controlled, high elevation ground based seeding and airborne seeding could be used to enhance the existing program. Figure 4 indicates that the 700 mb prevailing wind directions when remote generators are considered to be effective are predominately from the west-southwest to westerly directions. NAWC recommends that approximately five remotely controlled silver iodide generators be installed on the windward slopes of the target area mountains at higher elevations as far upwind of the barrier crest as possible. The crosswind spacing of the generators should be spaced approximately 8km apart. This spacing is somewhat greater than that indicated from an analysis of SF6 plumes observed in a Utah research program conducted over the Wasatch Plateau in Utah in the 1990's (Griffith, et al, 1992). This analysis suggested spacing of approximately 4-5 km apart.

5.4 Airborne Silver Iodide Seeding

Airborne seeding with silver iodide may be conducted when the temperatures near the mountain crest height are too warm for silver iodide released from ground-based sites to be effective and the clouds are seedable (e.g., they contain supercooled liquid water). Airborne seeding could also be effective in conditions where low elevation inversions exist. It appears from NAWC's analyses that low-level atmospheric temperature inversions are common in the Boise River valley during active winter storm periods. Assuming the ability to fly safely in the desired areas upwind of the intended target area, aircraft can be flown at a temperature level appropriate for immediate activation of the temperature dependent silver iodide nuclei. Convective clouds could also be seeded at their tops through aircraft penetrations as the tops pass through the -100 C level. If airborne seeding is to be conducted, it is recommended that turbine engine aircraft be used. This recommendation is based primarily on aircraft performance as it relates to safety considerations, given the airframe icing that commonly occurs during seeding operations. Given the size of the target area and from some analyses of the timing of the seedable events, it appears one aircraft could seed a large majority of these events (i.e., two aircraft would not be required). The suggested base of operations would be at the Boise Air Terminal/Gowen Field Airport.

5.5 Opportunity Recognition Criteria

For the proposed UBRB program, seeding criteria were developed to serve as opportunity recognition tools. Basically, these criteria have been designed to recognize the combination of weather events deemed to be "seedable" based on cloud top temperatures, 700 mb temperatures, winds and low level stability. Section 6.1 contains the rationale of using cloud top temperature to help determine "seedability". These criteria have been partitioned into three different categories, based upon the seeding mode to be used (ground based, low-elevation, manually operated generators; high elevation, remotely operated generators; and aircraft). These criteria are listed in Tables 3 - 6.

Table 3. Manually Operated Low Elevation Ground Generators Seeding Criteria

1. Cloud top temperatures expected to be $\geq -26^0$ C.
2. 700 mb level temperatures expected to be $\leq -5^0$ C.
3. Low-level atmospheric stability neutral to slightly stable.
4. Low-level wind directions expected to be favorable for the transport of the seeding material over the target barrier(s).
5. Cloud bases expected to be at or below target barrier crest height.

Table 4. Remotely Operated High Elevation Ground Generators Seeding Criteria

1. Cloud top temperatures expected to be $\geq -26^0$ C.
2. 700 mb level temperatures expected to be $\leq -5^0$ C.
3. Low-level atmospheric stability moderately to very stable.
4. Low-level wind directions expected to be favorable for the transport of the seeding material over the target barrier(s).
5. Cloud bases expected to be at or below target barrier crest height.

Table 5. Aircraft Seeding Criteria

1. Cloud top temperatures expected to be ≥ -26^0 C.
2. 700 mb level temperatures expected to be ≥ - 5^0 C.
3. Mid-level wind directions expected to be favorable for the transport of the seeding material over the target barrier(s).

5.6 Summary of Proposed Design

Components of the basic program design of the existing cloud seeding program in the Boise River Basin plus means of augmenting this basic design are summarized as follows:

- The target area will be the upper Boise River Basin above 1524 m (5,000 feet) MSL.
- The primary operational period will be November through March.
- Silver iodide will be the seeding agent. A formulation that produces fast acting ice nuclei is recommended (Finnegan, 1998).
- The existing program, that utilizes lower elevation ground based generators, will be augmented by extending the operational programs seeding period by one month. The existing program could also be enhanced through the addition of higher elevation remotely controlled ground based generators and aerial seeding.
- The UBRB would be operationally oriented, with the following goals: The stated goal of the program is to increase winter snowpack in the target area to provide additional spring and summer stream flow and recharge under-ground aquifers at a favorable benefit/cost ratio,without the creation of any significant negative environmental impacts.
- Due to the operational nature of the proposed program, i.e., the interest in producing as much additional water as possible, the seeding decisions would not be randomized. In other words, all suitable seeding opportunities would be seeded appropriately. In addition, there would not be an ongoing research component built into the program, although “piggyback” research components could be added to the core operational program if interest and additional funding from other sources is present, for example, the type of research that resulted from write-in funding to the Bureau of Reclamation for the recent Weather Damage Mitigation Program (six state research program conducted from 2002-2006).
- Evaluations of the effectiveness of the cloud seeding program would be based upon historical target and control techniques (target and control sites with corresponding regression equations were provided in the final report), and possibly some snow chemistry analyses verifying that silver above background levels is being observed at various sampling points in the target area.
- A qualified/experienced meteorologist should direct the seeding operations.
- If aerial cloud seeding is employed, a winter season program field office should be established near the target area. The logical location of this program office would be at the Boise Air Terminal/Gowen Field.

6. POTENTIAL INCREASES IN PRECIPITATION AND SEASONAL STREAM FLOW

6.1 Estimated Increases in Precipitation

Analysis of the variability in storm temperature structure over the proposed target area for an eight winter season period was performed and then applied in conjunction with cloud top temperature partitioned seeding results from a research program in Colorado (Climax I and II; Mielke, et al, 1981, and Hess, 1974) to estimate the anticipated seeding effects for the UBRB. The analysis applied the varying Climax seeding effects within cloud top temperature categories according to their seasonal occurrence in the UBRB cloud top temperature data that were identified during a multi-year analysis period.

NAWC performed an analysis of a number of the six-hour events (refer to section 4.2) that had cloud top temperatures in a “seedable” range of –5^{0} to –25^{0} C based upon the activation threshold of silver iodide and Climax I and II results. The lower limit of –25^{0} C is similar to indications of seedable conditions in northern Utah (Hill, 1980) and northern Colorado (Rauber, et al, 1986), both of which determined conditions to be seedable when the 500-mb temperature was –22^{0} C or warmer. Of the 386, 6-hour periods examined, 109 periods, only 28%, were considered “seedable” based on having cloud-top temperatures between -5 and -25^{0} C. Based upon the Climax I and II results, the seeding potential was considered to be +25% when cloud-top temperature was between –5^{0} C and –20^{0} C, +10% for cloud-top temperatures of –21^{0} to –25^{0} C, and 0% for cloud-top temperatures of –26^{0} C or colder (or warmer than –5^{0} C). This seeding potential was then sub-divided between different seeding modes or methods, including low elevation manual ground-based, high elevation remote ground-based, and aircraft seeding.

The seeding potential for a given 6-hour time period was assigned to ground-based seeding if a) the low-level air mass was classified as well-mixed or only slightly stable, and b) The 700-mb temperature was –5^{0} C or colder. Similarly, the seeding potential was assigned to remote, high-elevation seeding sites if low-level stability was classified as “moderate” or higher and the 700-mb temperature was –5^{0} C or colder. Seeding potential was assigned to aircraft-only for cases where the 700-mb temperature was above –5^{0} C regardless of stability considerations (Tables 3 – 5 summarize these categories). The percentages of “seedable” events by seeding modes were approximately 44% for manual ground based generators, 27% for remote ground based generators and 29% for aircraft.

An indication of average percent increases for the November through March period for all seeding modes combined was 4.7%. The breakdown in these estimated percent increases by seeding mode was as follows: 1.7% for lower elevation manual ground based (which is the mode currently being used in the conduct of the basic program), 1.6% for higher elevation remote ground based, and 1.5% for aircraft based upon consideration of Tables 3-5 which indicate under what conditions each seeding mode could be utilized. These estimated increases were then applied to the average April 1st snow water contents to estimate the potential average increases in snow water content values. Table 6 provides these results listed by seeding mode. Similar calculations were made for increases in November through April precipitation, with results provided in Table 7. Obviously, different seeding modes can be used in combination which may potentially provide additional increases in precipitation not indicated in this analysis. For example, using a combination of low elevation manual and high elevation remote generators may produce higherincreases than only considering the contribution of remote generators when manual generators are considered ineffective. In other words seeding with both manual and remote generators when conditions are favorable for manual generators would be conditions that are also favorable for remote generators. In this context, the results provided in Tables 6 and 7 are likely conservative since the cumulative effects of using multiple seeding modes are not considered.

Table 6. Estimates of Average Increases in April 1st Snow Water Content (inches) by Seeding Mode (Based on November-March storm periods)

Site	**Apr 1 SWE**	**Total Increase (4.7%)**	**Ground (1.7%)**	**Remote (1.6%)**	**Air (1.5%)**
Atlanta Summit	31.9	1.50	0.54	0.51	0.48
Soldier R.S.	10.0	0.47	0.17	0.16	0.15
Mores Creek Sum	34.6	1.63	0.59	0.55	0.52
Camas Creek Div	8.2	0.39	0.14	0.13	0.12
Trinity Mtn	39.5	1.86	0.67	0.63	0.59
Average	24.84	1.17	0.42	0.40	0.37

Table 7. Estimates of Average Increases (inches) in November-April Precipitation by Seeding Mode

Site	**Nov-Apr Precip**	**Total Increase (5.1%)**	**Ground (1.7%)**	**Remote (1.5%)**	**Air (1.9%)**
Atlanta Summit	33.3	1.70	0.57	0.50	0.63
Soldier R.S.	15.3	0.78	0.26	0.23	0.29
Mores Creek Sum	35.0	1.79	0.60	0.53	0.67
Camas Creek Div	15.0	0.77	0.26	0.23	0.29
Trinity Mtn	41.0	2.09	0.70	0.62	0.78
Average	27.92	1.42	0.47	0.42	0.53

6.2 Estimated Increases in Stream Flow

The estimated increases in snow water content (April 1st) and November through April precipitation were then used to estimate the potential average increases in March through July surface runoff based upon the three different seeding modes. Linear regression correlations and relationships between April 1st snow water content, November through April precipitation and March through July stream flow were calculated. Historical stream flow measurements were available at two points (USGS Station numbers 13185000, Middle Fork and 13186000, South Fork) above Lucky Peak Dam plus estimates of additional stream flow contributing inflow to Lucky Peak Dam below these stations. The average April 1st snow water content (representing an average season) or average November through April precipitation was increased by the calculated seeding effect. This value was then entered into regression equations to calculate the amount of augmented stream flow. Tables 8 and 9 provide these results. Again it should be noted that different seeding modes can be used in combination which may potentially provide additional increases in stream flow not indicated in this analysis. As in prior NAWC design studies in the Intermountain West, the calculated percentage increases in stream flow were higher than the calculated increases in snow water content or precipitation. For example, from Table 6, a 4.7% increase in April 1st snow water content resulted in an estimated increase in stream flow of 5.6% from Table 8. We believe this to be due to the fact that any evapo-transpiration and ground water recharge requirements are met by the non-augmented (or natural) snowpack such that increases assumed to be produced by cloud seeding are added to the snowpack after these base requirements are met.

Table 8. Estimates of Increases in Average March-July Stream Flow (acre-feet) based upon Estimated Increases in April 1st Snow Water Content

Stream Gage	Total Increase (5.6%)	Ground (2.0%)	Remote (1.9%)	Air (1.7%)
USGS#13185000	33,292	11,791	11,097	10,404
USGS#13186000	26,058	9,229	8,686	8,143
2-Gage Subtotal incr	59,350	21,020	19,783	18,547
Est Additional incr*	22,075	7,818	7,358	6,898
Est Total Incr	81,425	28,838	27,141	25,445

* Estimates of additional stream flow contributing inflow to Lucky Peak Dam below the two USGS stations.

Table 9. Estimates of Increases in Average March-July Stream Flow (acre-feet) based upon Estimated Increases in November – April Precipitation

Stream Gage	Total Increase (6.8%)	Ground (2.3%)	Remote (2.0%)	Air (2.5%)
USGS#13185000	40,967	13,656	12,049	15,262
USGS#13186000	31,361	10,454	9,224	11,684
2-Gage Subtotal incr	72,328	24,110	21,273	26,946
Est Additonal incr*	26,902	8,967	7,912	10,022
Est Total Incr	99,230	33,077	29,185	29,185

* Estimates of additional stream flow contributing inflow to Lucky Peak Dam below the two USGS stations.

Data from Table 8 (based upon estimated increases in April 1st snow water content) suggest that the estimated amount of average additional March-July stream flow being produced by the existing program, which uses manual generators, is 3.49 x 10^7 m^3 (28,838 acre-feet). The estimated increase in average March through July stream flow achieved by extending the seeding program into the month of April is 5.30 x 10^6 m^3 (4,239 acre-feet). Data from Table 8 suggest that the estimated amount of average additional March-July stream flow that could be produced by adding remotely controlled ground generators and aircraft seeding is 6.48 x 10^7 m^3 (52,586 acre-feet). As suggested in Section 6.1, this estimate is likely conservative since the cumulative effects of using multiple seeding modes were not considered in this analysis.

6.3 Cost Considerations

Table 10 provides estimates of the annual cost of producing the estimated increases in average March through July stream flow by the two alternate seeding modes (remote generators and aircraft). The estimated increases in stream flow are taken from Table 9, which is based upon estimates of increases in November through April precipitation. The estimated cost of additional runoff ranges from $0.005 to $0.01 per cubic meter ($5.94 to $12.45 per acre-foot). For comparison purposes, the calculated cost of increases using manual generators is $0.003 per cubic meter ($3.29 per acre-foot). The values in Table 10 are for an average water year. Estimated costs per acre-foot would likely decline in above normal water years and increase in below normal water years due to the application of a fixed assumed percentage increase applied to lower and higher than normal base amounts.

It was beyond the scope of this feasibility study to estimate the potential value of the increased runoff. Should such an analysis be attempted, estimations of benefit/cost ratios could be calculated. The additional water would benefit regional water supplies for agricultural and municipal use as well as hydroelectric power generation. If the value of the additional water volume to recreation, fisheries, tourism, threatened and endangered species, and other downstream uses could be quantified and included, the projected value would be even greater.

Table 10. Estimated Annual Average Costs to Produce Additional March – July Stream Flow, Remote Generators or Aircraft

	Remote Generators*	**Aircraft****
Ave. Cost to Produce Extra Water	$173,350	$460,400
Ave. Mar. – July Stream flow Increase	29,185 a.f.	36,968 a.f.
Cost Per Acre-foot	$5.94	$12.45

* It is assumed that a five-year program would be conducted and that the initial remote generator acquisition, siting and installation costs would be amortized equally over the five-year period ($45,000 per year).

** One aircraft may not be capable of seeding all the suitable storm events so these estimates may be somewhat optimistic.

7.0 Concluding Remarks

This feasibility/design study has determined that extending the time period being seeded and adding enhancements to the operational program (adding high elevation ground based remote generators and a seeding aircraft) could augment an operational winter cloud seeding program currently using lower elevation ground generators that targets the upper Boise River Basin. These additions to the basic operational program have the potential to increase the average November through April precipitation by an additional 3.4%, which is estimated to produce a 4.5% increase in March through July runoff in an average water year. The resultant estimated increase in March through July runoff is 8.16×10^7 m^3 (66,153 acre-feet) in an average water year. The estimated average cost to achieve these increases in March through July stream flow is $0.008 per cubic meter ($9.58 per acre-foot).

NAWC completed a feasibility/design study, similar to this study, for the Big and Little Wood River Basins in central Idaho (Griffith and Yorty, 2009b). Since the Big Wood River Basin is directly downwind of the upper Boise River Basin, the cloud seeding enhancements mentioned in this study would also impact the Big Wood River Basin and to a lesser extent the Little Wood River Basin. As a consequence, the expense to add these enhancements to the upper Boise River Basin program could perhaps be shared between the Boise River and Wood River interests in some prorated fashion.

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LOW-LEVEL ATMOSPHERIC STABILITY DURING ICING PERIODS IN UTAH, AND IMPLICATIONS FOR WINTER GROUND-BASED CLOUD SEEDING

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ABSTRACT. In mountainous regions where winter season cloud seeding is conducted for the purpose of higher-elevation snowpack augmentation, the frequency and character of low-level atmospheric stability can significantly impact transport of cloud-seeding material released from valley and foothill locations over higher elevation target areas. A two-surface-site (2SS) method was developed to estimate stability in the layer from the valley/foothill surface to mountain-top height (approximately 700 mb) in Utah, using available surface temperature and dew point data. The method yields approximations of integrated stability in the layer, which were classified according to their likely impact on operational seeding, and can be expressed in terms of the low-level warming, or upper-level cooling, required to yield a neutral lapse rate (well-mixed environment). The stability estimation method was applied to stormy periods during three winter seasons when mountain-top icing was documented via ground-based high elevation icing rate sensors, and when temperatures were adequately cold for activation of silver iodide particles as ice-forming nuclei. That partitioning method identifies periods when silver iodide seeding potential likely exists. The indications of the 2SS analysis method are that seeding material releases from most valley/foothill locations are likely to undergo timely and effective dispersion to mountain barrier crest height during a large percentage (~75%) of icing periods exhibiting apparent silver iodide seeding potential.

Comparisons of the 2SS method stability estimates to similar rawinsonde-derived estimates showed good correspondence in over 80% of the cases analyzed, providing some confidence in the utility of the 2SS method in the absence of available rawinsonde data. Comparisons were also made between 2SS stability estimates and modeled seeding plume behavior using the NOAA HYSPLIT (Hybrid Single Particle Lagrangian Intregrated Trajectory) model with NAM (North American Model) meteorological input data during icing periods. Agreement between modeled plume behavior and stability indications of the 2SS method was found in over 80% of the modeled periods. Results of these comparisons provide confidence in the overall stability climatology for icing periods as presented in this paper, as well as the real-time operational utility of the 2SS method in areas where other data (e.g., rawinsonde) are not available.

The analyses presented here comprise a portion of a more comprehensive study, based on data from several ice detector sites in Utah. Support for the establishment of these sites, and for analysis of the data, was provided by a consortium of Lower Colorado River Basin States.

1. INTRODUCTION

To affect precipitation increase by winter orographic cloud seeding with silver iodide, the seeding material must reach supercooled cloud regions at or colder than approximately –5 C to nucleate supercooled liquid water (SLW) droplets. Over mountainous terrain during the winter months in Utah, SLW has been shown to frequently develop at low altitudes (< 1 km) above the terrain on the windward slopes (Super, 1999). This is the pool of SLW to be tapped by cloud seeding. Complexities involved in the targeting of ground-based seeding material releases have been studied in Utah (Super and Huggins, 1992). One of the major factors involves potential thermodynamic stability of the atmosphere near and below crest height. If the stormy air mass has a stable temperature lapse rate, valley silver iodide releases can be trapped, i.e., their upward vertical transport inhibited. Conversely, in an air mass exhibiting an unstable lapse rate, seeding plumes are readily lofted by thermals and orographic lift.

During the winter season in Utah (December – February in particular), lower-level inversions commonly develop in basins and lower-elevation regions during periods of clear or fair weather. Surface snow cover can contribute significantly to the development of valley inversions. During stormy weather, increased wind, as well as mid- and upper-level cooling which typically accompanies a trough passage, will often dissipate existing valley cold pools or inversions in most areas. For this reason, analyses of low-level thermodynamic stability during stormy periods with seeding potential are particularly valuable. Warm and cold frontal zones, of course, can produce some degree of thermodynamic stability on their own. However, during the winter season it is commonly pre-existing lower level stabilityand inversion zones, formed during clear weather and persisting to some degree during a subsequent storm event, that can pose the most significant problems for ground-based seeding in terms of the dispersion of seeding material.

The nature of thermodynamic stability is such that, in cases where a high-resolution thermodynamic profile (such as a nearby rawinsonde sounding) is not available, temperature and dew point data from surface observations at differing elevations can be used to develop estimates of the integrated stability in the intervening layer. This type of thermodynamic stability analysis can provide an approximation of the amount of thermodynamic resistance (if any) that a valley- or foothill-based air parcel would need to overcome in order to reach a nearby mountain crest elevation. One primary advantage of this method is the ability to conduct a thermodynamic stability analysis in real time in any mountainous area where temperature and dew point data are available from sites at appropriate elevations.

2. METHODOLOGY

Ridge-top ice detector measurements from several sites in Utah were utilized in support of this low-level stability study. Analysis of periods during which icing was recorded at these sites yields results that are relevant to potential ground-based cloud seeding operations during storm periods. The ice detector site data includes icing and temperature data at 10 to 15 minute intervals, which allows the data set to be further refined to focus on periods when the crest-level temperatures is favorable for seeding with silver iodide (i.e., between –5 and –15 C). Ice detector data used in these analyses include data from Skyline in central Utah (9330’) and Brian Head in southwest Utah (10,900’) during the 2009-2010 and 2010-2011 winter seasons,and data from Snowbird (11,000’) in the Wasatch of northern Utah during the 2003-2004 season (Figure 1).

The Brian Head and Skyline ice detector sites are located in seeding target areas associated with a long-standing operational program in Utah (Griffith et al., 2009) and are being funded by a consortium of lower Colorado River Basin states as part of an ongoing study. The Snowbird ice detector site was part of a similar study conducted by North American Weather Consultants (Solak et al., 2005).

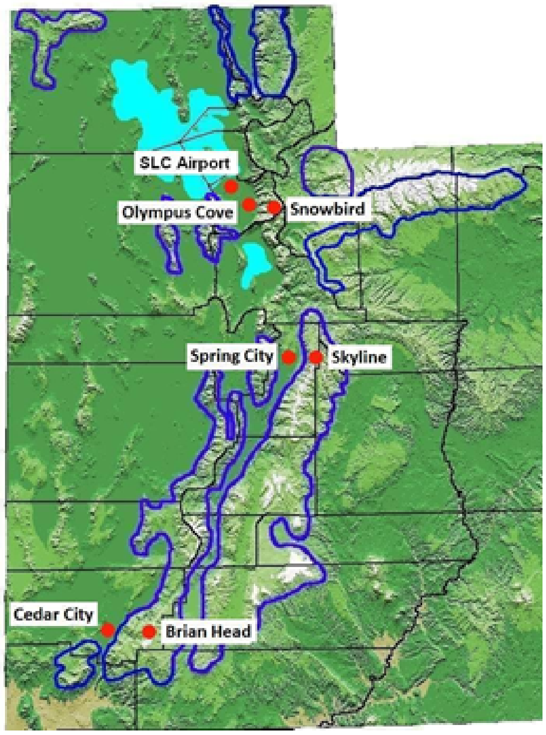

Figure 1. Map of 2-site-stability analysis locations, including the ice detector sites at Snowbird, Skyline, and Brian Head

Data from surface sites (typically two), comparing valley observations to nearby crest-level temperature data (referred to as the 2SS method), was used to estimate low-level thermodynamic stability during periods with recorded icing in the data set. Figure 1 shows the locations of the valley sites as wellas the mountain crest (ice detector) sites used in these comparisons. In central Utah, temperature and dew point information at Spring City (5,800'), south-southwest of the Skyline area, was compared to site temperatures at Skyline (9,330') during icing periods for the two seasons of data. The observed valley site dew point is used to determine the neutral lapse rate at which free mixing takes place if a parcel is lifted (i.e. dry adiabatic, pseudo-adiabatic, or, typically, a combination of the two). This analysis is easily conducted with the aid of a thermodynamic skew-T chart, comparing the resultant temperature of a parcel lifted from the valley floor to crest height with the observed temperature at the crest. The primary focus of the stability analysis was in the Skyline area because it is centrally located in Utah and is considered representative of much of the north-south oriented mountain/valley terrain profile in many of the state's seeded areas, as well as some other portions of the Intermountain West. In the 2SS analysis, the surface temperature at a valley site is thermodynamically adjusted to the elevation of the ridge-top site, using the appropriate lapse rate, for comparison with the observed ridge-top temperature. The observed dew point at the valley site is used for selection of the lapse rate (dry and/or moist) used in this adjustment. The comparison allows an estimate to be made of whether or not the atmosphere is freely mixing from the surface to the elevation of the downwind mountain barrier summit, and in cases where there is stability an estimate of the overall degree of stability in the layer. Thermodynamic stability was divided into four categories, based on the equivalent temperature increase at a valley location, or decrease at the crest height, that would be needed to overcome the stability and allow free vertical mixing in the layer:

- N Neutral or well-mixed (no apparent stability in the layer),
- SS Slightly stable (<2 degrees C of stability),
- MS Moderately stable (~ 2-4 C of stability) and
- VS Very stable (>4 C of stability).

A well-mixed situation implies that there is no thermodynamic restriction of upward vertical atmospheric motion that would impede the lifting of seeding material from a valley or foothill seeding site. A slightly stable situation would also likely be seeded in an operational setting, because there is potential for atmospheric forcing mechanisms to overcome such a minor amount of stability, and because local temperature variations of a few degrees may easily result in areas of free vertical mixing. Seeding from valley sites would generally be avoided in a moderately or very stable situation, although seeding material initially trapped by a thermodynamically stable atmosphere may become effective later as the situation changes.

In addition to the stability analysis for the Skyline area, similar analyses utilizing the two-surface-site method were conducted for the Salt Lake City/Snowbird area, as well as the Brian Head area (all shown in Figure 1). Results of the analyses utilizing the 2SS method are presented in Section 3.0.

Systematic comparisons were made between stability indications based on the 2SS method and those derived by alternate methods. This was an important aspect of this study, as it lends additional support to the results that are presented. These comparative analyses include weather balloon (rawinsonde) soundings, which generate detailed thermodynamic profiles of the atmosphere, and HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) modeling of ground-based plume dispersion. Section 4 presents further details regarding the methodology as well as the results of these comparative stability analysis techniques.

3.0 RESULTS OF THE TWO-SITE STABILITY ANALYSES

For 246 icing periods at the Skyline site during the November – April portion of 2009-2010 and 2010-2011 seasons, where the site temperature (at approximately the 700-mb level) was between –5 and –15 C, about 62% of the icing periods were associated with a generally well-mixed atmosphere down to the valley floor. Another 19% of the periods were rated as “slightly stable” for the two-season period, for a total of ~81% where seeding from valley or foothill sites would likely be effective. Figure 2 shows the overall November – April distribution of the 2SS method stability characterizations in the Skyline area. Another important indication in the analysis is that nearly all of the periods with MS and VS stability characterizations occurred from December through mid-February. This is illustrated in Figure 3, a scatterplot of the observed seasonal variation of stability.

Figure 4 shows monthly averages of the percentage of icing periods rated “N” (well-mixed periods) as well as those rated either N or SS (periods in which seeding from the valley would likely be effective).

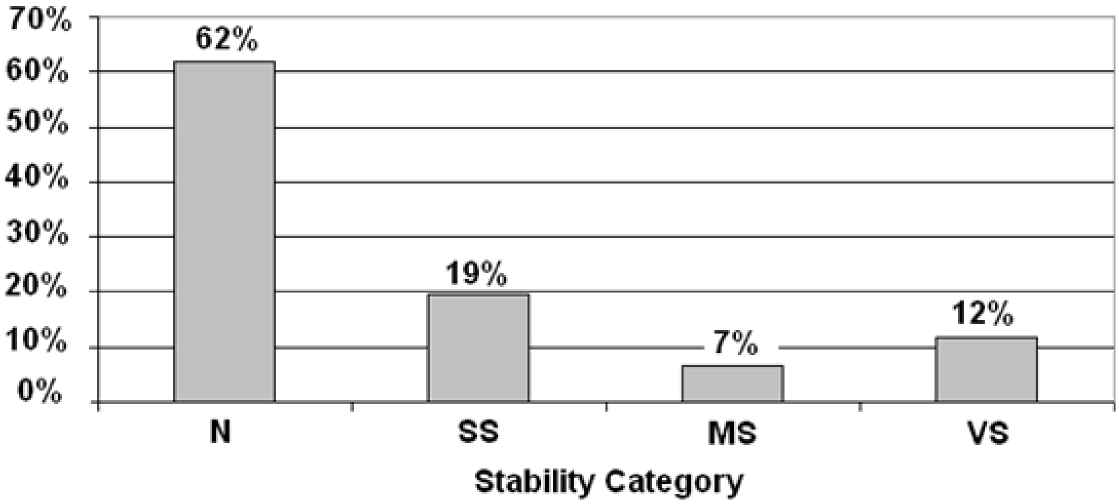

Figure 2. Skyline area stability analysis results for 246 icing periods associated with ridge-top temperatures between –5 and –15 C

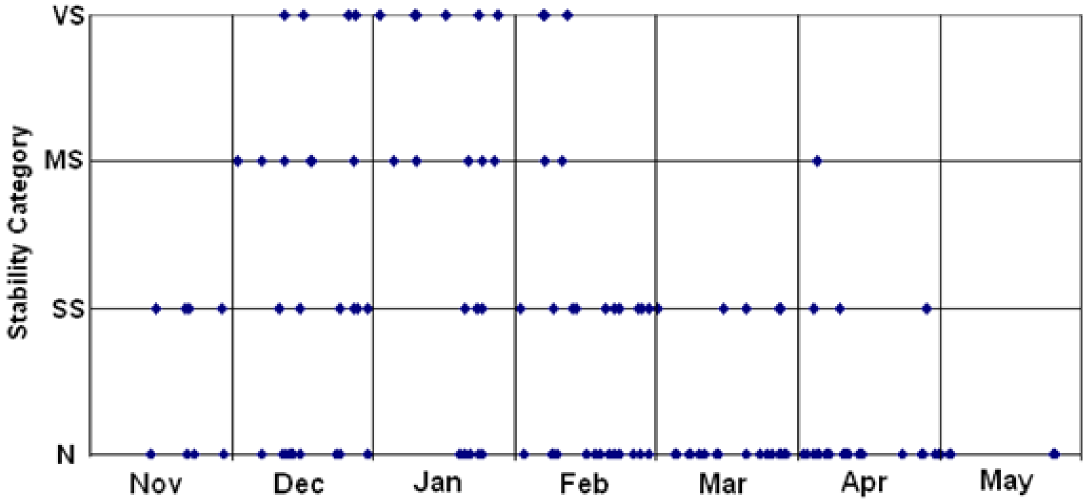

Figure 3. Seasonal distribution of low-level stability characterizations based on the 2SS method, during icing periods at the Skyline detector site associated with site (ridge-top) temperatures between –5 and –15 C.

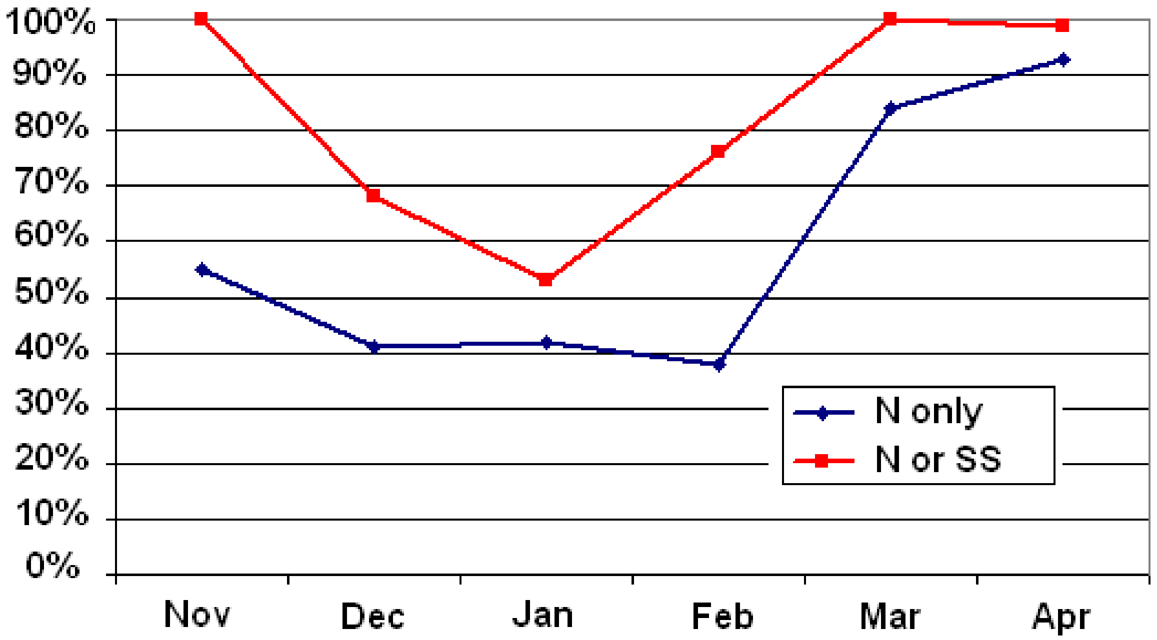

Figure 4. Monthly averages of the percentage of well-mixed (N) periods (blue), and N or SS periods (red) when SLW is occurring at the Skyline site and the site temperature is between –5 and –15 C. These characterizations are based on the 2SS analysis method.

A more abbreviated stability analysis was conducted for the Brian Head area using the 2SS methodology, focusing on periods with significant amounts of icing and site temperatures below –5 C during 35 storm events. That analysis used the Cedar City airport as a valley temperature comparison site. Approximately half of the periods examined appeared to be well-mixed or neutral (N), and another ~25% were rated as SS. About 20% were rated as MS and less than 5% as VS. These results are similar to those in the Skyline area, with seeding material likely to have reasonable vertical dispersion in about 75% of the storm events when crest-level temperatures are cold enough for effective seeding and crest height icing is occurring.

A comparison was also made between the 2SS evaluation results for Skyline icing periods between November 24 and April 4 of both (2009-10 and 2010-11) seasons and similar Salt Lake City/Snowbird area analysis results available during that seasonal period in 2003-2004. This comparison between the Olympus Cove/Snowbird and Spring City/Skyline 2SS method results suggested somewhat greater stability in the Salt Lake City area than in central Utah, although the differences probably fall within the normal range of season-to-season variability. For the Skyline area, approximately 75% of the icing periods in this November 24 – April 4 subset were rated as either N (53%) or SS (22%). In the Olympus Cove/Snowbird 2003-2004 data set, 59% of the icing periods were rated as either N (30%) or SS (29%).

Implications of these analyses are that seeding material releases from valley or foothill sites are likely to experience timely and effective dispersion to the barrier crest height in a large percentage (75% or greater) of periods when SLW is present at crest height and temperatures are cold enough for seeding with silver iodide. These findings are considered representative of most of the seeding target areas in Utah, and are significant and particularly relevant in that they focus on stormy periods when SLW is being generated by orographic lift. The focus on periods with seeding potential provides a refined and much more meaningful assessment of seasonal seedability and determination of the appropriate treatment strategy than would a general analysis of low-level stability apart from the ice detector data. It addresses head-on the question of the potential for ground-based seeding material releases from valley and foothill locations to effectively capitalize on seasonal seeding opportunities where SLW is known to exist.

4.0 COMPARISONS OF STABILITY ANALYSIS METHODOLOGIES

4.1 Two-Site-Stability vs. Rawinsonde Analysis

An initial set of 435 15-minute icing periods in the 2003-2004 Snowbird ice detector data, with a site temperature between –7 and –17 C (to approximate a generalized crest-height temperature of –5 to –15^{v} C) were evaluated using the 2SS method with data from Olympus Cove (a foothill site at 5,070 ft or approximately 850 mb) and Snowbird Hidden Peak (a mountain-top site at 11,000 ft or approximately 670 mb). Refer to Figure 1 in Section 3 for site locations. The 2SS stability categorizations for 67 of these periods were compared with stability estimates derived from corresponding Salt Lake City rawinsonde soundings. The 67 periods were selected from the set of 435 based on their occurrence within 3 hours of an available rawinsonde, and were found to be very well representative of the entire set.

The correspondence between stability as derived from the surface measurements, to that derived from the sounding data, was rated as good or excellent in 54 (81%) of the periods examined, meaning that in these cases there was agreement between the two analysis methods to within about one degree C of thermodynamic stability. Of the other 13 period comparisons rated as “fair” or “poor”, having a discrepancy of more than 1 C in the stability estimates, 7 had greater thermodynamic stability indicated by the sounding than that using the 2SS method, and in 6 cases the sounding indicated less stability. Thus, the composite stability evaluation results obtained using the 2SS method are very similar to those derived from the soundings (compare Figures 5 and 6). The primary difference was a few more cases rated SS rather than N when utilizing the sounding data, but with essentially the same total percentage (~60%) in these two categories as a whole for the atmospheric layer between the Olympus Cove and Snowbird elevations.

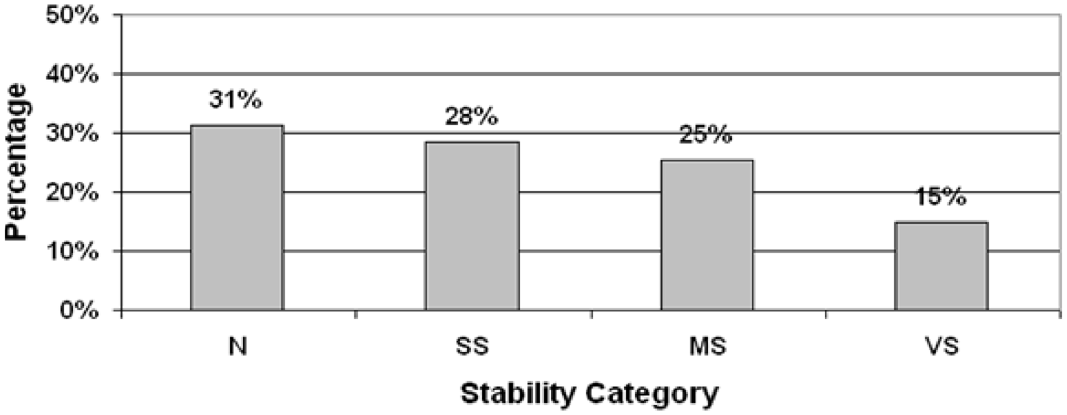

Figure 5. Two-surface site stability analysis results (Olympus Cove vs. Snowbird) based on 67 icing periods used in the comparison with rawinsonde data

A comparison was also made of the 2SS integrated stability between the Olympus Cove and Snowbird elevation (5070'/11,000') vs. the Salt Lake City airport and Snowbird elevation (4200'/11,000') in the rawinsonde data for the 67 periods (compare Figures 6 and 7). The result showed a substantial dependence on elevation in terms of the integrated stability, with only 35% of the analyzed periods rated as either N or SS from the airport surface elevation compared to 60% from the Olympus Cove elevation. Sounding analyses implied that only about 12% of the sounding analysis periods were entirely well-mixed from the airport elevation, compared to 27% from the Olympus Cove elevation. Analysis of the rawinsonde data showed that during the 67 periods overall, approximately 40% of the integrated stability in the Salt Lake City airport vs. Snowbird layer occurred below the elevation of Olympus Cove, i.e. in the lowest 870 feet of the atmosphere. This is an important finding in terms of site location for ground-based seeding operations, as foothill locations are likely to be substantially more suitable than valley bottom sites.

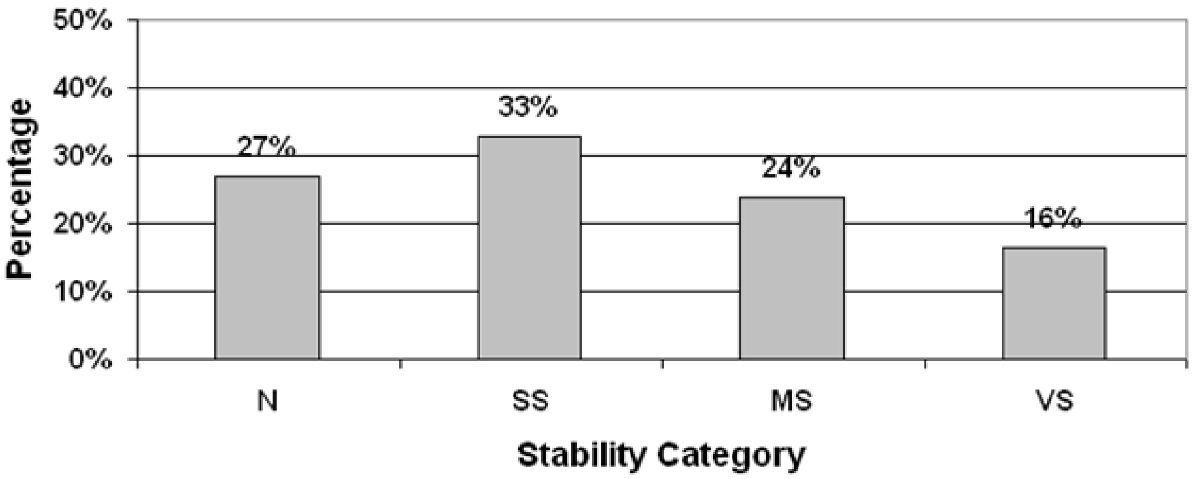

Figure 6. Rawinsonde analysis results between the Olympus Cove and Snowbird elevations, based on the 67 comparison periods

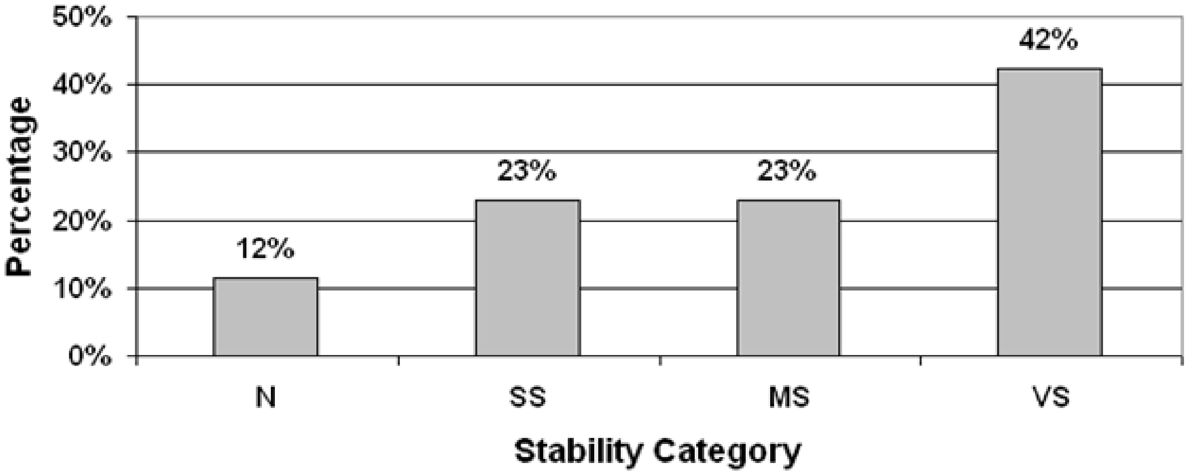

Figure 7. Rawinsonde stability analysis results between Salt Lake City airport and Snowbird elevation, based on the 67 comparison periods

4.2 Two-Site-Stability vs. HYSPLIT Modeling Analysis

A fairly rigorous analysis of plume dispersion in central Utah was performed using the HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) Model. The HYSPLIT model was developed as a joint effort between the U.S. National Oceanic and Atmospheric Administration (NOAA) and Australia's Bureau of Meteorology, and uses meteorological forecast and analysis data to approximate the three-dimensional trajectory and dispersion of particles emanating from a single point or multiple points, during a specified time period. The HYSPLIT model can be used in conjunction with either archived or real-time meteorological model analysis and forecast data. For this study, the model was used in the context of comparing ground-based (modeled) plume behavior with that inferred by the two-surface-site stability analysis in central Utah. Archived North American Model (NAM) 12-km resolution model data were used in HYSPLIT to simulate ground-based plume releases from three sites in central Utah. The HYSPLIT model accepts additional input data including latitude/longitude of the release sites and height of the release relative to the surface, start time and duration of the simulated particle release, emission rates, and the grid size and spacing for each modeled period. The terrain surface elevation at each release point is determined by the model data that is used (in this case, the 12-km NAM). Model terrain was examined and release points were selected to compare releases from various surface elevations (shown as sites A, B, and C in central Utah which are at approximately 4,600', 5,800', and 7,200' in elevation, respectively). The elevation differences allow for a comparison of the modeled plume dispersion behavior based on starting elevation. Figure 8 shows the terrain profile of the NAM model data used in the analysis, and the modeled release sites. This includes locations in the Salt Lake City area (sites 1, 2, and 3) which were used for a baseline analysis of HYSPLIT model performance in regard to atmospheric stability, which was conducted in the Salt Lake City area and is summarized in the following section.

4.2.1 HYSPLIT Model Performance Baseline Analysis

As part of the overall HYSPLIT modeling study on plume behavior and thermodynamic stability, a baseline analysis of modeled plume behavior was conducted. The baseline analysis utilized three hypothetical seeding sites selected in the Salt Lake City area, roughly 80-100 miles north of the Skyline area. The analysis compared upper air soundings at Salt Lake City to modeled plume behavior in order to assess the utility of the HYSPLIT modeling analysis as applied in central Utah. The three Salt Lake City area plume modeling locations, shown as 1, 2, and 3 in Figure 8, represent model terrain elevations of approximately 4200', 5000', and 6800', analogous to the three central Utah sites used in the comparison of HYSPLIT vs. 2SS stability indications. Sixteen soundings from the 2009-2010 and 2010-2011 seasons were selected for the HYSPLIT–rawinsonde comparison in the Salt Lake City area. A variety of thermodynamic profiles including well-mixed, shallow surface inversions, elevated inversions, and deep stable layers were represented in the comparison data. Figure 9 shows the comparison between a sounding profile with a near-surface inversion, and corresponding HYSPLIT output. In this case, a modeled plume release from site 1 remains trapped near the surface after 2 hours, while releases from the other two sites disperse quite well. The plume dispersion in this case illustrates not only the effect of thermodynamic stability, but also the utility of modeling plumes from different release elevations

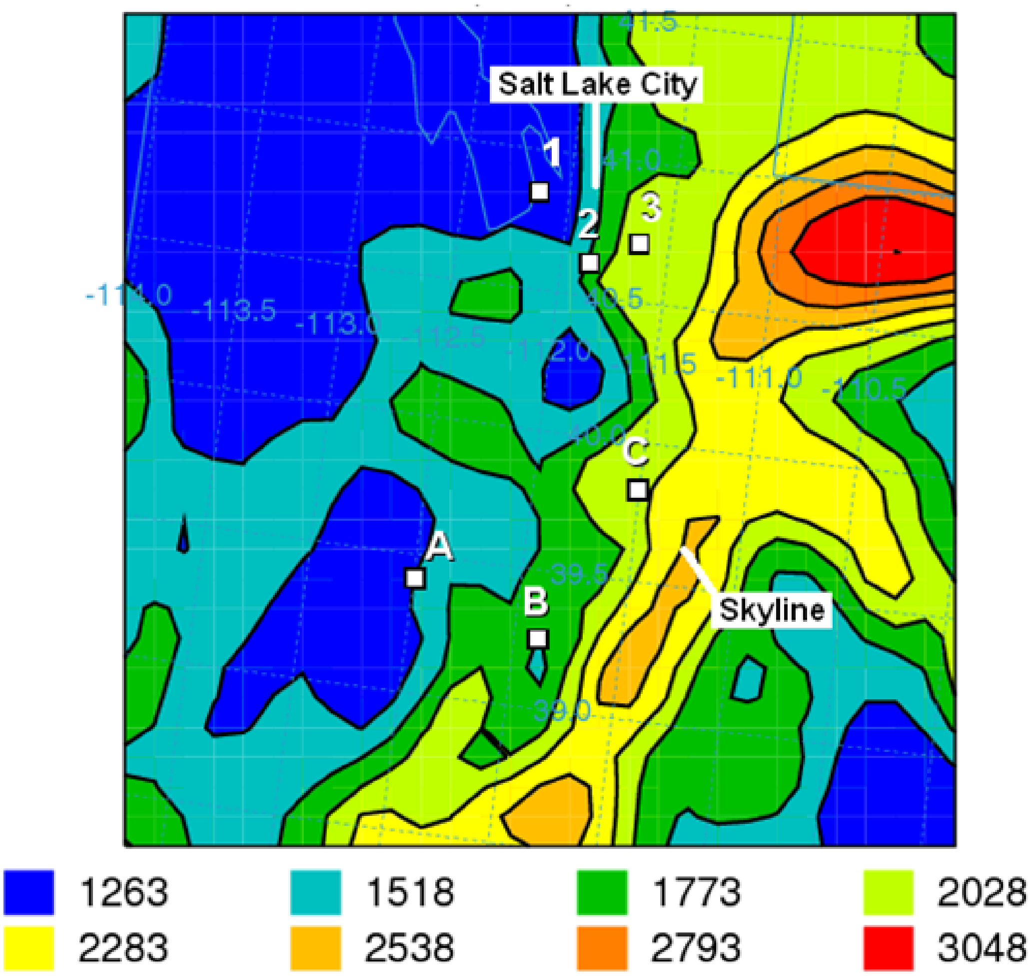

Figure 8. NAM model terrain profile and HYSPLIT plume modeling release site locations (units are in meters)

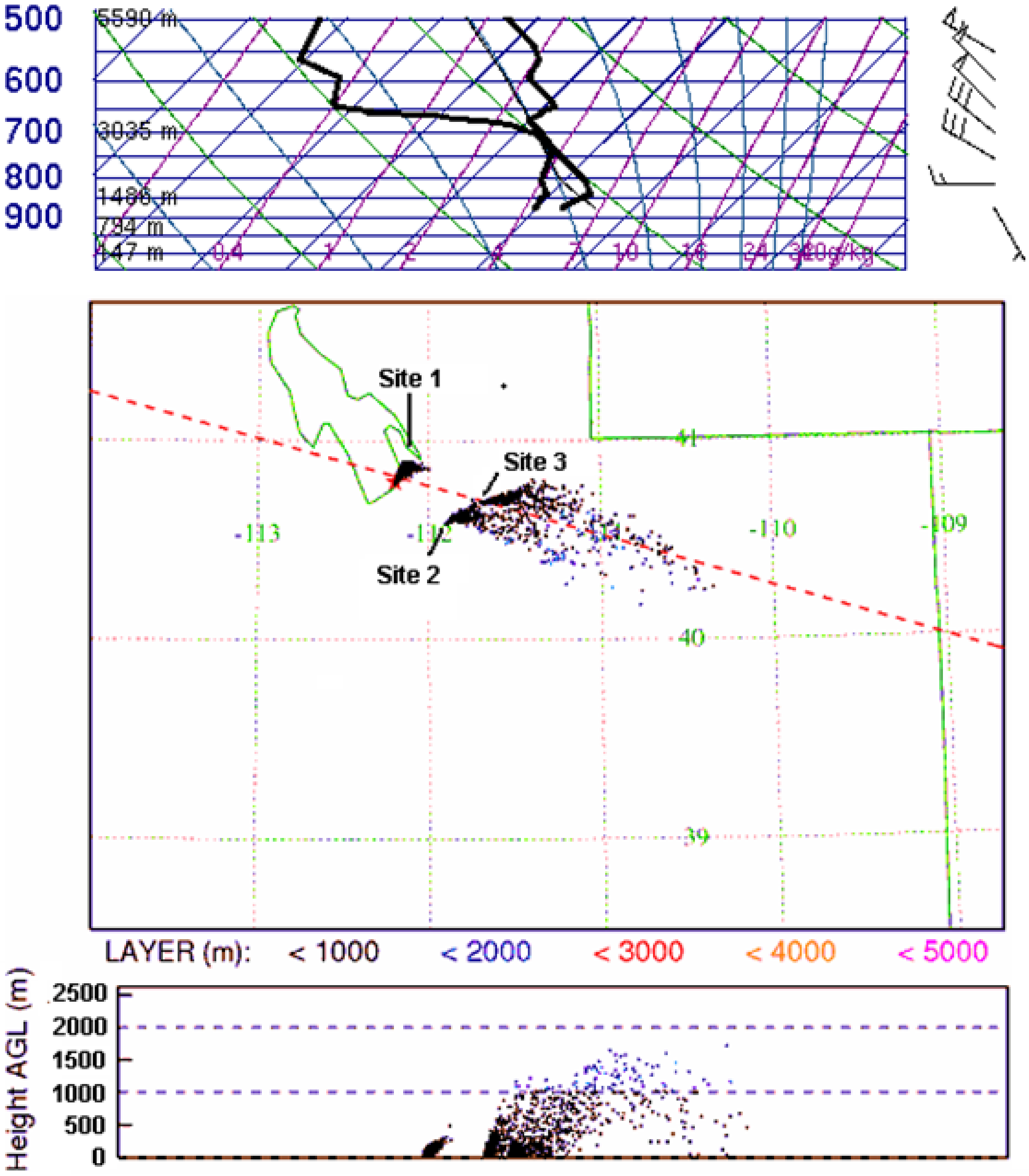

Figure 9. Salt Lake City rawinsonde skew-T diagram to 500 mb (upper panel), and corresponding HYSPLIT output for the morning of January 22, 2011. Middle panel shows plume locations and directional orientation of the vertical cross section (red dotted line), with the vertical cross section displayed in the lower panel. Note that the vertical cross section is plotted on an AGL scale in HYSPLIT, representing the height above the model terrain elevation at each point.

Generally good correspondence was found between the sounding profiles and HYSPLIT output in the analysis. The Salt Lake City area modeling results provided support for some general statements about indicated plume behavior in HYSPLIT, which, as a result, can be applied to the central Utah modeling analysis with reasonable confidence:

- In well-mixed cases without any thermodynamic stability, vertical plume dispersion in HYSPLIT tends to be very uniform without any sharp vertical gradients in concentration observed

- Examination of sites with differing release elevations is useful in comparing plume behavior, especially during shallow inversion situations

- The strength of the lower level wind field is an important factor affecting not only the horizontal but the vertical dispersion rates of the plumes due to turbulence

- The amount of restriction to vertical dispersion in a given layer (visually discernible as a vertical gradient in the concentration of a modeled plume) is correlated to the amount of thermodynamic stability in the layer.

The HYSPLIT–rawinsonde comparisons provided some validation of, and enhanced confidence in, the utility of the HYSPLIT model as a tool in our central Utah stability analyses.

4.2.2 Central Utah HYSPLIT Modeling Methodology

The primary HYSPLIT modeling analysis was conducted for the three central Utah locations (A, B, C in Figure 8), for 76 stormy periods where icing activity was identified in the Skyline 2009-2010 and 2010-2011 ice detector data sets, and represents a large subset of the data periods used for the two-site Skyline stability analysis (Section 3). Most of the periods used for the HYSPLIT simulation were 3 or 4 hours in length, although some were only 2 hours.

Plume modeling results for each of the 76 time periods were compared to the corresponding stability rating for that time period (N, SS, MS, or VS) based on the 2SS method. The comparison results were rated (excellent, good, fair, or poor) based on the agreement between modeled plume behavior and the stability ratings as defined in the 2SS method. For example, a case rated as “N” in which modeled plumes disperse upward quickly and uniformly would show excellent agreement, as would a case rated “VS” where the modeled plumes from the lower (valley) release sites remain essentially trapped near the surface. Of particular interest are the SS cases, in which thermodynamic stability is sufficiently weak that it might not be readily detected in an operational situation where detailed three-dimensional data are lacking, or in which seeding operations would probably not be curtailed due to the minor amount of stability. The SS cases are situations in which warming of less than 2 C at a valley release site or cooling of less than 2 C at crest height would be required to eliminate thermodynamic resistance to vertical dispersion of a plume within this layer. Model terrain height was the primary factor considered when selecting the three plume modeling sites in central Utah, rather than an attempt to replicate the exact latitude/longitude of the Spring City and Skyline surface measurement sites. This is because the NAM 12-km resolution model terrain height at those two locations is different than the actual terrain height, and modeled plume behavior is particularly sensitive to the surface site elevation (based on model terrain).

It is also worth noting that plume modeling site "B" is at essentially the same elevation as the actual elevation of Spring City.

Figures 10 and 11 show examples of HYSPLIT output for two of the modeled periods in central Utah. In Figure 10, an icing period with well-mixed northwesterly flow (rated N based on Spring City/Skyline data in 2SS analysis) shows excellent plume dispersion in both the horizontal and vertical, with all plumes traversing the crest. The model indicated plume dispersion to over 2,000 m (over 6,000 ft) AGL within a couple hours. In Figure 11 (rated "SS" based on Spring City/Skyline data in the 2SS analysis), a shallow but fairly strong inversion exists at lower elevations and traps plume A near the surface, shown here after 2 hours. Plume B (with a model elevation approximating the actual elevation of Spring City) exhibits good vertical dispersion in the model, although a light wind field limits the rate of horizontal dispersion. Plume C disperses quickly up to 1000 m AGL, bringing it up to roughly the crest height elevation.

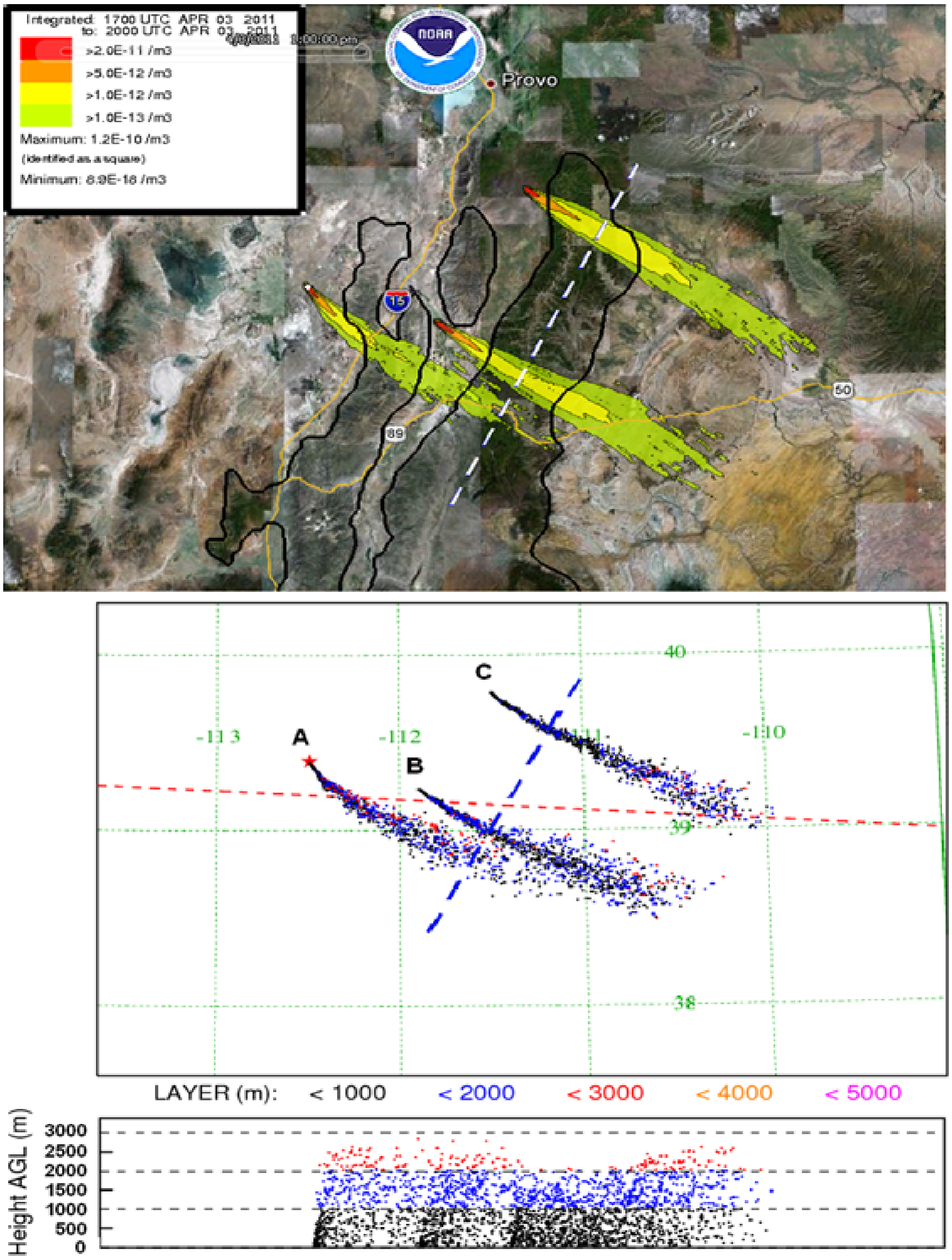

Figure 10. HYSPLIT output for simulated surface-based particle releases on April 3, 2011. White/blue dotted lines mark the approximate location of the main barrier crest in central Utah. The red dotted line in the middle panel depicts the orientation of the vertical cross section plotted below it.

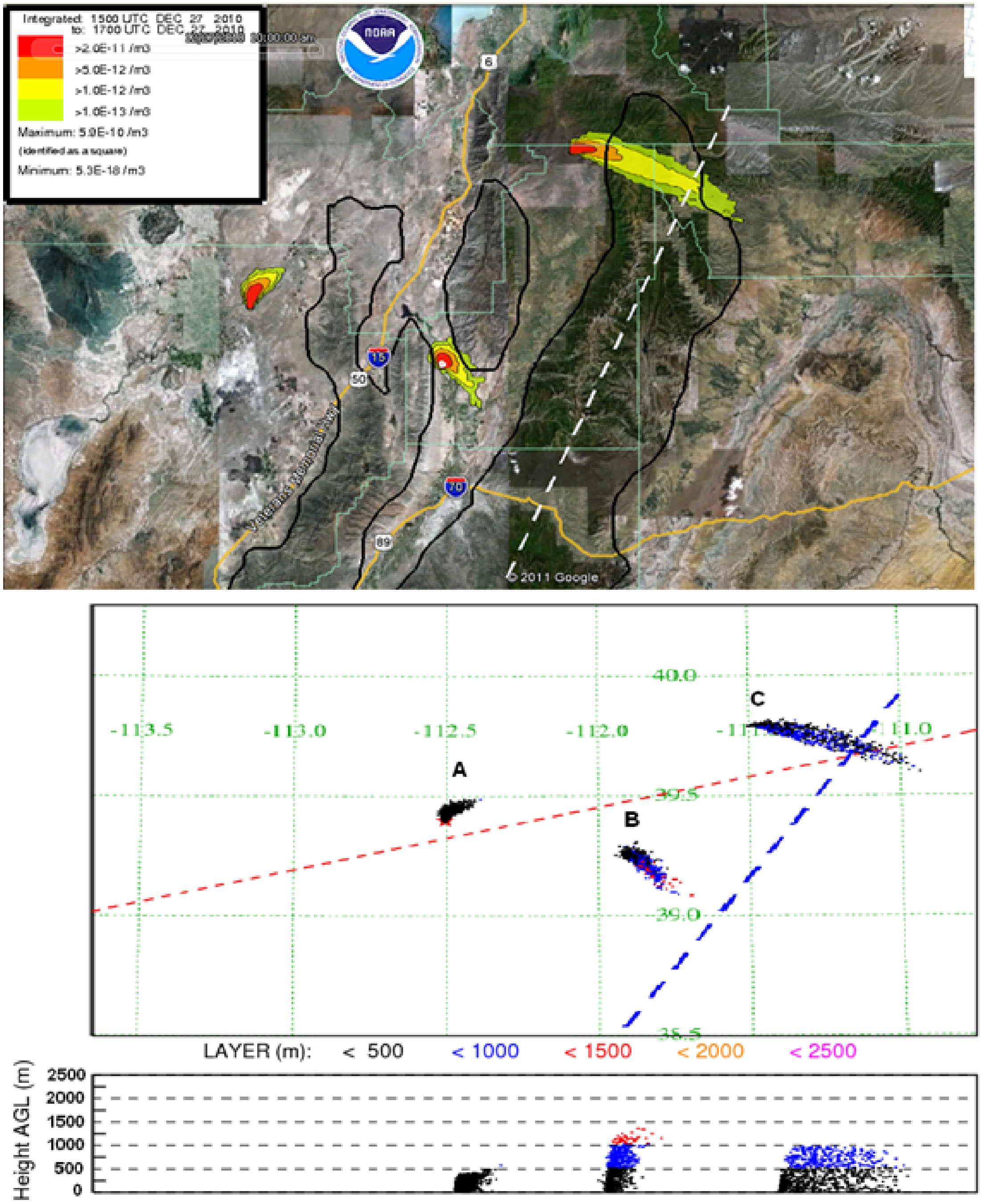

Figure 11. HYSPLIT output for simulated surface-based particle releases on December 27, 2010. White/blue dotted lines mark the approximate location of the main barrier crest in central Utah. The red dotted line in the middle panel depicts the orientation of the vertical cross section plotted below it.

4.2.3 Results of HYSPLIT Analysis

Overall, the results of the HYSPLIT analysis agree well with the stability ratings obtained using the 2SS method. For the 76 modeled periods in this comparative analysis, 40 (53%) had a comparison rating of “excellent”. An additional 22 (29%) were rated as “good”, for a total of approximately 82% rated as either “good” or “excellent”. This means that plume behavior as implied by the 2SS stability categorizations is very similar to indicated plume behavior using HYSPLIT. This result is also very similar to the 81% “good or excellent” agreement between the 2SS and rawinsonde analyses in the Salt Lake City area as discussed in Section 4.1.

For the 24 modeled periods which were rated SS in central Utah, a large majority exhibited plume behavior that showed some degree of lower-level trapping of material at valley sites A and B, but a significant amount of plume material (e.g. ~ 50% or more in many cases) was able to overcome the thermodynamic stability and disperse vertically to near crest height within a few hours. For these 24 modeled cases in particular, in which some minor inhibition to vertical dispersion would be expected, modeled plume behavior was in excellent agreement for 16 (67%) of the cases and good agreement in another 5 (21%) of the cases (for a total of 87% either “good” or “excellent).

The modeling results imply that in a large majority of periods rated as SS, and nearly all the cases rated as “N”, ground-based releases from valley and foothill locations would likely reach an effective seeding elevation in substantial concentrations within a couple of hours.

Closer examination of the 76 modeled periods with regard to wind direction showed that those with a northerly wind component throughout the valley – crest height layer (generally post-frontal situations) exhibit the least amount of stability overall, according to both the 2SS analyses and HYSPLIT model results. Periods with a southerly component throughout this layer (generally pre-frontal situations) exhibited a little more stability. Finally, periods where wind direction changed dramatically with height tended to have the most thermodynamic stability. The vast majority of this latter set had veering wind patterns, usually southerly at low elevations and west-northwest near crest height. Agreement between HYSPLIT and 2SS indications was also somewhat poorer in this latter set than in cases where wind direction was more consistent with height.

It is believed that the 14 (18%) periods with “fair” or “poor” agreement between HYSPLIT and 2SS indications are affected by some weaknesses or limitations inherent to each method. The 2SS method as currently utilized does not take wind velocities into account, and to do so would be very difficult since near-surface stability often results in nearly calm surface winds even though the wind field may be strong just above the surface. Such differential velocities in the near-surface layer can generate a good deal of turbulence and gravity waves, which may fairly quickly mix part of a surface-based plume into the overlying air mass despite the presence of an inversion (Heimbach and Hall, 1996; Heimbach et al., 1997). Conversely, there are a few cases in this analysis where even a small amount of low-level stability appeared to trap an entire plume near the surface because there was a deep layer of nearly calm winds and thus very little atmospheric turbulence. In such situations, the HYSPLIT model has the advantage of factoring in the three-dimensional winds and turbulence, which the two-site analysis method does not. On the other hand, there is some question as to how well the model can resolve shallow near-surface inversions given its resolution limitations, especially in terms of topography. A shallow near-surface inversion limited to a narrow valley (a valley which may not even exist in the model terrain) could present a real obstacle to surface-based seeding which would be accounted for via a surface observation but likely not in the model. In such cases, the two methods can be complementary. It is also worth noting that in the cases where stability implications were significantly different between the HYSPLIT modeling results and 2SS indications, these differences were observed in both directions (rather than one method showing a systematic bias toward greater stability). This is consistent with the comparison results of the rawinsonde vs. 2SS comparisons, and gives greater confidence in the overall 2SS analysis results when a reasonable sample size is available.

A related issue that was examined in the context of the HYSPLIT modeling is the depth of plume dispersion above crest. Plumes from site B in the model analysis were examined, due to a) its 1,768 m (5,800') model elevation, b) relative proximity to the main barrier, and c) the relative frequency of periods where this plume appeared to cross the barrier crest. For 44 modeled periods where the wind direction was favorable and a significant portion of plume B appeared to cross the barrier, a maximum dispersion height was estimated for the portion of the plume that was over the barrier. The estimates ranged from 500 - 2,000 m (approximately 1,600 – 6,500 feet), with a mean of approximately 1,150 m (~3,800') and a median value of ~1,000 m (3,300'). This is somewhat higher than, but still similar to, indications based on aircraft observations from experimental cloud seeding programs in this area (Super, 1999) which suggest that valley-based seeding plume dispersion is generally limited to less than 1,000 m above crest height during winter storm situations. Some of these experimental programs, which involved field observations as well as modeling, led to the conclusion that seeding plumes from valley release sites are sometimes confined to within several hundred meters above the barrier crest (Heimbach and Hall, 1994). Others have suggested frequent plume dispersion on the order of 1,000 m above the terrain especially during post-frontal and mildly convective situations (Griffith et al., 1992; Holroyd et al., 1995). Limited terrain resolution in the NAM model as used with HYSPLIT may influence the results obtained in the current study

In general, the HYSPLIT plume modeling results in central Utah show good agreement with the assumptions about the impact of thermodynamic stability on ground-based seeding effectiveness which are inherent in NAWC's 2SS method. This is encouraging, and lends additional support to the overall study results obtained using the 2SS method. Table 1 provides a summary of the comparisons between HYSPLIT and 2SS indications.

Table 1. Comparative Results of HYSPLIT vs. 2-Site-Stability Analyses, Frequency of Occurrence

		Stability Sub-Categories Based on 2-Surface Site Method				**Wind Direction Sector, Northerly vs. Southerly Component**		
Comparison Rating	**All Periods**	**N**	**SS**	**MS**	**VS**	**Southerly**	**Northerly**	**Mixed or other**
Excellent	40 (53%)	16 (53%)	16 (67%)	5 (45%)	3 (27%)	18 (53%)	14 (70%)	8 (36%)
Good	22 (29%)	11 (37%)	5 (21%)	2 (18%)	4 (36%)	10 (29%)	6 (30%)	6 (27%)
Fair	12 (16%)	2 (7%)	2 (8%)	4 (36%)	4 36%)	4 (12%)	0	8 (36%)
Poor	2 (3%)	1 (3%)	1 (4%)	0	0	2 (6%)	0	0
Total	76	30	24	11	11	34	20	22

The application of HYSPLIT modeling to periods with various stability classifications is somewhat analogous to modeling work presented by Heimbach et al. (1998) for various composite sounding profiles, although the current study is focused specifically on measuring integrated stability within the valley-to-crest layer and inferring probable material dispersion patterns during periods with SLW. HYSPLIT does not model SLW or any microphysical processes related to seeding effectiveness. Nevertheless, some of the observations presented in the Heimbach,1998 paper were also seen in the present analysis, such as the tendency for plumes to drift to the north or northwest near the surface in some stable cases despite westerly winds above the surface, as well as the important role of forcing mechanisms in the transport of seeding material from valley sites over the barrier.

One might ask at this point why the entire stability study is not based on HYSPLIT modeling rather than the 2SS method. There are a few reasons for this. One is that modeling of plume behavior for operational cloud seeding is a new application of HYSPLIT. A second reason is that the HYSPLIT modeling is much more time consuming than the two-surface site analysis method. This becomes a major factor operationally, or when analyzing a very large number of observed icing periods. A third reason is that the archived meteorological model data readily available for use with HYSPLIT has fairly coarse terrain resolution, with the NAM 12-km data being one of the higher resolution options. This makes it difficult to accurately represent a given ground-based seeding site using the model data, since the model elevation at a given location may differ from the real elevation by as much as 1,000 feet (300 m) or more.

Limited model resolution may also result in missing critical features such as strong but very shallow near-surface inversions at a given location, which a surface temperature analysis would take into account. For this reason, plume behavior as modeled using HYSPLIT with NAM data should not be interpreted as a "gold standard". However, this comparison between the two methods certainly provides useful information. It is likely that future modeling improvements, including better terrain resolution of operational meteorological models, will aid in the targeting of seeding material for this type of operational program.

5.0 SUMMARY AND POTENTIAL APPLICATION OF STABILITY ANALYSIS RESULTS

Several overall conclusions were derived from this study, regarding the frequency, strength, and seasonality of low-level stability occurrence in Utah during periods potentially seedable with silver iodide, as well as regarding analysis methodology. These can be summarized as follows:

Primary Conclusions Based on 2SS Analysis of Icing Periods

- During the primary operational cloud seeding season (November – April), for periods **when supercooled liquid water is present at temperatures favorable for seeding with silver iodide**, adequate dispersion of seeding material is expected from most valley and foothill sites approximately 75% of the time. Results vary seasonally, with a general maximum in low-level stability during December and January, and infrequent stability observed during March and April. These results are based primarily on two seasons of data and are not considered a complete climatology.

- Foothill locations may be substantially more suitable for ground-based seeding than valley bottom locations.

- Plume dispersion may reach 1,000 m (approximately 3,000 ft) or more above crest height in many cases, according to model estimates.

Analysis Methodology

- The two-site-stability analysis method is useful for evaluating the likely effectiveness of ground-based seeding from valley and foothill locations, both in real time and post-hoc, in the absence of rawinsonde data. The primary limitation of this method is the difficulty in measuring and assessing the impacts of wind on the dispersion of seeding material.

- The stability categorizations (N, SS, MS, VS) as defined in association with the 2SS method provide operationally useful partitioning of dispersion behavior. This partitioning can also be applied to rawinsonde data using the same methodology.

- The HYSPLIT model provides reasonable guidance regarding the likely dispersion of ground-based seeding material. One of the primary limitations is terrain resolution of the model data currently available for use with HYSPLIT.

We believe that the analysis results regarding the frequency, strength, and seasonality of low-level stability during icing periods are representative of much of Utah, and potentially of similar topography in other portions of the western United States. Experience with surface data analysis in support of ground-based seeding operations has shown that low-level stability can vary significantly from one locality to another, based on the wide variability of terrain profiles in Utah.

It is hoped that establishment of additional high elevation ice detector sites in other locations, as well as data from future seasons, will provide a more complete climatology of low-level stability during seedable storm periods in Utah.

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Evaluation of Hygroscopic Cloud Seeding Flares

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ABSTRACT. A test facility has been designed to provide a reproducible environment for combustion of flares and measurement of the resultant particles. The facility provides a simulation of the environment that a flare would encounter from an aircraft. The facility was used to evaluate the concentrations, sizes and chemistry of many flares with different chemical formulations.

Earlier studies of particle sizes produced by the South African flares indicated that a cooler burning flare could potentially produce larger particles. However, initial field studies in 2002 did not support this hypothesis. Small particles were dominant at both the beginning and end of the flare burn, when the burn was coolest,. In addition, comparison of the Ice Crystal Engineering (ICE) 65% and 70% potassium perchlorate-containing flares indicates that the 70% flare produced larger particles, despite having more oxygen present to yield a hotter burn.

The main characteristic of the production of particles by the flare during a burn is that the variations in the total concentration of the particles are small. However, the concentrations of larger particles (>1μm diameter) varies substantially during the individual flare burns and from flare to flare. The latter variations seems to be due to the manufacturing process, including variations in the chemical composition (mesh size, purity, reactions within chemical species, etc) and the cover tube the flare material is compressed in. These changes in the particle size need to be explored further.

Comparisons among the particle spectra from the ICE 65, 70 and 80% $KClO_4$ hygroscopic flares showed that an increase in the amount of the hygroscopic salt ($KClO_4$) seem to slightly increase the number of larger particles. The larger proportion of the oxidizing salt gives a higher burning temperature, shifting the final size distribution towards larger particle sizes. Based on Scanning and Transmission Electron Microscopy (SEM and TEM) analyses of the ICE 70% flare it seems that the larger particles produced by the flares are composed of aggregate mixtures of KCl and $Ca(Cl)_2$ and are not single particles. Aggregation or coagulation of particles is thus the primary mechanism producing larger particles.

Based on parcel modeling studies, the new ICE 70% flare produces substantially more drizzle drops at shorter times than the South African flare. After 1 minute, the new ICE flare initiates drizzle and concentrations of drizzle water reach a maximum, when the South African flare just starts producing drizzle size drops. In addition, the drizzle results in a more effective coalescence process, forming rain. Once drizzle is formed, the transformation to rainwater proceeds faster than with the original South African flares. After approximately 10 minutes, the new ICE flare produces nearly two orders of magnitude more drizzle water than the South African flare.

1. INTRODUCTION

In the past fifteen years, a new approach to hygroscopic seeding has been explored in summertime convective clouds in South Africa as part of the National Precipitation Research Programme (Mather et al., 1997; Terblanche et al., 2000), Mexico (Bruintjes et al., 2003; WMO, 2000; NRC, 2003; Silverman, 2003), and Queensland, Australia (Tessendorf et al., 2012). Since then many other countries have also started using this approach. This approach involves seeding summertime convective clouds below cloud base using pyrotechnic flares that produce small salt particles on the order of 0.5μm diameter in an attempt to broaden the initial cloud droplet spectrum and accelerate the coalescence process. The burning flares provide larger cloud condensation nuclei (CCN) (>0.3 μm diameter) to the growing cloud, influencing the initial condensation process and allowing fewer CCN to activate into cloud droplets (Cooper et al., 1997). The larger artificial CCN inhibit the smaller natural CCN from nucleating, resulting in a broader droplet spectrum at cloud base. These fewer cloud droplets grow to larger sizes and are often able to start growing more efficiently by collision and coalescence with other cloud droplets within 15 minutes as shown in a modeling study by Cooper et al. (1997), initiating the rain process earlier within a typical cumulus cloud lifetime of 30 minutes. The development of this seeding approach was triggered by radar and microphysical observations of a convective storm growing in the vicinity of a large paper mill, with apparent enhancement of coalescence in these clouds compared with clouds further away from the paper mill (Mather, 1991). Earlier observations by Hindman et al. (1977) and Eagan et al. (1978) also suggested a connection between paper mills and enhanced precipitation due to larger hygroscopic particles being emitted into the atmosphere.

There are significant operational advantages to hygroscopic seeding with pyrotechnic flares compared to large particle salt seeding as practiced in Thailand and other Southeast Asian countries. The amount of salt required is much less compared to large bags of salt, the salt particles are readily produced by flares, and the target area for seeding is an identifiable region at cloud base (updraft region) where the initial droplet spectrum is determined (Cooper et al., 1997).

Mather et al. (1997) reported results from a randomized cloud seeding experiment that was conducted from 1991 to 1996 in summertime convective clouds in the Highveld region of South Africa. The results of this experiment indicated that precipitation from seeded storms was significantly larger than from control (unseeded) storms at the 95% confidence level.

Exploratory analyses indicated that seeded storms rained harder and longer than unseeded storms. Mather et al. (1997) provided microphysical evidence that supported the physical hypothesis. It was remarkable that statistical significance was achieved on such a small sample set of 127 storms (62 seeded and 65 controls), suggesting that the seeding signal was strong and readily detected,

The promising results of the South African experiment led to the start of a new program in Mexico in 1996 using the South African hygroscopic flares. The Mexican program was conducted from 1996 to 1998 and included physical measurements and a randomized seeding experiment. Bruintjes et al. (2003), WMO (2000) and Silverman (2003) provide an overview of the experiments and results. The Mexican results were remarkably similar to the results from the South African experiment. Model calculations of Reisin et al. (1996) and Cooper et al. (1997) support the hypothesis that the formation of precipitation via coalescence is accelerated by the large salt particles produced by hygroscopic flares.

This paper reviews the history of the development and use of hygroscopic flares for seeding clouds to enhance rainfall, and the theory behind it, with special emphasis on the production of drizzle drops. As hypothesized by Cooper et al. (1997) the drizzle-size drops may be carried by the strongest updrafts to cloud top where they may spread and be carried down in the downdrafts and near cloud edges and would then spread throughout the cloud (Blyth et al., 1988 and Stith et al., 1990).

Airborne and laboratory measurements of the different particle size spectra will be presented and the possible impacts on the condensation/coalescence process will be explored. A recently developed test facility to evaluate the chemical composition, size and concentrations of the particles produced by hygroscopic flares will also be described and a preliminary evaluation of newly developed hygroscopic flares will be presented.

2. CCN CHARACTERISTICS: MODELING STUDIES OF CONDENSATION AND COALESCENCE RELATED TO HYGROSCOPIC FLARE SEEDING

Three important parameters underpin the principle of enhancing the coalescence process via hygroscopic seeding, i.e., chemistry (hygroscopicity), size, and concentration of the CCN produced from the flares or large particle salt seeding. The principle of flare seeding is to produce effective CCN (usually salts such as sodium chloride, potassium chloride, or calcium chloride) particles in larger sizes (large or giant nuclei) than occur in the natural environment. The effectiveness of seeding will also depend on the nature and concentration of natural background particles.

The flares used in the South African and Mexican experiments provided larger CCN (>0.3 μm diameter) to the growing cloud (Hindman et al, 1977). Cooper et al. (1997) showed that if the CCN introduced into the cloud from the flare are larger in size than the natural CCN, then the CCN from seeding will activate preferentially over the natural CCN and change the character of the drop size distribution in favor of coalescence and formation of rain. Thus, the larger artificial CCN inhibit the smaller natural CCN from nucleating, resulting in a broader droplet spectrum at cloud base. These fewer cloud droplets grow to larger sizes, and are often able to start growing by collision and coalescence with other cloud droplets within 15 minutes, initiating the rain process earlier within a typical cumulus cloud lifetime of 30 minutes.

The calculations of Reisin et al. (1996) and Cooper et al. (1997) support the hypothesis that the formation of precipitation via coalescence is accelerated by the salt particles produced by the flares. These studies found that for clouds with a maritime cloud droplet spectrum, hygroscopic seeding with flares has no effect, since coalescence is already very efficient in such clouds. The relatively high concentrations of large natural CCN prevent the seeded particles from dominating the growth. Thus, clouds with background CCN concentrations less than about 350 cm^{-3} at 1% supersaturation, in maritime environments, do not respond favorably to hygroscopic seeding, since the presence of the large natural nuclei produce large drops, preventing the seeded particles from growing.

Results from these calculations should be interpreted with caution, since they oversimplify the real process of precipitation formation. Cooper et al. (1997) allude to some of these shortcomings related to mechanisms that broaden cloud droplet size distributions, sedimentation, and the possible effects on ice phase processes. These models also do not simulate the complex dynamics in convective clouds. The modeling studies of both Reisin et al. (1996) and Cooper et al. (1997) indicate that the role of the background CCN (size and concentrations) is critical to determining the effectiveness of cloud seeding because the seeded nuclei compete with the background aerosols for the available water vapor.

Cooper et al. (1997) showed that the introduction of giant nuclei, larger than 10-μm diameter, lead to an earlier development of raindrops. Yin et al. (2000a; 2000b) found similar results in their modeling studies using a two-dimensional, slab symmetric cloud model. Yin et al. (2000a) corroborated the hypothesis of Mather et al. (1997) that using flares for seeding hygroscopic particles below cloud base could lead to the broadening of the cloud droplet spectra and an earlier formation of raindrops. These studies indicated that the most effective seed particles were those with radii larger than 1μm, and especially those larger than 10μm; and that particles less than 1μm always had a negative effect on rain development. Although these studies indicated that seeding with particles larger than 10μm in radius were the most beneficial for rain enhancement and promoted the formation of drizzle-droplets and raindrops, the drizzle drops formed were rapidly depleted once the few large privileged drops grew to raindrop size. Cooper et al. (1997) found that the rapid depletion of the drizzle size drops limited the production of other raindrops. As a result, rain develops early, but does not last very long and its contribution to the total rain on the ground is limited. It should be emphasized that the Cooper et al. model does not compute the effect of the drop breakup, a process that could possibly enhance the concentration of drizzle size drops. In contrast, introduction of much higher concentrations of 1 μm particles can lead to competition with the natural CCN. Activation of the seeded particles prevents activation of the natural CCN and in appropriate cases, leads to reduction in the total concentration and broadening of the drop size distribution. This results in initiation of an active coalescence process, in some cases leading to high concentrations of drizzle along with the production of rain. Yin et al. (2000a) found that when they repeated the seeding experiments in their model using the same mass for particles in the range 1-10μm and for those larger than 10μm, the concentration of drizzle drops was substantially larger with the seed particles between 1 and 10μm (Yin et al. 2000a).

Caro et al. (2002) used a detailed microphysical parcel model (Flossman et al. 1985; 1987) to confirm most of the results from the previous modeling studies. Their studies indicated that the most rapid formation of precipitation occurred in the model for very large particle radii (> 15μm). However, they also indicated that smaller seeding particles have the advantage of increasing the concentration of drizzle size drops, increasing the chance of the seeding material staying in the cloud and dispersing the seeding effect to larger parts of the cloud or neighboring clouds. Although seeding with larger particles increased the production of precipitation in the model, it also risked premature precipitation. For seeding to have an optimum effect, with sufficient concentrations of drizzle size drops, they suggested a mean seed particle diameter between 0.5 and 6μm. Segal et al. (2004) found similar results.

Yin et al. (2000a), Caro et al. (2002) and Segal et al. (2004) alluded to the potential effects on ice processes that could possibly enhance precipitation formation. Although the models used in these studies were different, one of the main conclusions that emerged is that the seeded particles have to be larger than 0.5 μm and preferably between 1 and 10μm diameter to produce substantial concentrations of drizzle size drops in a cumulus congestus cloud with updrafts near cloud base ranging from 1 to 4 ms-1.

3. AIRBORNE MEASUREMENTS OF FLARE PARTICLES

The only measurements of the particle spectra produced by the flares in the literature are those presented by Mather et.al. (1997; Fig. 7) from South Africa. These airborne measurements were obtained by flying an aircraft equipped with particle measuring probes about 50 m behind the seeding aircraft. Mather et al. used a Passive Cavity Aerosol Probe (PCASP) to measure the concentration of particles between 0.1 and 3μm in diameter in 15 size bins, a Forward Scattering Spectrometer Probe (FSSP-100) to measure the concentration of particles between 2 and 47μm in diameter in 15 size bins, and a 2-D Optical Array Probe to measure particles between 50 and 1000μm in diameter. The size distribution measurement of the dry particle sizes by Mather et al. (1997) indicate that a majority of the number of particles produced from the magnesium/potassium perchlorate flares are less than 0.5μm diameter. However, the measurements also indicated that a tail of larger particles was produced extending out to about 10μm diameter. These larger particles are extremely important as pointed out in the modeling studies discussed in the previous section. Most of the modeling studies used the South African spectra; however, these are the only measurement of the particle spectra produced by the burning flares and their reproducibility is unkown.

Another measurement campaign was conducted in Texas in 1997 to assess the particle spectra produced by different flares from different manufacturers as well as the original South African flare. The measurements were conducted in the same manner as the original South African measurements by flying an aircraft equipped with particle measuring probes about 50 to 100 m behind the seeding aircraft. The primary instruments measuring the particle spectra from the burn-in-place 1kg flares were a PCASP and FSSP-300 probe. The FSSP-300 is a modified version of the FSSP-100 probe measuring particles in 31 size bins between 0.3 and 20μm in diameter. In addition, a University of Wyoming CCN counter was flown on theaircraft to assess the CCN activity of the particles produced by the flares. The CCN counter was run at a constant supersaturation of 0.3%.

The purpose of the measurements was to determine the reproducibility of the South African measurements and any differences in particle spectra between flares from different manufacturers. The particle spectra of four different types of flares were measured: the original South Africa flare, a flare manufactured by Atmospherics Incorporated, a French flare, and a modified version of the original South African flare called D383 (containing less Mg, 2.5% versus 5.0% in the original South African flare and replacing the NaCl in the original flare with $CaCl_2$).

Figure 1 displays the combined size spectra measured by the PCASP and FSSP-300 aerosol probes for the four different flares (D383 – Modified South African flare (a), SA – original South African flare (b), AI - Atmospheric Incorporated flare (c), and French flare (d)). The measurements were obtained by flying the research aircraft behind the seeding aircraft while the flares were burning. The spectra were averaged over a ten second period. Differences between the spectra from the PCASP and FSSP-300 probes, especially for size ranges larger than 0.3μm diameter, could be due to deliquescence of hygroscopic flare particles at the ambient relative humidities encountered during the flight (between 50 and 70%). The PCASP de-icing heaters tend to dry the aerosols, thus measuring dry particle size, whereas the FSSP-300 measures their wet diameter. Strapp et al. (1992) in a study comparing measurements from the PCASP and FSSP-300 probe found similar results.

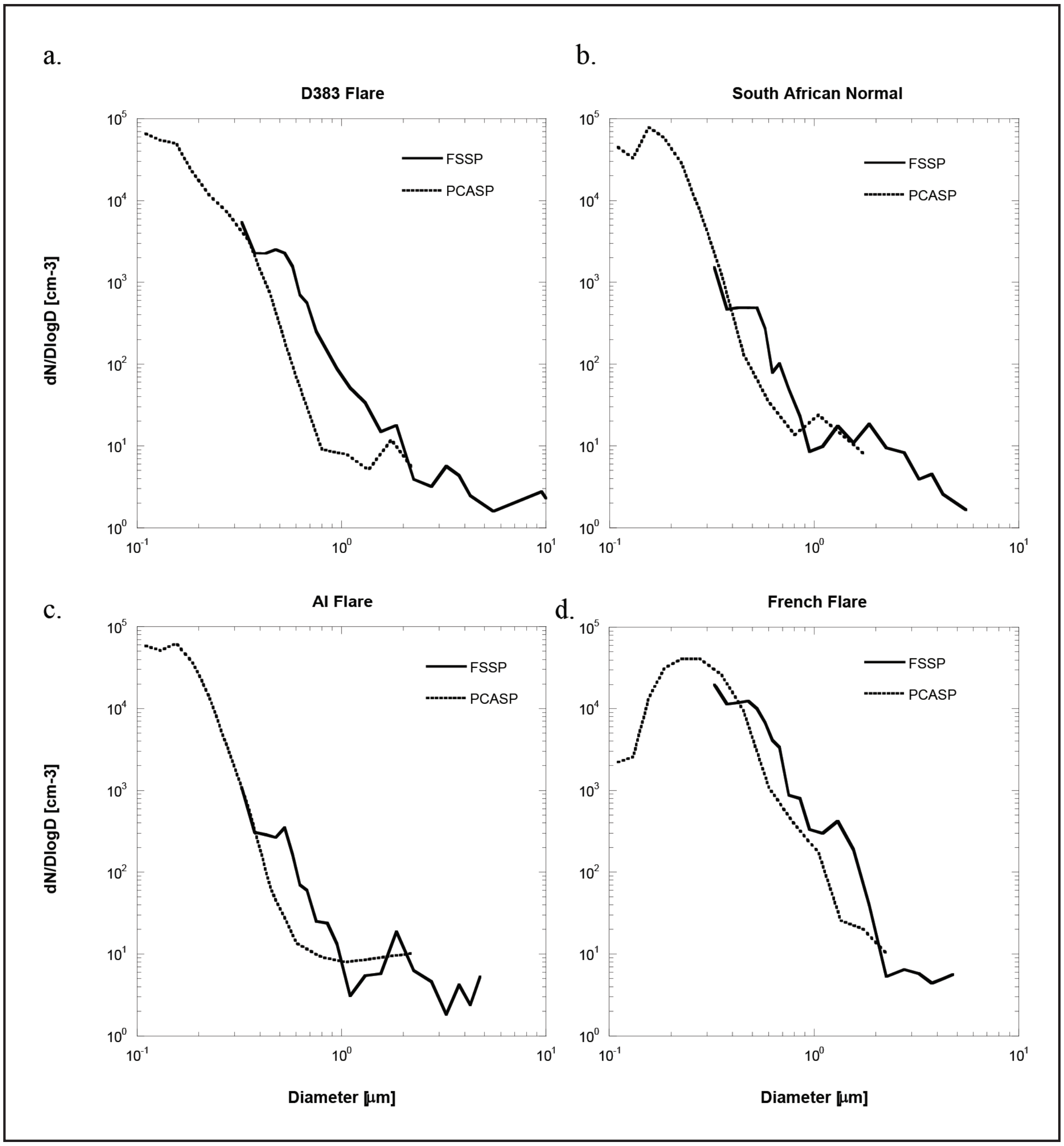


Figure 1. Combined dry aerosol size spectra from four different hygroscopic flares as measured by PCASP and FSSP-300 probes.

There are substantial differences among particle spectra produced by the different flares. The French flare produced the largest mean size, while the AI flare had the smallest mean sizes. Both the original South African and D383 flares produced more particles within the 0.3 to 1μm size range than the AI flare, but less than the French flare. Peak concentrations for the AI flare were around 0.2μm, the South African and D383 flares around 0.3μm and the French flare around 0.4 to 0.5μm. The CCN measurements indicated that all the flares produced particles that are highly active as CCN, resulting in concentrations of more than 2000 cm-3 for all flares.

All four flares showed a tail in the particle spectra extending out to several microns, with the D383 flare producing particles up to 10 μm diameter. Observed concentrations of large particles were highly variable during the burning of the flare, in part due to low concentrations and limited sampling volume. Hence, real concentrations in this size range are difficult to estimate accurately. Significantly, there were remarkable differences in the spectra obtained in Texas from the original South African flare compared with the Mather et al. (1997) measurements. Since modeling studies have highlighted the tail of the spectra as the most important size range for initiation and evolution of coalescence in a cloud, the differences in the South African flare spectra will be further addressed below.

It should be emphasized that it is difficult to obtain measurements of the particle sizes produced by burning flares in flight. It requires two aircraft, one to generate the seeding material, and another to make the measurements. Environmental changes in humidity, temperature, and speed changes of the seeding aircraft, all possibly impact the particle size distribution produced by the flares. In addition, the small size of the plume presentsproblems for sampling especially in a turbulent environment. However, airborne measurements are important as in situ evidence for particle behavior in the atmosphere.

4. FLARE COMPOSTION AND THE EFFECTS ON PARTICLE SPECTRA

Modeling suggested that most effective seeding for the formation of enhanced concentrations of drizzle drops occurs when the introduced CCN have a size of approximately 1μm or larger and the optimum seed particle sizes are between 1 and 6μm in diameter. In our study, we investigated flare composition to determine whether larger particles can be produced that more closely fit the parameters important for drizzle formation. In addition, the model studies suggested that the use of calcium salts in the seeding material could enhance the effectiveness and calcium salts were also included in the tests.

Most hygroscopic flares currently in use are based on the formula of Hindman (1978) developed to initiate fog for cover of military vessels. They are composed of potassium perchlorate, magnesium powder, and a hydrocarbon binder as the oxidizer and fuel respectively. They also incorporate sodium or calcium chloride and lithium carbonate. The products of combustion are a mixture of magnesium oxide, potassium and sodium chlorides, and lithium oxide. In laboratory analyses of South Africa flares, it was found that the flares consisted of a mixture of potassium perchlorate ($KClO_4$), sodium chloride (NaCl), Lithium Carbonate (Li_2CO_3), Magnesium (Mg) and a hydrocarbon binder. Mg powder provided the heat, while $KClO_4$ provided the oxygen for combustion. Stoichiometric analysis indicates that 72% of the oxygen for combustion was provided by the $KClO_4$ and the remainder from atmospheric oxygen.The laboratory particle analyses using scanning electron microscopy indicated that the particles produced in the combustion process closely represented the initial composition of the flares. Data for small and large (>10μm) particles indicated that the small particles constituted most of the mass.

Based on the TEM analysis, Table 1 shows that large particles have a slight enrichment in Mg and a reduction in KCl. In general, the mole fractions of chemical components present in the flare and individual particles were similar. Analyses were not able to detect Li_2CO_3 in the initial flare material or in the particles produced when burned. The reason for this is not known.

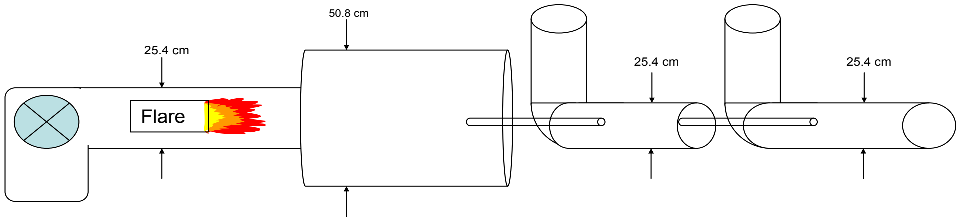
TABLE 1. Chemical composition of the original South African Flare and the relative chemical compositions of small (<10μm) and large particles >(10μm) from SEM data.

Chemical Components	Flare Composition	Small Particles	Large Particles
KCL ($KClO_4$)	0.54	0.58	0.42
Na Cl	0.20	0.23	0.25
MgO (Mg)	0.24	0.19	0.33
Li_2CO_3	0.03	Not detected	Not detected

Examination of SEM micrographs of seeding particles captured on glass slides suggest that the salt particles produced in the burning of flares nucleate on MgO (Kok and Mather, unpublished data, 1995). The combustion temperature of the flares is unknown, but is most likely in excess of 2000C (attempts were made to measure the temperature but elements that measured up to 2000C were all burned). Both NaCl and KCl melt at around 800C, and sublime or boil at about 1500C. Under these combustion conditions, the salts will volatilize and then re-condense rapidly, forming small particles. It was hypothesized that if the burning temperature of the flare could be reduced, there would be less volatilization, and consequently formation of larger particles. To test this theory, the South African D383 flare (discussed in the previous section) was manufactured. It contains less Mg (2.5% versus 5.0%) than the original South African flare) and uses $Ca(Cl)_2$ instead of NaCl . Although the D383 flare had higher concentrations of particles in the 0.5 to 1μm range, and had the largest particles present (Figure 1), the overall concentrations were not significantly different from the original South African flare. A flare that uses calcium salts and decomposition of an azorcarbamide compound has also been tested. The "fuel" in this flare is typically used in pyrotechnics, and burns at less than 100C. Several new flare formulations were developed by ICE in North Dakota in our attempt to increase particle sizes. These flare formulations use different salts (sodium chloride, potassium chloride or calcium chloride) and different types of organic binders.

5. FLARE TEST FACILITY

A test facility was designed and constructed to simulate the burning of flares on the wing of an aircraft to address the limitations of aircraft measurements of flare particle spectra and the need for a systematic study on the particles generated by airborne hygroscopic cloud seeding flares. This test facility provides a reproducible environment for the combustion of flares and the measurement of the resultant particles. The facility was used to examine the different commercially produced seeding flares as well as the new formulations described above. A schematic diagram of the test facility is shown in Figure 2.



	Burning chamber	Deasceleration/cooling stage		First dilution	Second dilution
				IDEAL CONDITIONS	
Diameter (m)	**0.254**	**50.8**		**0.254**	**0.254**
Wind speed (m/s)	**40**	**12**[a]	**10**[b]	**> = 12**	**> = 12**

[a] Meassured [b] Calculated

Figure 2. Schematic design of the flare test facility.

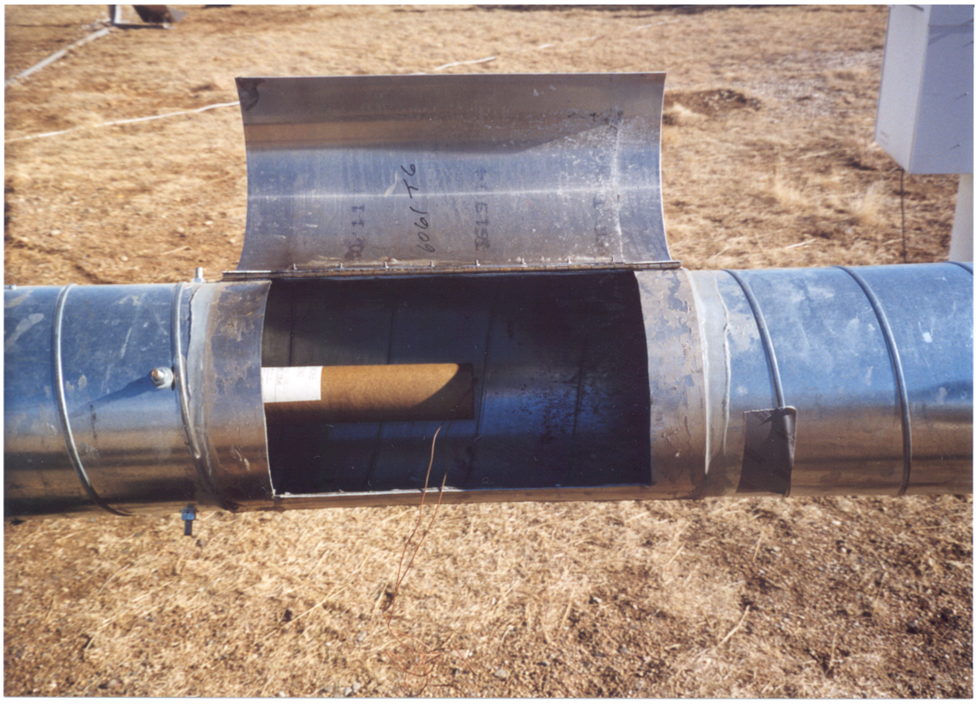
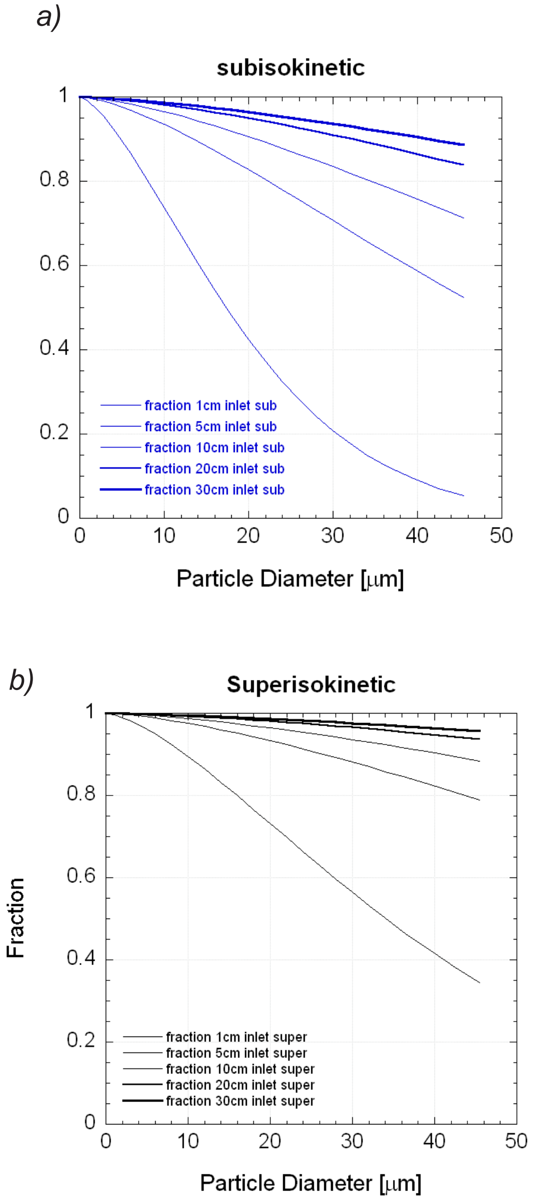


Figure 3. Photograph of the combustion section of the test facility with a flare mounted.

Flares are mounted near the head of the combustion section, aligned axially with the airflow (Figure 3). The burning end of the flare is on the downstream side. This simulates burning a flare on a rack mounted on an aircraft wing. The airflow is sufficient to disperse and cool particles as they are produced. During operation, the combustion section is closed, and the flare is ignited using an electrical igniter.

One of our main considerations when designing the flare testing facility was to ensure continuous sampling of the flare material, without enhancing the collection of eitherenhancing the collection of either small or large particles. Isokinetic sampling was the ideal method for obtaining size distributions of the particles produced by the flare. Figure 4 shows different sampling scenarios (sub-isokinetic, isokinetic and super-isokinetic) with their gravitational losses for different inlet sizes. In a sub-isokinetical sampling (Figure 4a) the gravitational losses of larger particles are enhanced. During a super-isokinetic sampling (Figure 4b) the gravitational losses of smaller particles are enhanced, During a super-isokinetic sampling (Figure 4b) the gravitational losses of smaller particles are enhanced, generating higher concentrations of larger particles and decreasing total particle concentrations. Preferential sampling of larger or smaller particles is evident as the sampling tube diameter becomes smaller. The test facility uses a sampling tube of 1 cm in diameter and 1m in length for both inlets in the dilution stages. This results in an isokinetic sampling procedure that gives a gravitational loss of less than 80% for particles smaller than 10μm diameter. Because we are mainly interested in the large particle tail of the size distribution we focused our analysis on the larger particles.



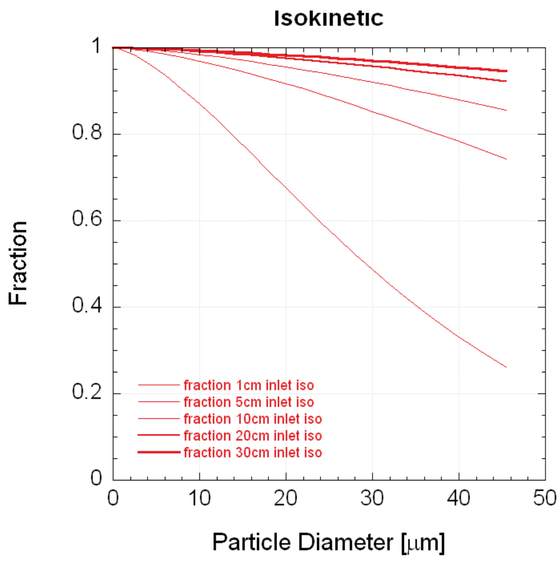
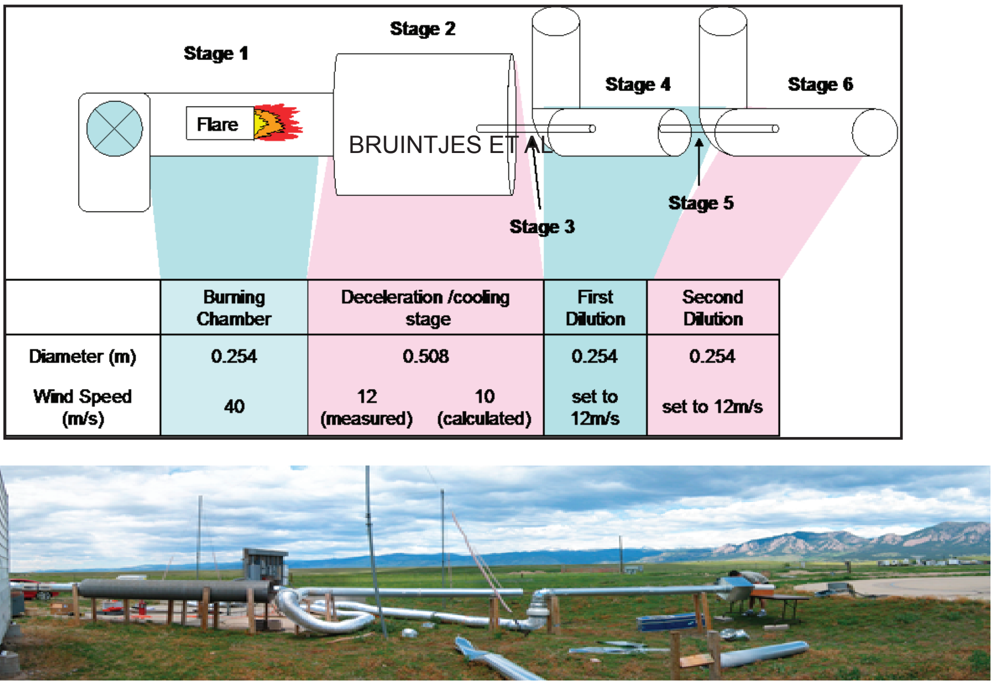


Figure 4. Gravitational losses in a 1 meter long inlet for a sample flow U_o and at a wind speed $U = 40m/s$ and different particle size. a) $U>U_o$, b)$U<U_o$, c) $U=U_o$

Figure 5 shows the characteristics of the completed flare facility, including the calculated and measured wind speeds that minimize gravitational losses and favor isokinetic sampling. A 156,000 lpm (liters per minute) blower is used to provide an airflow of 40 m s^{-1} (no differences were found by varying speeds from 30 to 60ms^{-1}) through the combustion section (stage 1), which is made of circular tubing of 25.4 cm in diameter and 1.5 meters long. The particles in stage 2 (Figure 5) are then collected by a circular copper tubing (stage 3), 1 cm in diameter and 1 meter long, and transported to the first dilution stage (stage 4). The first dilution is fed with clean air at a rate of 12 m/s to match the incoming wind speed ($U=U_o$) in order to sample the particles isokinetically. To dilute the particles further, to satisfy the counting limitations of the particle counters, a second stage dilution (stages 5 and 6) was implemented. The second stage dilution procedure is identical to the first, with a wind blower of 12 m/s to maintain a steady flow of particles to the measuring instruments.



	Burning Chamber	Deceleration /cooling stage	First Dilution	Second Dilution
Diameter (m)	0.254	0.508	0.254	0.254
Wind Speed (m/s)	40	12 (measured) 10 (calculated)	set to 12m/s	set to 12m/s

Figure 5. Dynamic characteristics and an actual photo of the flare facility design.

The diluted smoke is sampled by an array of instrumentation: 1) a CCN counter which measures particles from approximately 0.01-1.0μm diameter and 2) a PCASP which optically sizes and counts particles from 0.1 to 3.0 μm diameter, and 3) a FSPP which measures particles from approximately 3-8μm diameter. All of the data from these particle counters are recorded on a laptop computer. Auxiliary measurement of ambient temperature and relative humidity are also made at the site. Experiments carried out when the relative humidity is 40% or less to be able to compare dry particle sizes. At this relative humidity, particles may hydrate, but they will not grow in size. Ambient temperatures varied between 10 to 30C, but did not affect particle generation at combustion temperatures of >1500C.

6. FLARE TEST RESULTS

A variety of flare formulations were tested on a number of days. Here, we highlight the capabilities of the test facility and some of the differences observed between the different flare types. The initial tests had two major objectives; 1) to determine the reproducibility of particle spectra from the burning flares by burning several flares of the same type, and 2) to evaluate the particle spectra from newly developed and manufactured flares. More than 20 different flare compositions were evaluated at the test facility.

In addition, there were two important objectives in the evaluation of different flare compositions: to determine concentrations and sizes of the particles produced by the flares as a function of time; and to determine variations in different particle size. Many of the different compositions produced similar or smaller particle spectra to that obtained from the original South African flare, hence we will focus on flares that produced larger particles.

6.1 Particle concentrations and size distributions

Figure 6 a to d shows time series of particle concentrations for different threshold sizes for different flares measured in the test facility. Figure 6a displays the particles produced by flares with magnesium/aluminum alloy in place of the magnesium powder. Figure 6b and c display the particle concentrations and sizes of two flares manufactured by ICE with a similar composition to the South African flare, but with calcium chloride in place of sodium chloride. These flares have 65% and 70% potassium perchlorate, respectively. Figure 6d shows the particles produced by the “standard” South African (SA) flare. The SA flare also uses 65% potassium perchlorate as the oxidizer. The data provide number concentrations of the particles as a function of time in the size ranges 0.2μm and smaller, 0.2-0.4μm, 0.4-0.8μm, and greater than 0.8μm diameter. These size ranges delineate the important particle size regimes highlighted by the modeling studies. The utility and advantages of the flare test facility are clear from Figure 6, since complete time series of the particle spectra produced on flare combustion cannot be obtained from aircraft measurements.

Although total concentrations for the different flares are comparable and show very little variation, large variations as a function of time occur for particle sizes between 0.2 and 0.8μm diameter, with largest variations observed for the two flares manufactured by ICE.

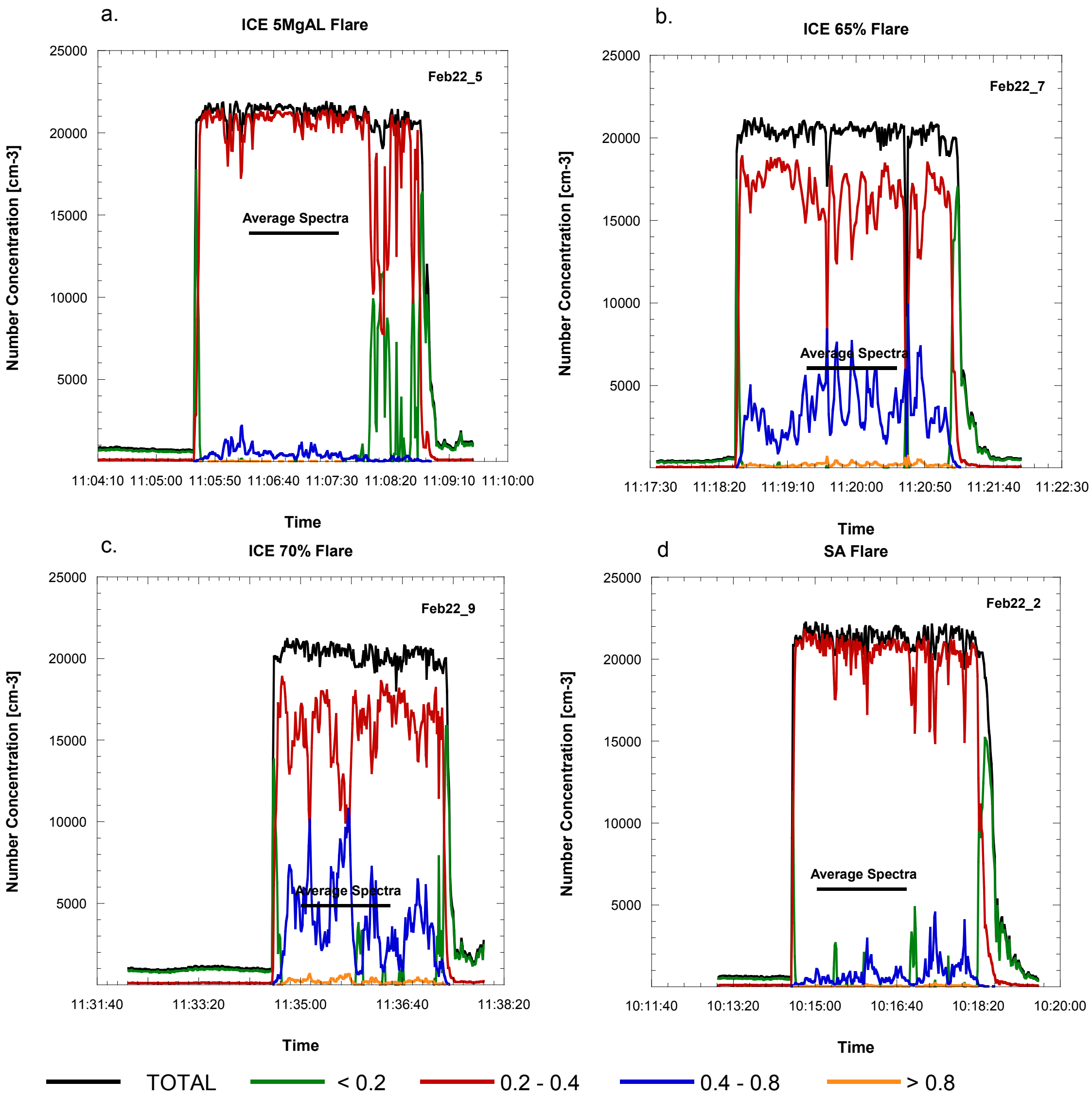


Figure 6. Time history of particle concentrations during flare burns with different compositions.

6.1 Particle concentrations and size distributions

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Although total concentrations for the different flares are comparable and show very little variation, large variations as a function of time occur for particle sizes between 0.2 and 0.8μm diameter, with largest variations observed for the two flares manufactured by ICE.

ICE flares produced significant larger concentrations of particles in the size range 0.4 to 0.8μm diameter than the SA flare (Figs. 6b, c and d). The majority of the particles produced by the SA flare are < 0.3μm diameter. Since the compositions are nominally comparable, differences in the grades of chemicals used, and in the manufacturing procedures must give rise to the differences.

Differences in the amount of potassium perchlorate used in the 65% and 70% ICE flares resulted in larger variations and at times higher concentrations of particles larger than 0.4μm diameter.

Figure 6a shows that modifying the metal fuel used in the flares from magnesium power to a magnesium/aluminum alloy resulted in very small particles. The reason for this change in particle size is not known, but is not beneficial for seeding.

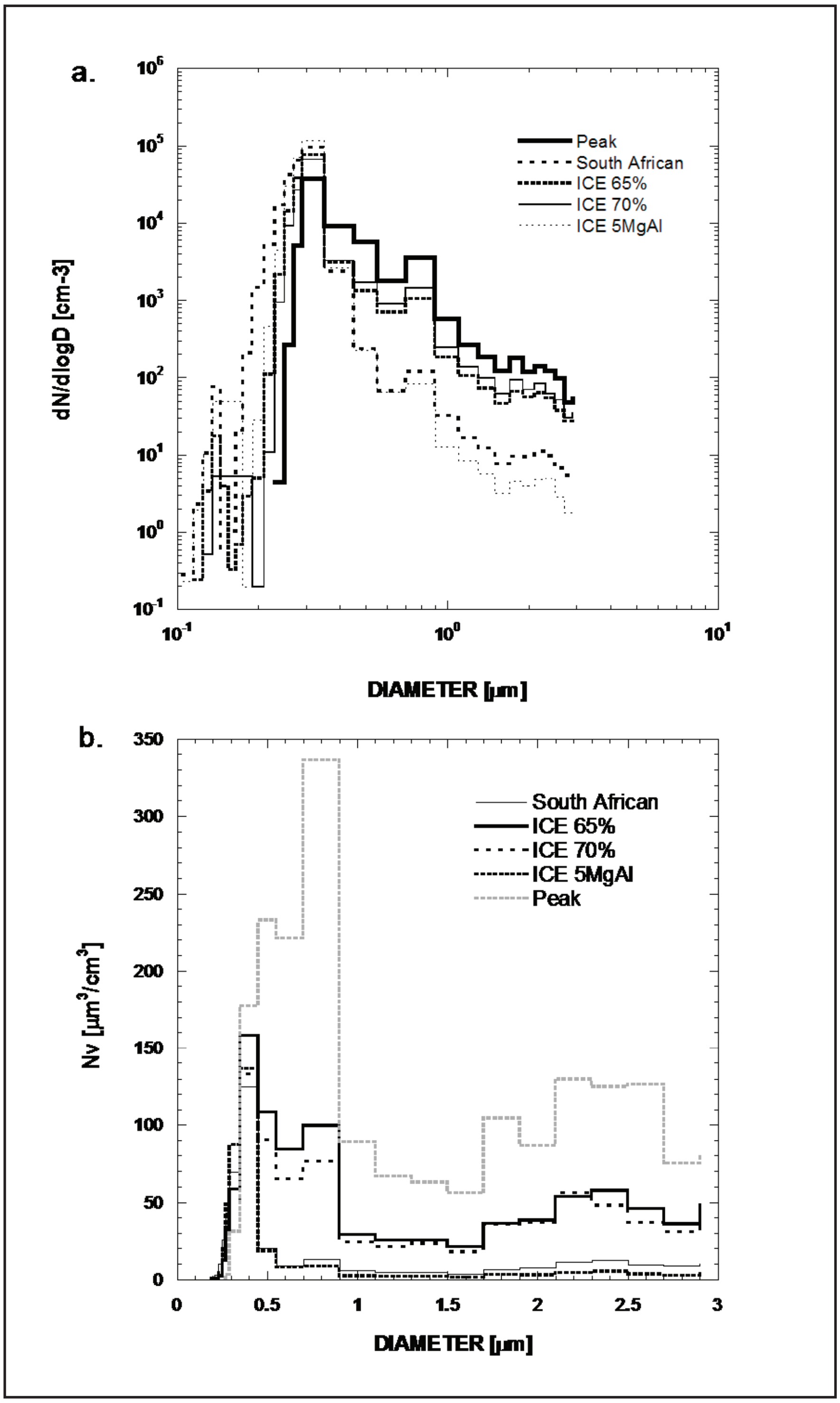

Figure 7. Number size and volume size distributions of flare particles in flares with different compositions

Figures 7a and b display the PCASP number concentration and volume distribution as a function of diameter. The spectra were averaged over the period represented by the horizontal bars in Figure 6. Again, total concentrations are very similar, but ICE 65% and 70% flares have substantially larger concentrations of particles in the size range 0.5 to 3µm diameter. Figure 7b highlights the volume, and hence the mass, of material that is actually produced by the flare. For the ICE 65% flare (Fig. 7b), the maximum number of particles peaks at around 0.3µm, similar to the SA flare, but there is a tail of larger particles that gives a substantial amount of material in the size range larger than 0.5µm. The volume plots for ICE 70% flare show somewhat more mass in the larger particle sizes.

Earlier studies of the SA flares suggested that a cooler burning flare would produce larger particles. However, the data gathered from our studies do not support this hypothesis. In fact small particles dominate the beginning and end of the flare burn when the burn is coolest and comparison between ICE 65% and 70% potassium perchlorate flares showed that the hotter ICE 70% produced larger particles. It appears that concentrations in the size ranges 0.2to 0.4µm and 0.4 to 0.8µm diameter are anticorrelated for the ICE flares, i.e., as particle concentrations in the size range 0.4 to 0.8µm increase, the concentrations in the size range 0.2 to 0.4µm decrease (Fig. 6b and c).

Variations in concentrations of larger particle sizes during the burn occurs for both airborne and ground-based tests and is related to the fact that the flare tube does not burn consistently with time. Burning of flare material can occur inside the tube, or when a section of the tube falls off, in the ambient air, resulting in erratic changes in temperature during the burn In general, larger particles are produced when the burn occurs inside the tube at higher temperatures, and smaller particles when the burning occurs in open air at cooler temperatures. This is consistent with the idea that higher burn temperatures produce larger particles, while cooler burn temperatures produce smaller particles. Different types of tubing could potentially stabilize the burn but these experiments fell outside the scope of the experiments described in the paper.

Ideally, information on the combustion temperatures of different flares is needed; however. Measuring burn temperature directly is very difficult and would require a very expensive optical pyrometer. To obtain relative information on the combustion temperatures of the flares, two platinum resistance temperature probes were mounted within the combustion section. The first probe measured temperature at the tip of the flare, the second measured temperature near the end of the combustion section. We were able to obtain a relative measure of the amount of heat generated during combustion from this temperature differential. Measurements indicated that combustion temperatures of the flares are in excess of 1500C.

Additional formulations were manufactured to study the effects of hotter burning flares on the particle size distribution. In addition, TEM samples were collected to study the chemical composition of different size particles produced by the flares. These tests were carried out on 23 June, 2004 at low relative humidities to measure the dry particle sizes (Fig. 8). Figure 9a shows the time history of the size concentrations of the combusted flare particles (ICE 65%), while Figure 9b displays the associated particle size spectra measured by the PCASP and SPP particle probes. Particle size spectra and burning characteristics were similar to previous flare tests and showed good reproducibility.

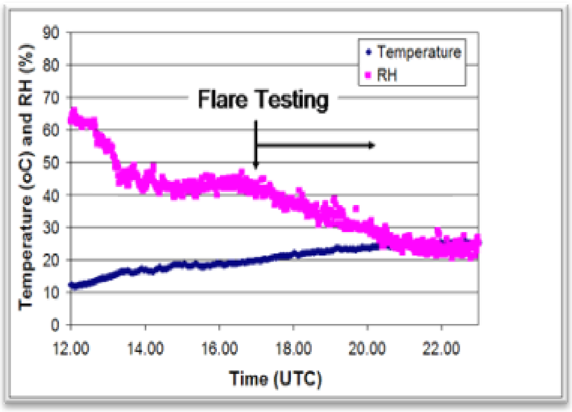

Figure 8. Temperature and relative humidity profile during flare testing on 23 June, 2004.

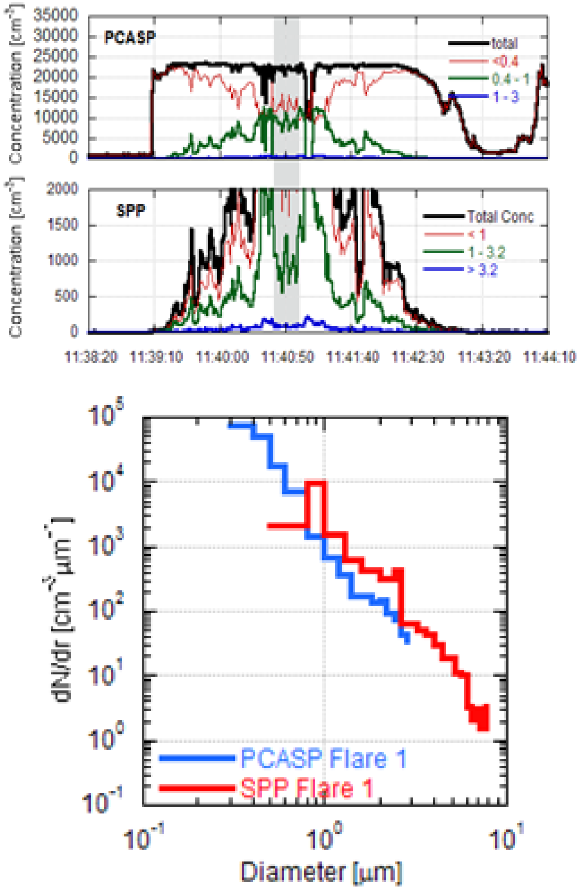

Figure 9. Time history of particle size distributions for combusted flares (a) associated particle size spectra measured by the PCASP and SPP particle probes (b) detailed size spectra for the shaded area in (a) on June 23, 2004.

To investigate the effect of $KClO_4$ on combustion temperature and particle size, flares with 65, 70 and 80% $KClO_4$.were tested. Figure 10 shows the number size distribution for these tests. These size distributions show that an increase in the amount of KClO4 slightly increased the number of larger particles. The ICE 80% flare closely reassembles its predecessor ICE 70%, with only a slight decrease in particle production measured by the PCASP probe and a small increase in concentration of larger particles measured by the FSPP probe. Thus, hotter burning temperature of the ICE 80% shifted the final size distribution towards larger sizes, but only by a small amount. The ICE 70% flare is now the most widely used hygroscopic flare in weather modification programs around the world.

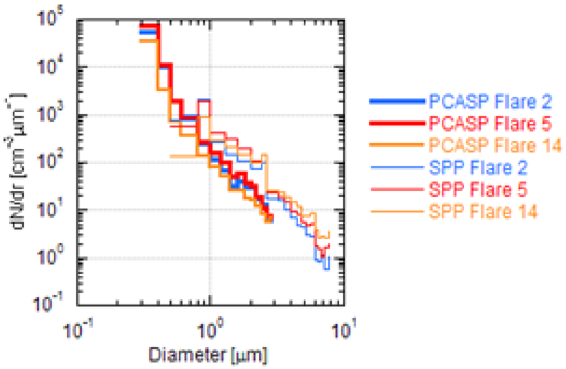

Figure 10. Particle size distributions from flares #2 (ICE 65%), #5 (ICE 70%) and #14 (ICE 80%).

6.2 Chemical composition of combusted particles produced by the ICE 70% flare

An important component of the flare test study was the investigation of the chemical composition of combusted particles, produced by the ICE flares. Individual particles were analyzed using transmission electron microscopy (TEM) at the John M. Cowley Center for High Resolution Electron Microscopy, Center for Solid State Science, Arizona State University.

This method has the unique advantage of providing size, shape, composition, crystallographic structure and speciation information for phase identification and determination to the extent of aggregation. Precise species characterizations can be determined for individual particles as small as 30 nanometers in diameter.

High-resolution imaging (HRTEM) was used to obtain details of features as small as a fraction of a nanometer, remnants of incomplete reactions, and surface coatings. Compositions were determined using energy-dispersive X-ray spectrometry (EDS) for elements heavier than Be.

Samples were collected on carbon-coated TEM grids during the flare tests on 23 June 2004 for the ICE 70% flare burns. Images from these samples show that particles are mixtures of single salt crystals (mostly KCl) and mixed salt aggregates (KCl and $CaCl_2$; Figure 11, 12). Single KCl crystals are typically euhedral and around 0.1µm diameter in size. Mixed salt aggregates are anhedral and typically between 0.8 and 1.5µm diameter. Thus, TEM data show that the larger particles produced by the flares are composed of mixed salt aggregates and are not single particles. Aggregation or coagulation of particles appears to be the primary mechanism producing larger particles.

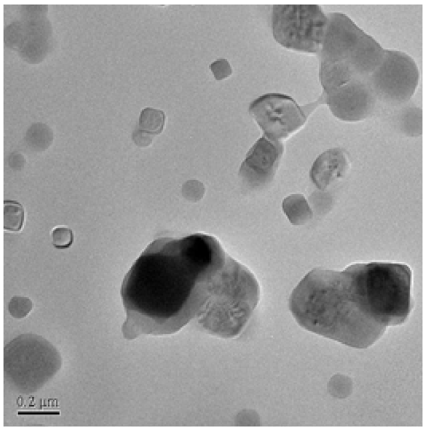

Figure 11. Bright-field TEM image of particles produced by the ICE 70% flare on a film carbon TEM grid.

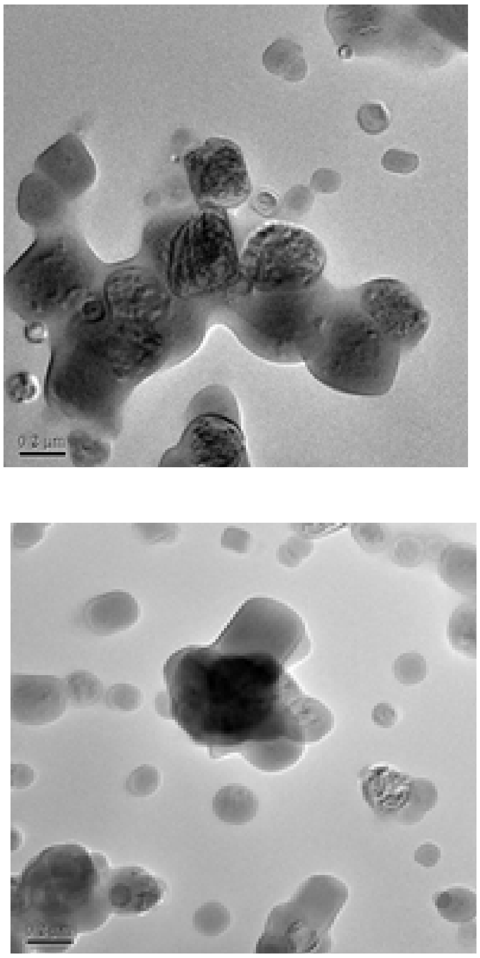

Figure 12. Bright-field TEM images of a) mixed salt aggregates (1.5µm) and smaller CaCl2 particles, and b) mixed salt aggregates (0.2-0.8µm diameter) and smaller CaCl2 particles produced by the ICE 70% flare.

EDS measurements on selected aggregate particles are shown in Figures 13 and 14. The analyses clearly show that cubic particles (~0.6µm diameter) are KCl and coatings are $Ca(Cl)_2$ (Figure 13), suggesting that $Ca(Cl)_2$ enhances aggregation because it remains longer in the liquid stage than KCl. No aggregates of solely KCl were observed.

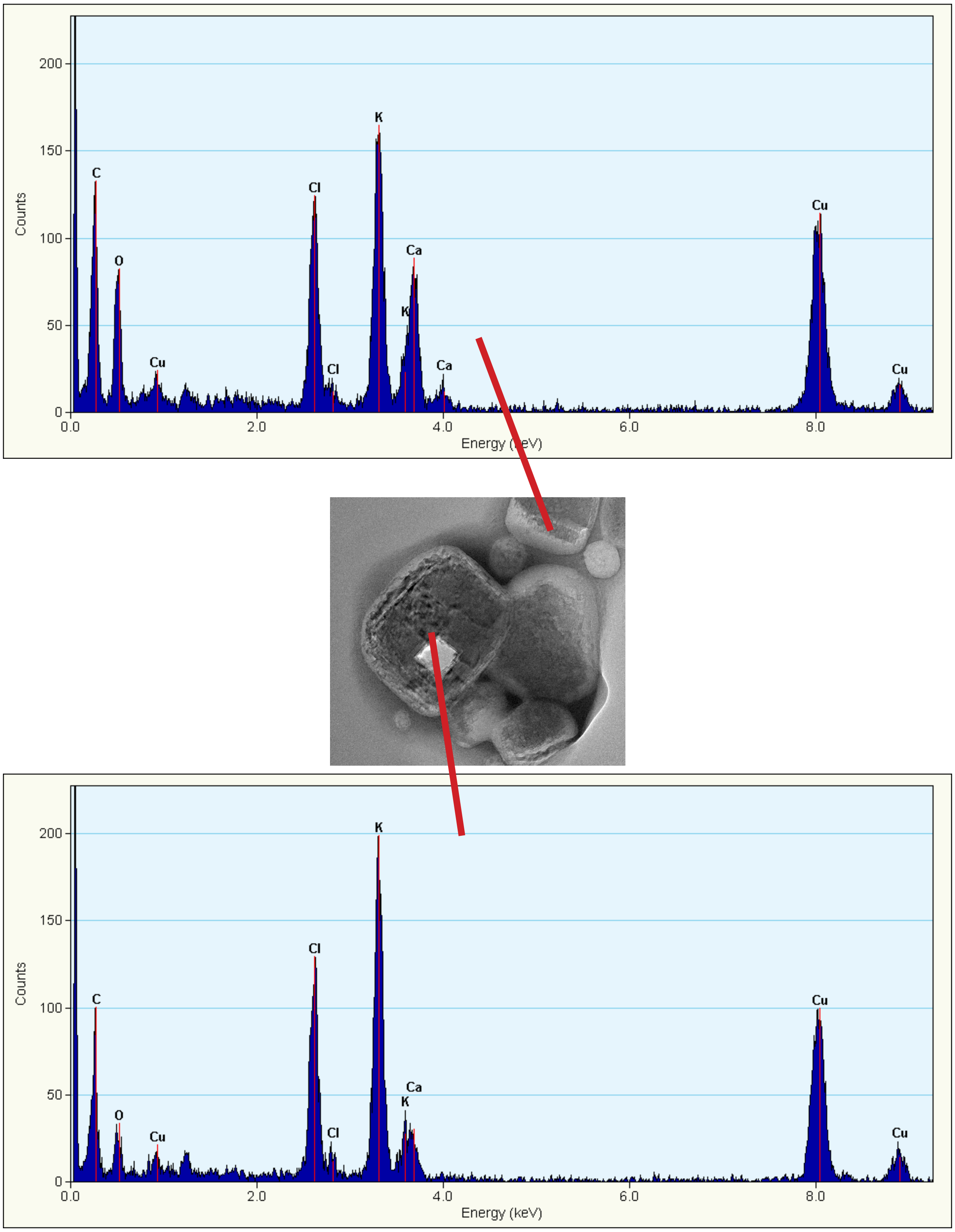

Figure 13. Bright-field TEM image and associated EDS analyses of a mixed salt aggregate (KCl and $CaCl_2$*) produced by the ICE 70% flare. Arrows show the locations of EDS measurements. Cu and C are background peaks related to the sample substrate.*

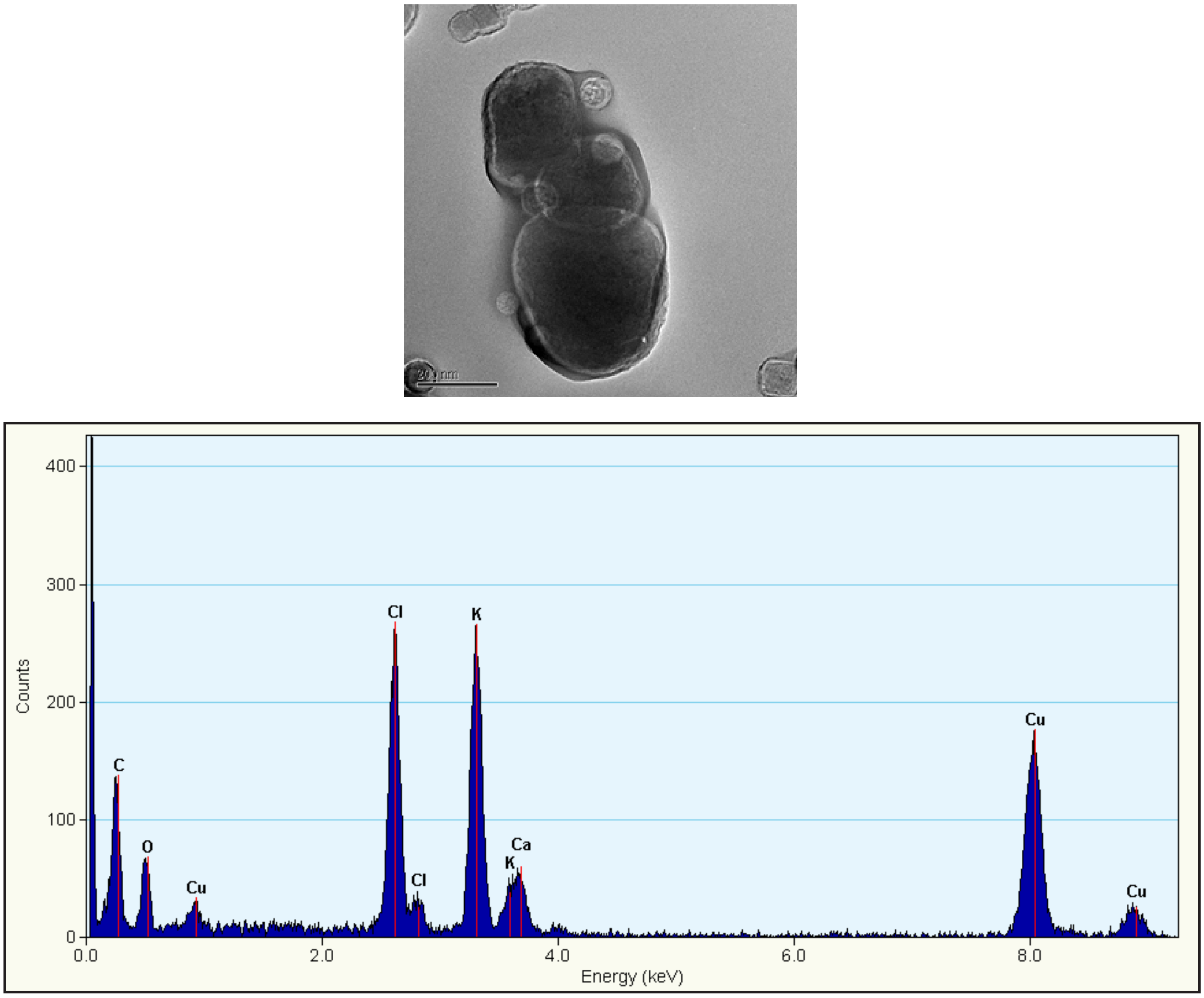

Figure 14. Bright-field TEM image and associated EDS analyses of a mixed salt aggregate (KCl and $CaCl_2$) produced by the ICE 70% flare. Cu and C are background peaks related to the sample substrate.

7. PARCEL MODEL CALCULATIONS TO DETERMINE EFFECTS ON DRIZZLE FORMATION

Combustion particles in the size range 1.0 to 6μm in diameter are substantially enhanced in ICE flares compared with previous flares, including the original South African flare based on the Hindman (1978) formula. We replicated the Cooper et al. (1997) parcel modelsimulations to investigate whether the ICE flare enhances drizzle production compared with the original South African flare, since this flare was specifically developed to increase drizzle concentrations.

The model represents the effects of condensation and coalescence during the adiabatic ascent of a parcel of air. Log-normal curves for particle size distributions from Cooper et al. 1997 and our test facility are displayed in Figure 15. The results of the model calculations are displayed in Figures 16 and 17. The model runs were conducted to show seeding effects, using the same run characteristics as Cooper et al. (1997). It is clear in Figure 17 that the new ICE 70% flare produces substantially more drizzle mass at shorter times than the South African flare. After 1 minute the new ICE flare initiates drizzle, concentrations of drizzle water reach a maximum at 10 minutes when the South African flare starts producing the first drizzle size drops. The drizzle results in a more effective coalescence process, forming rain faster than for the original South African flare. After approximately 10 minutes, the new ICE flare produces nearly two orders of magnitude more drizzle water than the South African flare. It is important to emphasize that the parcel model studies only indicate the initial response to seeding and after ten minutes the microphysics and dynamics interact and dominate the effects of seeding (Mather et al., 1997; Cooper et al., 1997).

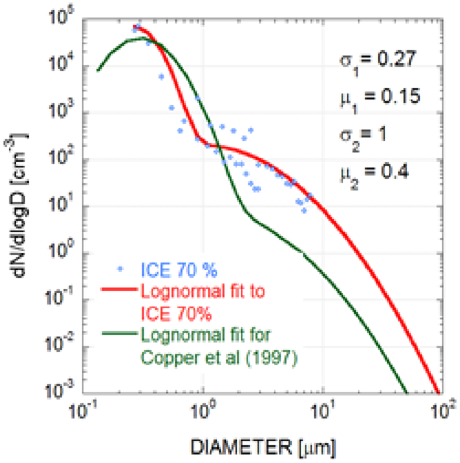

Figure 15. Size distribution of particles published by Copper et al 1997 for the original South African flare (green line) and as measured by our new flare test facility for the ICE 70% flare (red line). The blue dots represent the particle size distribution measured for the ICE 70% at the flare test facility. The characteristics of the 2 lognormal distributions for the ICE 70% flare are shown as an insert.

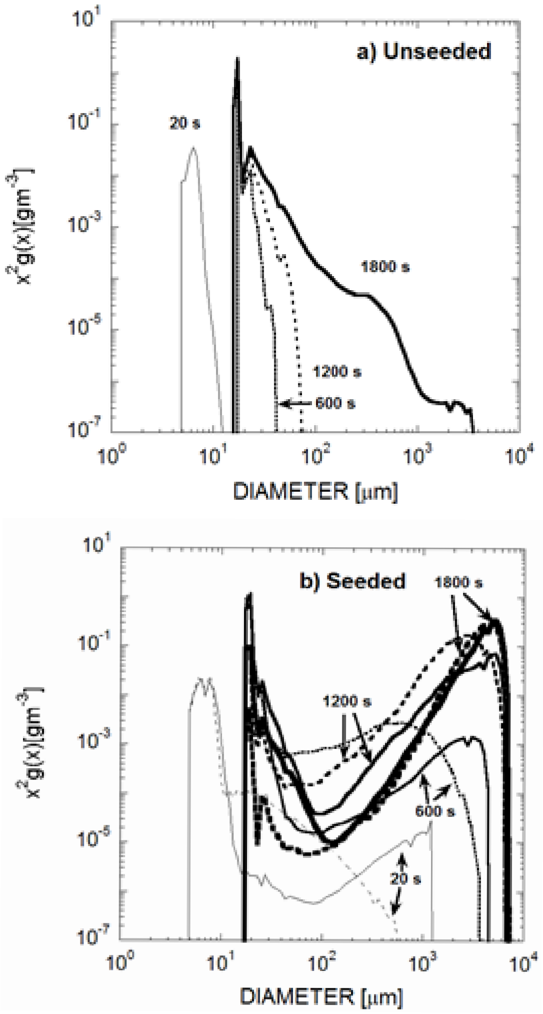

Figure 16. a) Mass distribution functions from Copper et al. (1997) for 20, 600, 1200 and 1800 seconds after passage through cloud base for the unseeded case. b) Mass distribution functions for the seeded case from Cooper et al. (1997) (solid line) and the ICE 70% (dotted line)

These results indicate that the ICE 70% flare is more effective in producing larger drizzle concentrations than the South African flare.

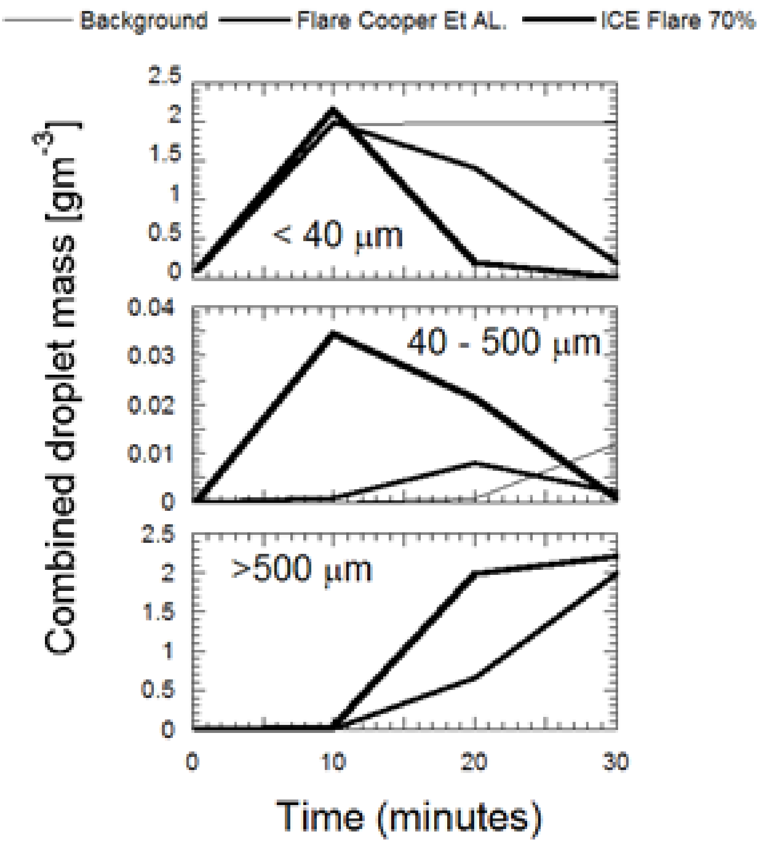

Figure 17. Changes in the distribution of the condensate between cloud droplets (<40μm), drizzle droplets (40 – 500μm) and rain drops (>500μm) after droplet activation: background case (thin solid line), Cooper et al (1997) (medium solid line), and the ICE 70% (thick solid line).

8. DISCUSSION AND CONCLUSIONS

The test facility was designed to provide a reproducible environment for combustion of flares and measurement of the resultant particles. The facility was used to evaluate the concentrations, sizes, and chemistry of flares with different chemical formulations Samples were collected isokinetically such that the characteristics of particle mass, number and size distributions remained unchanged between the different dilution stages. Diffusional and gravitational loss of particles was minimized through careful design of the facility.

In general, we found that variations in the total concentration of the particles produced by flares was small. However, the concentrations of larger particles (>1μm diameter) varied substantially during individual flare burns and among different flare types. These variations reflect both chemical composition (mesh size, purity, reactions within chemical species, flare material, cover material, etc) and manufacturing process.

Our first set of experiments evaluated formulations with cooler burn temperatures, since we surmised that there should be less volatilization, and consequently the possible formation of larger particles at lower temperatures. Although the new flare formulation (less Mg) had higher concentrations of particles in the 0.5 to 1µm range and the largest particles, the concentrations were not significantly different from the original South African flare. Our second set of experiments evaluated ICE 65, 70 and 80% $KClO_4$ hygroscopic flares. Contrary to earlier aircraft studies of flare material, our test data indicated that larger particles were produced by hotter burn temperatures.

The ICE 70% and 80% flares produced the highest concentrations of particles in size ranges important for drizzle formation.

The conclusion that hotter burning flares produce larger particles is somewhat supported by analyses of natural particles from flaming fires that produce numerous KCl particles (Li et al., 2002; Posfai et al., 2002). The size of the re-condensed KCl particles is likely related to cooling rate. Samples from biomass burning experiments indicate that KCl particles transform to potassium sulfate and potassium nitrate particles within 30 minutes of exposure to atmospheric sulfates and nitrates and these partciles are usually smaller than the original KCl particles and thus less effective in producing large cloud droplets. (Li et al., 2002; Posfai et al., 2002). These rapid transformations have implications for hygroscopic seeding. For example, if hygroscopic particles are not released at cloud base, where they can be directly incorporated into cloud droplets; then chemical reactions could take place that change their chemical and hygroscopic characteristics before they erach cloud based if dispersed from the surface. Such reactions have direct effects on the dispersal and effectiveness of hygroscopic seeding in polluted environments.

TEM analyses of the ICE 70% flare showed that the larger particles produced by these flares were aggregate mixtures of KCl and $Ca(Cl)_2$ and not single particles. Thus, aggregation or coagulation of particles is an important mechanism for producing larger particles. Chemical analyses identified $Ca(Cl)_2$ as a coating to all aggregates, suggesting this phase acted as a catalyst for aggregation. At this point, we do not fully understand how $Ca(Cl)_2$ acts as a catalyst. It could be related to the micro-scale meteorology around the burning flare, created by very small local regions of high humidity. In these regions, $Ca(Cl)_2$ could deliquesce, and wet other combustion particles, resulting in more efficient coagulation.

Our parcel model calculations for the new ICE 70% flare produced substantially more drizzle drops at shorter times than the original South African flare. Once drizzle formed the transformation to rainwater also proceeded at a faster rate than for the original South African flare. The model results suggest that the ICE 70% is highly suitable for hygroscopic seeding experiments.

Based on our experiments, it appears possible to tailor the particle size distribution of flares to suit specific seeding situations and environments. New flare development technology could explore the use of other materials such as desert dust and organic materials and their specific effects on water and ice nucleation, as well as other microphysical processes in clouds.

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2011 Annual Meeting

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Randy Julander, Park City Banquet Speaker

Comments on Current Dual Cloud Seeding Operations in Texas

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Jennifer Puryear[5], Robert Rhodes and Jonathon A. Jennings[6]

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ABSTRACT: Within the past three years, the weather modification programs in Texas have occasionally used hygroscopic flares as a complement for glaciogenic cloud seeding operations. Introduced at an exploratory level, those dual seeding (hygroscopic plus glaciogenic) operations have been systematically evaluated using TITAN in an attempt to obtain evidence of possible greater impacts on storm radar signals than those obtained only using AgI flares.   This article presents a summary of those evaluations.

1. Introduction

Operational programs in Texas have a relatively long history using glaciogenic seeding. In 1997 the already operating local programs introduced the use of the TITAN (Thunderstorm Identification Tracking Analysis and Nowcasting) software package which permitted a better interaction between the radar information and the operational meteorologists. Since TITAN also has an evaluation software package, corresponding quantitative evaluations were first introduced in 2000 in order to compare radar-derived properties of seeded and unseeded storms. The results have been systematically reported and have indicated positive signals in the radar variables associated with increases in precipitation for the seeded storms in comparison with their controls. In general terms, the cloud seeding operations have seemed to improve the dynamics of seeded storms.

The final conceptual model for glaciogenic cloud seeding operations in Texas was created after a research program led by the late W. G. Finnegan (2001), although it also owned features to previous research programs. In summary, seedable cells are selected among those with top temperatures about – 5^0 C but warmer than – 15^0 C. The glaciogenic material is released during the early stages of cell development, dosages are expected to reach the dynamic mode of seeding (~ 100 ice-nuclei per liter), and the operations should have a massive character (seeding of all possible seedable cells). Those operations are expected to modify the natural regime of the supercooled water in the seeded cells, empowering mainly the formation of ice-aggregates about – 5^0 C (Bates and Ruiz, 2002). As mentioned before, TITAN evaluations during the last 12 years have demonstrated positive results associated with the operations.

2. DUAL SEEDING

In August 1996, a case study and a non-randomized cloud seeding experiment were conducted on five convective clouds in Texas (Woodley and Rosenfeld, 1999 a and b).

The experiment offered an occasion to observe and compare radar measurements of seeded storms under different treatments (glaciogenic, hygroscopic or none). The authors reported that "the cloud seeded with hygroscopic flares 'out performed' the other three by a large margin and was anomalous relative to all other non-seeded clouds within the scan of the radar". The aforementioned case study (August 11th, 1996) involved a dual seeding operation with ejectable AgI flares near the cloud top (- 8° C) while hygroscopic flares were released at the base level. The test was evaluated as highly successful from an operational point of view. Although those results only allowed for heuristic interpretations, they suggested then that dual seeding (hygroscopic plus glaciogenic) might result in greater impacts than those expected with only one type of seeding.

Current dual cloud seeding operations in Texas are still at the exploratory level. There is a growing body of evidence that environmental conditions, like dust and other pollutants may be hurting the cloud efficiency for rain, especially at the warm levels (where the collision-coalescence mechanism dominates). An increased colloidal stability of natural clouds may also lead to a higher inception of precipitation at cold levels, with the subsequent higher probability for anvils (losses of humidity) and severity (intense precipitation, hail and gust at the surface). If this is the case, the hygroscopic part of the dual seeding action might help to alleviate those symptoms and also might allow for the formation of more graupel (soft hail about – 5° C) instead of hard hail at colder levels (about - 25° C). However, some observations are pertinent here. Seeding with hygroscopic materials in principle should conduce to slightly colder levels of droplet freezing, with a freezing point depression which is proportional to the number of solute particles per mole in the droplet (the van 't Hoff factor). Additionally, the high concentration of ions might slow down the natural nucleation rate of ice crystals, especially if Mg^{++} and Ca^{++} are present (Finnegan, 1998). Those counter effects might be detrimental for the purpose of empowering aggregation about – 5° C; therefore, a glaciogenic material would be necessary to reach the desired result. These statements constitute the basis for the current dual cloud seeding operation concept used in Texas:

1) Hygroscopic material is released in order to improve the collision-coalescence mechanism in seedable convective clouds, which in turn will produce larger droplets and eventually more graupel;

2) Glaciogenic material is simultaneous released with the purpose of counteracting the detrimental effects hygroscopic agents might have on ice-aggregation.

3. EVALUATION RESULTS AND BRIEF DISCUSSION

Within the past three years a total of 58 storms have received dual seeding in Texas. The details of this figure are offered on Table 1 below:

Table 1: Distribution of dual seeded cases per target area during the period 2009-2011 in Texas.

Project	Year	Dual Cases	Small Storms	Large Storms	Type B Storms
WTWMA (San Angelo)	**2009**	**5**	**3**	**1**	**1**
	2010	**4**	**1**	**1**	**2**
	2011	**4**	**1**	**2**	**1**
STWMA (Pleasanton)	**2010**	**7**	**3**	**3**	**1**
	2011	**9**	**5**	**3**	**1**
SWTREA (Carrizo Springs)	**2010**	**12**	**6**	**1**	**5**
	2011	**17**	**5**	**2**	**10**
Total		**58**	**24**	**13**	**21**

As Table 1 indicates, only 24 dual seeded cases (~ 41 %) were small clouds (precipitation mass less than 10 000 kton). Those are the clouds that usually get proper control matches by the TITAN evaluation (unseeded clouds with similar dynamics during their first 20 minutes of their evolution after TITAN assigns a track number) (see Ruiz-Columbié, 2004). Large and Type B storms (usually also large) rarely coexist in their regions with similar unseeded storms. For this reason, only the small seeded cases constitute the sample under analysis here. Table 2 shows the comparison with the sample of corresponding control cases:

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	73 min	45 min	1.62	62 (60)
Area	69.9 km²	45.9 km²	1.52	52 (42)
Volume	247.7 km³	150.4 km³	1.65	65 (45)
Top Height	8.3 km	7.6 km	1.09	9 (7)
Max dBz	53.5	51.9	1.03	3 (3)
Top Height of max dBz	3.6 km	3.5 km	1.02	2 (1)
Volume Above 6 km	74.7 km³	38.7 km³	1.93	93 (50)
Precipitation Flux	549.6 m³/s	332.9 m³/s	1.65	65(54)
Precipitation Mass	2590.5 kton	979.2 kton	2.65	165 (141)
Cloud Mass	204.8 kton	126.8 kton	1.62	62 (52)
η	12.3	7.8	1.58	58 (56)

Table 2: Seeded sample versus control sample (24 couples, averages)

A total of 111 BIP AgI flares and 24 hygroscopic flares were used in the sample with an excellent timing (98% of the seeding materials went into the targets in their first half-lifetime). The comparison seems to indicate that the seeded sample was favored by the seeding operations; whereas the dual character of those operations appears to favor the seeded clouds even with higher impacts than those usually reported in the evaluations of glaciogenic seeding. The increase in precipitation mass (141%) deserves special attention since typical increases are in a range around 100%. The increases observed here might indicate the existence of synergy due to the dual character of the seeding operation. Of course, this interpretation should be considered only heuristically because of the small sample, its pool nature, and the fact that the AgI dose was, on average about 55 ice-nuclei per liter which seems to be enough to produce a dynamic response by its own. However, the dual seeding operation seems to have clearly improved the dynamics of the seeded sample when compared with its corresponding control sample.

CONCLUSIONS

Exploratory dual seeding operations in three target areas of Texas were conducted on 58 convective storms during the seasons 2009, 2010, and 2011. The results of the TITAN evaluation for the 24 small seeded storms that obtained proper control storms appear to indicate that increases in precipitation mass might expect to be higher than those habitually observed in glaciogenic seeded cases. However, this preliminary result should be carefully handled and interpreted only as evidence and not proof of any potential synergy between hygroscopic and glaciogenic materials. There is a need for a randomized experiment using dual seeding in order to demonstrate its efficacy; such experiment should also have a strong microphysical component to prove the impacts that the hygroscopic action may have on the ice-phase.

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A NON-SILVER IODIDE CLOUD SEEDING NUCLEUS– Al_2O_3

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Forward (by Steven Chai)

Dr. William G. Finnegan, a chemist, devoted most of his research career to advancing our understanding of ice nucleation mechanisms and searching for new ice nucleus formulas as an aid to weather modification operations (especially directed toward enhancement of precipitation from cloud systems). This paper describes his final piece of research related to the development of a non-silver ice nucleus for weather modification applications in order to lighten the financial burden of weather modification programs impacted by the escalating price of silver. Mr. Lee Ates of Concho Cartridge in San Angelo, TX helped Bill on running the necessary experiments of this research project. Bill surely appreciated Lee's help. Bill said to me several times that without Lee nothing could be accomplished.

Bill and Lee started this research in early 2008. Bill would come up with a formula and Lee would run it in the cold box at Concho Cartridge. Since the acidity and the solubility of the ice nucleus is important in ice nucleation, Bill would calculate and recalculate the compositions of each chemical in a formula in order to have the right acidity and solubility. He once said "I was working on my new, hopefully effective, solution combustion mixture for ice nuclei generation. It's interesting chemistry, but whether or not it works is an unknown quantity. I'm working on that supposition that one should do something, even if it's wrong." The lack of a cloud chamber sometimes discouraged him. He said "I really wish the CSU cloud chamber was functioning." Not to be discouraged, he would then think and speculate that a cold box could establish various threshold temperatures and some idea concerning the density of ice crystal formation at cold temperatures could be ascertained. That's good enough for the new formula development. It still needed in-cloud testing to determine utility. When the news that there were plenty of ice crystals formed in an experiment executed by Lee, Bill would break out in a smile and said "Chemistry is really fun, when you get it to work." However, when an experiment failed, he would say "This is the way research goes. I will give Lee some new instructions and maybe we'll succeed next time." From these interactions we could see Bill's joy in working with chemistry. He thought about chemistry to his last day on earth. He was a genuine scientist and I deem it a privilege to know Bill and to discuss chemistry with him.

1. INTRODUCTION

Condensation-freezing ice nucleation has been proved to be a fast functioning winter cloud seeding mechanism (Feng and Finnegan, 1989, DeMott, 1995). The advantage of condensation-freezing nucleation (through use of silver iodide based hygroscopic ice nuclei) compared to contact nucleation (using pure silver iodide nuclei) is that the efficiency of ice nucleation does not depend on the slow collection rates between the ice nuclei and the super-cooled cloud droplets. Therefore, silver iodide based hygroscopic ice nuclei, e.g., AgI- 0.5 NaI or AgI-AgCl-4NaCl, are usually used in winter cloud seeding projects. Given the recent increase in the price of silver, the cost of silver iodide based seeding agents has become a large financial burden to weather modification projects. Therefore, there is impetus to develop a non-silver iodide based condensation-freezing ice nuclei. Based on research results of Finnegan and Chai (2003), the mode of adsorption and the hydrogen bonding of water molecules are the primary drivers for ice nucleation, not the structural match of silver iodide to ice crystals. Along this line of thinking we have recently identified an efficient ice nucleus and demonstrated its efficiency as a seeding agent.

2. THE CLOUD CHAMBER

Due to the absence of a functioning cloud chamber in the U.S. cloud physics community, a Sears and Roebuck 0.14m^3 deep freezer was used as a cloud chamber for testing the efficiencies of nucleation following the above-mentioned formulae. One of the authors, Lee Ates, set up the chamber in San Angelo, TX. The chamber uses an R134a refrigerant, with a precisely tuned thermostat. The temperature was verified with a National Institute of Standards and Technology (N.I.S.T.) certified thermometer. The chamber was operated at ambient pressure and a selected constant temperature during each execution of the experiments. A super-cooled water cloud was introduced by an ultrasonic nebulizer. A 2400 c.c. gas syringe was used to collect a Al_2O_3 nuclei sample from a burning pyrotechnic and followed by injection into the chamber. Observations were made through a glass window on top of the cold box. The box was illuminated by a light beam which shined across the box. Observations indicated how fast and efficient ice crystals form after injection of the nuclei sample into the chamber.

3. THE ICE NUCLEI FORMULA

Following the work of Finnegan and Chai (2003), it was hypothesized that hydrates, as a class, promote nucleation. A variety of non-silver iodide formulas were tested and it was found that AlF_3 formed abundant ice crystals in the chamber at -6°C as well as formation of ice crystals at -4°C. However, this formula only worked in pyrotechnics systems – it failed to work in acetone solution combustion systems. Further investigation identified Al_2O_3 as an excellent ice nucleus in the pyrotechnic system. Experimental replicates at temperatures -8, -7, -6 and -5°C in our chamber were all successful with many ice crystals formed in less than a minute after the sample was injected. The NS-1 (non-silver-1) pyrotechnic was commercially produced and further testing of the NS-1 flare is currently underway by a weather modification group in Texas to determine if the formula gives positive results at altitude.

This formula is also compatible with acetone solution combustion systems. Mr. Arlen Huggins of the Desert Research Institute tested the acetone-water solution of aluminum nitrate-9 hydrate ($Al(NO_3)_3$-$9H_2O$) that leads to the generation Al_2O_3 ice nuclei. Initial testing showed that ice crystals were formed after dipping a rod twice in solution and burned with a propane torch. Additional testing continues.

4. CONCLUSIONS

Although the cloud chamber used in these tests was less than ideal, results showed that large numbers of ice crystals were formed within a short time after the nuclei smoke was introduced into the super-cooled water cloud at the set stabilized temperature. The pending altitude tests of the NS-1 pyrotechnics are a necessary step to determine if this formula is effective for seeding.

ACKNOWLEDGEMENTS:

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