The Journal of Weather Modification

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Volume 38 April 2006

WEATHER MODIFICATION ASSOCIATION


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THE JOURNAL OF WEATHER MODIFICATION

COVER: Cover photos courtesy of Darryl O'Dowd. Top left: Littlefield, Texas 1999 – distant CB tops over 45,000 ft. catch the last rays of the sunset. Top right: Littlefield, Texas 1999 – Cessna 340 with ejectable flares, C-band radar in background. Center: Calgary, Alberta 2004 – replacing burn-in-place (BIP) flares after hail operations (J. Zimmer). Bottom left: Alberta 2004 – punching through daughter cells during hail suppression runs over Calgary. Bottom right: Olds-Didsbury, Alberta 2004 – WMI's C-band radar used in controlling three aircraft for hail suppression.

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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 38 volumes (40 issues).

Originally called the Weather Control Research Association, the name of the organization was changed to the Weather Modification Association in 1967. During its 55-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 $50 per black-white page is made for each page ($120 per color page) published in the final double-column format of the *Journal*. This fee is charged for all papers, foreign and domestic.

The general membership is open to all individuals and organizations who have an interest in any aspect of weather modification. The classes of membership and the present annual dues are:

Corporate:	$ 200
Individual:	$ 55
Retired:	$ 30
Student:	$ 15
Honorary:	$ 0
Associate Member	$2,000

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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Editor’s Message

It has been quite a year to move into the editorship of the *Journal of Weather Modification.* Steve Chai and Vikki Hall had everything very well organized, and will be helping us with getting Volume 38 printed at the Desert Research Institute printing facility. Last year, following the spring meeting, I was worried that maybe we would have trouble soliciting enough contributed papers to make a worthwhile Volume 38, and that my first year on the job would be a washout. As it turned out, at the very successful spring meeting in Silver Spring, and joint meeting in the fall with our European colleagues in Athens, there were many topics discussed and many presenters chose to contribute papers based on their recent work. We have five papers from Europe, and an additional seven papers from US authors. This is the largest collection of papers in one issue in many years. I want to thank the authors for their choice of the *Journal of Weather Modification* to publish their ideas and results, and the very helpful corps of reviewers who helped to review and improve these contributions prior to their acceptance for publication.

You will find that the range of topics discussed in Volume 38 is much broader than has been the case in recent past volumes. Publication of these papers does not imply endorsement of all they contain. In my view, the *Journal of Weather Modification* is a vehicle to facilitate technical exchange of ideas and information in the support of scientific and engineering progress. It is not a filter that passes only the lowest common denominator of accepted dogma. Please engage directly with the authors in response to the ideas they present, and consider the possibility of contributing next year to Volume 39 with your own ideas and results that may support or possibly take issue with those presented in Volume 38.

Much of the “boilerplate” material traditionally included in the Journal has been moved to the web site of the Weather Modification Association. Visit http://www.weathermodification.org to find our articles of incorporation, code of ethics, lists of certified operators and managers, committee rosters, lists of past award winners, and tables of contents for prior volumes.

Connie Crandall, publications specialist in the Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology, did the work of putting Volume 38 together, handling the organization and formatting of manuscripts as well as doing layout and design. Hilda Duckering provided her usual able assistance with organizational and financial matters. It has been a pleasure to work with them this year.

Sincerely,

Andy Detwiler, Editor

Dr. Joseph Warburton suddenly and peacefully passed away at home on Saturday, 30 April, 2005. He was born 16 May 1923, to Agatha and Joseph Leslie Warburton. He was a Born-Again Christian who served the Lord his entire life.

He served in the Australian Imperial Forces during World War II. Following graduation from Goulburn High School in Goulburn, NSW, Australia in 1946 he attended the University of Sydney, graduating with honors in physics and mathematics. Advanced studies in radio astronomy and the physics of the lower atmosphere led to a Master's Degree and Ph.D. at the University of Queensland. He was employed at C.S.I.R.O. in Sydney. He established 'The Warburton Family Science Award' at Goulburn High School to provide scholarships to outstanding science students.

In mid-1965, he, his wife Winifred and their seven children emigrated to Reno, Nevada, where he was appointed to a senior scientist position at the Desert Research Institute. In 1969-70 he served the University System as the President of DRI and later as the Executive Director of the Atmospheric Sciences Division from which he retired in 1993, the University Board of Regents awarding him Emeritus status. He was working on a weather modification program he developed for the Snowy Mountains Hydro-electric Authority in Australia, in addition to writing a book entitled "The Science of Weather Modification," when he passed away.

His scientific work is described in over 120 papers published in scientific journals in the US and other countries. He conducted research projects in Antarctica, France, Greenland, Switzerland, Canada, China, Australia, Morocco, Saudi Arabia, Iran and Spain.

Dr. Warburton was appointed a Fellow of the Australian Institute of Physics, a member of the American Meteorological Society, Secretary/Treasurer of the North American Interstate Council on Weather Modification, a member of the Antarctican Society and an alumnus of the University of Queensland. His scientific awards include the Antarctic Service Medal, the Vincent L. Schaefer Scientific award for outstanding original contributions in the field of weather modification, and his appointment as Visiting Fellow at the Australian National University in Canberra, Australia in 1996. He was recently honored for his work in the Antarctic by having a landmark named after him - "Warburton Ledge," located four miles east of Mount McClintock in the Britannia Range, Antarctica.

Joseph became a Master Mason in 1956. After coming to Reno, he joined Golden Lodge #50, F.& A.M. of Nevada where he served as Master in 1992 and 1993. He and his wife joined Adah Chapter #4, Order of the Eastern Star, of Nevada in 1984 and later affiliated with Naomi Chapter #16 in Yerington. He served as Worthy Patron of both Chapters. He was appointed as Grand Representative to the United Grand Chapter of Australia for 1994 and 1995. He was elected Grand Sentinel for 1996-97 and Worthy Grand Patron for 1998-99. Joseph was also a 32° Scottish Rite, Noble of Kerak Shrine and served in York Rite as Eminent Commander of Lahontan Commandery #7, Knights Templar and as Excellent High Priest of St. John's Chapter, Royal Arch Masons of Nevada and a member of KYCH. Joseph also was very active in the Rotary Club of Yerington.

He is preceded in death by his wife of 55 years, Winifred, his siblings Leslie, Ethel, George, Harold, William, and Florence. He is survived by his sister, Thelma Dugan of Sussex Inlet, and brother Neville (Marge) Warburton of Goulburn, NSW, Australia; his children in the USA - Denise (Les) Linaman, Anthony (Charlotte) Warburton, Alison (Jay) Degn, Gail (James) Jesch, Peter (Cammie) Warburton, Rebecca Cherti, and Catherine (Marc) Morea, 22 grand-children, and 10 great-grand-children. He is also survived by many nieces, nephews, close friends, and their families in Australia. He remained very close to Winifred's brother, Rupert Brown and his wife, Pat, in Canberra, Australia.

His contributions to the scientific community, Masonic fraternity and humanity were larger than life. He loved laughing, farming in Yerington, playing golf, the piano, telling funny stories and jokes, and spending time with his family and special friends. He will be greatly missed.

Funeral services were held at Trinity Episcopal Church on Island Ave., Reno, Nevada on Friday, 6 May 2005, preceded by a Masonic Funeral Service, at Walton's Funeral Home, Reno. In his memory, please make contributions to Trinity Episcopal Church or The Warburton Family Science Award Foundation at Citibank, 2375 S. Virginia Street, Reno 89502, to benefit science students at both Reno High School and Goulburn High School.

Joe and wife Winifred

Tom DeFelice

Note: As I began to construct my contribution, and before contributions from others started to arrive, Rick Stone effortlessly noted that Joe was an optimist, and one of the luckiest guys he had met, since you could count on him to stir something up. Joe was a notable mentor. RS is right, Joe was an optimist. Joe's optimism and general, successful approach toward everything he undertook, contributed to his ability to consistently "… stir something up", like funding to support weather modification efforts. Joe was accomplished, honest, understanding, and approachable. I count my blessings that I was able to stay in contact with Joe over the years, and will miss our frequent 'heart-to-heart' chats. All was well, and all will be well. Cheers Joe, thanks, and best wishes.

Rick Stone

"Tom's comments are pretty good and on the money. You might replace the word optimist with eternal optimist and always someone who thought the best of any situation that developed, good or bad! Joe was an extremely insightful scientist but someone that you would prefer not to work on the technical end of things. It's a trait that I've seen with a lot of good scientists and why he surrounded himself with some of the best technicians and engineers that I've had the pleasure to know and work with."

Neville Fletcher

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Dr. Joseph Warburton in Australia –

I first met Joe Warburton when I returned to Australia in 1956 after spending three years at Harvard. Both of us were then working at the Radiophysics Laboratory of CSIRO, the Australian Commonwealth Scientific and Industrial Research Organisation, in Sydney. The Laboratory, located then on the campus of Sydney University, had been founded in the early 1940s to advance Australia's wartime efforts in radar technology, and continued after the war in several other related areas. While some of these, like development of advanced aircraft guidance and landing systems, were straightforward though important extensions of radar technology, the laboratory also branched out into several new fields.

The first, and ultimately the most successful of these new fields was radio astronomy, in which scientists in the Division such as Joe Pawsey, John Bolton, Bernie Mills, Paul Wild, Ron Bracewell, and W.N. (Chris) Christiansen made notable pioneering advances. Australia has peculiar advantages in astronomy, since its skies are clear and its latitude gives it a clear view of the center of our galaxy. There are major optical instruments at the Anglo-Australian Observatory, and the Parkes radio-telescope, built in the early 1960s, continues to play a major role in space exploration as well as being part of the Australia Telescope interferometer array. A newer version of the Mills Cross is also in operation. I give this detail about radio astronomy because Joe began his research career at CSIRO in the radio astronomy group and worked with them for several years.

Other areas of research interest in the Division developed during the 1940s and 1950s under the leadership of E.G. (Taffy) Bowen, who had worked on radar in England during the war. One of these was semiconductor devices, which became of great industrial interest and was my own area of research when I joined CSIRO. The other was cloud physics, originally appropriate because of the possibilities afforded by radar examination of clouds and particularly the "melting band" in large cumulus clouds, but later concentrating on the possibilities afforded by the newly developing field of cloud seeding, with work on this in the Division beginning in the late 1940s. The possibility of increased rainfall is immensely important to Australia, since with one exception the country lacks inland rivers, suffers many years of drought interspersed with years of floods in tropical areas, yet relies for its international income largely on the export of agricultural products, together with coal and iron ore.

Adopting the philosophy that "physics underlies everything" so that physicists are infinitely flexible, the new field of cloud physics was staffed largely by research scientists drawn from other areas of the Laboratory. Among those involved were Joe Warburton, transferred from his former field of radio astronomy, and later myself transferred from semiconductor device physics. The major, and by then well established, researchers in the group were Pat Squires, Jack Warner, Jim Telford, Sean Twomey, Keith Bigg, Otto Adderley, and E.J. (Pat) Smith. Taffy Bowen was also very actively concerned with the program and had his own particular interests in long-range weather prediction and in the effect of meteor showers on rainfall. I mention these names since many of them moved to the US in the 1960s and 1970s at about the same time as Joe.

Cloud seeding became a major program of the Division in the 1950s, with particular emphasis being placed on carefully designed experiments using both control areas and randomized seeding. Initial experiments used dry ice pellets dropped from aircraft, but this technique was soon replaced by seeding using silver iodide smoke. Limited-area programs are the easiest to carry out for research purposes, and the areas chosen were in the mountains of Tasmania and in the Snowy Mountains area west of Sydney. Because both these areas provide water for major hydro-electric programs, as well as for agriculture, any increase in precipitation would be of considerable commercial value, thus justifying the use of aircraft for the experimental seeding program. The program made use of rather old aircraft supplied by the Royal Australian Air Force, and these were mostly adequate, but there was one fatal crash at an early stage. Joe was a major contributor to this experimental program, while my own interests were in the basic physics of nucleation and crystal growth, but the Division was a very "collegiate" environment in which people from all the research groups, including Taffy Bowen as Chief, regularly had morning tea, lunch and afternoon tea together, so we all knew each other and were generally aware of research progress in all the fields.

Throughout the program there was controversy between CSIRO and the Australian Bureau of Meteorology, then led by its Director C.H.B. (Bill) Priestley, though some of this was due to the unorthodox views of Taffy Bowen about meteor showers and about long-range weather prediction. Following Bill's retirement, collaborative relations were re-established by the new Director, John Zillman, later to be President of the WMO.

As with most cloud-seeding programs throughout the world, results were controversial, with suggestions of confusing persistence effects, though the general conclusion was that a useful increase in precipitation could probably be achieved over these mountainous areas with no significant decrease in precipitation downwind. The Tasmanian experiment, converted to an operational program and conducted by the Tasmanian Hydro-electric Authority, has continued until the present, using ground-based generators, though the Snowy Mountains experiment was terminated in the 1960s but has recently been revived, as will be related in another contribution.

The active involvement of CSIRO in cloud seeding ceased in the mid-1980s, following lack of success with a crucial test experiment in Victoria. I must confess that I was Director of the CSIRO Institute of Physical Sciences at the time, having returned to CSIRO in 1983 after twenty years as a Professor of Physics, and so I was ultimately responsible for the decision. This did not mean the end of related research in CSIRO, however, because there was already a major Division of Atmospheric Research in Melbourne, and many of the senior staff transferred there or to the Research Centre of the Bureau of Meteorology.

Joe Warburton's involvement with rainmaking experiments in Australia began again in about 2003, when Snowy Hydro decided to revive cloud seeding in their catchment area and Joe returned as their chief scientific adviser. His office during extended visits to Australia in 2003 and 2004 was in our Research School at the Australian National University, and we saw each other regularly at morning and afternoon teas in the staff common room and at lunch with our small group of retired Visiting Fellows. His contributions to the general field of cloud physics will be long remembered, and it is to be hoped that ultimate success with the Snowy Mountains scheme will serve as a lasting memorial.

Barry Dunn
Retired Executive Officer - Water, Snowy Hydro Limited

Dr. Joseph Warburton's involvement in Cloud Seeding in the Snowy Mountains - 1986-2005

Dr. Warburton first became involved with the current interest in cloud seeding in the Snowy Mountains as a result of a conference that he attended in Canberra in 1986. Eastern Australian was then in the grips of a long drought and authorities were keen to minimise its effect on the electricity and irrigation industries.

A desk study followed to evaluate balloon sounding data and determine whether local conditions would be suitable for cloud seeding. The results of this study were encouraging and Dr. Warburton was commissioned to undertake field data collection studies over the following two winters. Dr. Warburton spent the winters of 1988 and 1989 with his wonderful wife Winifred, in the Snowy Mountains and during that time they made many friends. His work involved the collation of data from radar, radiometer, ice crystal habit and balloon investigations. Some of the equipment can be seen with Dr. Warburton in the photo taken during the 1988-89 campaign at Khancoban.

Dr. Warburton's report of his field investigations verified the earlier desk study's findings that there were sufficient opportunities to successfully seed winter cloud systems passing over the Snowy Mountains (these findings have since been further strongly supported by results of the first two years of the current cloud seeding experiment).

His work led to the preparation of an environmental impact assessment which foundered at that time because of an overly powerful green movement and the absence of any political will. Dr. Warburton was undaunted by this temporary setback and continued to make periodic visits to Australia where he revised the experimental design to make it more environmentally acceptable, had meetings with politicians and officials and generally kept the cloud seeding dream alive. The current cloud seeding experiment owes its very existence to his unswerving persistence and sense of national pride and national good.

Dr. Warburton's two driving passions were his family and his science. He was born in the town of Goulburn some 200 km north of the Snowy Mountains. He never lost sight of his origins, or his love of science, so much so that he created a perpetual science award at his old school some eighteen months prior to his death.

Photos of Joe, family, friends and some colleagues, courtesy of Barry Dunn.

Daughter Denise, Son Peter, and Joe

Joe at Olson's Lookout

Equipment at Khancoban

COMPARISON OF THE HAILSTORM CHARACTERISTICS BETWEEN TWO DIFFERENT AREAS IN GREECE

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Abstract: The Greek National Hail Suppression Program using airborne seeding is applied in Central Macedonia and Thessaly in the period April to September, covering an area of 5,000 square kilometers. In the present study, the storm characteristics of the two protected target areas, during the period April to August 2005, are described and are compared. The analysis utilizes radar data recorded by the TITAN system. The results will contribute to the knowledge of the storms in the area.

1. INTRODUCTION

In the present study the storm characteristics are examined and are compared for two different areas in Greece. The areas, about equal in size, are the project areas, Area-1 and Area-3 and 3b (shown in Figure 1), where the Hellenic Agricultural Insurance Organization (EL.G.A) applies the Greek National Hail Suppression Program (GNHSP) using airborne seeding. (Tzoumaki, 2006). The aim of the study is the contribution to the knowledge of storms in the area and consequently to the planning phase of a pilot hail suppression project with the use of ground generators for cloud seeding, which EL.G.A has decided to implement.

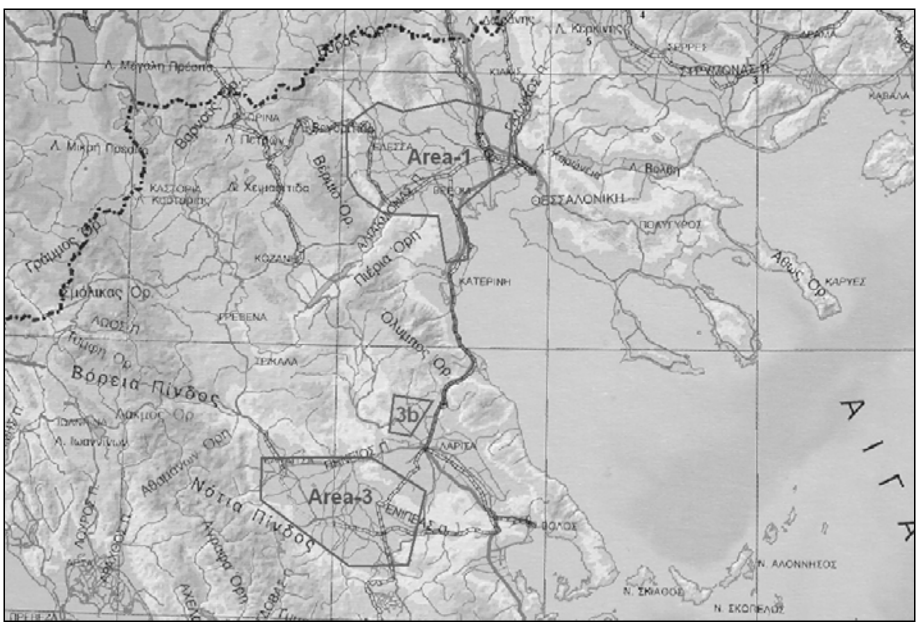

Figure 1: A map of northern Greece showing the location of the two project areas Area 1 and Area 3, 3b of the GNHSP.

2. CHARACTERISTICS OF STORM CELL COMPLEXES

The analysis utilizes radar data of the EEC S-band meteorological radars installed at Macedonia and Larissa Airports. It is mentioned that the distances of the radars from the center of the relevant target areas are about the same. The same procedure of calibration, providing both radars about the same level of sensitivity, is also followed. The data recorded by TITAN, Thunderstorm, Identification, Tracking, Analysis, and Nowcasting system described by Dixon and Wiener (1993), are being analyzed, creating a sample of Storm Cell Complexes structured data for each area. The data were recorded during the storm activity from April to August 2005.

Storm Cell Complexes (SCC) are defined as Radar echoes, convective in nature, with cell reflectivity equal or greater than 35 dBZ at the -5^0 C level or higher. The reflectivity threshold of 25 dBZ at the -5^0 C level or higher was used to identify the beginning and the end of the cell in the case where the SCC is consisted by one cell, and the beginning of the first and the end of the last cell respectively, when the SCC is consisted by more than one cells.

The SCC are composed of short-lived units of convection, referred to as ordinary cells and rarely of much more vigorous units of convection known as supercells.

Every SCC is identified with one of the classes of the primary and secondary hailstorm classification according to Browning (1977). The SCC categories are the Unicellular type that may consist of a Single isolated ordinary cell or a Supercell, the Multicell type with a cluster of cells, not forming in a distinct line, and the Line type containing cells along a line.

A Supercell type is a unicellular SCC with a single isolated supercell, which is long lived, severe, and shows a vault in a cross section. In the two observed cases they had started as multicell but gradually merged in a cell.

A typical Multicell type contains two or more radar cells at any given time, which are at a different evolution stage. New radar cell grows rapidly on the flank of the mature cell and becomes the storm center, meanwhile the previous cell begins to decay while another forms.

The Line contains cells along a line, moving perpendicular to its axis. A Multicell or a Line usually contains ordinary cells and rarely a mixture of ordinary cells and supercells.

In the sequence, the symbol “S” will be used for the Unicellular storms of a single ordinary cell, the symbol “SU” for the Unicellular storms of a Supercell, the symbol “M” for the Multicell storms and the symbol “L” for the Line storms.

A meteorologist, who was the radar data analyzer, did the SCC selection.

The SCC characteristics, which were examined, are:

- The SCC date of occurrence
- SCC number
- First appearance (“first echo”) time (UTC), when maximum radar reflectivity was 25 dBZ at the -5^0 C level or higher,
- Dissipation time (UTC), when maximum reflectivity became less than 25 dBZ at the -5^0 C level or higher
- Life time (min), subtracting the First appearance time from the Dissipation time
- “First echo” Region, in the project area or in the buffer zone using the West (W), North (N), East (E) and South (S) part of it in relation to the project area
- Storm classification Type
- Maximum reflectivity (dBZ) at the -5^0 C level or higher during entire lifetime
- Maximum height (Km) of the cloud top during the entire lifetime
- Motion: Direction - from (azimuth) and Speed (Km/h)

3. ANALYSIS

The monthly distribution of SCC and SCC days per area are given in Table 1. A SCC day is defined as a day when at least one SCC was recorded in the area by radar.

The daily distribution of SCC per area, within 3-hour time intervals in UTC (local time is equal to UTC plus 3 hours), is shown in Figure 2.

TABLE 1: Monthly distribution of SCC and SCC days

Month	Number of SCC days		Number of SCC	
	Area-1	Area-3, 3b	Area-1	Area-3, 3b
April	0	1	0	3
May	9	9	42	73
June	4	4	10	8
July	12	5	39	17
August	5	5	33	24
Total	30	24	124	125

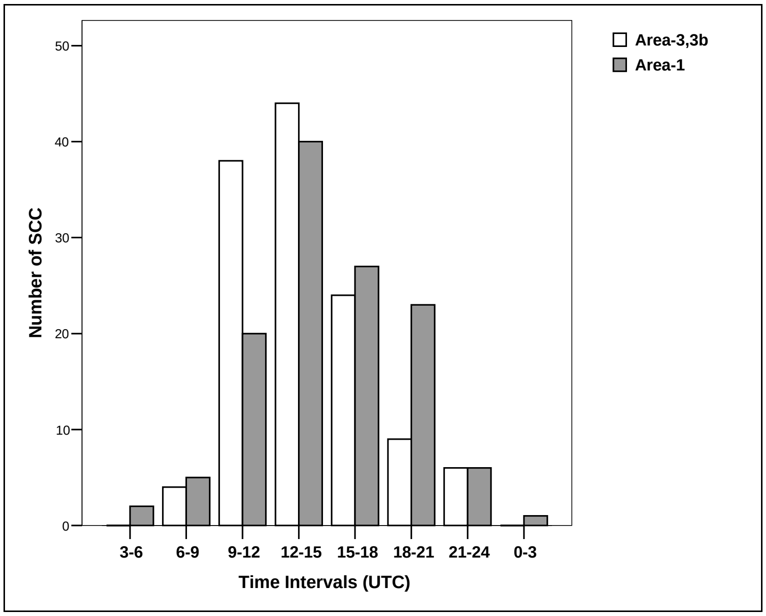

Figure-2: Frequency histogram of SCC according to time of day (UTC).

Table 2 gives the SCC "First echo" region per area, in the Area and in the north (N), west (W), south (S) and east (E) part of the buffer zone. It is remarked that only in this spatial distribution, the Area-3 is divided in the big part of Area-3 and in the small part, called as Area-3b, for more detail examination.

TABLE 2: SCC "First echo" regional distribution.

	Area-1		Area-3		Area-3b	
	Number	%	Number	%	Number	%
In Area	75	60.5	63	50.4	7	5.6
N buffer	8	6.5	31	24.8	4	3.2
W buffer	17	13.7	4	3.2	5	4
S buffer	11	8.9	6	4.8	0	0
E buffer	13	10.4	5	4	0	0
Total	124	100 %	109	87,2%	16	12,8%

Table 3 gives the SCC direction of movement distribution using the eight classes of azimuth orientations, e.g. a storm motion from the northeast is shown by the symbol NE and the stationary case with the symbol ST and Table 4 gives the SCC types per area.

TABLE 3: SCC Direction of movement distribution.

		N	NE	E	SE	S	SW	W	NW	ST
Area-1	**No.**	14	7	19	7	20	11	37	4	5
	%	11.3	5.7	15.3	5.7	16.1	8.9	29.8	3.2	4
Area-3, 3b	**No.**	35	45	2	0	5	12	7	8	11
	%	28	36	1.6	0	4	9.6	5.6	6.4	8.8

TABLE 4: SCC Types according to Area.

	Area-1		Area-3, 3b	
	Number	%	Number	%
S	54	43.5	47	37.6
M	70	56.5	75	60
SU	0	0	2	1.6
L	0	0	1	0.8

In the Table 5 are presented the statistics, including the mean (M), standard error (SE), minimum (Min), maximum (Max), lower (L) and upper (U) bound of the 95% confidence intervals of the mean and the total number (N) of SCC for the Life time (L.T.), Maximum Reflectivity (R), Maximum Height (H) and Speed (V) per area.

TABLE 5: Statistics of SCC Life time, Reflectivity, Height and Speed according to Area.

	Area-1				Area-3, 3b			
	L.T. (min)	R (dBZ)	H (Km)	V (Km/h)	L.T. (min)	R (dBZ)	H (Km)	V (Km/h)
M	55.1	50.3	8.9	26.4	69.1	53.7	8.5	18.3
SE	1.98	0.54	0.14	1.23	3.39	0.51	0.14	0.91
Min	22	39	5.5	0	19	35	5.5	0
Max	137	69	12	61	211	68	13	43
L	51.8	49.4	8.7	24.4	63.5	52.8	8.3	16.8
U	58.4	51.2	9.2	28.4	74.8	54.5	8.8	19.8
N	124				125			

The Kolmogorov – Smirnov test was applied and the Normal Probability plots were used to check the normality assumption for the distributions of the above four parameters in Area-1 and Area-3, 3b. The results show that the normality holds only for the Speed ($p > 0.20$). Therefore, the t-test applied for the Speed to check the difference in means between the two areas and the non-parametric Mann – Whitney test for the Lifetime, Reflectivity and Height.

In the first case, the Levene's test showed that equal variances were not assumed ($F=5.974$, $p = 0.015$) and the relevant t-test showed that, the difference in means of the Speed between the two areas was statistically significant ($t=5.254$, $df=227.95$, $p < 0.001$).

In the second case, the non-parametric Mann – Whitney test showed that the differences in means of the Lifetime and Reflectivity between the two areas were statistically significant ($U=6102.5$, $p = 0.004$ and $U=5085$, $p < 0.001$ respectively) whereas the corresponding difference of the Height was not ($U=6732.5$, $p = 0.071$).

Using 0.05 as the significance level led to all the above results. However if 0.10 had been selected as the significance level, the difference in means of Height between the two areas would have been indicated as statistically significant ($p = 0.071$). The statistical software of SPSS was used for the above analysis.

4. CONCLUSIONS

From the analysis above, comparing the values of the parameters that characterize the storm activity in the Area-1 and Area-3 we can make the following conclusions.

The number of SCC for Area-1 (124) is about equal with the number for Area-3, 3b (125), but the number of SCC days is greater (30 for Area-1 and 24 for Area-3, 3b). From the monthly distribution can be noted that the greatest number of SCC days was recorded in July (12) for Area-1, however the greatest number of SCC was 73 during 9 days in May for Area-3, 3b. For Area-1, the greatest number of SCC occurred in May (42). For Area-3, 3b, May recorded the greatest number of both SCC (73) and SCC days (9).

From the daily distribution can be noted that the afternoon hours from 09:00 up to 15:00 UTC (12 to 18 local time), the number of SCC for the south Area-3, 3b is greater than for the north Area-1 and the opposite happens for the rest of the day. In the 12:00-15:00 UTC interval (15 to 18 local time) was recorded the greater number of SCC for both areas.

From the SCC "First echo" region distribution it is noted that in both areas the greater number of SCC has the first appearance inside the areas (60.5% for Area-1 and 56% for Area-3, 3b), while the second region is the west part of the buffer zone (13.7%) for the Area-1 and the north part (28%) for the Area-3, 3b.

The 29.8% of the SCC for Area-1 have direction of movement from west and 36% for Area-3, 3b from northeast.

In both areas the Multicell storms are the most frequent type of SCC, which has been recorded. In the Area-1, only Unicellular storms and Multicell storms were observed, while in the Area-3, 3b all the types of SCC and specifically, one case of Line storms and two cases of Unicellular storms of a Supercell were observed.

The SCC cloud top Height for Area-3, was less than the mean Height for Area-1 but the differences were not significant. The mean SCC Reflectivity and Lifetime were significantly greater for Area-3 than Area-1, while the Speed was significantly less.

The 2005 storm season was the most active season in the history of the GNHSP. These results are only based on one year, therefore, more years should be analysed to see if these results are representative of the longer-term climatology for the region.

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SEEDING OPERATIONS IN THE GREEK NATIONAL HAIL SUPPRESSION PROGRAM

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Abstract. The Hellenic Agricultural Insurance Organization (EL.G.A.) is a public organization and the main insurance carrier of the agricultural production in Greece. The Meteorological Applications Centre (KE.M.E.) is the section of EL.G.A. which has conducted, since 1981, the Greek National Hail Suppression Program using airborne seeding, aimed at reducing insurance payments due to hail damage. The Program is being applied in Central Macedonia and Thessaly in the period April to September, covering an area of 5,000 square kilometers. The cloud seeding is performed by three aircraft releasing AgI in developing hail-bearing clouds as indicated by radar. The purpose of this study is the evaluation of the seeding operations that took place during the period April to August 2005. The seeding variables such as location, time and seeding rate are examined. In addition, the comparison of seeding rate between different types of storms is examined.

1. INTRODUCTION

The Greek National Hail Suppression Program (GNHSP) conducted by the Hellenic Agricultural Insurance Organization (EL.G.A.) in Central and North Greece is based upon airborne seeding. GNHSP is based on the conceptual model of beneficial competition (see for example English, 1986) using AgI as the seeding material. In the 1984-1988 operational and research period of the program a randomised crossover experiment took place for the protected area A1 (shown in Figure 1), giving encouraging results (Karacostas, 1984).

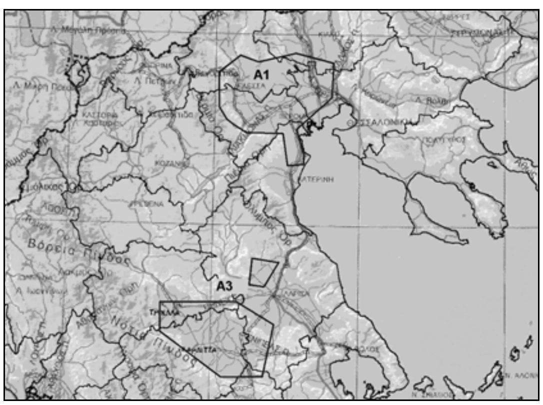

Figure 1. Map of Northern Greece showing the location of the two protected areas designated A1 and A3.

Nowadays and for the period 2004-2008, EL.G.A. designed the GNHSP to run for two areas with a special insurance interest (designated A1 and A3). GNHSP operates during the warm season of the year (April 1st to September 30th), according to climatological studies indicating this period as a hail risk period for the particular areas (Kotinis-Zambakas, 1989; Sioutas, 2003).

This study examines seeding parameters of the operational period April 2005 to August 2005 to support the research and development plans of the Meteorological Applications Centre (KE.M.E) regarding optimization of operations and preparation for future weather modification projects.

In general, there are three key parameters to be examined when assessing a seeding project. These are: seeding location, time of seeding, and seeding rate. This study analyzes the time and the seeding rate. Also the geographical location is analyzed but not relative to the storm.

2. OVERVIEW OF THE GNHSP

A brief description of the program routines is presented at this point for the understanding of the following study. The seeding operations are based upon the specialized forecast of hailstorm occurrence and the detection, tracking and recording of storms by two S-band meteorological radars (one for each area), 24 hours per day.

The equipment of the GNHSP consists of two EEC S-band meteorological radars, TITAN (**T**hunderstorm **I**dentification **T**racking **A**nalysis and **N**owcasting) radar recording, analysis, and display software as described by Dixon and Wiener (1993); forecasting means, a network of 138 hailpads installed in the project area A1 as described by (Rudolph et al., [1989]); and three prop-jet seeding aircraft of EL.G.A.'s contractor.

At GNHSP weather forecasting takes place twice a day, using nowcasting models, satellite images and other tools, for producing a daily hail risk index. This index besides radar observations determines the readiness status of the aircrew to be set at either 15 or 45 minutes. The radar controllers survey the weather on a 24-hour basis monitoring the TITAN displays by the two-radar network. When the first echo of the day appears the controllers make the following decisions:

- change the crew readiness status to 15 minutes
- launch a seeding aircraft
- identify the preferred seeding place and the seeding techniques (top or base)
- request the start of seeding
- request a seeding rate depending on thunderstorm intensity (general rule: one top flare every 5 sec, one base flare every 4 minutes).
- request the stoppage of seeding
- request the aircraft return to base
- change the crew readiness status to 45 minutes

It is mentioned that there is not a prioritization between the areas or inside each area.

These decisions affect the quantity and quality of the seeding. The parameters chosen for assessment are: Start Seeding Response Time, Seeding Time Duration, Useful Seeding Time, Extra Seeding Time, Mean Top Seeding Rate and Seeding Material Mass Consumption.

3. DATA

The data used for this study are the radar data and seeding data of the operational period April 1st – August 31st, 2005. For the radar data the entities that have been selected to be examined are Storm Cell Complexes (SCC) defining as *the radar echoes, convective in nature, with cell reflectivity equal or greater than 35 dBZ at the -5° C level or higher (Tsagalidis, 2006).* SCC were subjectively defined by the same analyst, utilizing the radar data recorded by the TITAN system.

The seeding data is the number of the ejectable and base flares that were used per SCC and the corresponding seeding time, provided from GPS by the RDTS (Radar Data Telemetry System) data of the aircraft. Top flares and base flares consist of 20 g and 70 g of pyrotechnical mass, respectively (shown in Figure 2).

The first parameter examined was the number of SCC that were seeded, in the examined period. For the seeded SCC only, the following six seeding parameters were measured:

1) Start Seeding Response Time is the actual response of the crew for start seeding comparing with the theoretical ideal start seeding time, valued as zero-point.
2) Seeding Time Duration is the actual seeding duration time.
3) Useful Seeding Time is the actual seeding time included in the theoretical seeding time.
4) Extra Seeding Time is the actual seeding time that exceeded the theoretical seeding time.
5) Mean Top Seeding Rate is the mean number of seeding top flares ejected every 5 sec, per SCC.
6) Seeding Material Consumption is the amount of pyrotechnic material used per SCC.

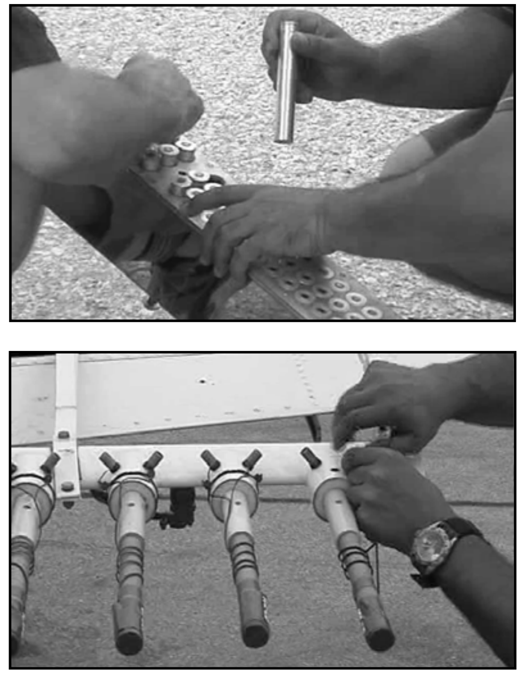

Figure 2. Top flares (top) and base flares (bottom) manufactured by Ice Crystal Engineering.

The theoretical start and stop times of seeding are defined by the radar "seeding criteria" as reflectivity greater than or equal to 35 dBZ in convective cells located either inside, or within 20 minutes of entering the project area, at altitudes corresponding to temperatures between -5 and -35 °C (Karacostas, 1984). In this particular study, for each SCC, the theoretical and the actual values have been set and measured, according to the meeting of "criteria", by the same well-experienced meteorologist, assuming, that any subjective error in measuring would be of a constant value.

The above parameters have been examined separately for each one of the two protected areas and also in the aggregate, for each type of storm according to hailstorm classification in single cell (S), supercell (SU), multicell storms (M) and line storms (L) (Browning, 1977). In the sequence, the SCC categories are the Unicellular type that may consist of a Single isolated ordinary cell or a Supercell, the Multicell with a cluster of cells, not forming in a distinct line and the Line, containing cells along a line.

Cell types were defined in a subjective manner by the same analyst and the storm type characteristics that were used are analyzed in an extended way to Tsagalidis et al. (2006).

4. ANALYSIS

In the hail suppression season 2005, from April 1st to August 31st, 249 SCC were detected in the two Project Areas. 101 SCC were identified as single cells (S), 145 as multi (M), 2 as supercells (SU) and one as line (L). 10 SCC of them are not further examined since GNHSP was not operational that day.

Of the remaining 239 SCC (94.2%), 225 SCC (90.4%) were seeded (110 SCC in the protected area A1 and 115 SCC in A3), while only 14 SCC were not seeded. Seeding was not conducted on these 14 SCC because of delays (5 SCC), seeding another cell (4 SCC), no aircraft availability (5 SCC). The analysis that follows is only for the 225 SCC that were seeded.

4.1 Start Seeding Response Time

The Start Seeding Response Time is shown for both areas and also separately in the time distribution charts in Figures 3, 4 and 5. Also, the accumulative frequency of occurrence is shown.

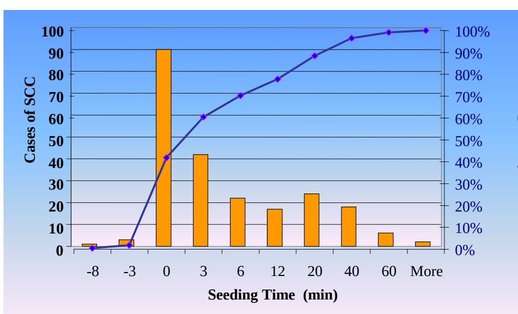

Fig. 3. Frequency of occurrence plot of Start Seeding Response Time for both areas A1, A3.

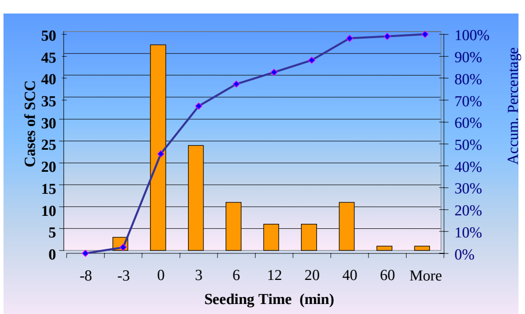

Fig. 4. Frequency of occurrence plot, of Start Seeding Response Time for area A1.

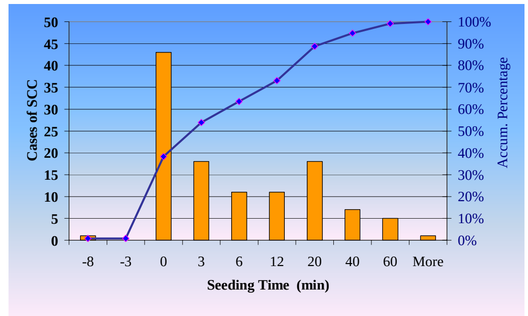

Fig. 5. Frequency of occurrence plot of Start Seeding Response Time for area A3.

From Figures 3, 4, and 5, an almost similar distribution of the Start Seeding Response Time is observed, with 158 SCC (70%) of the seeded storms, (77% A1, 64% A3) seeded within the first six minutes. It should be noted that the radar volume scan takes three to five minutes to be completed and the network for the data transmitting needs some time, therefore, six minutes represents a very good Start Seeding Response Time. It should also be noted that area A1 is closer to the aircraft base than area A3.

Another factor investigated was the Start Seeding Response Time for the first SCC of the day. In a total of 47 first SCC, 72% were seeded also in the first six minutes, and only in 10 SCC was the Start Seeding Response Time observed to be greater than 20 min.

4.2 Seeding Time Duration

The Seeding Time Duration for each protected area (A1, A3) and storm type (SU, L, M, S) is shown in Figures 6 and 7.

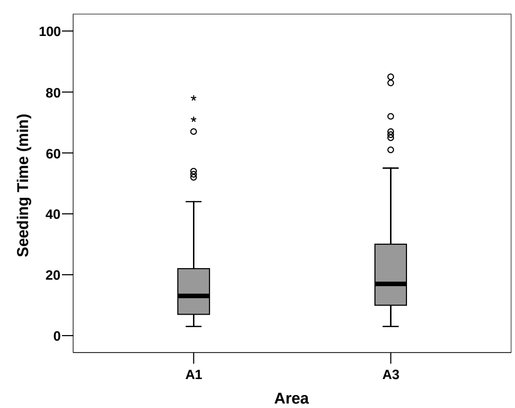

Fig. 6. Box plots of Seeding Time Duration, for protected area A1 and A3.

There is a difference in seeding time duration between areas A1 and A3. In A1 the mean seeding time was 18.0 min while in A3 it was 23.6 min.

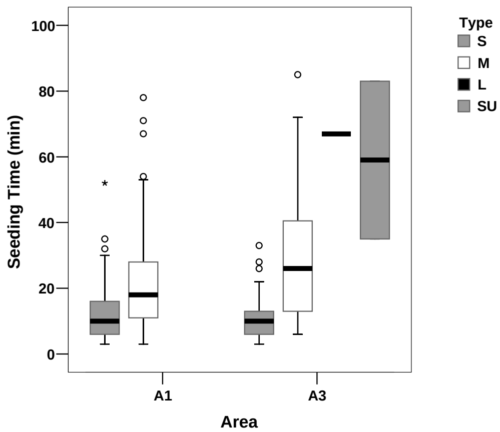

Fig. 7. Box plots of Seeding Time Duration for area A1 and A2 according to storm type.

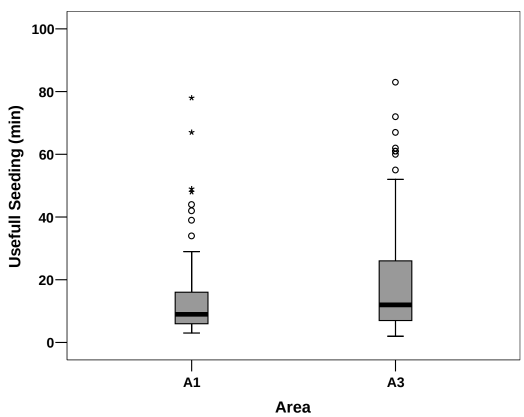

Fig. 8. Box plots of Useful Seeding Time for each area.

In the protected area of Macedonia, A1, the mean Useful Seeding Time was 13.6 minutes, while in the protected area of Thessaly, A3, it was 19.7 minutes. Another study of the same dataset (Tsagalidis, 2006) indicated that the mean lifetime of a SCC in A3 is 69.1 minutes while in A1 it is 55.1, and the storm motion in A1 is faster than in A3. These two factors can explain the observed difference in Figure 8. Also, Figure 9 indicates that it is due to the multicell type of storms.

In the same manner, the distribution of Extra Seeding Time for the 207 SCC with positive Useful Seeding Time is shown in Figure 10. In the aggregate, for all storm types, the mean value of the Extra Seeding Time for A1 is 4.4 min and for A3 is 3.9 min. This value is small and indicates there is little waste in the use of AgI. In 47% of the 207 effectively seeded SCC there was zero Extra Seeding Time.

This difference is due to the different seeding time spent to seed the multi storms for each area.

4.3 Useful and Extra Seeding Time

Further analysis of the seeding time duration leads to the identification of the Useful Seeding Time. From the 225 seeded SCC, 207 SCC were treated efficiently (positive value of Useful Seeding Time) and in 18 SCC the useful time was negative or zero (i.e.; the seeding was late). Half of this loss was due to delays and half due to seeding of other SCC in the same project area at the same time. The distributions of the Useful Seeding Time according to Area and Storm Type for the 207 SCC are shown in Figures 8 and 9.

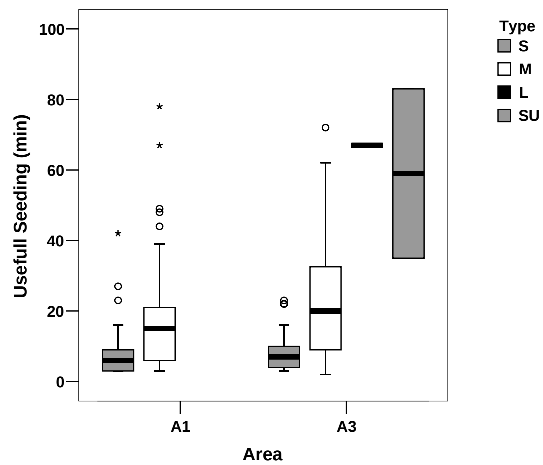

Fig. 9. Box plots of Useful Seeding Time for each area and according to storm type.

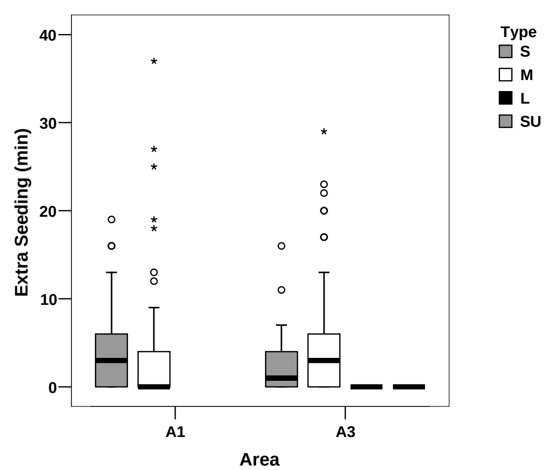

Fig. 10. Box plots of Extra Seeding Time for each area according to storm type.

Further analysis indicated that the Extra Seeding Time occurred mostly in the mature stage of SCC, and particularly to the storms that had high values of reflectivity and height. This likely produces psychological pressure to the controllers to prolong the seeding.

4.4 Seeding Mass and Rate

The distributions of Seeding Material Mass Consumption and the Mean Top Seeding Rate are shown in Figures 11 to 14.

It should be noted that only the Mean Top Seeding Rate was examined (and not the Base one) since 99% of the Seeding Material Mass Consumption was used in top seeding by top flares of 20 g.

The main reason for this is that visibility was poor in the majority of the cases due to embedded and not isolated cells, or due to nighttime flights. Also, because "*cloud base altitudes are near mountain top height which can be an important safety consideration in the relatively small project areas in Greece*" (Sioutas, 1998).

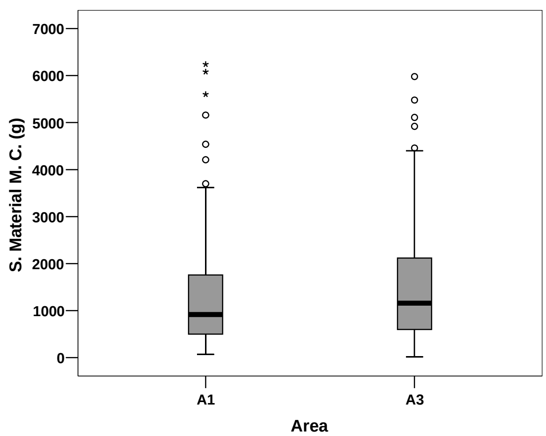

Fig. 11. Box plots of Seeding Material Mass Consumption for each protected area.

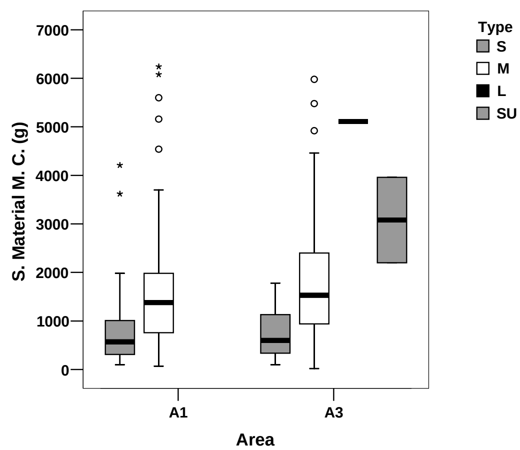

Fig. 12. Box plots of Seeding Material Mass Consumption for each area and per storm type.

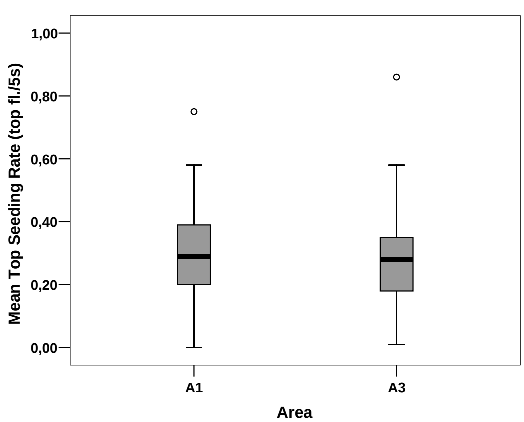

Fig. 13. Box plots of Mean Top Seeding Rate for each protected area.

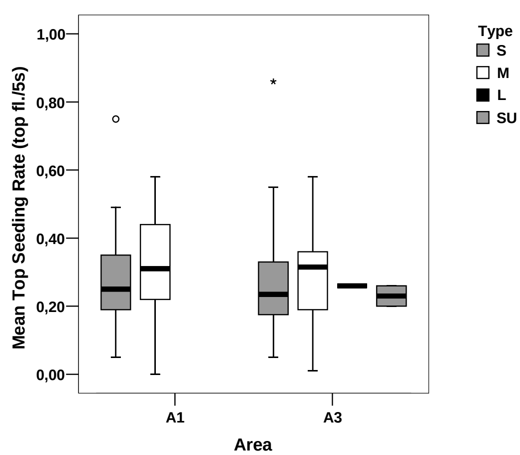

Fig. 14. Box plots of Mean Top Seeding Rate for each area and per storm type.

From Figures 11 and 14, storm type discrimination is evident. For this reason, the Confidence Interval of the means with a 0.05 significance level was calculated for the Seeding Material Mass Consumption and the Mean Top Seeding Rate per storm type, for the two areas combined. A statistical summary is given in Table 1.

TABLE 1: Lower (5%) and Upper (95%) Confidence Interval and Standard Error of the means for Seeding Material Mass Consumption and Mean Top Seeding Rate according to storm type.

Seeding Material Mass Consumption (g)						Mean Top Seeding Rate (top fl. / 5s)					
Type	**N**	**Mean**	**S.E.**	**Lower**	**Upper**	**Type**	**N**	**Mean**	**S.E.**	**Lower**	**Upper**
S	82	850.5	87.681	678.6	1022.3	S	82	0.27	0.015	0.24	0.30
M	115	1836.1	133.521	1574.4	2097.8	M	115	0.30	0.013	0.28	0.33

The difference of the means for the Seeding Material Mass Consumption per storm type (S, M,) is statistically significant with 0.05 significance level as it is shown from Table 1. The multicell storms received on average significantly more Seeding Material Mass Consumption than the single cell storms. The difference of the means for the Mean Top Seeding Rate per storm type was not statistically significant.

5. SUMMARY

The mean values of the six analyzed parameters are presented in Table 2 for each of the two protected areas and in the aggregates, for the 207 SCC that were seeded effectively (positive Useful Seeding Time).

TABLE 2: Mean values for the 207 SCC with positive Useful Seeding Time.

Protected areas	Start Seeding Response Time (min)	Seeding Time (min)	Useful Seeding Time (min)	Extra Seeding Time (min)	Seeding Material Mass Consumption (g)	Mean Top Seeding Rate (top fl./5s)
Total	5.9	20.8	16.7	4.1	1444.4	0.29
A1	4.4	18.0	13.6	4.4	1333.9	0.30
A3	7.3	23.6	19.7	3.9	1550.6	0.28

From Table 2 some logistical inferences can be made. The mean Start Seeding Response Time in the protected area A3 is greater than the one in A1 by 2.9 min. Taking into account that A3 is approximately 20 min flight distance from the airport of Thessaloniki, when A1 is only 10 min, this 2.9 difference in the Start Seeding Response Time shows a very good time estimation by the controllers of the GNHSP.

The mean Seeding Time in A3 is 5.6 min greater than A1's. The effective seeding time can be estimated by the ratio of the mean Useful Seeding Time to the mean Seeding Time, calculated to 80.3% for both areas (75% for A1 and 84% for A3). Also, the seeding time coverage can be estimated by the ratio of the mean Useful Seeding Time to the mean Ideal Seeding Duration, calculated to 70% for both areas (69% for A1 and 70.5% for A3). The Extra Seeding Time proved to be less in A3. Seeding Material Mass Consumption per SCC is higher in A3, but the Mean Top Seeding Rate is less.

6. CONCLUSIONS

This study was based on the data of the hail suppression season 2005, which proved to be the most active season in the history of the Greek National Hail Suppression Program. The results of the study are intended to contribute to future operations and planning purposes.

During the period April 1st - August 31st of 2005, 239 SCC appeared in the two Project Areas A1 and A3 of the Greek National Hail Suppression Program. Of them 225 SCC (94.2%) were seeded.

In 157 SCC (70%), seeding started within 6 minutes after the seeding criteria was met. The mean Start Seeding Response Time was 5.9 minutes and this value is considered as a reasonable threshold. The same result was found for the 1st SCC of the day.

In 207 SCC, corresponding to 86.7% of the detected SCC and to 92% of the seeded SCC, the Useful Seeding Time was positive. Additionally, the effective seeding time, estimated by the ratio of the mean Useful Seeding Time to the mean Seeding Time, was 80.3%.

The Mean Extra Seeding Time was only 4.1 min, while almost in half of the effectively seeded storms there was no Extra Seeding Time. Therefore, Seeding Material Mass Consumption was not wasted and the majority of storms were seeded according to the designed criteria.

Finally, the Mean Seeding Material Mass Consumption per SCC was 1444.4 g and with 0.3 top flares ejected every 5 seconds (Mean Top Seeding Rate). Seeding Material Mass Consumption was significantly greater for multi-cell storms but the Mean Top Seeding Rate was not significantly different.

The values of the examined parameters are not the same for the two project areas. Possible reasons could be finally attached to the geographical location of each area which affects both climatological storm characteristics and aircraft proceeding time.

In general, TITAN and RDTS (seeding data acquisition system) have been used since 1997 and this study is the first effort to the direction of parallel analysis of this dataset. Future plans indicate to continue the same way of analysis, in order to have more representative results for GNHSP performance.

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A CLIMATIC INVESTIGATION OF THE RELATIONSHIP BETWEEN SYNOPTIC FACTORS AND HAIL OCCURRENCE IN NORTHERN GREECE DURING THE DOMINATION OF 500-HPA LOWS

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ABSTRACT

An objective detection and analysis of 500-hPa cyclones (lows) is performed during the warm period (15 April-15 October) of the year for the central and east Mediterranean region and especially for northern Greece. The NCEP/NCAR reanalysis gridded data of geopotential height and temperature are employed in the detection of lows and in the calculation of the various dimension, shape and instability parameters. The parameters are used in the identification of hail days during a period of 13 operational hail seasons in northern Greece where the National Hail Suppression Program is conducted. The estimated conditional probability (8%) for hail occurrence under low domination indicates that hailfalls are rather rare and lacking severity. When however, the PVA advection centers, which usually accompany the lows are considered, hailfalls are more frequent (20%) and severe. This is attributed to the increased low-level instability at the PVA centers in the absence of extended cloud covers. Hail-related lows are larger and bear a greater resemblance to circles than the ordinary lows. They are usually moderate or negligibly elongated in the northeast to southwest direction and originate at the east coast of Adriatic Sea.

1. INTRODUCTION

Since the first synoptic charts, synoptic conditions have been considered as a first approach to the investigation of meteorological phenomena (Yarnal, 1993), which take place in smaller scales. Hailfall or hail occurrence is a sub-synoptic scale (Orlanski, 1975) phenomenon with a typical dimension usually in the range 10-100 km. Compared to the typical dimension of a synoptic system (1000 km), it is smaller by one or two orders of magnitude. There are many difficulties (Fujita, 1986) in relating phenomena of different scales. A probabilistic approach is required to overcome the lack of theoretical knowledge about the exchange of physical quantities (energy, momentum) between different scales. An intermediate scale is sometimes required to fill the continuity gap.

The 500-hPa lows or 500-hPa cyclones (Parker, et al, 1989; Bell and Bosart, 1989) are synoptic features, which are easily identified and in the absence of organized surface systems characterize the prevailing weather. In the Mediterranean basin, this situation usually occurs during the warm-dry season of the year, when surface depressions are rare (Reiter, 1975; Radinović, 1987). Especially in northern Greece, 500-hPa lows are related to persisting cloudy weather (Maheras, 1982), rain and sometimes hailstorms (Riley, 1989; Hadji, 1993). These weather conditions are harmful to economic activities such as tourism and agriculture. Common harm in agriculture results from fungi infections. The infections are favored (WMO, 1988) on the wet plant surfaces, when clouds block the sun rays. The cracking of smooth skinned fruits (mainly cherries) because of the osmosis effect is another common harm. It usually occurs when mature fruit skin remains wet long enough. Damage from storms is the third common harm in agriculture. Hail damages are generally considered the most important because of the mature stage of the crops (Dalezios and Spanos, 1995) and the irreversible effect. In order to assess the importance of the harm, estimations of hail occurrence frequency during the domination of 500-hPa lows are required. A climatic investigation is therefore conducted and presented in order to estimate the hail occurrence frequency and to possibly identify the particular shape and dimension characteristics of these lows. The investigation is extended to synoptic and sub-synoptic factors, which influence hail occurrence such as static stability and geostrophic vorticity advection.

2. DATA AND METHODOLOGY

In the present study an objective 500-hPa cyclone detection is performed during the warm period (16 April to 15 October) of the year for central and east Mediterranean region and especially for northern Greece. The NCEP/NCAR reanalysis gridded data (Kalnay et al., 1996) of geopotential height and temperature at various levels are used for the detection of lows and the calculation of the parameters. The data have a spatial resolution of 2.5 degrees and a temporal resolution of 6 hours (00, 06, 12, 18 UTC).

Lows are determined as local minima in each 3X3 matrix (Figure 1(a)) of geopotential height values within the area of investigation. A gradient criterion (Spanos et al., 2003) is additionally applied to exclude weak lows, which probably originate from the assimilation procedure. Eight distances of the maximum closed isohypses from the center of the low are calculated along the eight primary directions (Figure 1(b)). The average distance, which is termed typical radius, represents the horizontal dimension of the low. The sum of two distances along the opposite directions is also calculated for the four pairs. The difference between maximum sum and the normal to the maximum measures the elongation of the low. This difference normalized by the maximum sum (also in the appendix) is a shape parameter termed eccentricity. Eccentricity describes the departure of the lows from circular shape and tends to zero in case of circular lows. The direction of the axis corresponding to the maximum sum, which is termed the direction of the major axis, is additionally determined as a third parameter (Figure 1(c)).

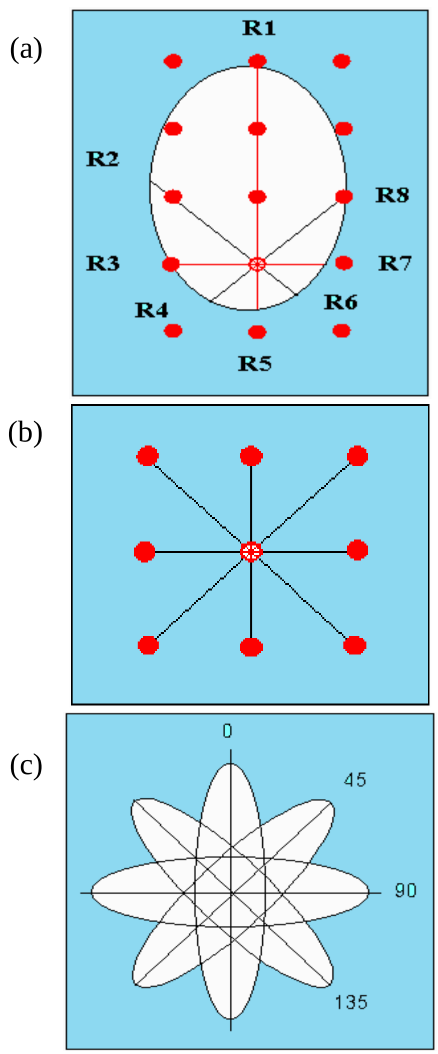

Fig. 1. Determination of synoptic parameters for the 500-hPa lows. Location is in (a), Typical Radius and Eccentricity in (b) and Direction of major axis in (c).

At the 500-hPa level, the geostrophic vorticity (ζ_g) is calculated from the horizontal Langrangian (i.e Holton, 1979) of geopotential height. Then the geostrophic vorticity advection is calculated through the Jacobian of geopotential height and the geostrophic vorticity ($J(\mathbf{Z}, \zeta_g)$). The formulae and the finite difference pattern (Fjortoft, 1952) used in the calculations are included in the appendix. Possitive vorticity advection (PVA) centers are determined as local maxima in each 3X3 matrix within the area of investigation. Centers with positive values are finally selected. A PVA center is assigned to each low according to the minimum distance from it. The detection of the lows and the calculation of the parameters carried out for a period of 13 hail seasons (between 1981 and 1998) in the area of Imathia-Pella (2340 km^2) where the National Hail Suppression Program (NHSP) is conducted. The calculation, which covers the entire number of low occurrences for the same period, is particularly focused on hail days. The verification of hail days is based on the hailpad network (Dalezios et al., 1991) and on radar-confirmed crop damage reports. In cases of lows persisting for more than one occurrence per day in northern Greece, the situation with the lower geopotential height is selected. Northern Greece (filled circles in Fig. 2) is used as an intermediate scale between the hail protected area (A1 in Fig. 2) and the entire central and east Mediterranean region.

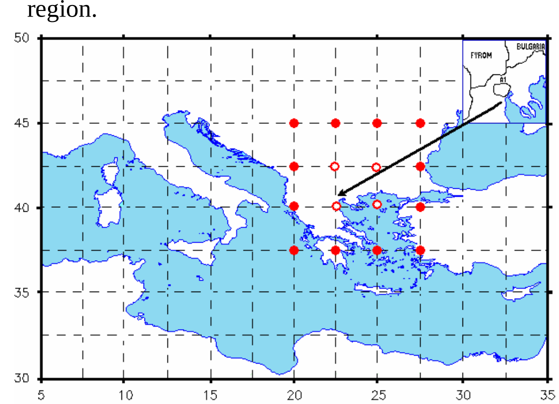

Fig. 2. Map of the investigation area, showing the grid-lines, the broader northern Greece (filled circles) and the grid-point boundary (outlined circles) of the project area (A1 at the right upper corner).

3. HAIL FREQUENCY, SYNOPTIC AND SUBSYNOPTIC CHARACTERISTICS OF LOWS

3.1. Hail frequency

Hail days occur under various synoptic regimes (Riley, 1989) such as northwest flow, cutoff low, southwest flow, zonal flow or even under ridge domination. There are numerous cases in which hail days are related to PVA centers accompanying a trough. These troughs are mostly short waves embedded in the northwest flow. During southwest flow hail is mainly attributed to frontal lifting and in case of ridge domination, air mass hailstorms are sometimes developed. The highest number of hail days occurs under the influence of northwest flow and the number of hail days during cutoff lows follows. The paper focuses in the last category, which is examined on a climatic basis.

The detection algorithm finally produced a number of 287 days with a low occupying the broader northern Greece. From NHSP archives, during the same period of years, 99 hail days are confirmed. Only 27% of these days are generally related either to the low presence or to the presence of a PVA center (accompanying the low) in northern Greece. Approximately half of these days (44%) are related only to low presence and the rest (56%) to a PVA center accompanying the low.

It seems that during the days, which are related only to low presence, the severity of hailfalls is considerably reduced. The various parameters that are used world wide to express hailfall severity are

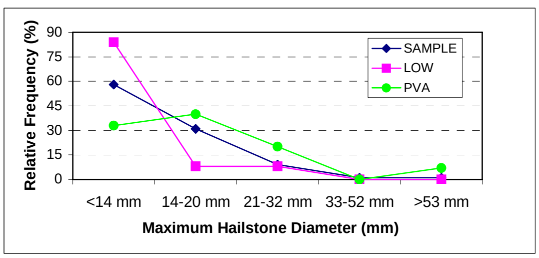

Fig. 3. Relative frequency distributions of maximum hailstone diameter for low situations, PVA centers accompanying lows and entire sample of hail days.

inter-correlated. In this paper severity is expressed in terms of maximum hailstone diameter deduced from the hailpad network. The categorization used in the paper was first introduced by Strong and Wilson (1981) and was adopted by NHSP. The first category is pea size, the second is grape size, the third is walnut size, the forth is golfball size and the fifth is greater than golfball size. The relative frequency distributions of these categories in the entire sample, in cases of low presence and in cases of PVA centers associated with lows, are shown in Fig. 3. The comparison depicts a reduction in severity when lows are present. This is consistent with what Hadji (1993) described as the main feature of a cutoff low situation. It is the increased frequency of embedded radar echoes and the small size of hail. On the other hand the severity is increased when PVA centers associated with lows are considered (Fig. 3). In this case pea size hail is less common while greater sizes occur more frequently.

The combination of the absolute frequency for all these categories provides the total hail occurrence frequency, which is then expressed relatively to the total number of lows or PVA centers affecting the area in the research period. The relative frequency (or probability) of hail occurrence is separately examined in cases of low and in cases of PVA presence in the area. Two areas are considered in this examination. The first is a broader area in northern Greece (Figures 2 and 4) and the second, which is included in the first, is the grid-point boundary (filled circles in Figure 4) of the protected area (A1). Relative frequency of hail occurrence for both areas is higher in the case of PVA centers (14% and 20% in the dotted line boxes in Fig. 4) than in the case of the low centers (7% and 8% in the continuous line boxes in Fig. 4). In the case of low centers, the percentage remains almost invariable (7% to 8%) in the two areas but when PVA centers are considered, there is a significant increase when moving from the first area to the second (14% to 20%). This behavior indicates that PVA centers determine the hail occurrence in space more accurately than the low centers.

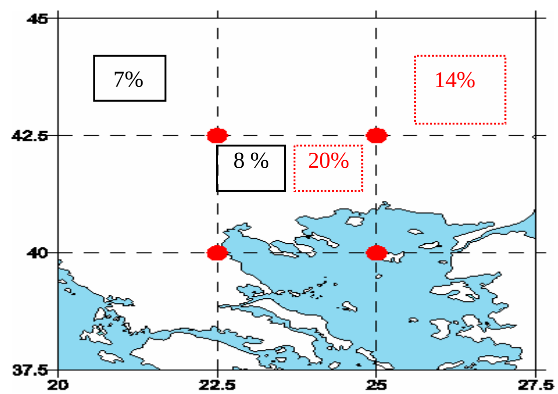

Fig. 4. Relative frequency of hail days when lows (continuous line boxes) and PVA centers (dotted line boxes) are present in broader northern Greece and in grid-point boundary A1 (filled circles).

3.2. Synoptic Characteristics

In an effort to identify the lows and the PVA centers, which are related to hail, some intensity and shape parameters are calculated. The average values are presented in Table 1, which also provides a comparison of these parameters among the three investigation areas. The second column of Table 1 indicates that the lows gradually become shallower as the area varies from the central and east Mediterranean region to the broader northern Greece and the grid-point boundary of A1 during hail days. A gradual increase in the representative dimension (typical radius) is observed in the third column. A gradual increase is also observed in the fourth column, which represents eccentricity. This variation indicates that the lows, which are related to hail, exhibit a more circular shape than the other lows in the area. It seems, however, that the behavior of the parameters is not a characteristic unique to hail occurrence. It probably constitutes a general characteristic of the 500-hPa lows in northern Greece, which is related to the origin and the evolutionary stage. No special pattern is deduced from column five which represents the variation of PVA values. The frequency distribution of the direction of the major axis of the lows is provided in the form of a circular diagram (Figure 5). The most frequent direction is NE to SW.

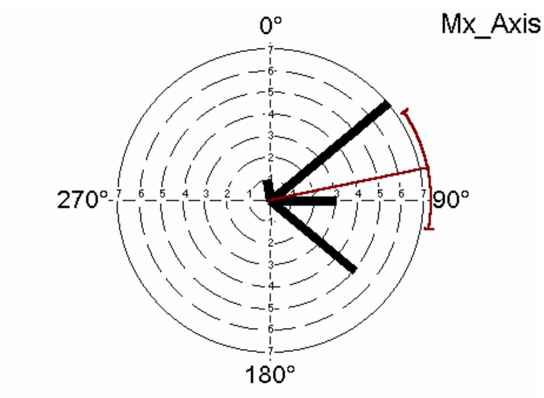

Fig. 5. Circular diagram of frequency distribution, for the orientation of major axis of the lows in broader northern Greece during hail days in A1. The thin line represents the circular mean and the brackets a 95% confidence interval.

3.3. Instability

To assess the role of synoptic factors in the modification of an instability environment necessary to the development of hailstorms, two static stability (instability) indices are calculated at the center of the low and at the PVA center. These parameters are the well-known vertical totals (Miller, 1967) and the Boyden index (Boyden, 1963). These indices are easy to calculate from the same data set but they do not incorporate the moisture factor. The temperature at 500 and 850 hPa levels is also provided for both low and PVA centers. Table 2 shows that on average, vertical totals is higher at the low centers than at the PVA centers. The Boyden index, which is a measure of instability at lower levels (1000-700 hPa), indicates the reverse. Moreover, 500-hPa temperatures at the center of the lows are generally lower than those at the PVA centers. The reverse is observed for the 850-hPa temperatures. It is evident that at the center of the low where a cold pool (Palmén and Newton, 1969) usually exists, instability increases because of the cold air masses aloft. On the other hand, at the PVA centers instability increases because of the warm air masses at the low levels. This is probably due to the warming by the sun in the absence of extensive cloud cover. The cloud cover, which accompanies a low, is observed either along the frontal surfaces when they exist, or around the center of the low when significant low-level convergence takes place. Sometimes, however, when conditions are favorable, extensive cloud masses are also formed at the PVA centers. These cloud masses are mesoscale features known as coma clouds (Browning, 1987; Barry and Carleton, 2001).

Table1. Average values of intensity and shape parameters for central and east Mediterranean region, broader northern Greece and grid-point boundary of A1.

Parameter /Area of Investigation	**Geopotential Height (gpm)**	**Typical Radius (km)**	**Eccentricity**	**PVA at Centers 10^{-9} sec^{-2}**
Central and East Mediterranean	5622	445	0.33	1.30
Northern Greece	5637	490	0.22	1.80
Grid-point Boundary of A1	5683	613	0.15	1.34

Table 2.Average values of instability parameters at low and PVA centers in grid-point boundary of A1 during hail days.

Average Values	**Vertical Totals**	**Temperature at 500 hPa**	**Temperature at 850 hPa**	**Boyden Index**
Values at Low Center	27.2	-17.2	10.0	96.2
Values at PVA Center	26.8	-15.7	11.1	96.7

4. SPATIAL DISTRIBUTION OF FREQUENCY AND ORIGIN OF THE LOWS

The spatial distribution of the frequency of lows, which are related to hail, is presented in Figure 6. The figure shows an absolute maximum to the northweast of A1 and a secondary maximum to the east or southeast. In the second case lows are found over the Aegean Sea while a ridge develops over west Greece. This combination places A1 under the influence of NW flow, which has been related to several cases of hailfall in the area (Riley, 1989; Hadji, 1993). On the other hand, the spatial distribution of PVA centers (Figure 7) shows a maximum to the northeast and an extension towards the southwest. The frequency maximum to the northeast of A1, indicates that hail in the area, occurs when PVA centers and the cloud cover which probably accompanies them moves east of the area. The area, however, is still under the influence of high PVA values. The circular diagram in Figure 8 also verifies the relative position of the PVA and low centers, which is seen in the comparison of the two figures (Fig. 6 and Fig. 7). Figure 8 shows the orientation distribution of PVA centers relative to the corresponding centers of the lows. The circular average lies in the range between 90º and 180º, which is at the SE of the lows.

The origin and simplified tracks of the 500-hPa lows, which are related to hail in Imathia-Pella, are presented in Figure 9. The majority of these lows come from the east coast of the Adriatic Sea. However, there are cases where the lows are generated at the northeast grid point of the grid-point boundary of A1. On the other hand, the origin of the lows with PVA centers related to hail is different (Figure 10). Most of these lows originate in the well-known (Radinović, 1989) cyclogenesis area of Genoa.

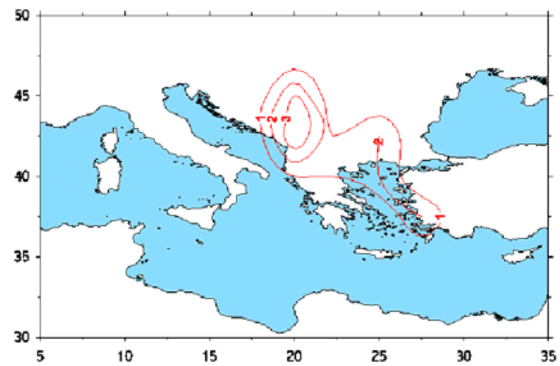

Fig. 6. Spatial distribution of low centers in broader northern Greece during hail days in A1 for 13 hail seasons.

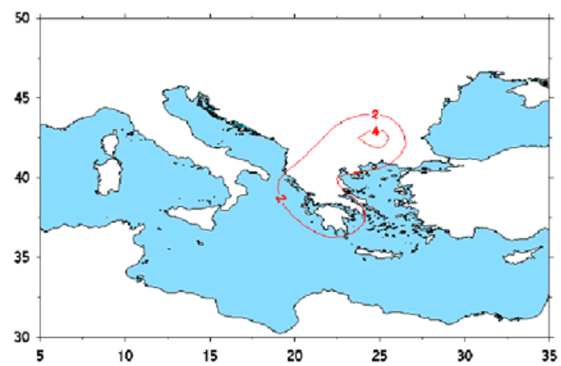

Fig. 7. Spatial distribution of PVA centers in broader northern Greece during hail days in A1 for 13 hail seasons.

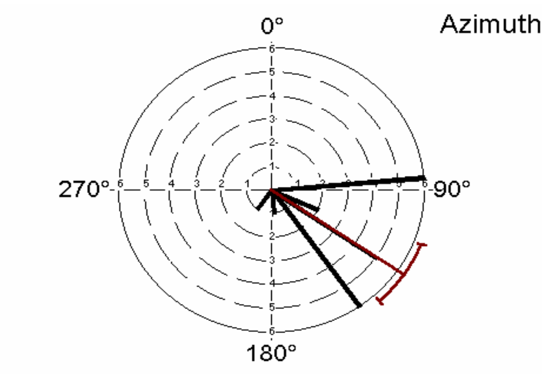

Fig. 8. Circular diagram of frequency distribution for the orientation of PVA centers relative to the lows in broader northern Greece during hail days in A1. The thin line and brackets as in Fig. 5.

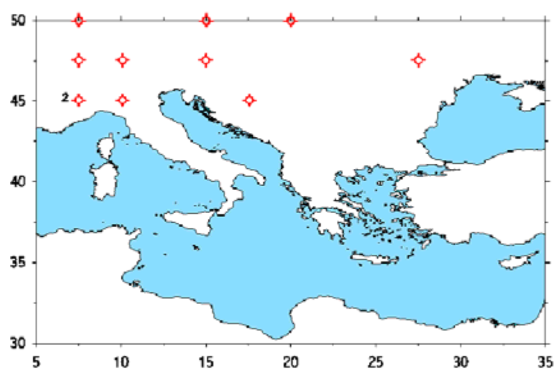

Fig. 9. Origin and simplified tracks of lows related to hail days in A1

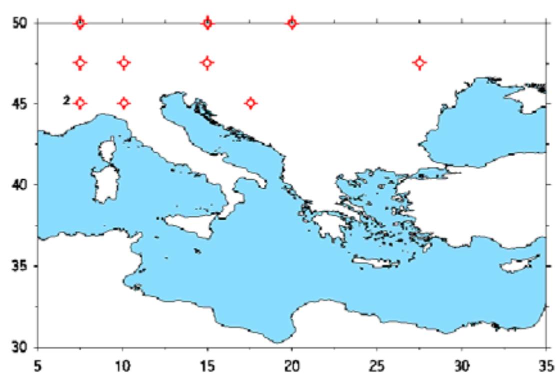

Fig. 10. Origin of lows with PVA centers related to hail days in A1.

SUMMARY AND CONCLUSIONS

The information presented in this paper suggests that the 500-hPa lows is the synoptic environment for one third of all hail days in Imathia-Pella (North Greece). In these situations, hail is almost equally attributed either to the increased instability due to the cold pool aloft, or to the action of PVA centers that usually accompany the lows. From the entire low population that affected northern Greece during 13 warm periods, only 7% is related to hail days. When the associated PVA centers are considered instead of the lows, this percentage is doubled (14%). The difference in these percentages indicates that hail is more common at the PVA centers than at the centers of the lows. The examination of the instability at the center of the two features showed that PVA centers are dominated by low-level instability and low centers by middle-level instability. It also showed that low-level instability is related to warm low levels and middle-level instability to cold middle levels (cold pool). A possible explanation for this combination is that it is the low-level warming (in the absence of significant cloud cover) that favors hailstorms. Low-level warming is usually blocked by cloud cover at the centers of the lows and the atmospheric environment is less favorable for hailstorm formation. In this situation convective clouds are weaker and embedded in stratiform clouds. This conclusion is further supported by the comparison of the two percentages for the grid-point boundary of the protected area (A1). For lows in this particular area the percentage remains the same (8%) but for the PVA centers in the same area it is considerably increased (20%). It is evident that the presence of a PVA center determines the hail occurrence in space more accurately than the presence of the low itself.

Specific characteristics of the lows, which are related to hail days, are further described for identification and forecasting purposes. The major axis of hail related lows mostly lies in the direction NE-SW. When compared to lows in the entire region, hail-related lows are shallower, larger in dimensions and bear a greater resemblance to circles. The PVA centers, which are related to hail, generally lie in the SE of the associated low centers. 500-hPa lows which are related to hail in Imathia-Pella, are usually generated on the east coast of the Adriatic while lows with PVA centers related to hail are generated in northern Italy and Europe.

APPENDIX

Figure 1(a) shows the pattern followed in the detection of 500-hPa lows with the low center at the middle of a 3X3 matrix of grid-point values. Figure 1(b) shows the determination of the eight distances ($R_1 \ldots R_8$) of the maximum closed isohypses from the center of the low. The distances are calculated by using the interpolation method between the successive grid-points. The typical radius (TR) is calculated by the formula:

$$\mathbf{TR} = [\sum_{1}^{8} \mathbf{Ri}\ ]/8 \qquad (1)$$

Eccentricity (E) at the same figure is calculated by the formula:

$$\mathbf{E=\{(R1+R5)-(R3+R7)\}/(R1+R5)} \qquad (2)$$

The four directions of the major axis of the low are presented in Figure. 1(c)

Geostrophic vorticity is calculated from (3) :

$$\zeta_g = \frac{\mathbf{g}}{\mathbf{fo}}\left(\frac{\partial^2 \mathbf{Z}}{\partial \mathbf{x}^2} + \frac{\partial^2 \mathbf{Z}}{\partial \mathbf{y}^2}\right) \qquad (3)$$

The term in brackets is the Laplacian of geopotential height at plane x,y and can be approximated by using finite differences for the derivatives along the x and y axis :

$$\frac{\partial^2 \mathbf{Z}}{\partial \mathbf{y}^2} = \frac{\frac{\mathbf{Z_2 - Z_0}}{\mathbf{d_1}} - \frac{\mathbf{Z_0 - Z_4}}{\mathbf{d_1}}}{\mathbf{d_1}} = \frac{\mathbf{Z_2 + Z_4 - 2Z_0}}{\mathbf{d_1}^2} \qquad (4)$$

In the same manner:

$$\frac{\partial^2 \mathbf{Z}}{\partial \mathbf{x}^2} = \frac{\mathbf{Z_1 + Z_3 - 2Z_0}}{\mathbf{d_2}^2} \qquad (5)$$

Subscripts 1,2,3,4 refer to the surrounding grid points of the low center (Figure 11).

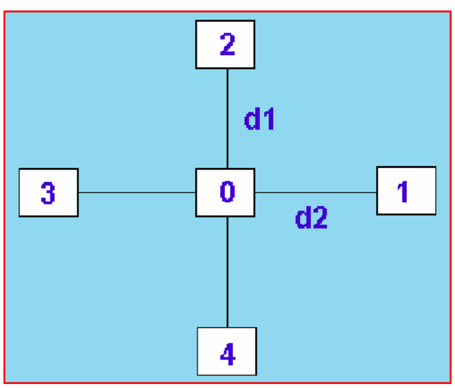

Fig. 11. Grid-point arrangement around the center (0) of a detected low for the calculation of vorticity advection in the finite difference pattern.

The geostrophic vorticity advection at point 0 is calculated from equation 6 where J represents the Jacobian of geopotential height and geostrophic vorticity :

$$-\mathbf{V_g}\nabla\zeta_g = -\frac{\mathbf{g}}{\mathbf{fo}}\ \mathrm{J}(\mathbf{Z}, \zeta_g) \qquad (6)$$

The Jacobian J(**Z**, ζ_g) is analyticaly given by the following formula :

$$\mathrm{J}(\mathbf{Z}, \zeta_g) = \frac{\partial \mathbf{Z}}{\partial \mathbf{x}}\frac{\partial \zeta_g}{\partial \mathbf{y}} - \frac{\partial \mathbf{Z}}{\partial \mathbf{y}}\frac{\partial \zeta_g}{\partial \mathbf{x}} \qquad (7)$$

The application of finite differences approximation to equation 7 results in equation 8 which is the calculation equation for the geostrophic vorticity advection:

$$\mathrm{J}(\mathbf{Z}, \zeta_g) = \left(\frac{\mathbf{Z_1 - Z_3}}{\mathbf{2d_2}}\right)\left(\frac{\zeta_2 - \zeta_4}{\mathbf{2d_1}}\right) - \left(\frac{\mathbf{Z_2 - Z_4}}{\mathbf{2d_1}}\right)\left(\frac{\zeta_1 - \zeta_3}{\mathbf{2d_2}}\right) \qquad (8)$$

Equation 8 considers a standard grid distance d1 along the y-axis and a variable distance d2 along the x-axis depending on latitude.

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A THREE-DIMENSIONAL MODELING STUDY OF HAILSTORM SEEDING

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Abstract

A three-dimensional cloud model is used to simulate transport and diffusion of an artificial ice nucleation agent in conditions of hypothetical hailstorm seeding. The microphysical parameterization use the bulk a second-moment scheme for all species. According to the beneficial competition criteria silver iodide is directly injected and released into an assumed embryo formation region, between -8^{0}C and -12^{0}C isotherms and 25-45 dBZ radar reflectivity contours on line with length of 1.5 km.

The results from the case study simulation have shown that agent typically has about 2-3 min to spread in the seeding zone after its activation and relatively low vertical extension of spreading from the axis of dispersion, which is less than 160 m. The agent activation leads to earlier ice initiation that causes earlier initiation of precipitation.

The implication of the seeding is that cloud seeding with a 6 min time frequency contributes in registration of the maximum hailfall decrease at the ground of about 11.01 %, compared to the unseeded case.

The maximum rainfall increase of 25.79 % and hailfall decrease of 10% is found in the experiment with 0.4 g/m initial seeding rate, 5.5 km seeding height and 10 km seeding distance, compared to the base run simulation, respectively.

1. Introduction

Over the past two decades a number of papers have investigated the cloud seeding using numerical modeling. For example, Hsie et al., (1980), Curic and Janc, (1990, 1993), Curic et al., (1997), Farley et al. (1994, 2004) have revealed that the seeded cloud exhibits the earlier initiation of precipitation, with crucial seeding effects that lead to increased precipitation, slight dynamics and microphysics interactions and differences in cloud history. At the same time Orville et al. (1984) showed that some seeding treatments where resulted in a reduced precipitation, and Orville and Chen (1982) found reduced total precipitation for seeding. Farley (1987) found that hailfall decreased and rainfall could be increased in some situations, although some redistribution in hail spectrum can be expected. Orville et al., (1986) determine that seeding-induced glaciation of smaller developing cells may lead to earlier enhanced vertical growth due to the release of latent heat. The seeded large, vigorous cloud may produce less precipitation because of additional snow, particles, created by the cloud seeding, being transported rapidly to the anvil Orville et al. (1989). Aleksic et al., (1992) from their model simulation have found that only 2-3% of the target volume is actually being seeded. The most sensitive problem according to them is the limited spread of the seeding agent and the time available for the agent diffusion and activation.

Observational evidence for limited dispersion is presented by Huston et al., (1991), together with the modeling study. These aspects are also discussed by Dennis (1980), Warburton et al., (1986).

This study has been focused on two aspects: a three-dimensional simulation of agent transport, diffusion and activation during supercell storm seeding case and the effects obtained from a number of sensitivity experiments by using different initial seeding parameters. Finally the results are summarized and the principal conclusion of the seeding criteria is given.

2. Model

2.1. Model characteristics

The present version of the model is a three-dimensional, nonhydrostatic, time- dependent, compressible system which is based on the Klemp and Wilhelmson [1978] dynamics, Lin et. al. [1983] microphysics, Orville and Kopp [1977] thermodynamics. The governing equations of the model include momentum conservation equations, thermodynamic and pressure equations, four continuity equations for the various water substances, a subgrid scale (SGS) turbulent kinetic energy equation (TKE) and continuity equations for chemical species associated with various cloud water species.

2.2. Microphysics parameterizations

For the parameterization of the microphysical processes we use the integrated (bulk) water parameterization by Lin et al., (1983) with significant improvement of hail growth parameterization. Instead of using the hail size spectrum from zero to infinity (idealized spectrum), Curic and Janc, [1995, 1997] proposed considering the hail size spectrum which includes only hail sized particles (larger than 0.5 cm in diameter; hereafter called realistic hail spectrum).

Seven different categories of the three phases of water have been considered in the model. Both bulk mass mixing ratios and number concentrations of cloud water, rainwater, cloud ice, snow, graupel and hail as well as the bulk mixing ratio of water vapor are also predicted in the model. Condensation and deposition of water vapor produce cloud water and cloud ice, respectively. Conversely, evaporation and sublimation of cloud water and cloud ice maintain saturation. Natural cloud ice is normally initiated by using a Fletcher-type equation for the ice nuclei number concentration. In this version of the model, cloud ice may also be produced by the Hallett-Mossop ice multiplication. Bergeron-Findeisen process transform some of the cloud water into cloud ice and to a certain extent both of them into snow. Rain is produced by the autoconversion of cloud water, melting of snow and hail, and shedding during the wet growth of hail. Hail is produced by autoconversion of snow, by the interaction of cloud ice and snow with rain and by immersion freezing of rain. Snow may be produced by autoconversion and the Bergeron-Findeisen growth of cloud ice and by the interaction of cloud ice and rain. All types of precipitation elements grow by different forms of accretion. Evaporation (sublimation) of all types of hydrometeors is also simulated.

Each of these number concentrations (N) or bulk mixing ratios (Q) has an equation with the following form::

$$\frac{\partial N}{\partial t} + \frac{\partial N U_j}{\partial x_j} - N\frac{\partial U_j}{\partial x_j} - \frac{1}{\rho}\frac{\partial \rho V_t N}{\partial x_3} = S + E_n \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial Q U_j}{\partial x_j} - Q\frac{\partial U_j}{\partial x_j} - \frac{1}{\rho}\frac{\partial \rho V_t Q}{\partial x_3} = S + E_q \quad (2)$$

where S is the sink or source term, V_t is the group terminal-falling-speed of any particular water category which was equal to zero for the cloud water and cloud ice in the model and E_n or E_q is the subgrid-scale contribution.

The equivalent radar reflectivity factors for hail and rain are computed using equations given by Smith et al., (1975) and empirical equation for snow by Sekhon and Srivastava (1970). More detail informations regarding the hydrodynamic equations, microphysics equations, turbulent closure and methods of solutions can be found in Telenta and Aleksic (1988) and Spiridonov and Curic (2003, 2005).

2.3. The calculation of agent dispersion

An additional conservation equation is considered here

$$\frac{\partial X_S}{\partial t} + \frac{\partial X_S U_j}{\partial x_j} - X_S\frac{\partial U_j}{\partial x_j} = S_{X_S} + E_{X_S} \quad (3)$$

where X_S is the mixing ratio of AgI particles, S_{X_S} is the sink or source term of mixing ratio and E_{X_S} is the subgrid-scale contribution. The activation of AgI is parameterized by the three nucleation mechanisms based on Hsie (1980) and Kopp (1988) which are deposition (including sorption) nucleation, contact freezing nucleation – Brownian collection and inertial impact due to cloud droplets and raindrop. These are the sink terms of X_S which can be calculated as:

1.) Contact freezing nucleation-Brownian collection, S_{BC}, and inertial impact due to cloud drops, S_{IC},

$$S_{BC} = -4\pi D_S R_C X_S N_C \quad (4)$$

$$S_{IC} = -\pi R_C{}^2 X_S N_C V_C E_{CS}; \quad (5)$$

2.) Contact freezing nucleation-Brownian collection, S_{BR}, and inertial impact due to raindrops, S_{IR},

$$S_{BR} = -2\pi D_S X_S N_{OR} \lambda_R^{-2} \quad (6)$$

$$S_{IR} = -2.54 E_{RS} \rho^{-0.375} X_S q_R{}^{0.875}; \quad (7)$$

3.) Deposition nucleation due to water vapor at ice supersaturation

$$S_{DN} = \begin{cases} m_s \dfrac{dN_{aD}(\Delta T)}{dt} & \text{when } 5°C \le \Delta T < 20°C \\ m_s N_{aD}(\Delta T) & \text{when } \Delta T \ge 20°C \end{cases} \quad (8)$$

where D_S is a diameter of AgI particles, N_C and V_C the concentration and terminal velocity of cloud droplet, R_C the cloud droplet radius, N_{OR} parameter of the raindrop size distribution, λ_R the slope parameter of rain, E_{CS} and E_{RS} are the collection efficiency of cloud water and rain water collecting AgI particles respectively, ρ the air density, N_{OR} the rainwater mixing ratio, ΔT supercooling and N_{aD} is the number of AgI particles active as a deposition nuclei at a supercooling ΔT, m_s the mass of the AgI particle. These are the sink terms of X_S, while the initial mixing ratio X_{S0} of agent homogeneously distributed in the seeding zone at the seeding moment is the source term of X_S.

An additional effort has been made in the study to consider the calculation of agent trajectories and its dispersion. In the rocket seeding, AgI is normally released as the line source with the length of 1 km, in a cylinder with a diameter of 10 m. Since the model dispersion of the agent is in its initial phase on a subgrid scale, the advection and diffusion should be parameterized. This problem is solved by considering the seeding line as a series of ten individual spherical puffs, each with a radius of 10 m. The agent spread is than simulated by the movement and spread of each individual puff. Its advection is calculated by a bilinear interpolation of the wind from the four adjacent grid points. The trajectories of the puffs are computed in the model. The radius σ of these puffs has been calculated for each step as a function of the turbulent diffusion coefficient (Georgopoulos and Seinfeld, 1986) by the solution of the equation

$$\sigma_{i+1}^2 = \sigma_i^2 + 2K\Delta t \quad (9)$$

where K is the turbulent diffusion coefficient calculated using bilinear interpolation taken from the four adjacent points σ_{i+1} is the radius of puff in time interval i+1 , σ_i is the puff radius in the previous time step, and Δt is the time step. The concentration of each puff is calculated by the following equation

$$C_{PUFF}(L) = \frac{4 \cdot Q_{PUFF}}{\pi \cdot D_{PUFF}(L)^2} \quad (10)$$

where L=1, LCS where LCS is the total number of puffs, Q_{PUFF} is the seeding amount in g/m, and $D_{PUFF} = 2\sigma$ is the diameter of the puff. The initial AgI mixing ratio is then computed by the following term

$$X_{S0}(I0,J0,K0) = X_{S0}(I0,J0,K0) + C_{PUFF}(L) \quad (11)$$

Here, I0=INT(XPUFS)+1, J0=INT(YPUFS)+1, K0=INT(ZPUFS)+1 are the integer values of puffs coordinates in each direction x,y and z, respectively.

$$\begin{aligned} &XPUFS=XPUF(L)/H; \\ &YPUFS=YPUF(L)/H; \\ &ZPUFS=ZPUF(L)/D-0.5 \end{aligned} \quad (12)$$

where

$$\begin{aligned} &XPUF(L)=XPUF(L)+UINT\cdot\Delta t; \\ &YPUF(L)=YPUF(L)+VINT\cdot\Delta t \\ &ZPUF(L)=ZPUF(L)+WINT\cdot\Delta t \end{aligned} \quad (13)$$

In the above terms XPUF(L), YPUF(L) and ZPUF(L) are the corresponding dimensions of puffs, H is the horizontal grid step, D is the vertical grid step and UINT, VINT and WINT are the bilinearly interpolated velocity components.

2.4. Numerical technique

Model equations are solved on a semi staggered grid. All velocity components u_i are defined at one-half grid interval $0.5\,\Delta x_i$ while scalar variables are defined at the mid point of each grid. All velocity components and the horizontal and vertical advection terms are calculated by the centered fourth-and second-order differences, respectively. Since the model equations are compressible, a time splitting procedure with second-order leapfrog scheme is used for the portions which do not involve sound waves to achieve numerical efficiency. Forward-backward time differencing scheme is used for the acoustic part of the equations. An Eulerian fourth order central difference advection scheme has been used to calculate the puff advection.

2.5. Boundary conditions

The normal component of the velocity is assumed to vanish along the top and bottom boundaries. In order to remove suspicions that the vertical oscillations in the numerical simulation are caused by the rigid top boundary in a model, the model is upgraded by a radiative upper boundary condition, according to suggestions given by Klemp and Duran, (1983). The lateral boundaries are opened and time-dependent, so that disturbances can pass through with minimal reflection. Two different cases with regard to the wind velocity are considered according to Durran (1981). When the component of velocity normal to the boundary is directed toward the domain (inflow boundary), normal derivatives are set to be zero.

2.6. Initial conditions and initialization

Initial impulse for convection is an ellipsoidal warm bubble with the maximum temperature perturbation in the bubble center ($T_0 = 2.5°C$). The model domain covers 20x20x15km with (0.5x0.5x0.25km) resolution for the first three-dimensional simulation and 30x30x15 km (1x1x0.5km) for the second run, respectively. The temporal resolution of the model for integration of the dynamics, microphysics and chemistry is 5 and 10 s, and a smaller one is 1 and 2 s, for solving the sound waves. A representative sounding taken at 01 UTC from Petrovec on May 18, 2003 with the corresponding wind profile is presented in Fig.1. The sounding is unstable and moist and the cloud develops very quickly in response to the initiating perturbation.

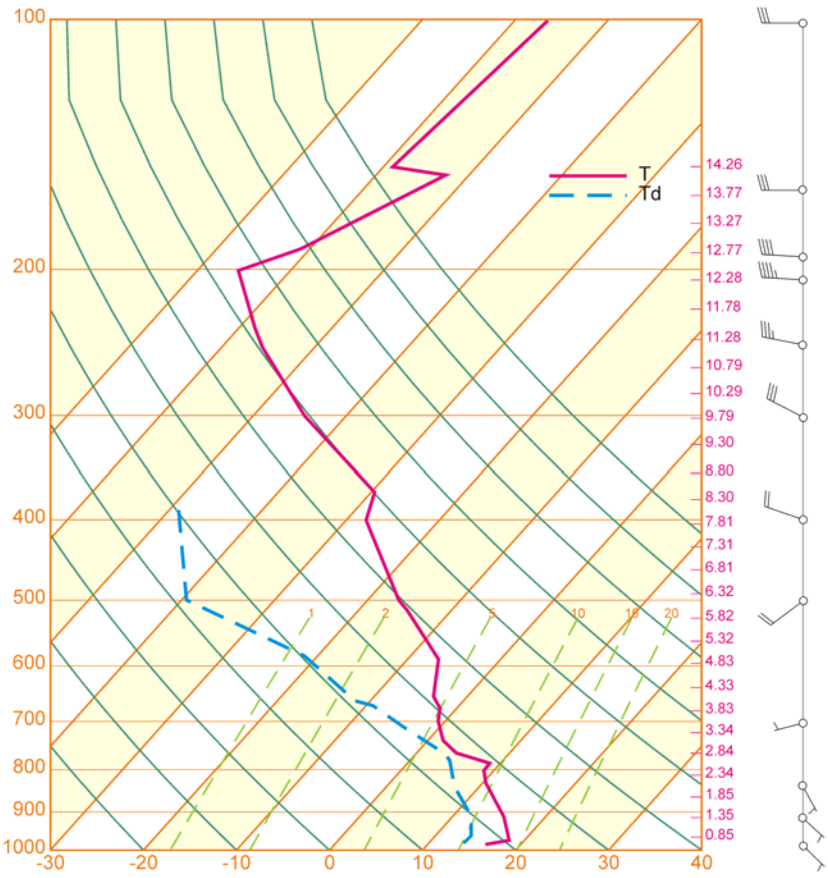

Figure 1. The 1200 UTC atmospheric sounding for Skopje, on May 18, 2003. Coordinate lines denote pressure (hPa) and temperature (°C). The solid line represents the temperature profile and the dashed line represents the moisture profile. Symbols on the r.h.s. of the same figure denote wind vectors (direction and velocity).

3. Results

3.1. A three-dimensional simulation of hailstorm seeding

A three-dimensional simulation of the May 18 case indicates that the results are sensitive to the initial conditions. If it is sufficiently strong, the model cloud penetrates through the stable layer and then experiences explosive growth. Fig. 2a shows three-dimensional views of the cloud life cycle at 10-min intervals. The modeled cloud penetrates the stable layer and than experiences explosive growth, developing into vigorous storm, accompanied by the formation of large amount of ice phase particles. The mature phase of the storm appears after 30 min of the integration time when extensive precipitation occurs. The time evolution of AgI and (AgI+cloud) field at 1.6-min intervals starting at 23.3min, viewed from the southeast (SE) is depicted on Fig. 2b and Fig. 2c, respectively. According to the hail suppression method the silver iodide agent is directly injected into the simulated cloud in its developing stage at 5-min repeat seeding at 16.6 and 21.6 min, in the area between -8° C and -12°C isotherms and 25dBz-45dBz echo contours at 5.5 and 5 km height, respectively. The time evolution of the AgI field in the X-Z cross sections is depicted in Fig.3a. The AgI field is represented with an outer contour of 0.05 μg kg^{-1} for 16.6 and 20.0 min and 0.015 μg kg^{-1} contours for 23.3 min, with contour interval of 0.01μg kg^{-1}. After seeding the agent is advected and diffused within the cloud by the turbulent flow field. Some of the AgI has been activated; small part tends to be drawn back into the cloud as it descends to the lower levels by the downdrafts, while the large portion is transported outside the target volume above -12°C isotherm. The limited time spread of agent is may be due to the strong air circulation within the cloud. Only 9.6% of the AgI remains unactivated as a result of less than optimal placement of the seeding agent and the limited advection time of 2-3 min that limits the time available for agent diffusion. The maximum agent spread within the target area during simulation time is less than 90 m from the axis depending on the local turbulence. Fig. 3b shows the X-Y cross sections at z =5.5 km. The AgI boundary field and the contour interval are taken to be the 0.01μg kg^{-1} contour. It is seen from this figure that after the seed was introduced into the target area the AgI is slowly diffused in response to the existing horizontal wind field at that level. The AgI mixing ratio decreases from 0.28 μg kg^{-1} at 16.6 min to 0.065 μg kg^{-1} at 26.6 min. Most of the AgI has been activated during the first five-minute interval. The unactivated AgI is initially transported toward southeast and downward. After repeat seeding two separated AgI fields are propagated and distributed toward eastern quadrant of the cloud model domain.

3.2. Evolution of physical and agent dispersion properties

The most sensitive hailstorm seeding problem appears to be the limited spread of the seeding agent and limited time available for the agent diffusion and activation in the target volume. In order to gain a qualitative understanding of hailstorm seeding we investigate the seeding methods and conditions with varying assumptions regarding the seeding in order to determine optimal seeding parameters such as: seeding amount, time repetition of seeding, initial time of seeding, seeding height and distance. We have first investigated the influence of time interval of seeding on the total rainfall and hailfall on the ground.

Table 1 lists the parameters that distinguish ten numerical experiments using a second-moment model. The first run is chosen as a standard non-seeded case which serves as a basis for comparison with other experiments.

We compare rainfall and hailfall totals which were accumulated in the same total model integration time. The integration time was selected so that all precipitation were ended before the end of all simulations. It is evident that the total rainfall increases and hailfall decreases for all experiments relative to the base run case. One sees that the greatest rainfall increase of 25.79% is observed for a four-minute repeat of seeding for simulation A4. The experiment A1 indicates a peak rainfall increase of 6.23%. Hail amounts were much smaller but indicated decreases of 11.01% for case A7 and the minimum effect of seeding of 0.33% hailfall decrease is evidenced for run A1.

As is shown in Table 1 (columns, 3-7), most of the seeding agents act as deposition nuclei. In case A3 only 4.8% of the AgI particles remained unactivated. The seeding agent through inertial impact and Brownian collection by clouddrops and raindrops show very small effect on AgI activation. The next goals of this investigation is to examine the sensitivities of cloud seeding, including agent dispersion, to the physical processes which take place in-cloud and in the near cloud environment. As can be seen in Table 2, the maximum spread of the puff diameter within the target region is less than 90m, depending on the intensity of turbulence. The vertical extension of the seeding zone depends on the regular placement of the seeding and the windflow within the cloud, and organization of its downdrafts and updrafts. One sees that the agent dose rate of 0.1 g/m contributes a larger vertical extent of the seeding zone of 87.6m. After seeding the AgI particles are advected and diffused within the cloud before the activation occurs. The artificial ice-phase particles produced by seeding lead to increase of the cloud ice mixing ratios relative to the unseeded case. The mixing ratios of other hydrometeors with except of snow slightly differ, comparing to those given from the base run simulation. It is also found that the seeding amount do not influence significantly on the total horizontally summed rainfall and hailfall on the ground in case of very large vigorous cloud. The seeding amount of about 0.4g/m, initial seeding time of 16.6min, on height 5.5km at distance of 10km in case B2 contribute in peak rainfall depth increase by about 25.79% and hailfall decrease of about 10.01 %.

These percentage numbers refer to the maximum rainfall increases calculated in the simulation time, after the initial cloud seeding. The effect of AgI seeding in respect to their microphysics is apparent if we consider the time evolution of reflectivity patterns of the unseeded and seeded cloud (Fig. 4). There is a slight similarity between the reflectivity echo contours after the initial seeding. The seeded case exhibits earlier development of precipitation and transformations in respects to its microphysics. The difference in the reflectivity echo fields between these runs becomes more evident as the cloud enters its mature stage. While the calculated reflectivity of the seeded case is within the range between 5 and 25 dBz at 60 min of the simulation, in the unseeded case the reflectivity zone with 35 dBz contour still exists.

4. Summary

According to hail suppression hypothesis it is logical to expect significant decrease of hail at the ground as in the other carefully setup hail suppression experiments. Despite positive statistical results from a number of numerical studies our sensitivity experiments indicate peak rainfall increased by about 25.79% and smaller hailfall decrease of 11.01%. This result may be due the limited spread of the seeding agent and the relatively low time of its diffusion and activation in the case of very large vigorous clouds. Numerical models should be enabling to correctly simulate the agent dispersion that is in its initial phase on a sub-grid scale. However, it is not possible easy to say that the seeding does not have any effects considering the differences especially in respect to their microphysics.

The results from the case study simulation have shown that agent typically has about 2-3 min to spread in the seeding zone after its activation and relatively low vertical extension of spreading from the axis of dispersion, which is less than 190 m. The agent activation leads to earlier ice initiation that causes hailstorm modification, earlier initiation of precipitation and difference in respect to microphysics, especially in cloud mature stage.

The implication of the seeding is that cloud seeding with 6 min time frequency contributes in registration of the maximum hailfall decrease at the ground of about 11.01 %, compared to the unseeded case. The maximum rainfall increases of 25.79 % and hailfall decreases of 10% is found in the experiment with initial seeding rate of 0.4 g/m, 5.5 km seeding height and 10 km seeding distance relative to base case.

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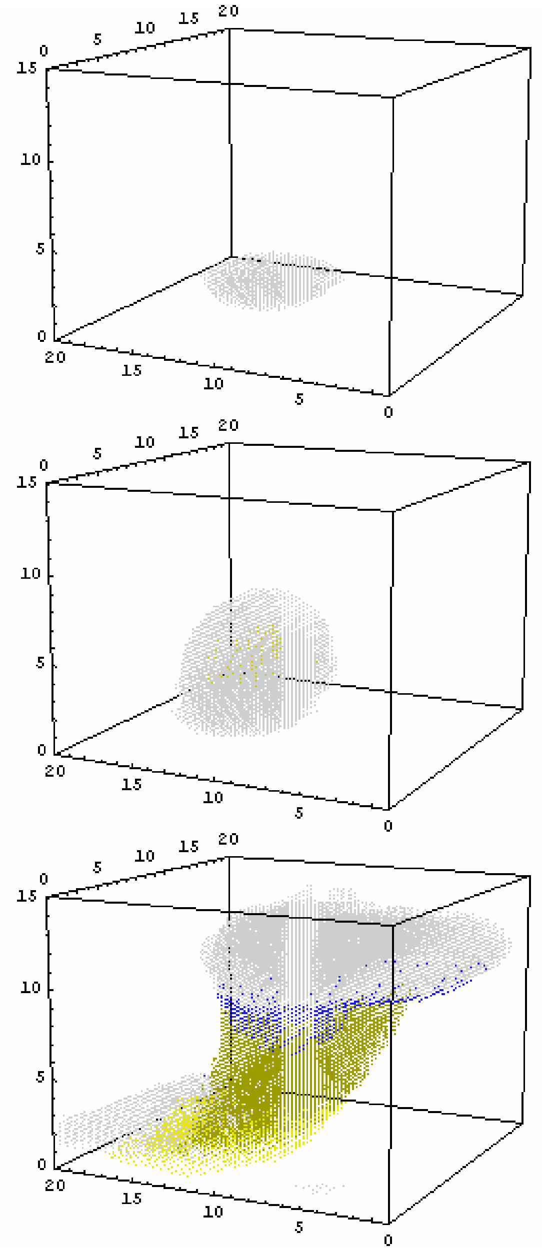

Figure 2a. Model simulated three-dimensional surfaces of the given mass mixing ratios (g/kg) at 10 min time intervals, starting at 10 min of simulation time. Gray plots represent total non-precipitating water (cloud water +cloud ice) with the cloud outline of 0.01 g kg^{-1}.The precipitating fields are blue, brown and yellow representing the mixing ratios of snow, hail and rain ≥0.1 g kg^{-1}. The domain dimensions are 20x20x15km^3.

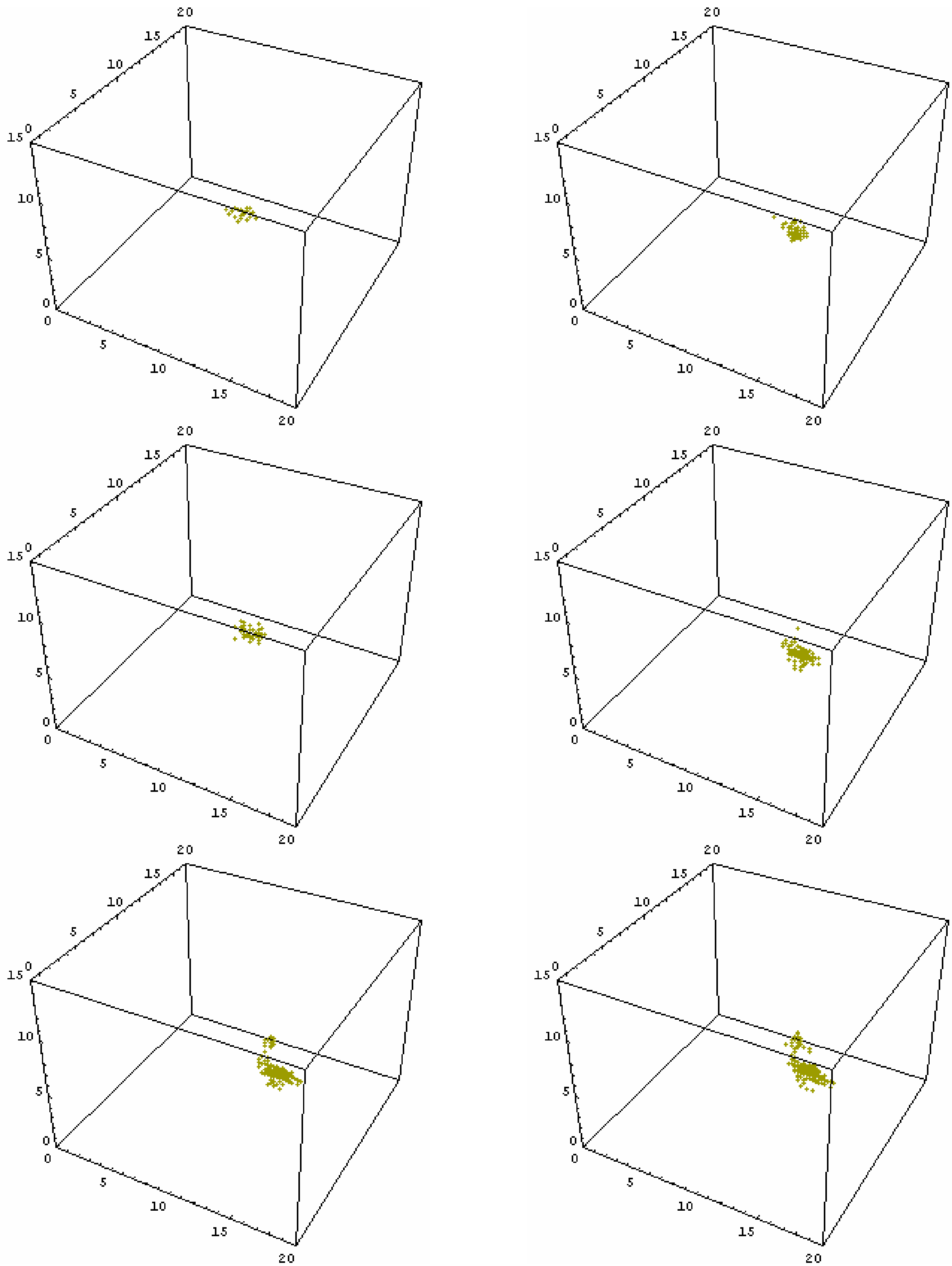

Figure 2b. Three-dimensional depictions of the AgI field viewed from SSE at 5 min intervals starting at 23.3 min of simulation time. The 0.1 µg kg^{-1} surface is indicated in these plots.

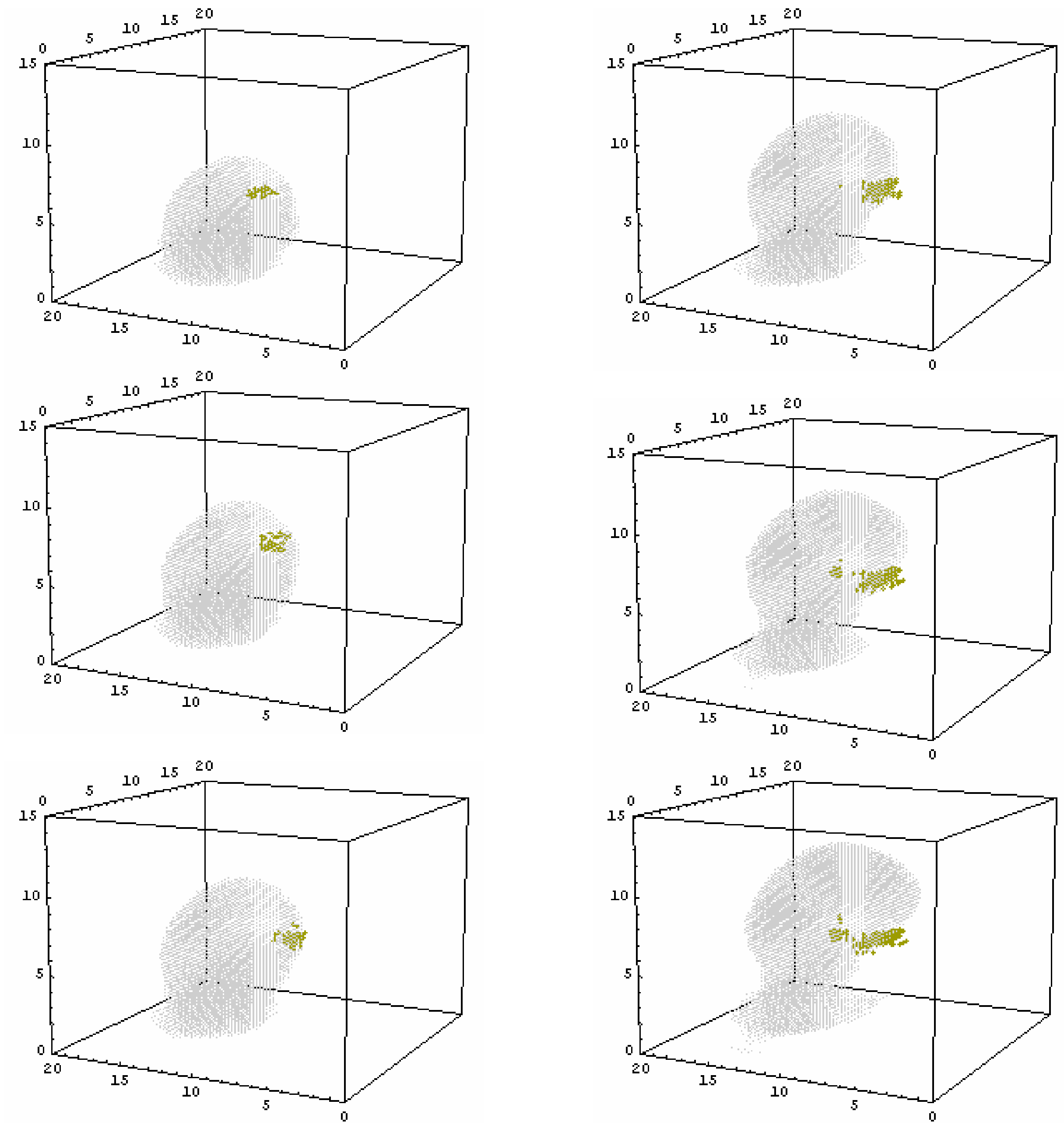

Figure 2c. Three-dimensional depictions of (cloud water + AgI field) viewed from SE at 5 min intervals starting at 23.3 min of simulation time. The cloud outline is indicated by 0.001 g kg^{-1}. The 0.1 μg kg^{-1} surface is indicated for AgI field in these panels. .

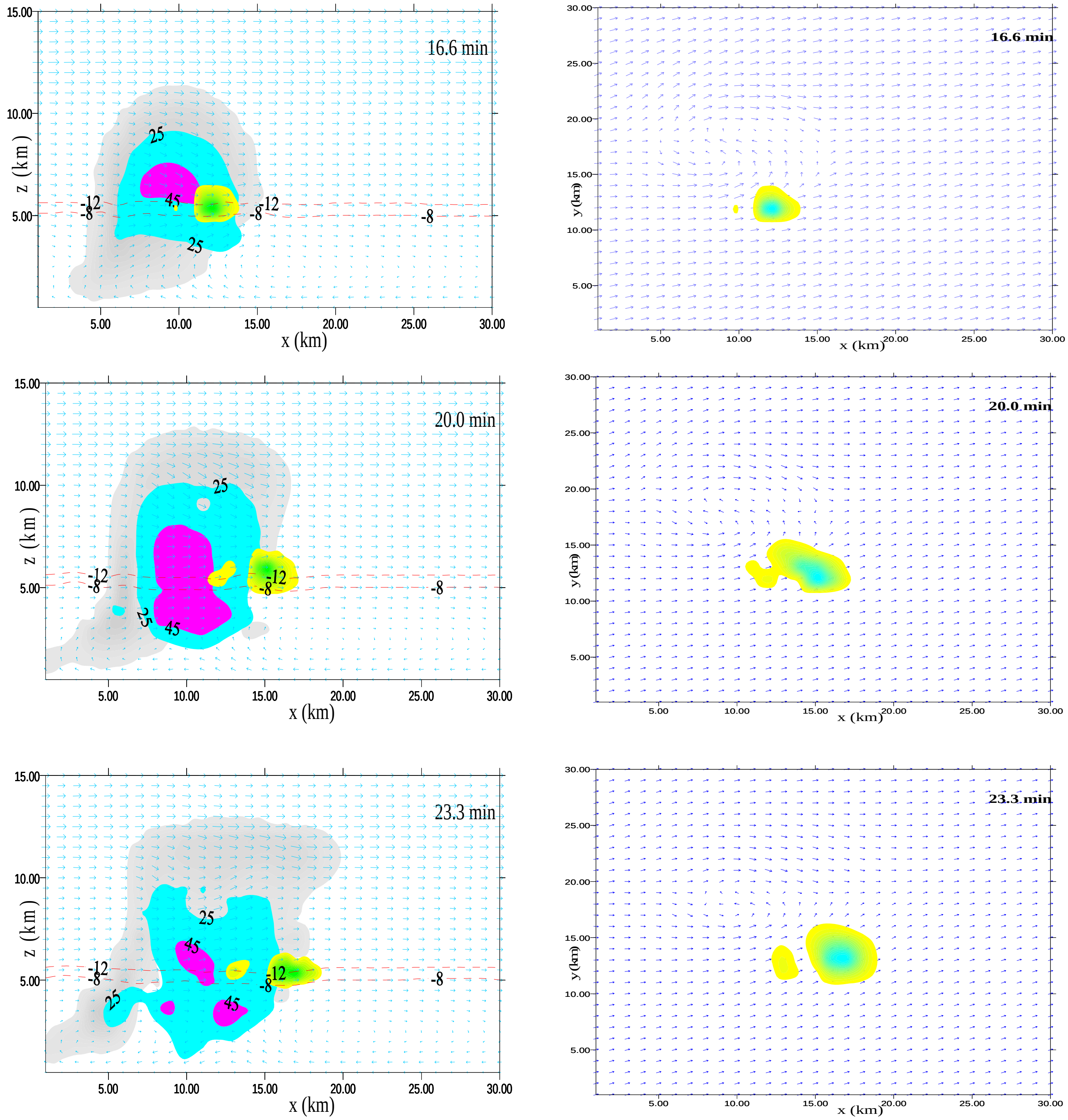

Figure 3. a) Time evolution of AgI (μg kg^{-1}) in the x-z plane at y = 15 km (left panel) for Negotino storm on May 18, 2003, in 16.6, 20.0, 23.3 and 26.6 min of simulation time. The domain dimensions are 30x30x15km^3. Cloud surfaces (gray) with cloud outline contour of 0.01 g kg^{-1}. AgI fields are (green and yellow), while the reflectivity contours are represented with light green and violet color. **b)** Time evolution of AgI (μg kg^{-1}) in the x-y plane at z = 5.5 km in 16.6, 20.0, 23.3 and 26.6 min of simulation time. The domain dimensions are 30x30x15km^3 (right panel).

Table 1. Maximum percentage values of each sink term representing the five nucleation mechanisms (Brownian collection and inertial impact due to cloud droplets and raindrops and deposition nucleation) and the total rainfall and hailfall accumulated on the ground expressed in (kg/m^2) and (%), in different time frequency of seeding.

Run	Time frequency of seeding (min)	Brownian collection cloud drops	Inertial impact cloud drops	Brownian collection raindrops	Inertial impact raindrops	Deposition (sorption)	Rainfall (kg/m^2)	Hailfall (kg/m^2)	Rainfall (%)	Hailfall (%)
Base run A	Unseeded						**150.51**	**18.18**		
A0	0 (20min)	0.143	0.014	0.004	0.048	87.6	159.89	18.12	6.23	0.33
A1	1 (20,21,22)	0.482	0.031	0.003	0.053	78.1	167.32	17.23	11.16	5.22
A2	2 (20,22,24)	0.645	0.026	0.003	0.060	84.6	174.44	16.76	15.89	7.81
A3	3 (20,23,26)	0.560	0.044	0.005	0.077	95.2	176.01	16.22	16.94	10.78
A4	4(20,24,28)	0.793	0.052	0.006	0.071	91.4	189.333	16.36	25.79	10.01
A5	5 (20,25,30)	0.711	0.058	0.004	0.083	90.3	182.87	16.37	21.50	9.95
A6	6(20,26,32)	0.538	0.045	0.002	0.074	89.7	177.29	16.18	17.79	11.01
A7	7 (20,27,34)	0.469	0.037	0.000	0.062	84.8	170.48	16.98	13.26	6.60
A8	8 (20,28,36)	0.333	0.027	0.000	0.054	84.4	163.60	16.55	8.69	8.96
A9	9 (20,29,38)	0.265	0.034	0.000	0.043	83.0	156.20	16.73	10.42	7.97
A10	10 (20,30,40)	0.201	0.029	0.000	0.048	78.5	155.18	17.00	9.74	6.49

Table 2. Model sensitivity experiments to the physical and AgI dispersion processes. The parameters listed in columns (5-12), represent the maximum calculated values during simulation time of puff concentration (g/m^3), spread of the puff diameter (m), vertical extent of puff (m) and AgI mixing ratio together with the total accumulated rainfall and hailfall in (kg/m^2 and %) on the ground, using different initial amount of seeding (g/m), seeding time (min), seeding height (km) and seeding distance (km), given in columns 1-4 in the same Table.

RUN	Seeding amount (g/m)	Initial seeding time (min)	Seeding height (km)	Seeding distance X,Y (km)	QPUFF Conc. of puff (g/m^3)	DPUF Spread of the puff diam. (m)	ZPUF Vert. extent of puff diam. (m)	RN AgI mixing ratio (g/kg)	Total acc. rainfall at the ground (kg/m^2)	Total acc. hailfall at the ground (kg/m^2)	Rainfall (%)	Hailfall (%)
Base run B	/				Unseeded case	/	/	/	150.51	18.18		
B1	0.1	15.0	5.5	11, 11	$0.52x10^{-5}$	87.6	6967	$0.72x10^{-9}$	155.04	18.12	3.00	0.33
B2	**0.4**	**16.6**	**5.5**	**10, 10**	$0.20x10^{-4}$	**79**	**6992**	$1.71x10^{-9}$	**189.33**	**16.36**	**25.79**	**10.01**
B3	0.6	15.0	5.0	10.5, 10.5	$0.31x10^{-4}$	77.5	7023	$2.03x10^{-9}$	182.13	16.51	21.00	9.18
B4	0.8	16.6	6.0	11, 11	$0.40x10^{-4}$	77	6889	$2.74x10^{-9}$	178.13	16.77	18.35	7.75
B5	1.0	16.6	4.5	9.5, 9.5	$0.56x10^{-4}$	75	6863	$3.90x10^{-9}$	169.23	17.28	12.43	4.95
B6	1.5	16.6	5.0	10,10	$0.79x10^{-4}$	77.5	7016	$6.45x10^{-9}$	165.84	17.16	10.18	5.61
B7	2.0	16.6	5.5	10,10	$0.98x10^{-4}$	78.5	6751	$8.83x10^{-9}$	158.08	17.25	5.03	5.11

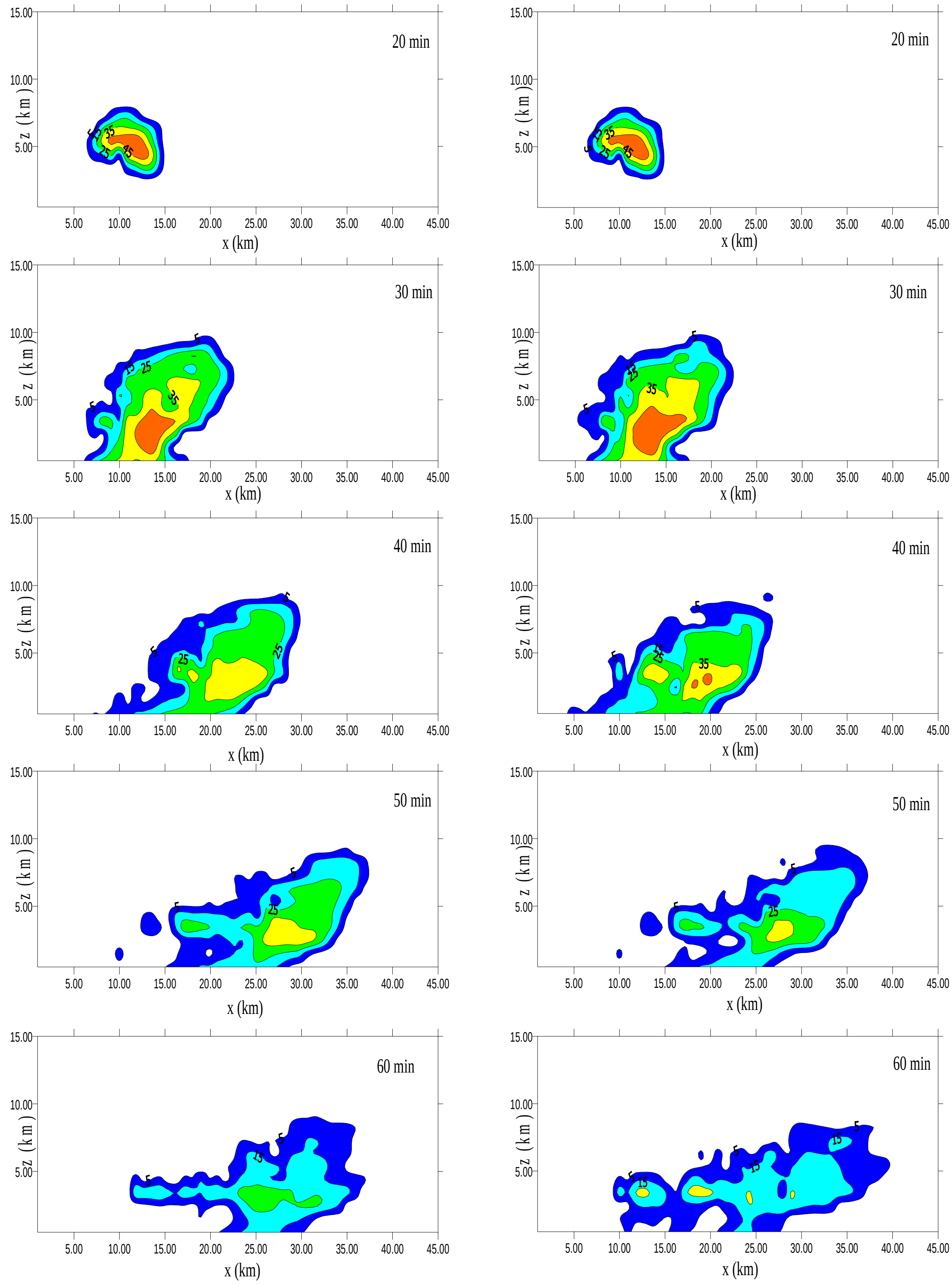

Figure 4. The vertical x-z cross sections of reflectivity patterns of the unseeded (l.s. panels) and seeded cloud (r.h. panels) at 20,30,40,50 and 60 min.of the simulation time running a two-dimensional version of the model with dimensions of 45x15km^2.

A SENSITIVITY TEST FOR HAIL PREVENTION ASSESSMENT WITH HAILPAD MEASUREMENTS

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Abstract

The evaluation of the French hail prevention project with silver iodide ground generators is based on daily correlations between the running time of the generators and the intensity of point hailfalls as indicated by hailstone number determined with hailpads. A normalization of these two parameters by their daily mean values allows the aggregation of hail days, and the setting-up of larger data samples for a statistical examination in which the random nature of hail becomes less important. In this paper, the evaluation is made from the 1948 point hailfalls recorded in an area of 16,000 km² of the Midi-Pyrénées region during 17 hail seasons. A cumulative method of correlation between the seeding and hailfall data shows that only the major hail days, with at least 15 point hailfalls measured in a hailpad network of 7 km mesh, may enable the detection of a seeding effect from a ground generator network of 10 km mesh. With this observation, the correlation between the seeding and hailfall data for 438 hailfalls on 18 major hail days indicates a beneficial effect of the seeding on 15 days, with a hail decrease of 40% for the correctly seeded events. This ratio amounts to 50% when the hailfall kinetic energy is considered instead of the hailstone number.

1. Introduction

The French hail prevention program of the Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques (ANELFA) has been operated continuously since 1952 without any change in its principle (Dessens 1953), which consists of the preventive seeding of the developing hailstorms with ice-forming silver iodide nuclei released from ground generator networks. For many years, the seeding effects were evaluated from cloud physics measurements and hail insurance statistics (Dessens 1986). In 1988, hailpad networks were added to the generator networks, and after 8 years of combined exploitation, correlations were detected between the amount of seeding delivered to the hailstorms and the severity of the hailfalls (Dessens 1998). A second data set, obtained a few years later, allowed to refine the first results and to improve the efficiency control by performing a geographical partition in the data processing (Dessens et al. 2003).

This paper presents an updating of the results in the most documented area of the project with three more years of experimental data. A slight change in the correlation computations is also introduced in the normalization of the data by their daily mean values. The results are summarized on graphs giving the cumulated effect of the seeding day after day. Such a cumulative method, which is motivated by the variability of the hail phenomenon, was successfully used with the double mass curves of the hail insurance loss-to-risk ratios (Dessens 1986). In this paper, it will allow the determination of the minimum number of daily point hailfall measurements necessary to the detection of a possible seeding effect.

2. Method used for the evaluation of a seeding effect

The data available to determine a seeding effect of the ground generator emission on hailfalls are the following:

- The starting time and duration of each generator emission, for days with a hail warning correctly transmitted to the operators (details available in Dessens 1998). In 2004, 698 generator stations were deployed in 15 local networks in the main hailed regions of France. The total area covered by the operation is 55,000 km². From April to October, each year, there are some 20 warning days per local network, a typical event lasting around 10 hours. One generator burns 8.6 g of silver iodide per hour and produces 2.0 x 10^{11} s^{-1} ice-forming nuclei active at -15°C.

- The characteristics of each point hailfall recorded on the 1104 hailpad stations (in 2004) installed in the same areas. Each emitting station is also a measuring station, and extra hailpads are located in areas immediately surrounding the target areas. The observers note the exact time of each hailfall. All the hailpad stations are located close to where the observers live, and in each local network a technician is in charge of the pad collection the day after the hailstorm. The hailpad sensor is a 0.1 m² extruded polystyrene plate (Dessens et al. 2001) and an image analysis system gives the hailstone numbers in 0.2 cm diameter classes from 0.5 to 1.7 cm, and in 0.4 cm classes above 1.7 cm.

The difficulty, if not the impossibility, of measuring a seeding effect by comparison of hailfalls from seeded or unseeded days is well known in weather modification, even for a randomized experiment. For this reason, a specific method has been developed by the ANELFA (Dessens 1998). The method consists in comparing the hailfall intensity to the amount of seeding material released in the area where the storm was located during its development stage. The comparison is made on a day-by-day basis, after a normalization of the data by their daily average. This normalization allows the aggregation of individual days together and then the increase of the data sample. The application of the method to the 1988-1995 hail prevention campaigns has shown that the number of hailstones larger than 0.7 cm in a point hailfall is basically responsive to the amount of silver iodide released during the 3 hours before the hailfall time in a circle of radius R = 13 km centered on the location of the developing cell 80 min before this time (the "development area"). The data collected over 6 more seasons have confirmed these parameters (Dessens 2003).

Based on these results, the whole data sample of the 1988-2004 period is examined in the next two sections of this paper, with a new illustration of the results.

3. Sensitivity of the method in the Midi-Pyrénées region

Four geographical areas of France are now equipped with generator and hailpad networks, the most homogeneous and best documented of these areas being the Midi-Pyrénées region (Fig. 1). In this region, an average of 152 generators and 283 hailpads covered an area of approximately 16,000 km² during the 17 hail seasons of the 1988-2004 period.

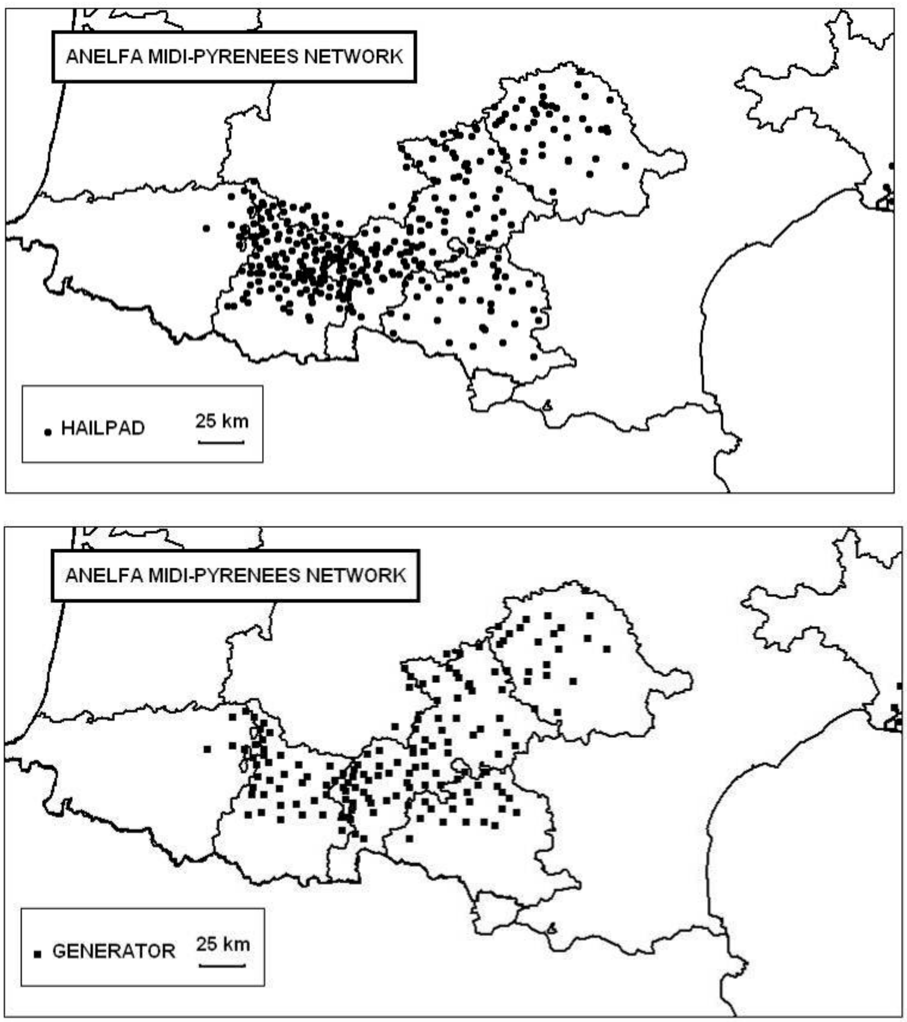

Fig. 1. Maps of the hailpad and seeding stations in the Midi-Pyrénées region in 2004.

The seeding and hail data considered in this paper are those already used in the first physical evaluation of the project (Dessens 1998):

i, measured point hailfall on a given day,
n, number of point hailfalls for the day,
N_i, total number of hailstones larger than 0.7 cm at this point,
N_m, mean value of N_i for the day,
$\Delta N_i = N_i - N_m$,
S_i, amount (in g) of silver iodide released in the development area during the 3 hours preceding the hailfall time,
S_m, mean value of S_i for the day,
$\Delta S_i = S_i - S_m$.

On a given day, the variations in the S_i values essentially depend on the relative positions of the point hailfalls and of the generator stations, since all the generators of a local network run simultaneously (except in the cases when an operator is unavailable or when there is a technical failure)

The determination of the development area is described in Dessens (1998), but a slight correction has been introduced in Dessens (2003). The center of the circle is now computed by considering a mean value of 27° for the deviation of the storm to the right of the wind direction at the 600 hPa level, instead of 31° before. The storm velocity is still estimated to be 18% lower than the wind velocity at the same level. The other two parameters for the localization of the development area are unchanged: $\Delta T = 80$ min, R =13 km.

In this paper, the estimate of the seeding effect is based on the correlations between $\Delta S_i/S_m$ and $\Delta N_i/N_m$, instead of ΔS_i and ΔN_i before. The aim of this normalization will be explained in section 5a. The physical principle of the method remains that, if there is a beneficial effect of the seeding, the hail cells which have developed over dense parts of the generator network will produce hailfalls of lesser intensity. For a visual display of the seeding effect, the cumulative deviations of the parameters are also graphically represented.

The total sample examined here amounts to 1948 point hailfalls distributed over 425 days. The number of hailfalls per day varies from 1 to 43, with more than half of the occurrences being relative to days with only one or two hailfalls (minor hail days).Out of these 425 days, there were only 82 days with 860 hailfalls for which a hail warning was followed by at least some seeding (S_m >0), and for which at least two hailfalls were measured (n>= 2). This difference is explained by the forecasting rules which specify that warnings are issued only in severe situations. The distribution of the 82 hail days according to the number of hailpads per day is given in Fig. 2 which shows, for example, that 55 hailfalls occurred on days when only 2 or 3 hailpads were impacted.

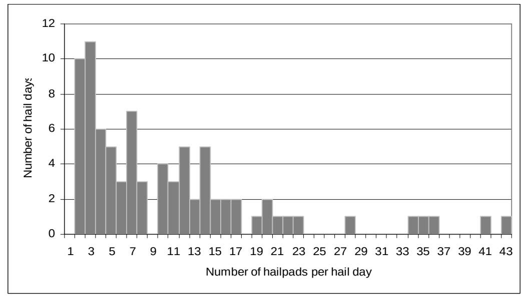

Fig. 2. Distribution of 860 hailfalls measured during 82 days with seeding.

The coefficient of the linear correlation between the independent 860 data pairs ($\Delta S_i/S_m$, $\Delta N_i/N_m$) of the 82 seeded days is r = -0.105, which corresponds to the 0.01 significance level. The graph in Fig. 2 is drawn with the cumulative values of $\Delta N_i/N_m$ as a function of the cumulative values of $\Delta S_i/S_m$. The right part of the graph is for the 323 hailfalls seeded more than average, and the left part for the 537 ones seeded less than average. On the right part of the graph, when the normalized number of hailstones is below the daily average (beneficial seeding effect), the curve goes down. On this graph, the hailfalls have been ordered chronologically (day, hour) from the point of coordinates (0, 0). On the whole, the right curve is observed to go down, and does not seem likely to return to the x axis in the future. This means that, on a daily average, more seeding corresponds to less hail. The left part of the graph gives a nearly reversed image, since at the end of each day, the cumulative values of the parameters are exactly opposite.

A careful examination of Fig. 3 indicates that the slope of the curves is higher for the heavily hailed years, suggesting a better efficiency of the seeding during major hail days. This observation is confirmed when the day-by-day correlations are considered, but the explanation is probably that the seeding response is only visible when many hailfalls are recorded. For the days with only a few hailfalls measured, the correlation is masked by the natural random distribution of hailfall severity. This effect is highlighted in Fig. 4, which is a rearrangement of Fig. 3 once the days have been ordered by increasing number of impacted hailpads from n = 2 to n = 43. The oscillations of the curve around the x axis show that no seeding effect can be clearly discerned if n is lower than 12 to 14, which corresponds to the point where the curve intersects with the x axis for the last time. The effect is even better visualized in Fig. 5 where the cumulated daily values of ΔN_i for $\Delta S_i > 0$ are plotted as a function of n, the seeding amount not being taken into account. The curve for the less-seeded-than-average hailfalls is not reproduced, since it is exactly symmetrical to the one for the positive ΔS_i. Obviously, no seeding effect can be systematically observed for the days with less than 14 or 15 recorded hailfalls. This observation is quantitatively confirmed by the values of the correlation coefficients: r = -0.04 for the 422 hailfalls for days with 2 to 14 hailpads, and r = -0.16 for the 438 remaining hailfalls.

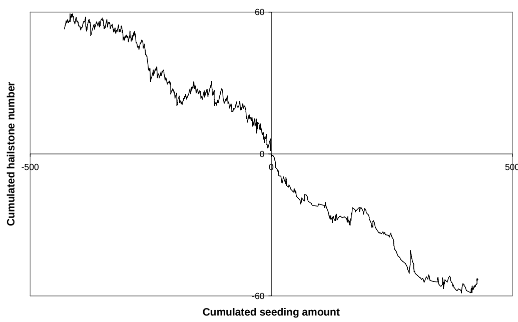

Fig. 3. Cumulated values of $\Delta N_i/N_m$ as a function of the cumulated values of $\Delta S_i/S_m$ for 323 hailfalls seeded more than average (right part), and for 537 hailfalls seeded less than average (left part). The days are chronologically ordered.

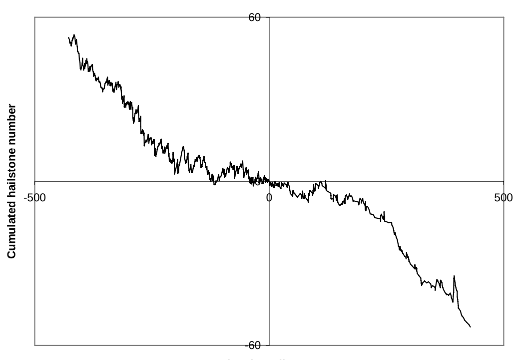

Fig. 4. Same as Fig. 3 but with days ordered by increasing number of impacted hailpads.

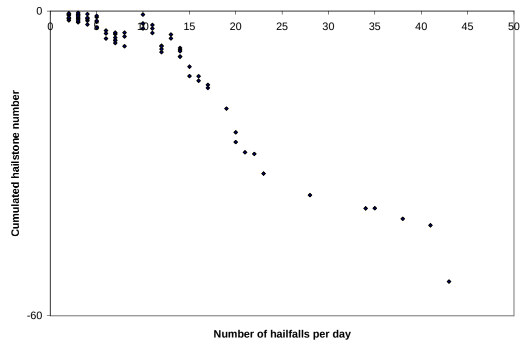

Fig. 5. Daily cumulated values of $\Delta N_i/N_m$ for 323 hailfalls seeded more than average. The cumulated values are plotted at the end of each day. The hailfalls are relative to 82 days ordered by increasing number of impacted hailpads.

Results for 18 major hail days

For the quantitative determination of a seeding effect, the sample is then reduced to the 438 hailfalls recorded on the 18 days with at least 15 recorded hailfalls. These few days are evidently the major hail days for which the hail prevention system has been developed, and luckily the control method is adapted to these events. The graph in Fig. 6 gives the curve relative to the 156 hailfalls seeded more than average, each point being computed at the end of a new day. As in Fig. 5, it is not useful to reproduce the curve for the 282 less-seeded-than-average hailfalls. The days are ordered chronologically.

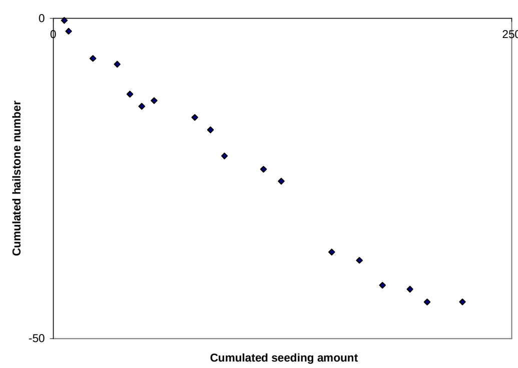

Fig. 6. Cumulated values of $\Delta N_i/N_m$ as a function of the cumulated values of $\Delta S_i/S_m$ for 156 hailfalls seeded more than average and relative to 18 major hail days. The cumulated values are plotted at the end of each day, and the days are chronologically ordered.

The graph in Fig. 6 shows a rather regular decrease of the hailstone cumulated number as a function of the seeding surplus. Among the 18 days, 15 well contribute to the appearance of a beneficial seeding effect, 2 days are neutral, and only one day gives the impression that the seeding has increased the hailfall severity. The daily values of S_m, N_m, and of the correlations between $\Delta S_i / S_m$ and $\Delta N_i / N_m$ are given in Table 1. All but one day have negative r values, but a significant level is reached only for the day with most impacted hailpads. For each day, the correlation in parentheses is also computed with all the hailfalls until this date (and including it). A statistically significant correlation is observed from day N° 11 at the 0.05 level, or from day N° 13 at the 0.01 level. The last days of the series reduce a little the coefficient r, which nevertheless remains at the 0.01 level.

Table 2 summarizes the seeding and hail data for the major-day hailfalls. The N values given in Table 2 allow the computation of a mean seeding effect. The hailfalls seeded less than average have received a small amount of seeding and, if we suppose a linear response to the seeding, their mean hailstone number is slightly lower than it would have been without any seeding. The hailstone number N for S = 0 can be computed with the equation:

$$(N - 1514)/17.7 = (N-1315)/57.2 \qquad (1)$$

which gives N = 1603. The seeding efficiency based on the reduction in the number of hailstones is then:

$$[1- (955/1603)] \times 100 = 40.4\%. \qquad (2)$$

Table 1. Number of recorded hailfalls (n), mean seeding amount (S_m, g/3h) and mean haistone number (N_m, m^{-2}) for major-day hailfalls. The correlation coefficient (r) between the normalized values of S_i and N_i is given by day, and, in parentheses, for all the days together until that day.

Day	Date	n	S_m	N_m	r
1	17/05/90	22	130	1007	-0.04 (-0.04)
2	13/08/90	17	191	296	-0.27 (-0.11)
3	27/09/92	28	20	2077	-0.29 (-0.20)
4	05/07/93	16	20	641	-0.12 (-0.14)
5	16/05/94	20	72	803	-0.27 (-0.15)
6	18/06/94	20	98	1392	-0.26 (-0.16)
7	31/07/94	16	101	1318	-0.10 (-0.15)
8	02/07/95	34	46	1510	-0.06 (-0.13)
9	17/05/97	15	12	1144	-0.14 (-0.13)
10	01/07/98	19	48	934	-0.21 (-0.13)
11	02/07/98	36	56	2158	-0.15 (-0.14)
12	26/09/98	15	7	1091	-0.17 (-0.14)
13	29/04/99	43	33	1479	-0.46 (-0.19)
14	18/05/99	41	91	1216	-0.11 (-0.17)
15	02/06/99	23	17	1661	-0.31 (-0.18)
16	13/05/00	17	5	1174	-0.10 (-0.17)
17	01/06/03	21	33	843	-0.20 (-0.17)
18	28/08/03	35	56	1317	+0.05 (-0.16)

Table 2. Mean seeding amount, hailstone number and kinetic energy for major-day hailfalls seeded respectively more and less than average.

Parameter	All hailfalls	Hailfalls seeded more than average	Hailfalls seeded less than average
Number of hailfalls	438	156	282
Mean seeding, g/3h	57.2	128.5	17.7
Mean hailstone number, m^{-2}	1315	955	1514
Mean kinetic energy, $J.m^{-2}$	99.3	63.6	119.0

4. Discussion

The results presented in this paper reinforce those already given in Dessens (1998), because they are relative to a larger sample of major hail days in a more homogeneous region. They also suggest a few points not discussed before, among which:

a. Normalization of the data

The normalization by S_m and N_m has initially been adopted because it gives better values for the correlation between seeding and hailfall intensity. For example, with the normalization, the correlation coefficient increases from -0.082 to -0.105 for the 860 hailfalls of the total sample, and from -0.139 to -0.162 for the 438 major-day hailfalls. The normalization, however, does not deeply change the analysis, as shown in Fig. 7, where the graph of Fig. 6 is redrawn with the non-normalized data. The curve progression in Fig. 6 is simply more regular than that of Fig. 7.

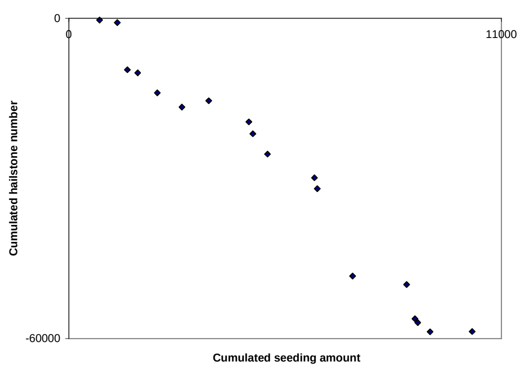

Fig. 7. Same as Fig. 6 but with cumulated values of ΔN_i (in m^{-2}) as a function of the cumulated values of ΔS_i (in g/3h).

b. Statistical significance of the evaluation

The coefficient of the correlation between the paired values ($\Delta S_i / S_m$, $\Delta N_i / N_m$) gives an estimation of the seeding effect significance level. A paired t-test can also be applied to the daily differences between the mean value of $\Delta Ni / N_m$ when $\Delta S_i > 0$, and the mean value when $\Delta S_i < 0$. For the 82 hail day sample, the averaged difference is -0.196, its standard deviation is 0.946, and the 95% confidence interval is 0.205, which means that the null hypothesis cannot be strictly rejected. For the 18 hail day sample, the averaged difference is -0.468, the standard deviation is 0.359, and the 99.9% confidence interval is 0.278; the null hypothesis is rejected. Unlike the correlation computation, the t-test results are the same with or without the normalization.

c. Virtual seeding

The Midi-Pyrénées sample also contains 921 hailfalls recorded on 173 days without any seeding and with at least 2 impacted hailpads. A sort of placebo method consists in computing the seeding amount for these hailfalls as if the generators had been running. A graph like that of Fig. 3 for these hailfalls (not reproduced here) does not show any seeding effect. If the same process is repeated for the 11 days with at least 15 impacted hailpads, a hail decrease tendency is nevertheless observed (not significant at the 0.05 level). In the future, a few more major hail days without seeding will possibly confirm some persistent effect already observed with silver iodide (Bigg and Turton 1988).

d. *Direct correlation between S_m and N_m*

The significant measured effect of the seeding on the number of hailstones makes it possible to observe a direct correlation between S_m and N_m. For the 18 seeded major hail days listed in Table 1, the correlation coefficient is $r = -0.38$, which is not far from the significant level. The correlation, however, is mainly driven by day N° 2. On that day, the 0°C isotherm was at an altitude of 4 km, the maximum value for the sample. The reduction of the hailstone number is probably due to the combined effect of the melting and the seeding. This observation illustrates the interest of a differential method correlating the parameters on a daily basis.

e. Evaluation based on the kinetic energy

Instead of the hailstone number, the total kinetic energy of a hailfall is often used as a measure of its severity. This parameter was not used in the former evaluations of the ANELFA project with the hailpad data because of a problem of data normality due to the small number of hailfalls with very large hailstones (Dessens 1998), but the problem has decreased now that a larger data sample is available. When the evaluation for the major-day hailfalls is made with this parameter, the hail decrease computed as in Section 4 for the hailstone number amounts to 50.2%, the result being significant at the .01 level.

6. Conclusion

A sensitivity test for the control of hail prevention by silver iodide ground seeding has been conducted in one of the most hailed regions of France. In this region (Midi-Pyrénées), there is a generator station releasing silver iodide nuclei on days with a hail forecast each 10 km, and a hailpad station each 7 km. These distances are comparable to the dimensions of hail cells. With this geographical disposition, the correlations between the amount of silver iodide presumably delivered to a developing hail cell, and the intensity of the subsequent hailfall show that, probably due to the random nature of hail, no seeding effect can be properly detected if less than about 15 hailfalls have been measured. It is not sure that this number can be reduced by an increase of the hailpad density, because such an increase may introduce redundant measurements and then reduce the independence of the data.

With this restriction in the hailfall sample, the differential method of control of the ANELFA hail prevention project for 18 major hail days having occurred in the Midi-Pyrénées region from 1988 to 2004 confirms the results already published (Dessens 1998): hail cells seeded by generators networks with a density of about 10 generators par 1000 km² produce 40% fewer hailstones larger than 0.7 cm and 50% less kinetic energy. The reduction in crop losses is of the same order (Dessens 1998). Until now, the respective localization of the developing hail cell and of the resulting hailfall is determined with a mean storm displacement estimated from wind soundings. An improvement in the control could certainly be obtained from a better knowledge of the ice-forming nuclei dispersion in the lower atmosphere, and from hailstorm simulation. To this aim, an application of the Meso-NH simulation model (Pinty et al. 2001) is now underway at the Laboratoire d'Aérologie of the University of Toulouse in collaboration with the ANELFA.

A more global and simple correlation between the mean seeding for a day and the mean number of hailstones in the hailfalls of that day is becoming statistically significant. With a data sample increasing year after year, it will soon be possible to work on the Principal Component Analysis for the major hail days by considering as variables the altitude of the 0°C, the wind shear, etc…, and the seeding intensity.

By developing its differential method, the ANELFA wants to demonstrate the possibility of hail prevention control without randomization. The new results of the French program are coming at a time of increasing confidence in hail prevention operations (American Society of Civil Engineers 2003, World Meteorological Organization 2005), and they could be useful to the development of experimental or operational programs in other countries.

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POTENTIAL WATER AUGMENTATION FROM CLOUD SEEDING IN THE COLORADO RIVER BASIN

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Abstract. A spatially-distributed snow energy and mass balance model, updated with all available snowpack observations, is used to assess the potential for water augmentation by winter orographic cloud seeding in the Colorado River Basin. The modeling system outputs snow water equivalent (SWE) on a 1 km grid throughout the continental United States. The April 1 SWE from the last two years are horizontally integrated across existing and potential seeding target areas in the basin and multiplied by approximately 0.1 to calculate water yields from an assumed seeding-induced increase of 10 percent. Major uncertainties in this method, including snowpack ablation and target area selection, are described. Given those uncertainties, it is estimated that in an average precipitation year, about one million acre-feet of additional snowpack water could be produced by seeding. Somewhat more could be produced in a wet year and about 500,000 acre-feet in a dry year. These figures are reasonably close to those from older studies of augmentation potential in the basin.

1. BACKGROUND

Seeding of orographic (mountain) clouds in the cool season has been done in the Upper and Lower Colorado River Basin since the 1960s, on an operational and research basis. Several studies have been done in that time to estimate the potential water augmentation from seeding in the basin. The following are some of the older such studies and their estimates of water yield, as cited in a Bureau of Reclamation report (Water and Power Resources Service 1980):

Table 1. Previous water yield estimates from cloud seeding in the Colorado River Basin

Source	Dates	Water Yield Estimates (Acre-ft)
Bureau of Reclamation (Grant 1969)	1967-1968	1,870,000
Stanford Research Institute (Weisbecker 1974)	1971-1972	1,150,000*
North American Weather Consultants, Twelve Basin Investigation (Elliott et al. 1973)	1972-1973	1,315,000 (liberal)† 903,000 (conservative)†

* Figure from this document is halved because it assumed a 20% increase, whereas today the often accepted increase is 10%

† Figures from this study do not include estimates from the Gila River Basin in Arizona, which is in the lower basin and most of which is below 9,000 feet elevation.

These figures are for seeding *all* target areas in the basin, with areas selected based on the differing criteria of each study. Since these studies are over 30 years old, it was desired to update them with more recent information. Also, motivation was added by the letter of 25 August 2005 from the seven Colorado Basin states to Interior Secretary Norton. This letter requested a long-term plan for operating Lakes Powell and Mead during hydrologic drought, and included a recommendation that Reclamation develop a plan for water augmentation through cloud seeding. Also, the funding and context for the current work were provided by the Colorado Water Conservation Board's (CWCB) "Winter Storm Climatology" study, of which Reclamation had a part.

2. AUGMENTATION ESTIMATION PROCEDURES

We assumed a 10% increase in April 1 snow water equivalent (SWE) in existing and potential target areas, with SWE provided by the Snow Data Assimilation System (SNODAS; Carroll et al. 2001). The SNODAS consists of a spatially-distributed snow energy and mass balance model, updated with all available snow water equivalent, snow depth, and snow cover (from surface, aircraft, radar, satellite) data. Model outputs include SWE, snow depth, snowmelt, pack temperature, and sublimation. Daily and historical model output for the state of Colorado may be found online (Hunter 2004). The output has been available nationwide since October 2003, and for some areas before that date. Therefore data exist for two winters only, a short climatological record compared to the more traditional Snow Telemetry (SNOTEL) and snow course datasets. Unlike these datasets, however, SNODAS provides spatially continuous data at 1 km resolution. The model has been validated (Cline et al. 2004) in the Colorado Mountains against the Corps of Engineers widely-validated SNTHERM model.

2.1 Determination of Target Areas

A major variable in estimating water yield from seeding will be selection of the seeding target areas. We split this task into two sections: *existing* areas already being seeded by operational programs (in Utah and Colorado only), and *potential* new areas. Geographic Information Systems (GIS) maps were obtained for the former. Selection criteria for existing areas vary, but are in general elevation-based. In Utah, this criterion is 7000 feet or higher, whereas in Colorado it is above 8000-9000 feet. These criteria were informally adopted and reflect the higher elevations in Colorado. In any event, the existing areas were used as provided, with no modification except to exclude parts outside the Colorado River drainage area. The existing target areas are listed in Table 2.

Table 2. Existing Target Areas

Colorado	Utah
1. Upper Arkansas†	11. Fishlake Mtns.†
2. Gunnison North	12. Boulder Mtn. †
3. Gunnison South	13. Uinta Mtns. South
4. Vail	14. Dixie Natl. Forest†
5. Beaver Creek	
6. Grand Mesa North	
7. Grand Mesa South	
8. San Miguel Mtns.	
9. Western San Juans	
10. Eastern San Juans	

† Portion of area outside Colorado River Basin

For *potential* areas, a strict 9000 foot base threshold was used as a criterion in the Colorado basin regions of Arizona, New Mexico Colorado, Utah, and Wyoming. This criterion follows that specified in a planning document for a winter cloud seeding research project called the Colorado River Snowpack Enhancement Test (CREST; Super et al. 1993). Further criteria from this document were that the candidate region usually has at least 20 km west-east extent of 9000 feet elevation area and that it is largely or wholly outside designated wilderness areas. These criteria were used to select proposed areas for cloud seeding *experimentation*, whereas this document is concerned with all potential target areas for *operational* seeding. It would be impractical to conduct experimentation within a wilderness area, since key instrumentation would not be allowed. Some operational projects target wilderness areas, although their seeding generators are located outside the boundaries of those areas. So for the present study, several additional areas, including those with wilderness designations and barriers no wider than 5 km, have been added. Finally, the potential new areas were included only if they are outside existing target areas.

The CREST locations were given spatial extents through use of GIS software, since the planning document gave only general text descriptions of locations (the authors had to manually search 1:1,000,000 aeronautical charts). Based on the slightly different criteria (stated above) and more sensitive mapping with GIS software, we identified five additional potential target areas (Table 3). The Bureau of Reclamation report (Water and Power Resources Service 1980) identified the entire Mogollon Rim in Arizona as a potential target, whereas we exclude all of it (except for the San Francisco Mountains) because it is largely below 9000 feet elevation. The snowfall at such low elevations, particularly if they are at southerly latitudes as in Arizona, would frequently occur at relatively warm subfreezing temperatures, during which silver iodide would be ineffective. Seeding by liquid propane gas expansion, which can create ice crystals at warmer temperatures (thresholds -1°C vs -5°C for silver iodide), might be a viable alternative for such locales.

An essential point is that, despite the CREST criteria application, there is still substantial subjectivity in selecting any seeding target area. All new potential areas are listed in Table 3. Both existing and potential areas are shown by the map in Fig. 1.

Table 3. Potential Target Areas

Colorado	Utah	Wyoming	Arizona
15. Park Range	20. Uinta Mtns. North	24. Wyoming Range	26. Kaibab N.F.#
16. Elkhead Mts.	21. La Sal Mts.	25. Wind River Mtns. West#	27. Chuska Mts. AZ/NM)
17. White R. Plateau	22. Mt. Ellen#		28. White Mts.
18. Uncompahgre Plateau	23. Abajo Pk. #		29. San Francisco Peaks#
19. Central Rockies@			

Areas not identified in CREST document
@ Area was operationally seeded in previous years by Denver Water utility

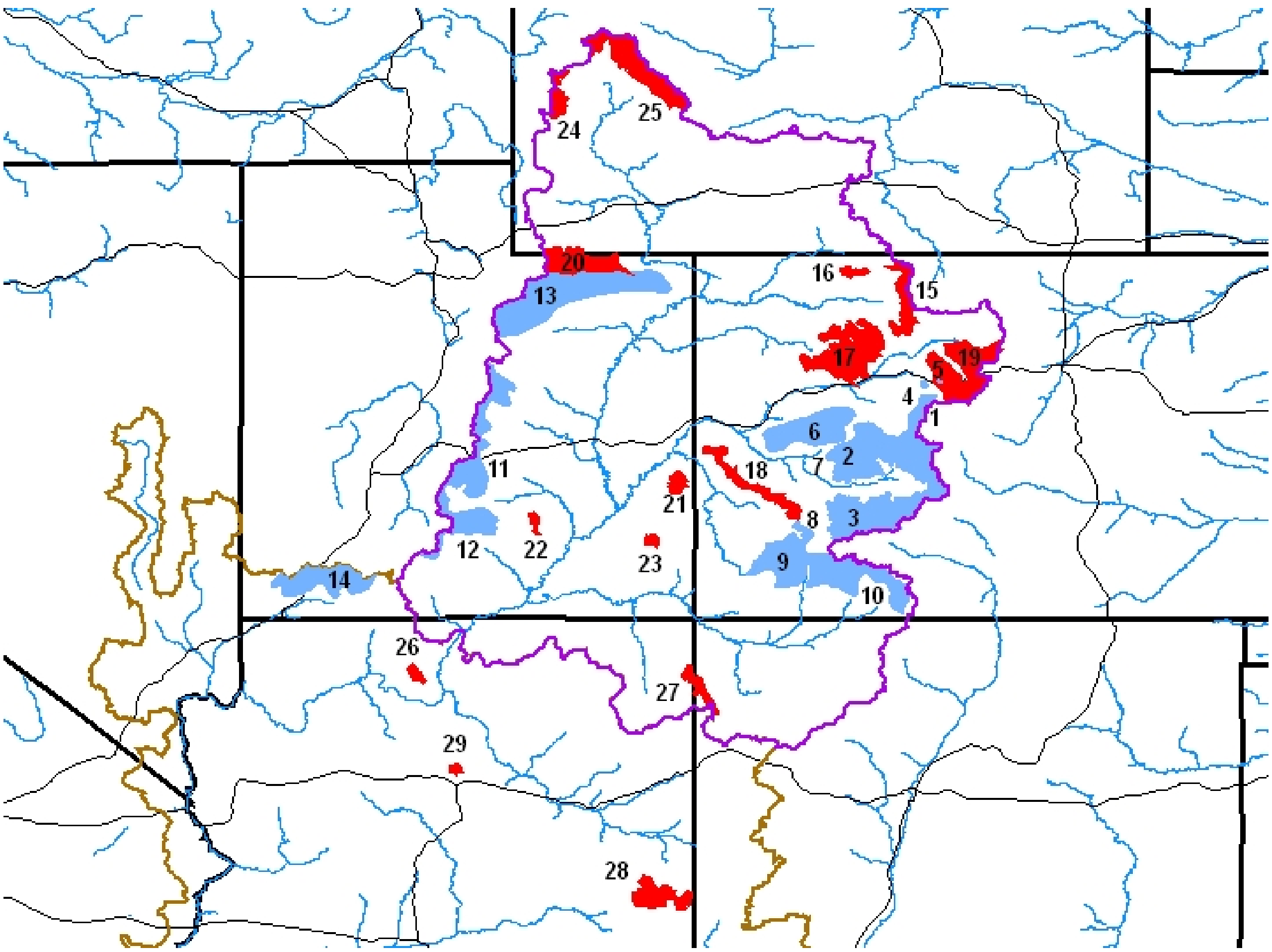

Figure 1. Existing (operational) cloud seeding target areas (blue) and potential target areas (red). Areas are indexed with numbers corresponding to those in Tables 2 and 3, respectively. Purple and brown polygons are Upper and Lower Colorado River basin outlines, respectively.

2.2 Nature of Calculations

For the current application, we integrated SNODAS 1 km SWE data over seeding target areas at the traditional end of the mountain snow accumulation season, April 1 (also the traditional beginning of the snowmelt runoff season). To estimate water volumes produced by seeding in *potential* areas, these integrations are divided by ten, since there is statistical, physical and modeling evidence for about 10 percent augmentation of natural precipitation (snowfall) by orographic cloud seeding (American Meteorological Society 1998). Physical cause-and-effect relationships have yet to be fully demonstrated, however. Since seeding has been conducted in *existing* areas, it is assumed that SNODAS SWE already reflects the 10% increase, or 110% of natural snowpack. Therefore the integrated SWE is divided by 11 in these areas. These calculations were made for both 2004 and 2005 April 1 SWE data. The year 2004 was an unusually dry one in the Upper Basin and 2005 was a relatively wet one. See Fig. 2 for a graphical representation of the precipitation in the basin.

That the calculations are based on "snapshots" of the snowpack on April 1 requires a caveat. They are representative of cloud seeding augmentation of snowfall to the extent that the snowpack has continually increased and melted little over the preceding winter. Such would not be the case in relatively warm southerly and/or low elevation mountains, as in Arizona. Because some melt occurs even in colder climates and/or higher elevations, the April 1 SNODAS SWE will be lower than SWE from accumulated seasonal *snowfall*. The latter is actually the more appropriate variable for augmentation potential, but is only measured at a few points. Therefore the seeding-generated 10% increases of the April 1 SNODAS SWE, as presented below, might be expected to *underestimate* in proportion to seasonal snowpack ablation (melt, sublimation [ice to vapor] or evaporation). Snowfall measurements from gauges have significant errors as well. Moreover, some of the gauged precipitation could have fallen as rain.

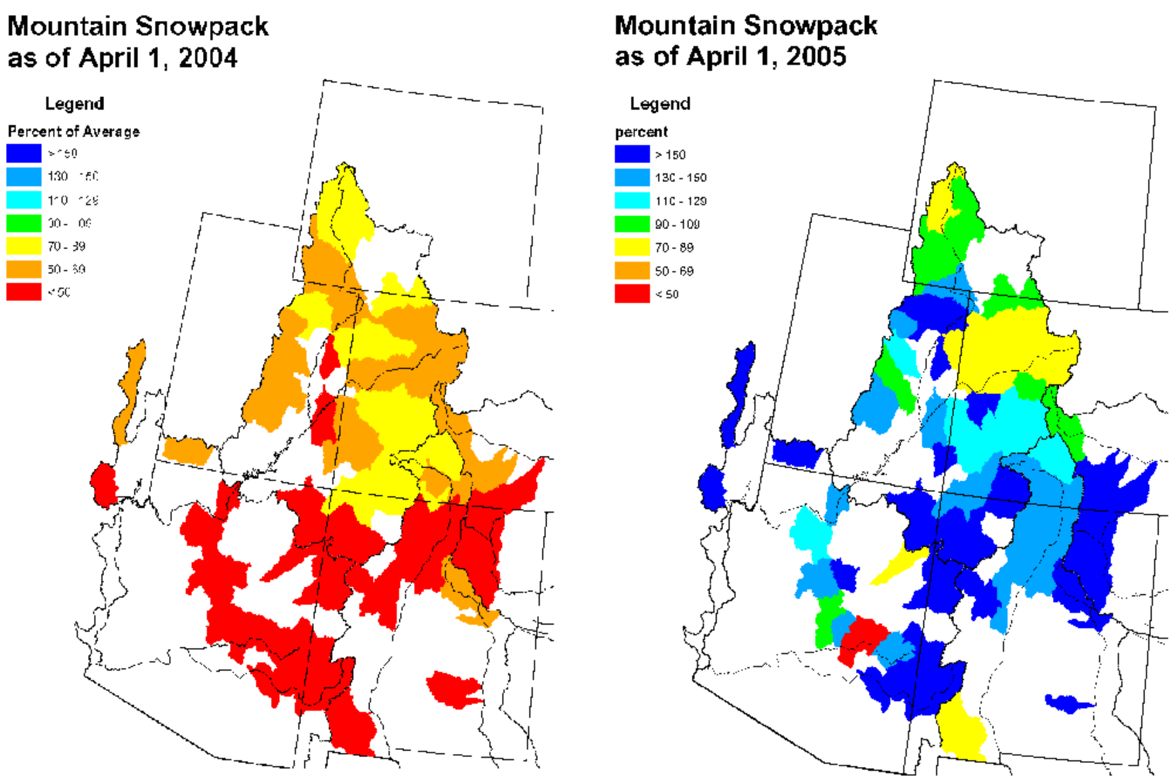

Figure 2. Snowpack expressed as percent of 30-year average in various sub-basins of the Colorado River basin, as of 1 April 2004 (left) and 1 April 2005 (right). Data are from SNOTEL sites operated by the National Resource Conservation Service (NRCS) and figures are from the NRCS National Water and Climate Center.

2.3. Use of SNOTEL Precipitation Data to Estimate Snowpack Ablation

To estimate snowpack ablation, we compared November 1 to April 1 accumulated gauge snowfall at 16 SNOTEL sites against April 1 SNODAS SWE there. November 1 is a nominal date after which most precipitation falls as snow rather than rain. The 16 sites were from Colorado, Utah, Wyoming, and Arizona, at dispersed geographic locations and elevations. Interestingly, the SNOTEL precipitation-to-SNODAS SWE ratios were 1.22 in 2004 and 0.89 in 2005, respectively. The latter ratio, indicative of greater snowpack water than precipitation, might reflect a problem with gauge precipitation measurement or the arbitrary November 1 start date of the snowfall season. There is significant gauge under catch of snowfall in wind-exposed locations that might explain much of the problem. The bottom line is that we cannot trust the SNOTEL gauge-measured seasonal precipitation to estimate seasonal melt of the snowpack. There is one other option to estimate melt. The SNODAS model outputs snow melt at the base of the pack. We post daily melt products on our Colorado web site (Hunter 2004). To generate seasonal melt, we would have to sum the daily values over an entire winter. This is beyond the scope of the current study but may be pursued later.

3. RESULTS AND INTERPRETATION

The reader is cautioned that water volumes resulting from increasing existing April 1 snowpacks via cloud seeding *do not necessarily equal runoff increases*. The latter increases may be changed by a given basin's hydrologic processes such as soil infiltration, antecedent soil moisture, slope and aspect, and vegetative cover. Other factors affecting a basin's precipitation-runoff relationship are spatial distribution of the snowpack, amount and timing of any rainfall on the pack, temperature, and evapotranspiration of snowmelt water.

There was a CREST-related analysis (Super and McPartland 1993) of snowpack-runoff relationships for fourteen watersheds in Colorado, Wyoming and Utah. The selected watersheds were not significantly affected by upstream trans-mountain or trans-basin diversions and not regulated by upstream reservoirs. This analysis performed a long-term linear regression of snow course/snow pillow SWE and stream gauge data and assumed 10% SWE increases from seeding. Correlation coefficients between the two datasets was low for some watersheds, usually because the snow courses/snow pillows were relatively low in elevation and didn't reflect higher altitude snowpack (this shortcoming could be alleviated by the spatially continuous SWE fields of SNODAS, if one were to do a new regression analysis with that system). Given the assumed 10% SWE increase, April to July seasonal runoff increases varied from 6% to 21%. This variation was attributed either to poor representation of the snow course/snow pillow SWE data or to differing basin hydrologic or meteorological characteristics, as related in the preceding paragraph. Porous geology such as sinkholes may divert meltwater away from stream gauges, leading to decreased runoff measurements, whereas impermeable soils such as clay may increase runoff percentages. Again, these complex factors will affect any additional runoff produced by seeding-induced precipitation increases and should be weighed when selecting target areas. It is logical to assume that the farther the target area is from the mainstem of the Colorado River, the greater the runoff losses at the river. Examples of such areas are the Wyoming potential targets at the northern extremity of the basin (see Fig. 1). On average, however, 10% runoff increases might be expected to result from 10% snowpack increases (Arlin Super, personal communication).

Table 4 lists the water volumes produced by 10% increases of the snowpack SWE on April 1 for existing target areas and for the potential target areas.

Table 4. Areas and water yields for 10% snowpack SWE increases from seeding, for existing (operational) seeding targets and potential new targets.

	Area (km^2)	**April 1, 2004 (Dry) Yield (ac-ft)**	**April 1, 2005 (Wet) Yield (ac-ft)**	**Mean Yield 04-05 (ac-ft)**
Existing Areas				
Utah	12,992	128,902	294,527	211,715
Colorado	17,767	240,852	499,190	370,021
Total	30,759	369,754	793,717	581,736
Potential Areas (All States) Total	13,611	217,890	352,978	285,434
Existing + Potential Areas Total	44,370	587,644	1,146,695	**867,170**

It seems unlikely that two years of SNODAS data would convey the long-term variance of precipitation across the Colorado River Basin, even if those two years exhibited a large variation about the mean in precipitation amounts. Nevertheless, **SNODAS** SWEs at the 16 Basin SNOTEL locations (see previous section) were compared to the 30-year (1971-2000) **SNOTEL** SWE averages. The 2004 SNODAS SWE mean for all sites was 12.5 inches and the 2005 mean was 20.5 inches. The 30-year average SNOTEL SWE for the sites is 17.9 inches, intermediate to the SNODAS SWE for the two years, and close to their mean of 16.5 inches. This calculation lends confidence that the target area-integrated means of the two-year SNODAS data represent a climatologically average year. These means are presented in the right-most column of Table 4.

It is instructive to compare these means with those of Table 1. The wet year (2005) is close to the Stanford Research and Twelve Basin liberal figures, whereas the mean is very close to the Twelve Basin conservative value. Using half of the Stanford figures again, that report states that "One year out of three, it [the yield] might be either lower than 550,000 or higher than 1,800,000 acre-feet." The dry snow accumulation year ending April 1, 2004 is very close to the low figure of the Stanford study. The high figure of that study seems optimistic, especially since both Colorado and Utah suspend seeding operations when snowpack SWE exceeds certain percentages of normal. If one attempts to account for seasonal snowmelt (see previous section), the mean yield at lower right of Table 4 might be near 1 million acre-feet. This figure is close to that from the Stanford study and is intermediate to the conservative and liberal Twelve Basin values. This amount of water is significant for the Colorado River basin water balance; for example, it is two-thirds of the 1.5 million acre-feet of the river's annual flow that is legally obligated to Mexico.

These values should be considered approximate. Since they compare favorably to the estimates of two earlier studies, however, we have more confidence in them. There are many variables in determining the effectiveness of seeding, which could lead to substantial deviations from the assumed 10% augmentation used herein. Besides the choice of target areas, there are natural hydrologic and meteorological variables. Then there are those associated with seeding methods. For those methods to be effective, seeding materials must be dispersed in sufficient concentration in cloud regions with adequate supercooled liquid water and temperatures cold enough for the seeding materials to function as intended. An examination of these variables is beyond the scope of this study. There is an in-depth examination, however, in a recent Colorado seeding feasibility study (Super and Heimbach 2005).

4. CONCLUSIONS

Within the limitations of the SNODAS data set and stated uncertainties of our calculations we estimate that, for an **average** precipitation year in the Colorado River Basin, cloud seeding could generate an additional **one million acre feet** of water storage in the basin-wide snowpack. In drought years, seeding might produce about half that amount, or 500,000 acre feet. In wet years, more than one million acre feet could be produced, but how much more would be limited by seeding suspension criteria. These estimates are close to those of two older studies. Therefore, application of a modern, sophisticated snow modeling and assimilation system has produced similar water yields as the older studies and gives confidence that such yields are representative.

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Simulations of Snowpack Augmentation in the Colorado Rocky Mountains

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Abstract. In this paper we summarize a project designed to evaluate the feasibility of using a mesoscale model to support cloud seeding operations and the physical evaluation of seeding responses. The model used was the Colorado State University Regional Atmospheric Modeling System (RAMS). RAMS provided forecasts of precipitation and winds for the 2003-2004 winter season. Detailed evaluation of model forecast orographic precipitation was performed for 30 selected operational seeding days. In addition, the model was run to emulate cloud seeding operations performed by Western Water Consultants. It was shown that the model can be a useful forecasting aid in support of the seeding operations. But, the model over-predicted precipitation, particularly on moist southwest flow days. This was likely due to over-simulated convection when little or only relatively shallow convection actually occurred. The model also exhibited virtually no seeding response in terms of precipitation. Possible reasons for that are discussed.

1.0 INTRODUCTION

The Colorado Weather Damage Modification Program (WDMP) research project involved a physical evaluation of the Denver Water (DW) operational winter orographic cloud seeding program in the central Colorado Rockies for the winter season 2003-2004 using the Colorado State University Regional Atmospheric Modeling System (RAMS). The project was piggy-backed onto the DW operational program contracted by Western Water Consultants (WWC), LLC. The target area was the Blue, Upper Blue, Snake, Williams Fork, and Upper South Platte River drainage basins above 9,000 feet elevation (see Figure 1). The area within the target boundary was about 3,700 km^2. From February 10 through March 2004 only the Upper South Platte River basin and along the Continental Divide above the Upper Blue River basin was to be targeted. A collaborative generator network (funded by DW, ski areas, and other entities) consisted of up to 56 generators that were available for seeding operations. Using a finest grid spacing of 3-km, RAMS was run first in real-time to provide operational support to the DW cloud seeding program. RAMS was subsequently rerun for the period of operations with a number of improvements derived from assessments of the real-time runs, and then rerun with simulated seeding generators releasing seeding material (AgI) at rates, time periods, and locations consistent with the operational program (Hartzell et al., 2005).

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In Section 2.0 we describe the RAMS setup, in Section 3.0 we summarize the results from this project, in Section 4.0 we provide an overall discussion of the results and in Section 5.0 we provide recommendations for future operations.

2.0 RAMS SETUP

The 2003-2004 prototype real-time forecast version of RAMS@CSU was based on version 4.3. The physics of the model is described in some detail in Cotton et al. (2003). Briefly, the microphysics of the model is a bulk microphysics scheme in which the size-distribution of all hydrometeors is determined by a prescribed generalized gamma distribution. In contrast to most bulk models, however, the physics is explicitly represented by emulating a bin model including explicit activation of cloud droplets and ice particles on cloud condensation nuclei (CCN) and ice nuclei (IN), stochastic collection among all hydrometeors using state-of-the-art collection kernels, and a bin representation of sedimentation of hydrometeors. The ice phase is composed of pristine or vapor-grown ice crystals including a variety of habits defined by temperature, snow which represents partially-rimed vapor-grown ice particles, aggregates, graupel, and hail or frozen raindrops.

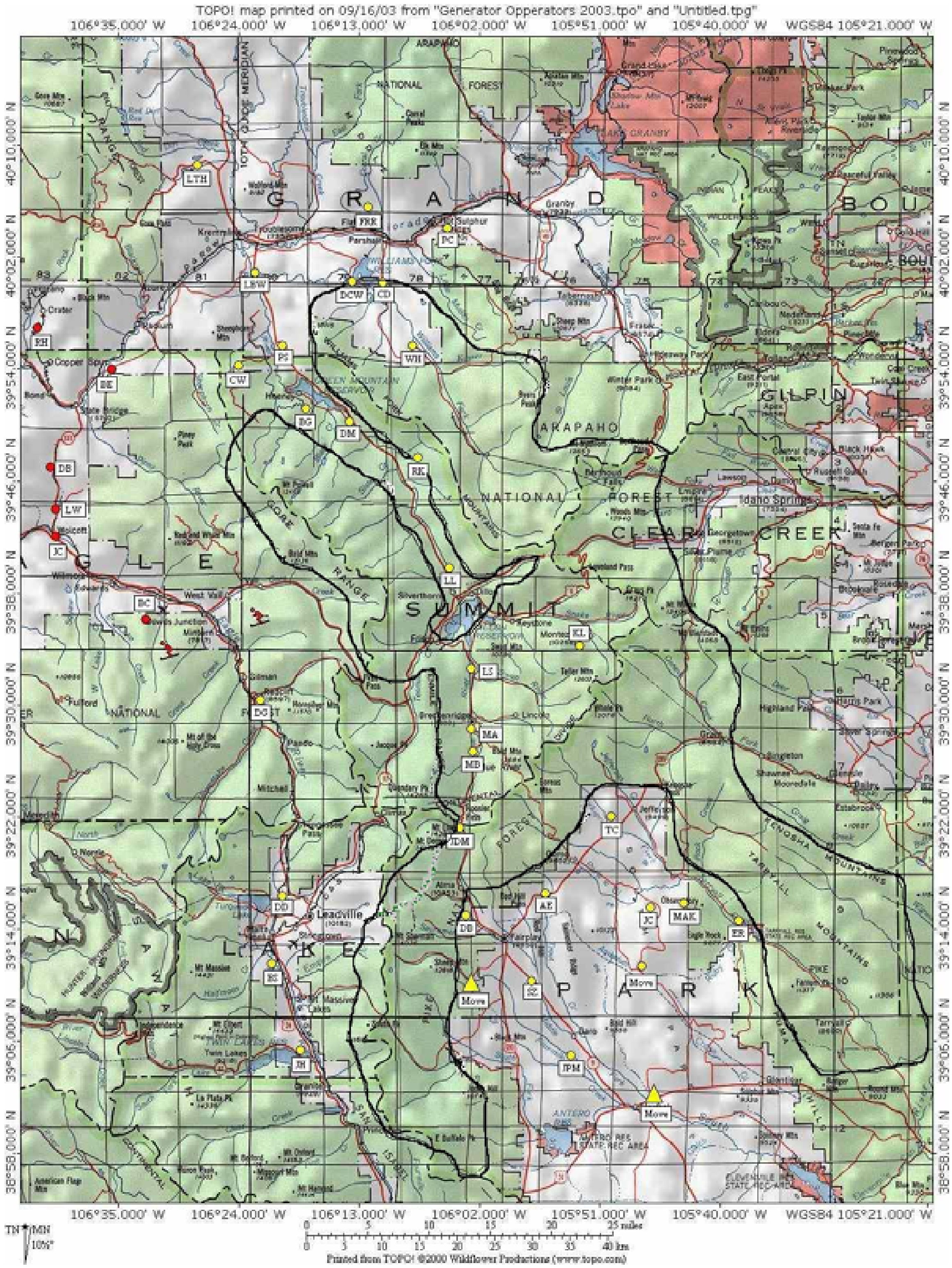

Figure 1. Intended target area for the DW 2003-2004 Program. Generator sites are indicated by yellow circles and triangles (operated by Denver Water) and by red circles (operated by Vail ski area). Several of the 56 total generators are off the figure to the south and west.

Natural ice activation is simulated using a generalization of the Meyers et al. (1992) formula:

$$N_i = N_{IFN} \exp[12.96(S_I - 1)];$$
$$T<-5C;\ r_v > r_{si}$$

supersaturation with respect to ice, and

$$T<-2C;\ r_v > r_{rw}$$

supersaturation with respect to water.

The variable N_{IFN} is a forecast variable in RAMS which can vary both vertically and horizontally whenever such data are available. Normally we use measurements in field campaigns with the CSU continuous flow diffusion chamber to infer N_{IFN}. In the absence of those measurements N_{IFN} is based on the estimates reported in Meyers et al. (1992) and allowed to drop off in concentration with height consistent with observed lapse in large aerosol concentrations. Recent measurements at the Storm Peak Laboratory in the Park Range of Colorado by DeMott (personal communication) suggest that IFN concentrations are probably lower than Meyers original estimates. However, sensitivity experiments using these lower background IFN values did not change the results appreciably.

Secondary ice particle production by the rime-splinter mechanism following Mossop (1976) is also simulated.

A seeding algorithm was added into the model based on sources of IFN from ground-based seeding generators. Figure 2 shows the activation data that we used to simulate IFN production at each generator site. AgI was then added as another prognostic IFN field.

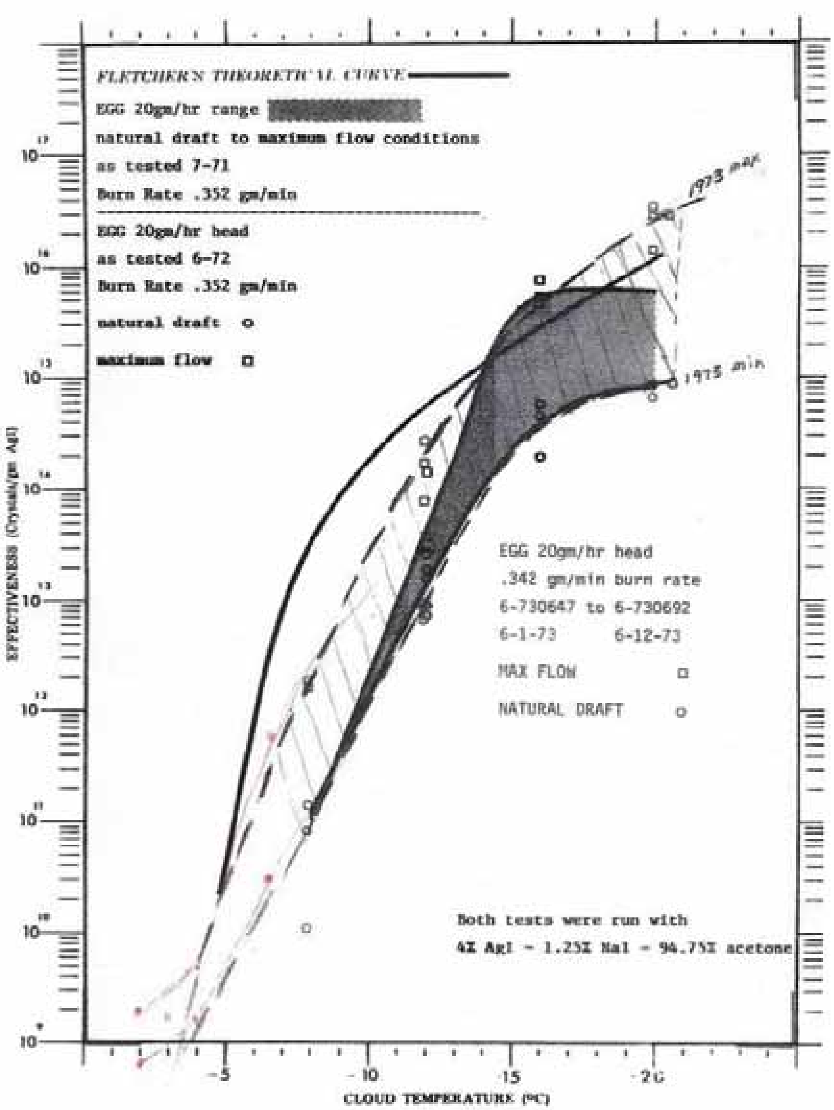

Figure 2. Calibrated AgI activity for the generators used by WWC. The dashed line labeled "1973 max," including the acetone-induced activation enhancement at warmer temperatures, is the fit used in the model. Provided by Larry Hjermstad. (WWC used a 4% AgI solution with sodium iodide as a carrier in acetone along with 1% moth balls to improve nuclei activation between –2.5°C and –8.0°C.)

The model was set up on a cluster of PCs. The forecast model configuration has three interactive nested grids. Grid 1 has 48-km grid spacing that covers the entire conterminous United States. Grid 2 has 12-km grid spacing that covers all of Colorado, most of Wyoming, and portions of adjacent states. Grid 3 has 3-km grid spacing for 98 x 98 grid points covering a 294 km x 294 km area (86,436 km^2) that is relocateable anywhere within Grid 2. Figure 3 shows RAMS Grid 1 covering the contiguous U.S. with nested Grids 2 and 3. Figure 4 shows the 12-km regional grid, and Figure 5 shows the 3-km fine grid with the project target area and some town IDs.

Vertical grid spacing on all grids starts with 300 m spacing at the lowest levels and is stretched to 750 m aloft, with a total of 32 vertical levels extending into the stratosphere. The model is initialized with 0000 UTC Eta model analysis fields and run for a period of 48 hours, with the lateral boundary region of the coarse grid nudged to the Eta 3-hr forecast fields. A 48-hr run typically begins at 0300 UTC (2000 MST) when the 0000 UTC Eta forecast data are available. The run takes 4-5 hours of computer time to finish, and is completed by 0200 MST. Because RAMS has been able to reproduce high-elevation snowfall amounts with considerable accuracy (Gaudet and Cotton, 1998; Wetzel et al., 2004), it was believed that RAMS could be useful in forecasting the effects of cloud seeding on precipitation for an entire winter season.

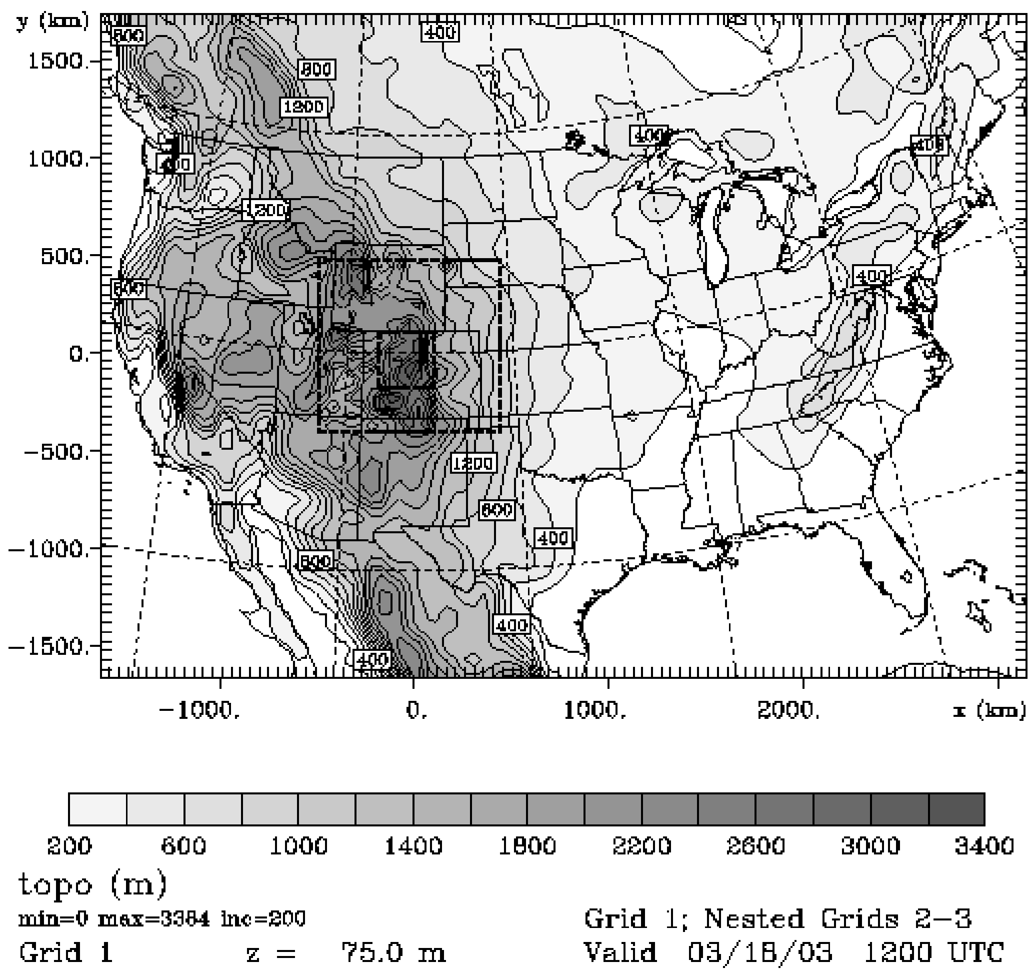

Figure 3. RAMS Grid 1 (48-km parent grid with nested Grid 2 and Grid 3).

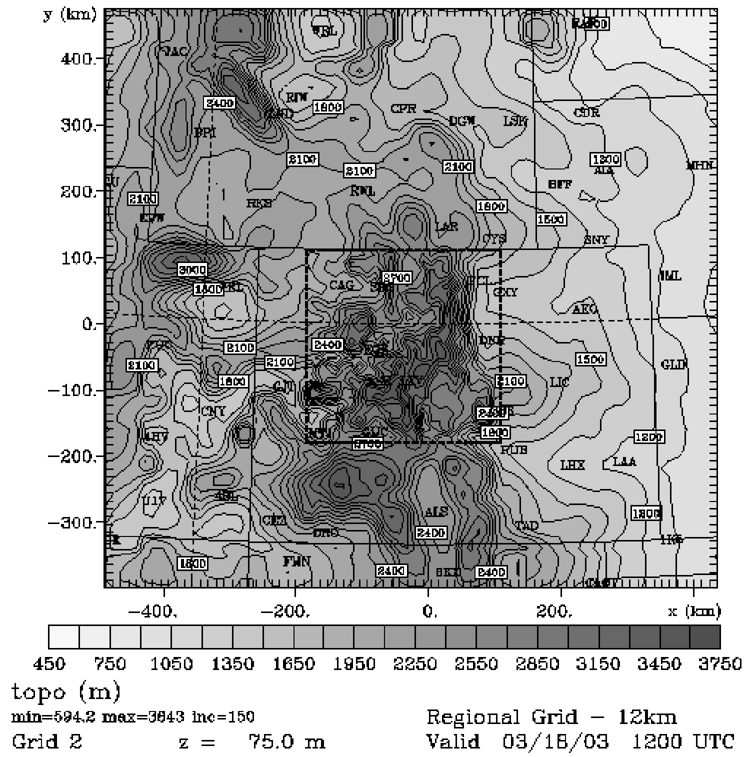

Figure 4. RAMS Grid 2 (12-km regional grid).

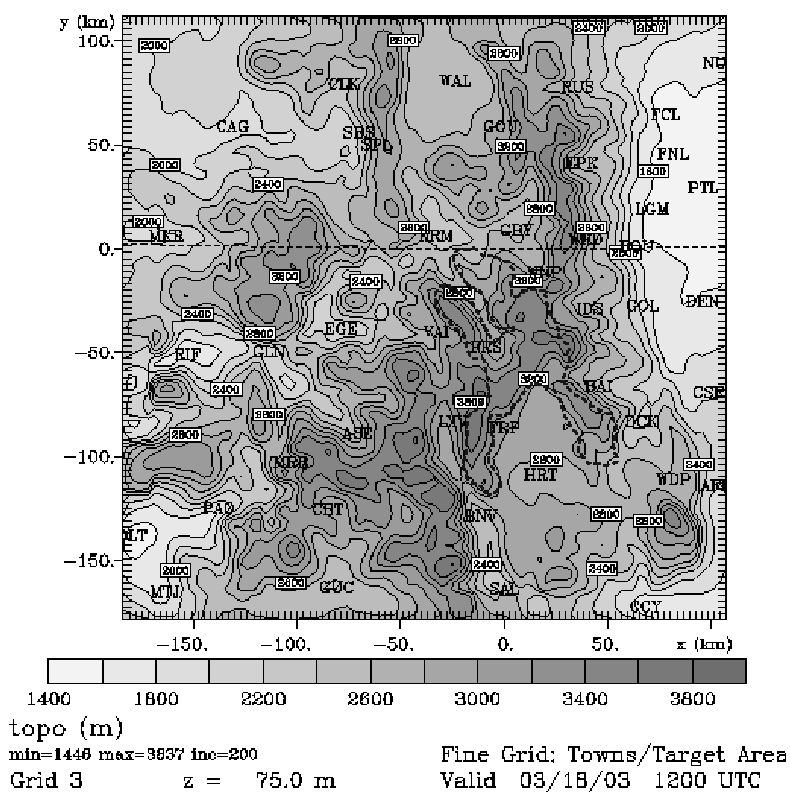

Figure 5. RAMS Grid 3 (3-km fine grid with target area).

3.0 RESULTS

We briefly summarize the results of this project. For further details the reader is referred to the final technical report (Hartzell et al., 2005) at the website: http://rams.atmos.colostate.edu/clseeding/prog-reports.html

The major results of this research project are as follows:

- WWC (Larry Hjermstad) pointed out the forecast model exhibited a warm temperature bias at 700 mb which reduced its effectiveness as a decision tool for determining if seeding operations should proceed. Causes of the warm bias were determined and fixes were made in mid-February 2004. The entire winter season was re-run to provide a better estimate of natural and seeded precipitation. However, the model fixes did not entirely eliminate the low-level warm bias.

- WWC (Larry Hjermstad) found that after the model fixes had been implemented in mid-February 2004 and the RAMS real-time forecast 0000 UTC cycle was run on the new PC cluster, the forecast output that was posted on the Web site was very useful. The low-level warm temperature problem had been greatly reduced and the model provided timely input for operational cloud seeding decision making. There were numerous forecast products and parameters to evaluate. In addition to the 2-hr forecast presentations, the animated forecast loops provided a quick visual picture of changes over time.

- The thirty cloud-seeding days were selected for use in detailed post-season research evaluations. The 30 days were chosen as the "best" representative examples of cases with potential seedability, with a characteristic "targeting wind" for each case ranging from south-southwest through west to north-north-west. When compared to measured 24-hr precipitation at 61 SNOTEL sites the model exhibited a mean precipitation bias of 1.88. The highest bias areas included the Target Area. The lowest bias areas were in more upwind areas in northwesterly and southwesterly events. Possible sources of those biases are discussed in the final report and are currently still under investigation.

- The model control simulations produced a reasonable qualitative pattern of total precipitation and its topographic dependence for the 30 selected days. The 30-day simulated precipitation total showed only light precipitation over the entire SE leg and south half of the SW leg of the target area. Thus the model suggests little orographic precipitation potential and perhaps little cloud seeding potential over the two south legs of the target area.

- The model forecast precipitation data were evaluated against SNOTEL data using MRBP statistical analysis procedures. The results from the evaluation show that the model is describing the non-seeded and seeded simulation equally well. While the signal of the fits is strong (all P-values about 1.0E-6 or less), the agreement measures are not outstanding (all fall between 0.18 and 0.26).

- Comparison of model-predicted non-seeded precipitation (control) versus seeded precipitation revealed that there was essentially no difference between the 86-day seed and control average totals (difference of -1.0 mm) for the 30 days selected for model precipitation evaluation seed and control average totals (difference of -0.2 mm).

- Lagrangian trajectory analyses of six selected days of the subset of 30 days selected for precipitation evaluation revealed that particles are generally being transported to the target area as intended. On average, 54% of those particles are 50-500 m AGL, with another 34% in the layer 500-1000 m AGL, which are levels suitable for AgI seeding.

- The Lagrangian analyses confirm that generators should not be used when the targeting wind would not carry their plumes over the target area. Low level trapping of particles can become moderate in nocturnal inversions, but significant numbers of particles escape the inversions and are transported by the targeting wind as intended. It appears that generators located on the lee side of mountain ranges may be in stagnation zones or rotors associated with high amplitude mountain waves, leading to moderate local trapping.

4.0 DISCUSSION

The very small differences between seed and control precipitation predicted by the model were very disappointing and not expected at the onset of this project. Possible causes of such low seedability:

- The model predicted seedability could be real; however, because of the model over precipitation prediction bias and low amounts of supercooled liquid water content, this possibility is doubtful.
- The background CCN and IN concentrations are unknown but instead are determined by our selected background concentrations. Too low a background CCN concentration would make clouds more efficient in natural precipitation formation thereby lowering seedability. Too high background IN concentrations would likely lead to lower seedability.
- There is circumstantial evidence that the model-predicted supercooled liquid water content is too low, thereby lowering seedability.
- The evaluated over-prediction bias in precipitation may lead to reduced opportunities for precipitation enhancement in the model.
- Banded patterns of seed - no seed differences on daily totals suggest a possible very weak dynamic response to seeding. This pattern of differences results in much of the target area being in regions of reduced precipitation.
- The low-level warm temperature bias in the model results in delayed AgI nuclei activation and reduced effectiveness of the seeding agent. However, this effect has overall a small impact on seedability.
- The simulated transport and diffusion of seeding material from the generator sites is getting into the clouds too far downwind of the generator sites. However, the particle modeling suggests that seeding material is delivered to the target area at levels suitable for seeding, which argues against the notion that seeding material is not getting into the intended seeding zones.

5.0 RECOMMENDATIONS

It is recommended that additional modeling studies are warranted because this was only a one-year contract and research funding was limited. One of the first things that needs to be done is to determine the cause of the model over-prediction bias in precipitation. Another is to explore the various hypotheses that have been put forward to explain the very small differences between seed and no-seed precipitation amounts. Still another area to explore is the low amounts of SLW in the 2-hr vertically integrated maps over the target area; additional sensitivity tests would be useful. Also, it would be desirable to rerun all or at least the 30 selected days with higher resolution to determine if increased resolution reduced the precipitation bias and/or the seed, no-seed differences.

In support of future operational cloud seeding projects in which a model is used as part of the evaluation technique, it is urged that background CCN and IN concentrations be measured. Preferably this would be airborne but in lieu of that longer term ground-based measurements, particularly from higher-terrain sites, would be desirable. Other items that would be very useful in such a project would be a vertically-pointing radiometer near the summit on the target mountain barrier for SLW detection, and the use of scanning cloud radar for identifying regions of liquid water in the clouds and to follow precipitation morphology. In addition the combination of model predictions and new observations such as cloud radar and radiometers could be used in a very sophisticated method of evaluation of an operational seeding project.

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APPLICATION OF A HYDROLOGIC MODEL TO ASSESS THE EFFECTS OF CLOUD SEEDING IN THE WALKER RIVER BASIN OF NEVADA

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Abstract. The focus of this study is to use a physically-based, distributed hydrologic model to estimate the impacts of cloud seeding efforts on the streamflow generated within the areas of the Walker River Basin targeted by the Nevada seeding program. The hydrologic model is calibrated using GIS information, model default values, and manual calibration to fit observed streamflow at a USGS surface water station within the Walker River Basin. The calibrated model is then used in two case studies that are designed to simulate a non-seeded condition and a seeded condition with a 10% increase in precipitation on the five target areas. The results from the two modeling case studies indicate that the additional precipitation applied in the seeded case results in increases in evaporation and runoff from the target areas but does not significantly impact the storages of moisture in the groundwater and soil zone for all of the five target areas. The fraction of seeding-increased precipitation that resulted in streamflow varied from 49% to 89% among the different target areas. The remainder of the additional precipitation resulted in evapotranspiration from the target areas.

1. INTRODUCTION AND SCOPE

There are more than a dozen wintertime cloud seeding programs in the western U.S. whose primary goal is to increase snowfall over specific drainage basins in order to subsequently increase stream runoff in the spring and summer months. An accurate assessment of the impacts of any cloud seeding operation on streamflow runoff requires detailed knowledge of the spatial and temporal increases in precipitation due to the cloud seeding activities and the watershed response to the additional precipitation. Obtaining this knowledge is often difficult or impossible due to the budget and time constraints associated with the field effort required to collect the necessary data. For projects in the western U.S. the documentation of seeding effects has been accomplished by assessments of randomized experiments such as in Mooney and Lund (1969), and by highly focused nonrandomized experiments. Latter experiments studied in-cloud microphysical changes, snowfall characteristics and precipitation rate changes at the surface, and evidence of the seeding material in snow layers in seeding target areas (e.g., Super, 1999, Deshler et al., 1990 and Warburton et al., 1996). Some operational projects have compared stream runoff from seeded and unseeded basins as part of their evaluation (Henderson, 1966). Also, McGurty (1999) used snow chemistry and a relationship between snow density and silver concentration to estimate increases in snowfall and runoff in a Sierra Nevada target area. While the prediction of additional runoff due to seeding efforts has not been routinely attempted, there have been preliminary studies conducted in the Upper Colorado River Basin (Super and McPartland, 1993).

Within Nevada's Weather Damage Modification Program (WDMP), a cooperative research effort with the U.S. Bureau of Reclamation (Hunter et al., 2005), hydrologic modeling has been incorporated into the research to predict how changes in the snowpack from cloud seeding will alter runoff in the affected streams of targeted basins. This research involves the application of a hydrologic model to simulate watershed response to additional precipitation from cloud seeding activities through the different hydrologic processes (snowpack evolution, evaporation and transpiration, infiltration, soil moisture movement, runoff, and streamflow). This research component was "piggy-backed" onto cloud seeding operations that are routinely conducted in the Walker Basin by the State of Nevada.

This paper presents results from the hydrologic modeling of the Walker River Basin whose headwater region is on the eastern (mainly downwind) side of the Sierra Nevada just north of Yosemite National Park. During the winter of 2003-04 this headwater region was targeted by several ground seeding generators and occasionally by aircraft seeding. The hydrologic model is initially calibrated during a period when there were no known cloud seeding operations. Next, the hydrologic model is used to investigate the impacts of cloud seeding in the Walker River Basin through two case studies. In the first case study, the model is run forward in time through the 2003-04 winter, assuming the target areas are not impacted by ground or aircraft cloud seeding activities. In the second case, cloud seeding activities are assumed to increase the total precipitation on the target areas during the 2003-04 winter by 10%. Although storms over the Walker Basin were routinely seeded in 2003-04 and snow profiles verified the presence of seeding material in a high percentage of snow layers in several specific sub-basin regions (Huggins et al., 2005), the actual percentage increase in snowfall was not verified physically. The components of the water balance (evapotranspiration, groundwater, soil moisture, and runoff) are estimated and compared for both cases.

The paper is organized as follows: Section 2 contains a description of the Walker River Basin study area, the available data, and a discussion of the Nevada cloud seeding operations. The hydrologic modeling approach is described in section 3. Results of the model case studies are presented in section 4, and the results and future extensions of the research are discussed in section 5.

2. STUDY AREA

2.1 Description of Walker River Basin

The Walker River Basin area is approximately 7,029 km^2, and ranges in elevation from 1,300m near Walker Lake to over 3,500m in the headwater areas of the Sierra Nevada (Figure 1). The Walker River generally flows from south to north until reaching the confluence of the West and East Walker Rivers, where it then flows southeast to the terminal Walker Lake. This study is focused on the upper portion of the Walker River (above the confluence of the West and East Walker Rivers), where the majority of its streamflow is generated through snow accumulation and melt processes (Figure 1).

2.2 Streamflow and Meteorological Data

The United States National Resources Conservation Service (NRCS) maintains five SNOpack TELemetry (SNOTEL) sites within Walker River Basin that provide real-time daily estimates of snow water equivalent (SWE), snow depth, precipitation, and temperature at each site (Figure 1). All of these sites are at generally high elevations (2,195 to 2,866m), with historic SWE, snow depth, and precipitation data available from the early to mid 1980s to the present. Temperature data for each site are generally available from the mid to late 1980s to the present.

The United States National Weather Service (NWS) maintains four weather stations within the Walker River Basin that provide real-time daily estimates of precipitation and temperature (Figure 1). All of these sites are generally lower in elevation (1,311 to 1,972m), with historic precipitation and temperature data available from before the1980s to the present.

The United States Geological Survey (USGS) maintains ten surface water stations that provide continuous daily streamflow estimates at various locations within the upper Walker River Basin (Figure 1). Some of these stations have historic daily records available from before the 1980s through the present, while others date back to the early 1990s. Many of these stations, however, have significant ungauged diversions, returns, or reservoir operations within the area, altering measured streamflow at the station. In some cases the stations had significant periods of missing values and therefore were not useful for this study.

Basin	Area (km^2)	Mean Elevation (m)	Vegetation Type	Soil Type
Sierra Crest	619	2808	95% trees 5% grasses	100% sand
Sweetwater Mountains	259	2735	96% trees 4% grasses	100% sand
Bodie Hills	202	2454	100% trees	61% sand 39% loam
Pine Grove Hills	249	2223	100% trees	93% sand 7% loam
Wassuk Mountains	195	2124	100% trees	100% sand

Table 1. *Hydrologic characteristics of the five areas targeted by cloud seeding.*

2.3 Nevada State Cloud Seeding Program Operations in the Walker River Basin

There are five high altitude areas within the Walker River Basin that are targeted by the Nevada State Cloud Seeding Program's operations: Sierra Crest, Bodie Hills, Wassuk Mountains, Sweetwater Mountains, and Pine Grove Region (Figure 1). These are mountainous, snow-dominated areas that range in size from almost 200 km^2 to over 619 km^2, and in elevation from 2,124m to 2,808m (Table 1). The vegetation is predominantly coniferous forest in the Sierra Crest, with a mix of pinion pine forest, desert shrub and grasses in the other areas (Table 1). The soils range from mostly sand for the Sierra Crest, Wassuk Mountains, and Sweetwater Mountains, to a mix of sand and loam for the Bodie Hills (61% sand and 39% loam) and the Pine Grove Region (7% sand and 93% loam).

Cloud seeding in the Walker Basin dates back to the 1980s. The current Nevada program that includes eight ground-based seeding generators and about 10 aircraft seeding flights per season, however, has existed for only the past three seasons. The locations of the eight ground generators and the most commonly used seeding flight tracks are shown in Figure 1. Both ground generators and aircraft solution-burning generators currently use a mixture that produces silver chloroiodide – salt ice nuclei similar to those described by Feng and Finnegan (1989). In water-saturated conditions at temperatures below -5^{o}C, these particles are fast acting condensation freezing nuclei. Ground generators release about 25 g h^{-1} of seeding material, and each aircraft burner releases about 150 g h^{-1}. The aircraft on occasion also use burn-in-place flares manufactured by Ice Crystal Engineering, which also produce fast-acting condensation freezing nuclei.

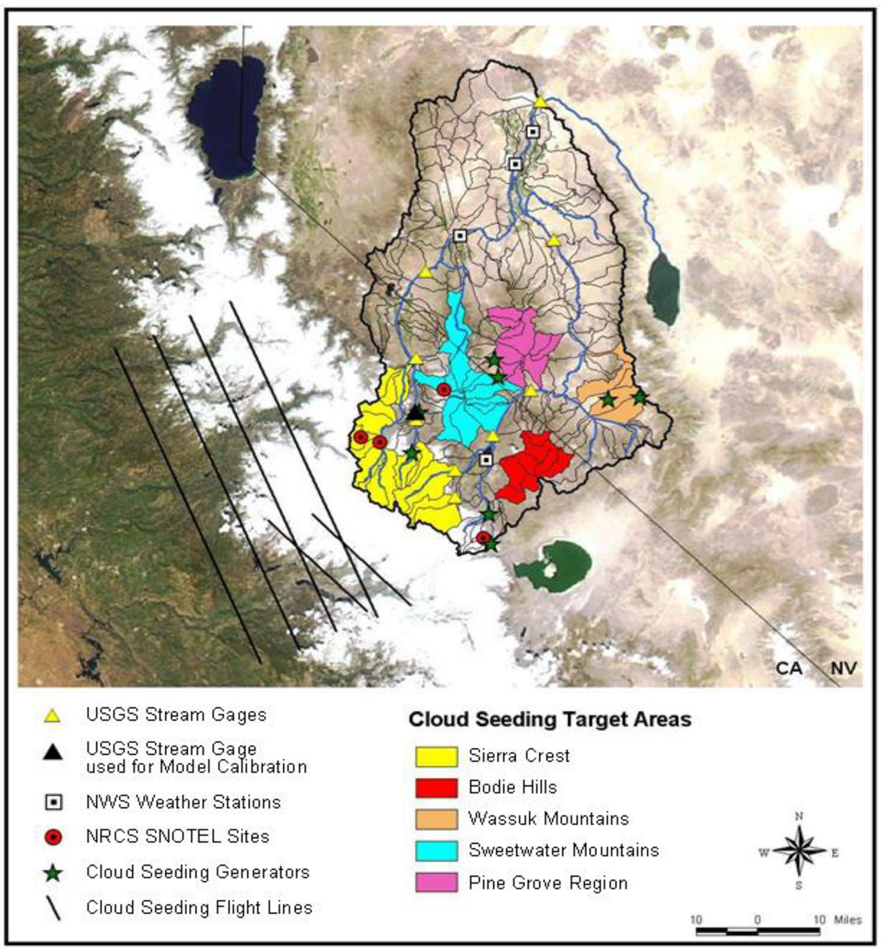


Figure 1. *Location of Walker River Basin study area and five target areas affected by the Nevada cloud seeding activities.*

During the 2003-04 season the Nevada Program conducted 26 ground seeding operations in the Walker Basin, with a total of about 1015 hours of generator operation and the release of 27,400 g of seeding material. There were 12 aircraft flights targeting the Walker Basin, during which an additional 3,350 g of seeding material was released. The collection and trace chemical evaluation of snow samples at four sites in the Walker Basin were undertaken within a separate WDMP research task. The high percentage of silver found in the snow profiles at the Sierra Crest, Sweetwater Mountains and Bodie Hills sites indicated that they were routinely targeted by seeding operations (Huggins et al., 2005). Samples were not obtained from the Wassuk Mountains or Pine Grove region due to access limitations. Although lacking a target-control evaluation to quantify seeding results, the trace chemical assessment supports the distribution of estimated seeding results that are used in simulations involving the hydrologic model, which is the subject of the following section.

3. HYDROLOGIC MODELING OF WALKER RIVER BASIN

3.1 Overview of Modeling Approach

This section presents a description of the hydrologic modeling approach applied to the upper Walker River Basin, to estimate the impacts of cloud seeding on the streamflow within the areas targeted by the Nevada seeding program in water year 2004. In the following subsections, a brief description of the hydrologic model, the calibration process, and seeded and unseeded cases are provided. Results from the calibration process and the two cases are provided in Section 4.

3.2 Precipitation Runoff Modeling System

The USGS Precipitation-Runoff Modeling System (PRMS) (Leavesley et al., 1983, Leavesley and Stannard, 1995, and Leavesley et al., 2006) is a modular design, distributed-parameter, physical-process watershed model. The PRMS model was developed to evaluate the effects of various combinations of precipitation, temperature, and land use on watershed response, e.g., snowpack, soil moisture, groundwater, evapotranspiration, and streamflow. The PRMS software is available within the USGS Modular Modeling System (MMS) (Leavesley et al., 1996 and Leavesley et al., 2006) as a set of process algorithms that together simulate the dominant processes of the watershed response. While MMS supports the development, integration, and application of new process modules, the standard MMS-PRMS modules were selected for use in this study.

The MMS-PRMS allows the user to partition the watershed into hydrologic response units (HRU) based on different characteristics of a watershed, e.g., slope, aspect, stream network, elevation etc. The delineation, characterization, and parameterization of the watershed can be carried out with geographic information system (GIS) technology within the ArcInfo (ESRI, 1992) computer software and USGS Weasel interface (Leavesley et al., 2002 and Leavesley, et al., 2006). The GIS Weasel is used to delineate, characterize, and parameterize topological, hydrological, and biological basin features, for use in the MMS-PRMS modeling approach. The GIS Weasel utilizes relationships developed for commonly available spatial estimates of soil, vegetation, and topographical properties, to estimate values for various MMS-PRMS model parameters, for each HRU. For MMS-PRMS parameters that are not estimated using the GIS Weasel, default parameter values and ranges are provided in the MMS-PRMS software.

To simulate the watershed response in a daily mode, the MMS-PRMS requires daily estimates of precipitation, minimum daily temperature, and maximum daily temperature at the centroid of each HRU. Since measurements of these driving variables are almost never available at the centroid of each HRU, several methods have been developed to relate measured values at known locations (e.g., NRCS SNOTEL and NWS stations) to each HRU centroid (Hay et al., 2002). One approach utilizes the spatial (4km x 4km) relationships of average monthly precipitation and temperature from the Spatial Climate Analysis Service at Oregon State University (Daly et al., 2001) using a Parameter elevation Regressions on Independent Slopes Model (PRISM). In this approach, the daily value for each driving variable (e.g., precipitation) at the centroid of each HRU is estimated by multiplying the observed daily precipitation value (from NRCS SNOTEL and/or NWS stations) by the ratio of the average monthly PRISM precipitation value at the HRU centroid to the average monthly precipitation value at the observation site. Then a time series for each driving variable can be developed at each HRU centroid. If there is more than one observation site available, the same process can be used to estimate a time series at the HRU centroid from each observation site. During the model run, the average value from the available time series is used for each time step. This approach works well when there are periods of missing data at one or more of the observation sites.

3.3 Application and Calibration of MMS-PRMS Model

In this study, the MMS-PRMS model was applied to the entire upper Walker River Basin. The delineation of the upper Walker River Basin and partitioning of the HRUs were carried out with ArcInfo computer software and the USGS Weasel interface, based on the location of USGS surface water station locations and hydrologic characteristics of the watershed (e.g., slope, aspect, stream network, elevation, etc.). The modeling extent, HRU delineation, and target areas are shown in Figure 1.

Average monthly precipitation and temperature estimates from PRISM were used to develop spatial-temporal relationships between precipitation and temperature observations at the four SNOTEL and four NWS stations and the centroids of each HRU. With these relationships, the time series of daily values of precipitation, minimum temperature, and maximum temperature from each of the SNOTEL and NWS sites was available for use on each HRU for the period 1 October 1980 through 30 September 2004. These relationships were used to estimate the daily value of each driving variable (precipitation, minimum temperature, and maximum temperature) at an HRU from all of the four SNOTEL and four NWS sites.

The GIS Weasel was used to estimate initial values for all HRU parameters related to soils, vegetation, and topography, based on the digital elevation model, spatial soils information, and spatial vegetation information. All remaining MMS-PRMS model parameters were initially assigned default values from the MMS-PRMS documentation and software.

The MMS-PRMS model was initially run using the combination of GIS Weasel and default parameters to simulate observed streamflow at the West Walker below the Little Walker surface water station, for the period 1 October 1980 through 30 September 1992. This surface water station was selected because of its extensive historic record and because there are no significant diversions, returns, or reservoir operations within the area contributing to the station. The period was selected because there were very minimal cloud seeding operations in the Walker River Basin prior to the 1992-93 winter. Based on the initial results from this model run, the following four additional parameters were manually adjusted (same value of each parameter for each HRU) to improve the simulation of streamflow at the West Walker below Little Walker surface water station: (1) *snowinfl_max* - maximum infiltration rate for snowmelt, in cm/day (snowinfl_max set to 10 cm/day); (2) *soil2gw_max* - the amount of the soil water excess for an HRU that is routed directly to the associated groundwater reservoir each day (soil2gw_max set to 0.5 cm); (3) *tmax_allsnow* - if HRU maximum temperature is less than or equal to this value, precipitation is assumed to be snow (tmax_allsnow set to 1.1 ^{o}C); (4) *tmax_allrain* - if HRU maximum temperature is greater than or equal to this value, precipitation is assumed to be rain (tmax_allrain set to 7.2 ^{o}C).

The results of the calibrated model are described in section 4, below. Unfortunately, the remainder of the surface water stations within the upper Walker River Basin could not be used for calibration, since each had at least one of the following: insufficient historic record, significant number of missing values, significant ungauged diversions, returns, or reservoirs. As a result, the parameter values for the remaining HRUs (those not directly contributing to the West Walker below Little Walker surface water station) were set at a combination determined by the GIS Weasel, MMS-PRMS default values, and values determined through manual calibration on the West Walker below Little Walker.

3.4 MMS-PRMS Non-Seeded and Seeded Modeling Cases

Since the state of Nevada has been performing different types cloud seeding operations in the Walker River Basin from 1992 to present, the development of a non-seeded case over that entire period would be difficult. Rather than try to understand their impact over the entire period, this study is focused on understanding how the Nevada cloud seeding operations over the 2003-04 winter may have impacted streamflow from only the target areas. To accomplish this, two cases or scenarios (non-seeded and seeded) were designed for the target areas that, when compared with each other, provide an estimate of how additional precipitation from cloud seeding moves through the hydrologic cycle in the target areas (based on the MMS-PRMS model). Several assumptions were made in the development of each case, as described in the next two paragraphs.

For the non-seeded case, it was assumed that three of the four SNOTEL sites which are located within a target area were impacted by the cloud seeding operations. It was also assumed that in target areas only, cloud seeding operations resulted in a 10% increase in precipitation over what would have occurred without cloud seeding. As a result, the observed time series of precipitation for each of the three SNOTEL sites within the target areas was reduced by 11% (non-seeded precipitation = seeded precipitation/110%) during the months of November through March, when cloud seeding operations were underway. These modified time series were used with the remaining SNOTEL and four NWS sites (which were assumed to not be impacted by cloud seeding since they are outside the target areas) to drive the MMS-PRMS model forward from 1 October 1992 through 30 September 2004, to simulate the non-seeded case.

The seeded case utilized the same modified precipitation time series that was used for the non-seeded case, except that the precipitation from November through March was increased by 10% for the HRUs located in the target areas. While there are other ways to develop these cases, given the constraints of the approach used to spatially distribute precipitation from the observation sites to the HRU centroids, this approach provides a reasonable way to estimate how additional precipitation from cloud seeding moves through the hydrologic cycle in the target areas.

4. RESULTS

4.1 Calibration of MMS-PRMS Model

The streamflow simulated with MMS-PRMS for the West Walker below Little Walker is plotted in Figure 2 with observed values for the calibration period, 1 October 1980 through 30 September 1992. The plot reveals that the MMS-PRMS model does a reasonable overall job of simulating the observed daily flows. While the model generally matches the systematic rise and fall of the observed hydrograph, it tends to over predict a few of the early peaks and under predict a few of the mid to late peaks. These behaviours are most likely related to poor or missing temperature data. For example, several of the high altitude SNOTEL sites used in this study did not begin recording daily temperature until the mid to late 1980s. Furthermore, the lower elevation NWS sites tend to be in areas susceptible to temperature inversions in the late winter and spring, when snow melt may be occurring higher in the watershed. In the MMS-PRMS model, daily input temperature determines the form of the precipitation (snow or rain) so subtle errors in temperature data on days with large precipitation amounts when the temperature is near freezing can cause disproportional errors in runoff and water balance resulting in lower efficiency measures. These suspected low temperature errors were the primary reason for selecting the four MMS-PRMS parameters (snowinfl_max, tmax_allsnow, and tmax_allrain) for adjustment in the calibration process.

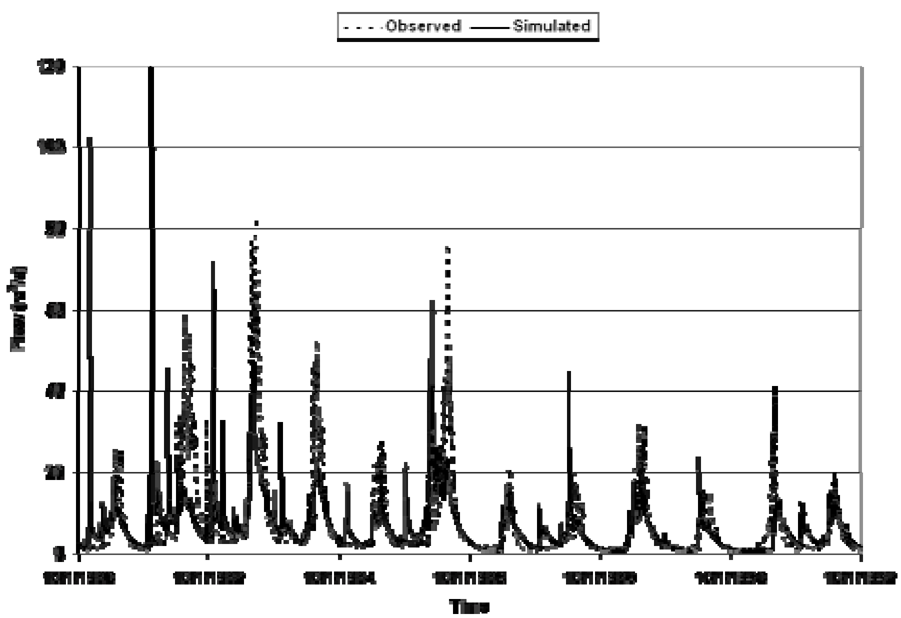


Figure 2. *Streamflow hydrograph for the calibration period on the Walker River below the Little Walker. The streamflow simulated with MMS-PRMS is shown as a black line and the observed streamflow is shown as black dots.*

Basin	ΔPrecip. from seeding (cm)	ΔET (cm & % diff)	ΔRunoff (cm & % diff)	ΔGround Water Storage (cm & % diff)	ΔSoil Storage (cm & % diff)
Sierra Crest	6.61	2.64 (40%)	4.12 (62%)	-0.17 (-2%)	0.02 (0%)
Sweetwater Mountains	4.30	2.25 (52%)	2.11 (49%)	-0.05 (-1%)	-0.01 (0%)
Bodie Hills	2.75	0.95 (34%)	1.81 (66%)	0.00 (0%)	-0.01 (0%)
Pine Grove Hills	3.13	1.08 (35%)	2.04 (65%)	0.01 (0%)	0.00 (0%)
Wassuk Mountains	2.51	0.26 (10%)	2.23 (89%)	0.02 (1%)	0.00 (0%)

Table 2. *Changes in simulated components of annual water balance in cm/year (volume divided by target area) due to 10% increase in precipitation in the five target areas.*

Three efficiency measures were used to evaluate the performance of the MMS-PRMS in terms of overall fit to the observed streamflow; the Nash Sutcliff (NS) efficiency measure, the root mean square error (RMSE), and the percent overall bias (PBIAS). The NS value of 0.49 and the RMSE value of 7.4 $m^3 s^{-1}$ indicate that while the model did a reasonably good job of fitting the general behaviour of the overall hydrograph, there were some problems in the fitting some of the higher flows. The PBIAS value of -6.8% indicates that while the MMS-PRMS model did a good job of simulating the overall volume of streamflow during the calibration period, there was a slight overall underestimation of the total volume. The quality of the calibration of the MMS-PRMS model for this basin is fairly typical for watershed models of the northern Sierra Nevada (Jeton, 1999 and 2000).

4.2 <u>MMS-PRMS Non-Seeded and Seeded Modeling Cases</u>

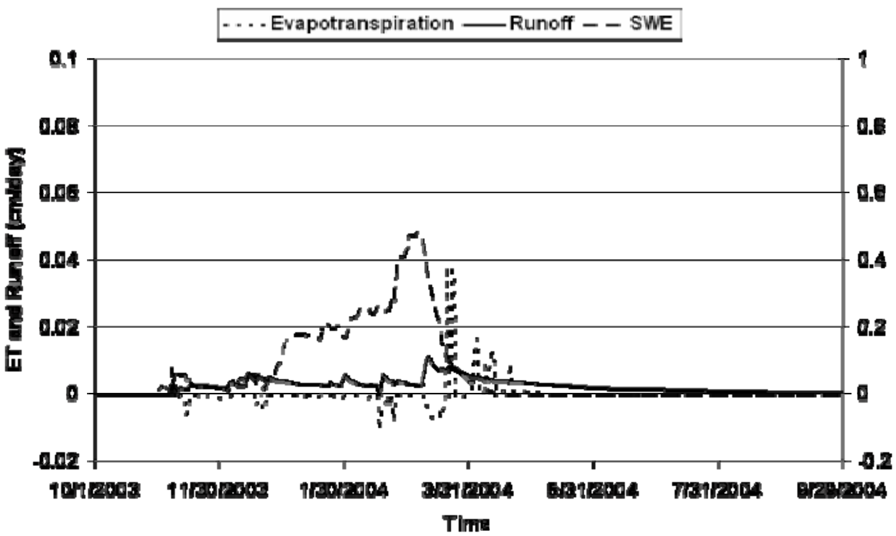
The results from the MMS-PRMS model runs for both the non-seeded and seeded cases are shown for all five target areas in Table 2. Column 2 of the table presents the additional 10% precipitation applied to each target area over winter 2003-04 for the seeded case. Columns 3-6 present the additional amount of evapotranspiration, runoff, change in ground water storage, and change in soil moisture (in cm and %) resulting from the additional 10% precipitation, applied to each target area during the period 1 October 2003 through 30 September 2004. For example, in the Sierra Crest target area, 40% (or 2.64 cm) of the additional precipitation (6.61 cm) resulted in evapotranspiration and 62% (or 4.12 cm) resulted in runoff, 2% (or 0.17 cm) remained in the groundwater storage, and approximately 0% (or 0.02 cm) remained in the soil moisture zone. Notice that the additional 10% of precipitation in the seeding case resulted in additional evapotranspiration and runoff but did not significantly increase (or decrease) the amount of water stored in the groundwater or soil moisture zones for any of the five target areas.

While the Sierra Crest target area had the largest amount of additional runoff (4.12 cm), the Wassuk Mountains target area had the greatest fraction of runoff (89%) from the additional precipitation (2.23 cm). Also, while the Bodie Hills target area had the least amount of runoff (1.81 cm) from the additional precipitation (3.13 cm), the Sweetwater Mountains target area had the lowest fraction of runoff (49%) from the additional precipitation (4.30 cm). These results are primarily attributable to the differences in evapotranspiration from the additional precipitation between the areas (52% or 2.25 cm for the Sweetwater Mountain target area and 10% or 0.26 cm for the Wassuk Mountains target area).

Figure 3a-b present the temporal distribution of the volumetric differences in evapotranspiration, runoff, and SWE for the seeded and non-seeded cases in the Wassuk Mountains and Sweetwater Mountains target areas. In these plots, the daily values of ET, runoff, and SWE simulated in the non-seeded case were subtracted from the daily values of ET, runoff, and SWE simulated in the seeded case for both the Wassuk Mountains (Figure 3a) and the Sweetwater Mountains (Figure 3b) target areas. Notice that the majority of the increase in runoff for both target areas occurs after the peak in the increase in SWE and remains high until the increased SWE is depleted. The primary differences between the two target areas are that the increased SWE values are much larger and last much longer into the season for the Sweetwater Mountains target area than those in the Wassuk Mountains target area. Evapotranspiration begins for both target areas at nearly the same time; however, the values for the Sweetwater Mountains target area are much larger and last much longer into the season that those in the Wassuk Mountains target area.

The MMS-PRMS simulation time series of snow water equivalent, soil moisture, and evapotranspiration for the Sweetwater Mountains (dashed line) and Wassuk Mountains (solid line) target areas are plotted in Figures 4a-c. Figure 4a shows the timing of the evapotranspiration for the Sweetwater Mountains and Wassuk Mountains target areas. The vertical dash-dot line on the plot represents the approximate date (10 April 2004) when the potential evapotranspiration demand can be satisfied by the moisture in the soil zone through transpiration from the vegetation. The significant difference in snow water equivalent simulated by MMS-PRMS for the Sweetwater Mountains and Wassuk Mountains target areas is clearly shown in Figure 4b.

(a)



(b)

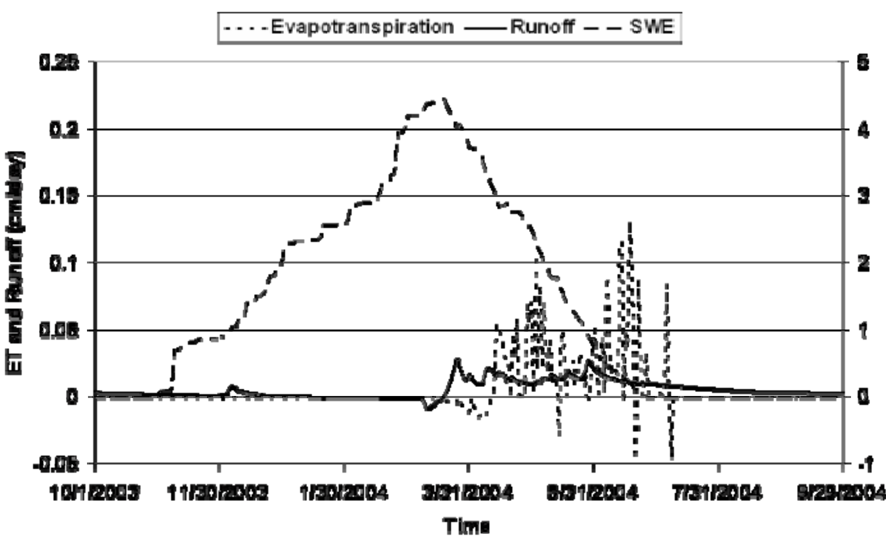


Figure 3. *Temporal distribution of the simulated volumetric differences in evapotranspiration (dots), runoff (solid line), and SWE (dashed line) for the seeded and non-seeded cases in the Wassuk Mountains (a) and Sweetwater Mountains (b) target areas.*

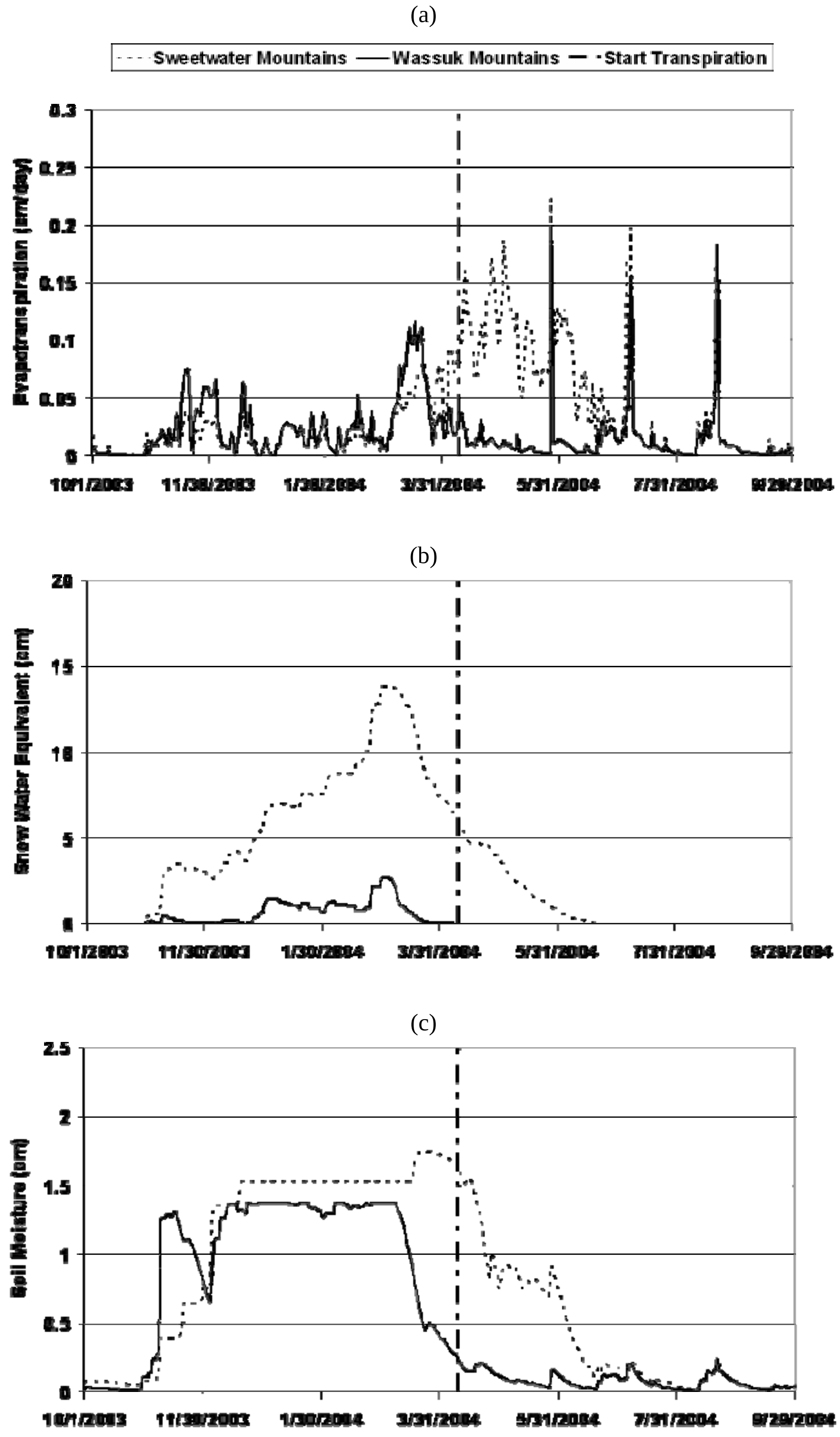


__Figure 4.__ Temporal distribution of the simulated evapotranspiration volume (a), snow water equivalent volume (b), and soil moisture volume (c), for the Sweetwater Mountains (dots) and Wassuk Mountains (solid line) target areas. The vertical dash-dot line represents the approximate date when the potential evapotranspiration demand can be satisfied by the moisture in the soil zone through transpiration from the vegetation.

This difference is most likely related to the differences in elevation and meteorology of the two target areas. The Sweetwater Mountains target area is higher than the Wassuk Mountains target area (2,735m vs. 2,124m) and receives more precipitation in the form of snow than the Wassuk Mountains. The Sweetwater Mountains target area is also impacted less by rain shadow effects from the Sierra Crest than the Wassuk Mountains target area and thus receives more precipitation. Notice that the snow pack has completely melted in the Wassuk Mountains target area prior to 10 April 2004, while significant snowpack remains in the Sweetwater Mountains target area. As a result, the potential evapotranspiration demand in the Wassuk hills after 10 April 2004 can only be satisfied by the amount of moisture already in the soil zone (see Figure 4c), while the Sweetwater Mountains target area has sufficient snowpack remaining to recharge the moisture in the soil zone well after 10 April 2004.

5. SUMMARY AND CONCLUSIONS

In this paper, the MMS-PRMS model was applied to five target areas in the Walker River Basin to investigate the watershed response to the Nevada cloud seeding operations. Parameter values for the MMS-PRMS model were estimated using GIS information, model default values, and manual calibration to fit observed streamflow at a USGS surface water station within the Walker River Basin. The calibrated model was then used in two case studies that were designed to simulate a non-seeded condition and a seeded condition with a 10% increase in precipitation on the five target areas. A comparison of the hydrologic components (evapotranspiration, runoff, groundwater, and soil moisture) from the hydrologic model simulations was then made to understand how the precipitation from the cloud seeding efforts might impact the watershed response.

The two modelling case studies indicated that the additional precipitation applied in the seeded case resulted in increases in evaporation and runoff from the target areas, but did not significantly impact the storages of moisture in the groundwater and soil zone for all of the five target areas. The fraction of the additional precipitation that resulted in streamflow varied from 49% to 89% among the different target areas. The remainder of the additional precipitation was found to leave the target areas as evapotranspiration. A detailed analysis of the MMS-PRMS estimates of evapotranspiration, SWE, and soil moisture fluxes indicated that the timing of the transpiration from the vegetation, in combination with the timing of the snowpack melting, were directly related to the amount of soil moisture available to satisfy the potential evapotranspiration demand in each target area. In general, the target areas with larger overall snowpack had a larger fraction of the additional precipitation result in evapotranspiration, because there was more melt water available to recharge the soil moisture and satisfy the potential evapotranspiration demand. This point was highlighted in the Wassuk Mountains target area where the lowest amount of additional precipitation was derived from seeding, yet the area produced the second highest amount of additional streamflow. The lower mean elevation of the Wassuk Mountains may have been an important factor in the early runoff for the target area – the snowpack was able to melt earlier in the season before significant transpiration processes began. The vegetation and soils were similar in all five target areas and did not appear to be significant factors in differences among the target areas.

The results and conclusions presented in this study are limited to the uncertainties related to the application of the MMS-PRMS model to each target area under the seeded and non-seeded conditions. The calibration process indicated, however, that the model reasonably simulated the overall watershed streamflow response at the USGS surface water station at Walker River below Little Walker. There are no known additional hydrologic data to evaluate the model's ability to accurately partition the precipitation into the different hydrologic components on the target areas. As a result, the authors of this paper do not claim that the results presented in this study accurately reflect the increase in streamflow to the Walker River Basin from the Nevada State Cloud Seeding Program cloud seeding operations in the winter 2003-04. There are still too many unknowns concerning the ability of the cloud seeding operations to achieve the assumed 10% seasonal increase in precipitation. Rather, we intend for the results to provide the operators of the Nevada State Cloud Seeding Program and water managers in the Walker River Basin with a better understanding of how the different targeted regions of the watershed respond to additional precipitation (volume and timing of additional runoff), which in turn may promote more efficient cloud seeding and water management activities.

Research aimed at further understanding the relationship between the Nevada State Cloud Seeding Program's cloud seeding activities and impacts to the watershed response is ongoing. Future work will include the use of trace chemistry results from WDMP snow sampling efforts to better define the targeted areas affected by cloud seeding, plus additional hydrologic modeling sensitivity tests. The results of this work will be reported as soon as practicable and we invite dialog with others interested in these topics.

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ROLE FOR LIGHTNING IN TORNADOGENESIS AND POSSIBLE MODIFICATION

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Abstract. New consideration is given to the action, under severe storm conditions, of repeated, spatially-localized, intracloud lightning flashes providing enhancement of updraft wind velocities towards initiation of a tornado. The basis for the updraft wind enhancement comes from lightning-generated H^+ and OH^- ion concentrations that are driven for energy release to opposite lower and upper cloud levels, respectively, by the residual electric field of the thunderstorm. The model consideration is related to recent reports of intracloud flash rate measurements associated with tornadic activity. The required spatial localization of the intracloud-containing flash rate may be a contributing factor to tornadoes being relatively rare occurrences in such storms. Nevertheless, cloud seeding is proposed to alleviate updraft velocity build-ups by promoting "in-situ" recombination of the lightning-generated concentrations of ions.

1. INTRODUCTION

An insignificant role for storm-generated lightning in tornadogenesis had been concluded from earlier scientific debate (Wilkins, 1964; Davies-Jones and Golden, 1975; Watkins et al., 1978; Trapp and Davies-Jones 1997). For example, Grasso and Cotton (1995) have described numerical models for tornadogeneses without cloud electrification parameterizations; and, Spratt et al. (1998) have reported cases of tornado occurrences when little or no lightning occurred at any level. Alternatively, Williams et al. (1999) have reported systematic observations of lightning being a precursor under severe weather conditions to the production of strong ground winds, hail, and tornadic activity. More recently, Buechler et al. (2000) have reported supporting satellite observations of intracloud lightning/tornadic associations. The latter results give support for further investigation of those special characteristics of electrification that might contribute to tornadogenesis.

Here we report on such renewed examination of the electrification basis for tornadic activity being associated with the occurrence of lightning in a severe thunderstorm system. This has involved focusing on the original charged water particle basis proposed by Moore and Vonnegut (1957) and, in greater detail, by Vonnegut (1960), as the key source of significant enhancement of updraft wind velocities potentially leading to tornadic activity. Such model evaluation, that fell short of predicting requisite wind velocities, is now extended in the following report. The results to be described are consistent with the detailed observations reported for intracloud lightning activity by Williams et al. and Buechler et al. From this basis and connection with other observations too, a further aspect of the present investigation, then, was to explore the possibility of interfering at an early stage with the proposed mechanisms supporting tornadic development (Glenn 2001).

2. THE VONNEGUT ELECTRIFICATION MODEL

It is important to begin by mentioning that development of a tornado only under appropriate vertically deflected lateral wind velocity and sufficient vertical thermal gradient is not disputed, rather, the present concern is to investigate whether there is a role for electrification under severe storm conditions. That electrification forces could be involved in tornadogenesis stems from pioneering research done by Vonnegut and colleagues; see, for example, a further updated article by Moore and Vonnegut (1977). Originally, Vonnegut (1960) had concluded that a below-cloud energy density required for achieving wind velocities of 200-250 m/s, say, over a circular area of 100 m diameter, was not achievable without a role to be played by lightning and, in particular, concluded even so that repeated strikes "through the same path for a sufficient length of time" was required to sustain tornadic action. The updraft velocity has been specified, on previous model and current experimental grounds, as a unique indicator for reaching tornadic development, then growing to hydrodynamic description. Employment of such updraft velocity as a marker is prevalent in the herein referenced articles and in current research investigations whether pro or con for electrification influence. For a horizontal, or vertical, wind velocity of 250 m/s, Vonnegut estimated that ~10^{11} J/s was required to sustain a tornado of the 100 m diameter, appreciably less than the ~10^{15} J available within an average thunderstorm cell. The mechanism by which the tornadic winds were to be generated was by the vertical motion of electrically charged water particles driven by the strong electric field of the thunderstorm.

Vonnegut (1960) provided a sample calculation for charged water particles of 20 micron radius being driven by an electric field, **E** = 300 kV/m, to produce the same force on a cm^3 of air containing 2 g/m^3 of the charged particles as a 20 °C temperature rise. The temperature rise was proposed to be enhanced by subsequent particle condensation. Rathbun (1960) had independently added to the thesis of lightning importance by arguing that tornadoes were electromagnetically fostered, first, through generation of hydrogen ions by water decomposition in cloud-to-ground lightning strikes and, then, the hydrogen ions being accelerated upwards in spiral motion to combine with the negatively-charged ion concentration at the lower cloud level, thus, again producing a temperature rise for updraft enhancement. Through sample calculations for birth of a mini-tornado, Rathbun proposed that a charge density of 10^{10} positive ions/cm^3, taken to be generated within a potential gradient of 2 kV/cm, would produce, through neutral air collisions, a wind velocity increment of ~52 m/s (~116 mph) within a tubular vortex having a radius of 1.75 m and a wall thickness of 10 cm.

3. THE SUPERCELL DEVELOPMENT

The initial charge generation process responsible for establishment of the global electric field of a thunderstorm supercell has been attributed generally to the collision of ice particles. The latest consensus on the modeled process is that the supercell electrification occurs by a "graupel-ice mechanism" (Rakov and Uman, 2003). The graupel-ice mechanism exhibits a temperature discrimination of the charging process that has been confirmed in a simulated laboratory experiment (Jayaratne et al., 1983). A chemical reaction type equation for the collision mechanism has been given on a conservation of mass and electronic charge basis by Armstrong and Glenn (2005). For example, at relatively higher cloud altitudes, corresponding to lower temperatures, say, in the range of -20 to -24 °C, the mechanism may be described schematically for one collision in a chemical-type van't Hoff reaction isotherm, as

$$(\mathbf{m}\, H_2O)_{graupel} + (\mathbf{n}\, H_2O)_{ice} = \{(\mathbf{m}\, H_2O)\mathbf{p}OH^-\}_{graupel} + \{([\mathbf{n} - \mathbf{p}]\, H_2O)\mathbf{p}H^+\}_{ice} \qquad (1)$$

where **m** is the number of H_2O molecules in a mm- to cm-sized, riming, graupel particle, **n** is the smaller number of H_2O molecules in the colliding smaller sized ice crystal, say, ~10 μm in diameter, and **p** is the number of generated ions of either sign; the mechanism also occurring within a cloud liquid water environment, say, of water content, **L** = 1 g/m^3. Thus, under these conditions in the specified temperature regime, equation (1) applies for the smaller ice crystals being positively charged. With **p** = 1, the equation would apply for the decomposition of a single molecule from a graupel-ice particle collision. A reverse attachment of ions was shown to occur at higher temperatures than -20 °C, thus, being characteristic of collisions at lower altitudes.

The laboratory inference in the demonstrated graupel-ice mechanism is that ice particles and graupel charges build-up by repeated collisions to the measurements able to be made with 10^{-15} Coulomb level sensitivity in both actual and laboratory electrification experiments. The measurements correspond to graupel-ice crystal charge levels, however, involving ~10^4 or more ions. Also, an interesting aspect of the reversed temperature-dependent charging processes is that the lower mass, positively charged ice crystals are created at higher altitudes consistent with the higher main residual supercell pole being electrically positive. In such charge generation processes, a fundamental role is assigned to the already present existence of a strong intracloud updraft whose supercell-forming charge-generation process overrides, at first, a reverse flow of negative charge to the lower cloud level (Dye et al. 1986; MacGorman and Rust, 1998). Rakov and Uman summarize the situation thusly, "In this mechanism, the electric charges are produced by collisions between graupel and small ice crystals in the presence of water droplets and the large-scale separation of the charged particles is caused by gravity." (Rakov and Uman, 2003).

4. LIGHTNING-SOURCED CHARGE CARRIERS

Recent attention has been drawn to the mysterious aspects of lightning occurrences within a thundercloud (Gurevich and Zybin 2005). In particular, attention was directed to high energy "runaway electrons" being accelerated in the electric field of the thundercloud and, especially relevant to the present consideration, losing energy by ionization of encountered (water) molecules. Such ionization should principally involve production of OH^- and H^+ ions from the total concentrations of water molecules. The simplified van't Hoff reaction isotherm for the lightning-based production of singly-charged H_2O decompositions is

$$\mathbf{q}\,(H_2O)_{\mathbf{i}} = \mathbf{q}\,OH^- + \mathbf{q}\,H^+ \qquad (2)$$

where the subscript **i** refers to ionization occurring for either graupel and ice particles as well as individual water particles containing q molecules. Equation (2) accounts in the simplest terms for a new concentration of hydrogen and hydroxyl ions that are generated by the lightning flash and are now to experience influence of the residual electric field of the supercell. The oppositely-charged ion concentrations are respectively driven, along a path centered on the vertical lightning strike, to their opposite poles so as to recombine with the main charges constituting the global electric field. Thus, the OH^- and H^+ charges are driven in opposite up-and-down directions, respectively. Such dual hydrogen and hydroxyl ion fluxes are the counterpart action to Rathbun's description for H^+ motion in a cloud-to-ground lightning strike. Even so, the energy released in the lightning strike is small compared to the energy stored in the supercell.

5. DUAL MECHANISMS OF UPDRAFT ENHANCEMENT

The lightning-sourced H^+ ions are driven downward within the intracloud chamber to recombine with the main particle-attached OH^- charge concentration of the lower cloud structure, and vice versa for the lightning-sourced OH^- ion concentration. A schematic description of the mechanism for energy gained by the lightning-spawned and downward-driven H^+ ions is given in a single van't Hoff equation form relating to equation (1) as

$$\mathbf{q}\,H^+ + \{(\mathbf{m}\,H_2O)\mathbf{p}OH^-\}_{graupel} = \{([\mathbf{m} + \mathbf{q}]\,H_2O)[\mathbf{p} - \mathbf{q}]OH^-\}_{graupel} \quad (3)$$

in which a summed exothermic energy is liberated both in ion recombination and ice or water transformation at the lower cloud level. The ionic recombination energy, is ~ 20 times greater than the condensation energy to water. Only immediate recombination on site or at higher altitude of the lightning-generated ions will reduce this thermal driving force from having its main influence on updraft wind velocity enhancement at the lower cloud level.

The hydrogen ions have negligible cross-sections and therefore produce an insignificant influence of any downward directed collisional influence or momentum exchange with air mass. On the other hand, the more massive and relatively, very substantially-sized, hydroxyl ions, that are driven in the counterpart upward direction by the same electric field are proposed to add a substantial pressure in that direction as they sweep all in their way to the upper cloud level. At that level, they react in accordance with a reversed-charge assignment in equation (1) as

$$\mathbf{q}\,OH^- + \{([\mathbf{n} - \mathbf{p}]\,H_2O)\mathbf{p}H^+\}_{ice} = \{([\mathbf{n} - \mathbf{p} + \mathbf{q}]\,H_2O)[\mathbf{p} - \mathbf{q}]H^+\}_{ice} \quad (4)$$

At the upper cloud level, the thermal effect of such liberated recombination energy is easily tolerated at the lower existent temperatures whereas in process of arrival the electric-field-driven hydroxyl ion flux delivers an additional upward pressure influence for wind velocity enhancement, much more so than had been attributed by Rathbun (1960) to the reverse case of neutral air collisions from upward directed hydrogen ions produced by cloud-to-ground lightning strikes. Thus, the respectively oppositely charged intracloud ions caused by lightning each contribute in their own way to enhancing the updraft wind velocity.

6. ELECTRICAL FORCE EVALUATIONS

Vonnegut (1960) was concerned, in focusing on the role of lightning-induced ionizations in cloud-to-ground strikes, that the hydrogen ions driven upward should be attached to heavier water particles so as to accomplish effective momentum transfer to the air. On this basis, he derived the relationship for the electric force, **F**, on such particles as:

$$\mathbf{F} = 9\,\mathbf{E}^2\,\mathbf{L} / 4\,\pi\,\mathbf{a} \quad (5)$$

where **E** is the electric field, **L** is the liquid water content (mentioned earlier in connection with the graupel-ice mechanism), and **a** is the charged water particle radius. For **E** = 10 ESU/cm (= 3 kV/cm), **L** = 2 g/m^3, and **a** = 20 μm, a relatively small force of 0.07 dynes (= 0.7 μN) was found to act on a cubic cm of the cloud. The force was estimated to produce a somewhat disappointing equivalent updraft of a temperature rise of ~20 °C.

Figure 1 is a key presentation of the electric force associated with differently charged ion and water/ice/graupel sizes, incorporating the relationship derived by Vonnegut. The closed circle point applies for Vonnegut's reported **F** = 7 x 10^{-7} N and **a** = 2 x 10^{-5} m (20 μm) chosen as a representative water droplet size (consistent with the described laboratory experiment for the graupel-ice mechanism). The inverse dependence of **F** on **a,** obtained in the Vonnegut relation of equation (5), is shown to be extended from the specified closed circle point in Figure 1 both to smaller particle and larger graupel sizes, say, in the latter case, between 2 mm and 5 cm, that are encountered in tornado-producing supercells. Negligible electrical forces act on the graupel. Dashed Vonnegut lines for larger or smaller values of **L** are drawn parallel to the solid line.

The electrical force, **F**, acting on either species of a fully ionized concentration, **L**, in g/m^3 of water, is obtained analogously to the derivation of equation

(5) by multiplying **E** by the total effective charge **Q** = **q** (**N L** / 18), thus,

$$\mathbf{F} = \mathbf{E}\,\mathbf{q}\,(\mathbf{N}\,\mathbf{L} / 18) \qquad (6)$$

in which **q** is the electron charge, 1.6 x 10^{-19} C, and **N** is Avogadro's number, 6.02 x 10^{23} of molecules contained in 18 grams of water. The fraction **L**/18 is the proportional mass of water molecules in **L**. For 100% ionization of **L**, the filled square point is obtained in Figure 1 at **F** = 3.2 x 10^{3} N corresponding to **a** = 0.96 x 10^{-10} m for the OH^- bond length. At 0.1% ionization of **L**, say, accomplished by immediate recombination of the ions, the filled square point is correspondingly shifted downward. The same electrical force would be obtained for the counterpart lightning-generated H^+ concentration and could be plotted to the left in Figure 1, possibly, at the effective physical size of the proton radius of 1.44 x 10^{-15} m.

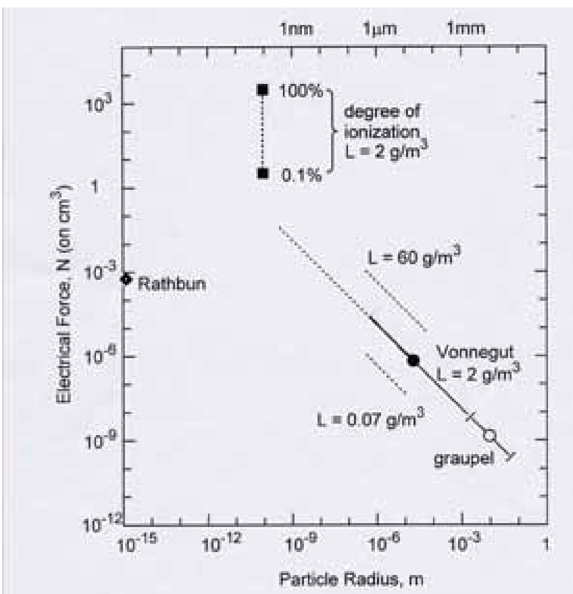

Figure 1. Electric force versus H^+ and OH^- ionic radii and charged water droplet and charged graupel radii

The downward acceleration of the lightning-sourced H^+ concentration would be enhanced relative to the OH^- acceleration by a factor given by the seventeen times ratio factor of the hydroxyl-to-hydrogen ion masses. Instead of plotting in Figure 1 the shifted **F**-**a** point for the H^+ ions, the value of **F** is plotted as a filled triangle that applies for the 10^{10} H^+ ions/cm^3 considered by Rathbun (1960) to have sufficient force and momentum capability to sweep air upwards from the below-cloud influence of a lightning strike. Thus, compared to both Rathbun and Vonnegut evaluations, Figure 1 demonstrates that orders of magnitude greater electric forces apply for lightning-generated ion populations under the same conditions previously considered for the two other situations.

7. DISCUSSION

MacGorman and Rust (1998) had reported that both total and intracloud flash rates were large in tornadic supercell storms at the time of tornado occurrences (see also Rakov and Uman, 2003). Both Williams et al. (1999) and Buechler et al. (2000) reported far greater intracloud, as compared with below cloud, flash rates preceding tornadogenesis. In fact, Williams et al. reported "jumps" in intracloud lightning flash rates of 3 to 8/s that were associated with sudden increases in wind velocities of 50 to 70 mph at ground level, and, very significantly, these winds were found to lag behind the flash rate jumps by 5 to 20 minutes. Such lightning precursor to the onset of a severe weather condition was interpreted, however, in terms of an enhanced updraft producing the lightning activity rather than the other way around. The present analysis gives evidence for considering that the reverse situation applies, that is, whatever the current level of updraft in a severe storm, if a sudden increase in intracloud lightning flash rate occurs, and it is of sufficiently high level, then, a very significant generation of hydroxyl and hydrogen ions occurs. The hydrogen ions are driven faster to reaction at the lower cloud level, and thereby, produce an additional lower cloud thermal influence to the updraft, one that to the authors' knowledge has not been considered previously. The much larger OH^- ions, in turn, push upwards, producing a rising pressure influence to the updraft. Both actions add to enhancement of the wind updraft.

The need for repeated lightning strikes provides an additional spatial requirement if they are to build from an embryonic mini-tornado. By analogy with screw dislocation behavior in solid mechanics, such mini-vortices repel each other when having the same rotation vectors and annihilate each other if having the same sign rotations. Thus, the only mechanism by which truly high wind velocities might build to tornadic condition through the added influence of electrification, as considered here, is if the repeated lightning strikes occur within the spatially localized "core" of the vortex. The requirement is proposed to be a contributing factor to the observation that tornadoes are a relatively rare outcome even of severe weather dissipations.

Lastly, there is the issue of how the tendency towards tornadogenesis under severe storm electrification conditions might be modified according to the present model interpretation so as to prevent build-up to tornadic activity. A particular version of cloud seeding provides a possible solution. The aim would be either to interfere with the needed spatially localized lightning flash rate or to promote recombination of the lightning-sourced H^+ and OH^- concentrations as near as possible to the localized regions of generation. In both cases, selective cloud seeding actions might be useful. For example, conductive material particles or ribbon segments might be employed to beneficially influence the areal spread of the flash rate. Cloud seeding of lighter-than-air, neutral or charged, nanoparticles might be employed to effect "in-situ" recombination of the lightning-sourced concentration of ions. The employment, for example, of suitable fly-ash-like particles would have significant lifetimes for effecting such recombinations and, with pre-imposed negative charges, could be directed just above the lower cloud level to preferentially combine with the relatively more influential H^+ concentration.

8. SUMMARY AND CONCLUSIONS

New consideration of a role for severe thunderstorm electrification in tornadogenesis is described for such event occurring within the intracloud environment and is shown to constructively relate to the preceding pioneering researches of Vonnegut and colleagues. Lightning-sourced H^+ and OH^- particles are more driven than charged water particles by the thunderstorm electric field and add to wind velocity build-up. Evaluation of the electrical force on these primary particles shows it to be greater by orders of magnitude than those associated with relatively small-sized water droplets. The hydrogen ions are driven downwards to recombine at the lower cloud level with the resident main concentration of hydroxyl ions, presumably, particle-captured, and through ionic recombination add significant thermal influence to the updraft. The lightning-generated hydroxyl ions are driven upwards to effect significant sweeping action on the various air particles in the intracloud chamber. Repeated lightning strikes, however, are required to be spatially localized within an established vortex "core" in order to lead to tornadic activity. The flash rate requirement is in line with recent experimental observations associating severe wind velocity build-ups; and, the required spatial localization of the "lightning rate jumps" is in line with tornadoes being relatively rare occurrences.

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A Preliminary Assessment of Inducing Anthropogenic Tropical Cyclones Using Compressible Free Jets and the Potential for Hurricane Mitigation

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Abstract. We have conceptually studied the potential for mitigation of natural hurricanes by inducing anthropogenic perturbations prior to or in front of an advancing hurricane. We propose actual hardware for the task. It consists of multiple jet engines mounted on barges or ships that will be dispatched to strategic locations in the ocean where the sea surface temperature is high and the vertical temperature profile and atmospheric conditions are such that the potential for development of a hurricane or tropical storm is high. The engines will direct compressible high momentum, high-speed free jets skyward causing entrainment of even larger amounts of additional air to form plumes and updrafts. The unstable humid updraft will itself produce conditions for additional entrainment and evolution of tropical cyclones. These anthropogenic perturbations will extract enthalpy from the ocean, cooling the ocean surface and depriving the advancing natural hurricane of its needed thermal energy.

The barrage of hurricanes and adverse impacts on human life and property in the Southeastern United States and Caribbean Basin during 2004-2005 has revived an interest in hurricane mitigation (Hoffman 2004, 2002). Reputable atmospheric scientists have developed a few ideas for hurricane mitigation over the past 60 years (Gray et al. 1976; Simpson 1981). Only two programs have involved actual field or laboratory experiments (Willoughby et al. 1985; Alamaro 2001). The most well known was the Stormfury project that lasted for more than 20 years, under which NOAA used cloud seeding by silver iodide to try to nucleate supercooled water in the hurricane's clouds. The hypothesis was that the heat of fusion released upon nucleation would increase the hurricane eyewall diameter, leading to a decrease in the maximum wind speed. Through radar observations it was eventually discovered that the clouds contain ice and little or no supercooled water, so the project was abandoned (Willoughby et al. 1985). Another attempt was undertaken at the Air-Sea Interaction Laboratory at the Massachusetts Institute of Technology, where a monolayer film was used to retard evaporation in a wind wave tank in which the airflow over the water surface was comparable to that of hurricane (Alamaro 2001). The hypothesis was that spreading a monolayer film on the ocean in the front of the hurricane would retard the evaporation that fuels the hurricane with latent heat. Unfortunately, at a wind speed of about 10 m/sec or higher the film tends to break apart and becomes immersed in the water due to high-speed airflow and wave action, and loses its effectiveness (See: http://alamaro.home.comcast.net/Evaporationretardation.htm).

We propose to induce atmospheric perturbations in front of or prior to an advancing hurricane or potentially dangerous cyclone. These induced perturbations will extract enthalpy from the ocean surface, leading to a decrease in the sea surface temperature (SST). As such, the approaching naturally occurring hurricane will be deprived of its source of enthalpy. It is hypothesized that the hurricane intensity will then be much reduced prior to landfall.

Compressible free jets generated by multiple jet engines mounted on barges or ships will induce the perturbations. They will be dispatched to strategic locations in the ocean during an advancing hurricane. Alternatively, the jet generator vessels will continuously patrol the western Tropical Atlantic, inducing cyclones during the hurricane season to reduce the SST up to a few hundred miles from the shoreline.

The proposed method is analogous to backfires created by firefighters when confronting an advancing firewall. Small and controlled fires are started in front of the advancing, uncontrolled and larger fire. By the time the main fire advances, its fuel supply has been consumed causing it to be reduced in intensity and if properly executed, extinguished. Just as firefighters maintain distance between the backfires and the larger fire so they do not merge, it would be necessary to keep a distance between the induced cyclones and the natural hurricane so they do not merge to form a larger hurricane.

Compressible Free Jets and Plumes. A free jet is an unbounded flow of one fluid into another and is generated by pressure difference at the orifice of the jet. A plume is an updraft of air due to buoyancy forces (Lee and Chu 2003). Free jets are usually turbulent and turbulent mixing causes transport of momentum, energy and species to the surrounding fluid. The effective mass transfer rate of the jet is increased with the distance from the jet orifice due to entrainment as its velocity is reduced. The momentum flux of a free jet is preserved during entrainment.

The airspeed in the updraft of a hurricane is on the order of 1-10 m/sec. We have concluded that generating such incompressible low airspeed by a free jet is impractical since to achieve a substantial air mass flow and momentum a fan of impractical large cross sectional area would be required. Moreover, the momentum flux imparted to a jet is proportional to the square of its speed and as a result the mass rate of the entrained air is proportional to the square of the initial jet speed.

Therefore, we suggest the use of a compressible high-speed free jet generated by surplused, retired or decommissioned jet engines. For example, a Pratt & Whitney JT3D-3B jet engine that was used to power airplanes such as the Boeing 707, or its military equivalent the TF33-3 engine that was used to power the B-52 provide roughly 50,000 N of thrust, with an air mass flow of approximately 110 Kg/sec and a compressible free jet speed is about 460 m/sec. Twenty such jet engines mounted on a barge will provide a total momentum flux of about 10^6 N. By the time the entrained jet airspeed decreases to 10 m/sec and subsequently to 1.0 m/sec the ascending entrained air mass will have reached a flow rate of 10^5 Kg/sec and 10^6 Kg/sec, respectively. This ascending air mass rate is due to the initial momentum provided by the jet engines and does not include plumes. It is roughly 3-4 orders of magnitude smaller than the ascending air mass in the updraft of fully developed hurricane[1]. It is expected that if this is done at locations where the SST is higher than 26^0C - 27^0C, where the atmosphere is humid and the gradients along height of potential temperature is negative causing instability, the free jet will eventually grow to produce large and unstable plumes and updrafts of tropical storm or hurricane proportions.

The approximated chemical reaction of combustion in the jet engine is:

$$CH_2 + 3/2\ O_2 = H_2O + CO_2$$

The combustion gas excluding nitrogen (which is not affected by the combustion) and unburned oxygen is a mixture of water vapor and carbon dioxide, the molecular weight of which is 31, slightly heavier than that of air. Since the ratio of combustion gas to air in the jet of turbofan jet engine is small, it is not expected that the increase in the molecular weight of the jet will impede its upward motion. Turbulent mixing with ambient air would result in an immediate reduction of the jet density approaching that of the ambient air. Furthermore, injection of water in the high temperature jet will add water vapor to the jet and increase the humidity of the entrained air, increasing the buoyancy.

Implementation. We conceptually studied two scenarios for implementation of the proposed technology. In the first, the natural hurricane's path is predicted. Barges towed by ships as shown in Figure 1 carry the jet engines and fuel, and are dispatched in the Western Tropical Atlantic or the Caribbean, westward of the advancing hurricane. Because there is always some uncertainty about the track of a hurricane that is traveling westward, multiple free jet facilities will be situated in rows that are generally extended from south to north to account for any deviation from the predicted path of the hurricane.

The power and total energy of a tropical storm is less than the power and total energy of a hurricane. The power of moving air is proportional to the cube of its velocity. If the air speed of a tropical storm is (¾) that of a hurricane, the power per unit area of the ocean surface of a hurricane is approximately $1/(¾)^3$ or four times that of a tropical storm. In this example it will be required that approximately four tropical storms travel in front of a hurricane, and deprive it of enthalpy intake. Therefore, multiple tropical storms are required in advance of the advancing hurricane.

[1] An order of magnitude estimate for the mass rate of updraft air in a hurricane has been calculated based on the following approximations: Total power of a hurricane 10^{12} -10^{13} Watt. This estimate enables to find the rate of water vapor ascending using the latent heat of evaporation approximated as 2.5 10^6 J/kg. From knowing the rate of water vapor ascending and the water vapor density over SST at 27 Degree Celsius and assuming 100% relative humidity, we can arrive with an estimate for the rate of ascending air.

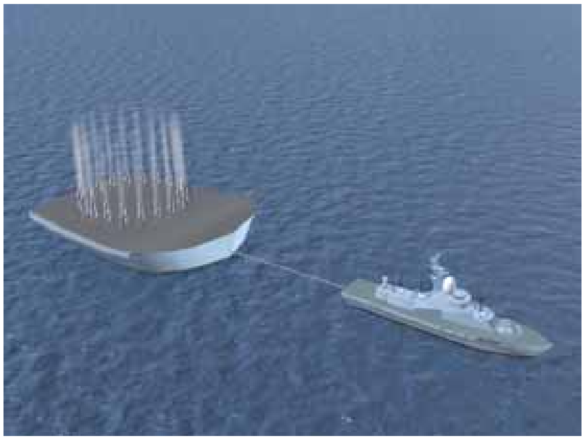

Fig. 1: Artistic view of multiple jet engines directing jet skyward for inducing anthropogenic atmospheric perturbations

Logistically, this scenario may be difficult to execute since once a hurricane is evolved there is not much time to determine where the barges should be dispatched, and for actual dispatching of the barges and free jet implementation. Even if successful, it may be possible that multiple tropical storms would reach the shoreline causing high winds and flooding. This, combined with the inherent uncertainties of the outcome of weather modification and the lack of confidence that indeed the induced cyclones will alter the trailing hurricane, may lead to an erosion of public support for the hurricane mitigation program.

In an alternative scenario, the SST of the ocean up to a distance of a few hundred miles from the shoreline will be kept lower by a few degrees during the hurricane season. For that, barges or ships equipped with compressible free jet systems will continuously patrol the oceans and be dispatched to locations where the SST is high. The initiation of tropical storms in this case will be done in advance of the evolution of hurricanes. The timing of the generation of anthropogenic tropical storms may include, in addition to hurricane mitigation, the requirements for rainfall at specific regions on land and the potential landfall locations of the hurricane. As more experience is gained, the proper spatial and temporal distribution of the anthropogenic storms can be developed to optimize effects and to avoid landfall of multiple storms at one location during a short period of time.

The preferred mode of operation in this case is the following: The first anthropogenic tropical storms will be initiated as close as possible to the shoreline regardless of an existing or advancing natural hurricane. By the time these induced man-made cyclones arrive on shore their intensity will be minimal and it is possible that they will decay before arriving on shore. At the same time or afterward, a second row of barges will start a second row of tropical cyclones Eastward of the initial row. The second row of cyclones will travel westward and eventually will travel over lower SSTs that had been caused earlier by the first row. At the same time or afterwards a third row of tropical cyclones will be started eastward of the second row, and so forth. It may be sufficient to cool the ocean surface by 2-3 degrees Celsius, up to a distance of a few hundred miles from the shoreline, to ensure that an advancing natural hurricane that is formed in the Mid or Eastern Atlantic would travel over lower SSTs, substantially reducing its potentially destructive energy before landfall.

The cost of full scale implementation to protect the Southern US, Caribbean Basin and Central America is estimated at \$0.5 –0.75 billion per year. A substantial portion of this budget could be in-kind or overhead contributions by the military and various government agencies.

Atmospheric Conditions. Other or alternative effects and processes resulting from the anthropogenic cyclones may also contribute to the weakening of a natural hurricane as well. For example, the large-scale overturning subsidence associated with the secondary circulation of the anthropogenic storms may suppress convection and increase the vertical shear of horizontal wind in the inner core region of the approaching natural hurricane (Wang and Holland 1995). It is hypothesized that the hurricane intensity may also be reduced by this mechanism prior to landfall. Another possible consequence is the direct interaction between the anthropogenic perturbations and the natural hurricane. Such an interaction could change the track of the hurricane. It is possible that the anthropogenic cyclones could be "designed" to steer the natural hurricane from landfall at highly populated coastal regions or be steered back out to sea and away from any landfall (Hoffman 2004; Y. Wang, 2005 personal communication).

A more general application of anthropogenic modification is to modify the tropical atmosphere where it is most sensitive to small perturbations that will grow in amplitude and scale over several days to the point that some characteristics of a subsequent tropical cyclone will be altered. This does not necessarily involve direct creation of another tropical cyclone. It may instead involve tropical waves or other large-scale features. It may not be possible to entirely prevent a given tropical cyclone, but it might be possible to, for instance, alter the track of the storm slightly so as to miss large population centers or areas prone to devastating storm surge effects or inland flooding (C. Davis, 2005 personal communication). Calculations of sensitivity in the tropics are still in their undeveloped stages and require much better models than exist now, including calculations that are capable of resolving individual cumulus towers (or at least a much improved representation of their effects).

Many calculations of the response of the tropical atmosphere to small perturbations are required to understand what may result from a perturbation of the type envisioned to be created from arrays of jet engines. This study has many practical implications for understanding the sources of errors in dynamic prediction in the tropics, and so carries importance beyond anthropogenic modification scenarios (C. Davis, 2005 personal communication).

In the tropic oceans under direct solar radiation (the sun is not partly or completely covered by clouds) the stratification of the atmospheric layer over the sea surface is rather stable. Figure 2 shows average gradients of potential temperature $\Theta = T(1000/P)^{0.286}$ during 24 hours time, where T is the air temperature in ^{0}K, and P is the atmospheric pressure at the level of measurements. Curve 1 in Figure 2 is for tropical ocean areas. These data were obtained during numerous measurements made on expeditions in the Pacific Ocean and South China Sea (Pudov and Korolev 1990). Positive values for potential temperature gradient indicate stability while negative values indicate instability, a factor that may be necessary for inducing unstable updrafts by the proposed jet. The jet operation, therefore, may better be done at nights and/or in the presence of initial cloudiness of a fraction no less than 6-7.

The higher the relative humidity (f %), the lower the condensation height level where evaporation heat will be released from the ascending humid air. The height of the condensation level (h) can be roughly estimated as h = 22 (100-f %), where h is in meters above surface. For example, for a relative humidity of 80% the condensation level is about 400 meters. To reduce the condensation height it may be necessary to inject water into the exhaust nozzles of the jet engines.

The jet engines might be sufficient for disturbing the stability of the air layer near the water surface in the tropics, especially in the late afternoon or at night. In the extra-tropical zones it may be possible to create convective clouds with the help of vertical jets most of the day.

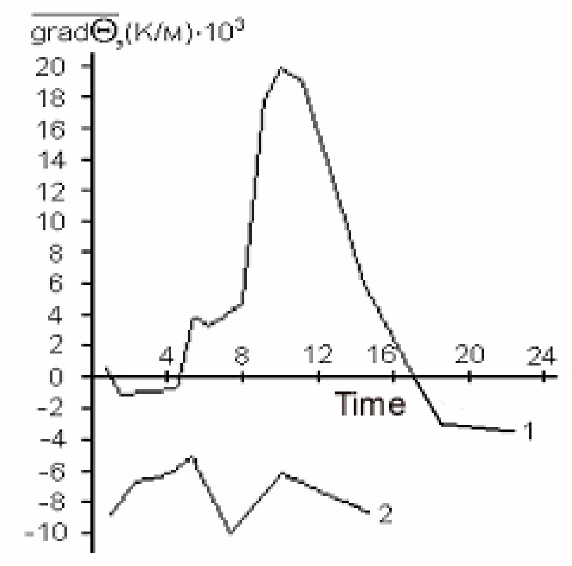

Fig. 2: Gradients of potential temperature along height vs. time; Curve 1 for over tropical ocean; Curve 2 for extra-tropical ocean (Pudov and Korolev 1990).

Legal and Policy Considerations. A report of The National Research Council states: "The Committee concludes that there is still no convincing scientific proof of the efficacy of intentional weather modification efforts." (p. 3). The report also states: "If simple precipitating cloud systems cannot be modified in significant ways, it is very difficult to believe that a strongly organized large dynamic system such as a hurricane can be modified" (NRC 2003).

The fundamental problem of weather modification is that controlled experiments are difficult if not impossible. There is always uncertainty that the outcome of the modification, such as enhancing rainfall, is due to the modification or the natural variability of weather. This uncertainty is less of a problem in this proposal since if a tropical storm is generated consistently a few times after applying jet engines, cause and effect will become clear. Even if a well-supported theory of hurricane modification existed, the legal ramifications of weather modification on this scale are daunting. A few of the many possibilities include (R. Anthes, 2005 personal communication):

1. The storm is not modified at all, but some people perceive that it is, suffer personal damage or injury and file lawsuits.

2. The storm is modified according to theory, but still does significant damage and some people blame the modifiers on the damage,

even though the modification actually reduced overall damage and impact.

3. The modified storm produced “winners” and “losers” and the perceived “losers” sue. For example, what if the hurricane abruptly changed course? The people affected by the new course might well blame the modification effort and sue (R. Anthes, 2005 personal communication).

It is clear that first it would be necessary to further the theory and then to design experiments that do not have the potential to cause harm. Only then it would make sense to develop policy for international treaties to enable implementation under the supervision of international advisory committee, to assure public acceptance of hurricane modification. For example, according to future international treaties, hurricane damage will be compensated regardless if the hurricane has been modified or not. But suing will not be an option.

Pilot Development. Tropical cyclones involve complex fluid dynamic processes, including rotating and stratified flows, boundary layers, air-sea interaction and multiphase thermodynamics (Emmanuel 1991). It is impossible to scale down these processes in a laboratory experiment. The only avenue for development is to test the concept over the high seas. The first milestone would be the creation of an anthropogenic perturbation or tropical storm by a free compressible jet. This may be done anywhere in the ocean outside of the hurricane season, nominally before June or after November, to assure that the induced storm does not become a hurricane, or is perceived to have done so. To assure success of the pilot program we recommend employing as many jet engines as possible in the first trial runs and then to reduce the number if possible.

The projected cost of such a pilot project is estimated to be $25 - $40 million, most of which could be in-kind contributions from government agencies and the military. Old and retired jet engines can be donated by the Air Force for example, at scrap value or less. Airlines may also wish to donate such retired engines in exchange for write-offs against taxable income. Such arrangements can be made with the US Government and others, such as the Russian Government. The cost of a flight-worthy reliable jet engine is substantial but the reliability of the jet engines necessary for this project is not an issue. It would be entirely acceptable if 10 - 30% of the stationary jet engines used for the pilot program and subsequent implementation break down during operation.

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Appendix: Review of Free Jet and Strategies for the Application of Jet Engines

Introduction and definitions

The following is basic information on and calculations for compressible free jets produced by jet engines.

A "Free Jet" is a flow of one fluid into another. The other fluid is a surrounding fluid at rest or in a motion relative to the jet. Walls or ducts do not confine the free jet. The jet flow is impeded only by shear stress with relation to the surrounding fluid.

The term "compressible" does not refer to the fluid of the free jet. For example, the jet can be of air, which is a compressible gas. However, the flow can be compressible or incompressible. In any flow where the Mach Number (M) is less than 0.3 the flow is incompressible. At M > 0.3 the flow is compressible. For air at ambient temperature the flow is incompressible when the air speed is lower than approximately 100 m/sec. Flow from jet engines used in commercial airplanes is usually at about sonic speed so the free jet considered is initially compressible. However the compressible jet velocity is rapidly reduced by entrainment of air that joins the jet, and the free jet becomes in-compressible at a point about 20 meters from the jet engine nozzle.

The following analysis is intended to provide a cloud modeler a fundamental familiarity with the performance of a typical jet engine mounted vertically for cloud formation.

Geometry of circular jet

The schematics below describe the following:

a. Jet engine and a nozzle of diameter d_o and cross sectional area A.

b. Approximately uniform velocity profile or "plug flow" at the jet nozzle.

c. Divergence lines where the flow velocity is half the maximum velocity in the Gaussian profile or the lines of $\overline{U}_{0.5}$.

d. The maximum average velocity $\overline{U}_m$ at the center of the circular Gaussian velocity profile.

e. $\overline{U}_{0.5}(x)$, while x is the distance from the jet nozzle.

f. Flow of entrained air.

Fundamental equations

For a circular jet, the radius at the point where the air velocity in the Gaussian profile is half of the maximum velocity at the same radial distace from the nozzle is given by:

$$r_{\overline{U}_{0.5}} = 0.085 \cdot x \tag{1}$$

The most important property of a free jet is its momentum flux. The momentum flux at the exit from the nozzle is:

$$J = \dot{m}U_0 = \rho_0 \ AU_0^2 \tag{2}$$

Where U_0 is the speed at the exit from the engine which is approximated as uniform, A is the cross sectional area of the nozzle and ρ_0 is the density of the gas. The momentum flux is also equal to the thrust provided by the jet.

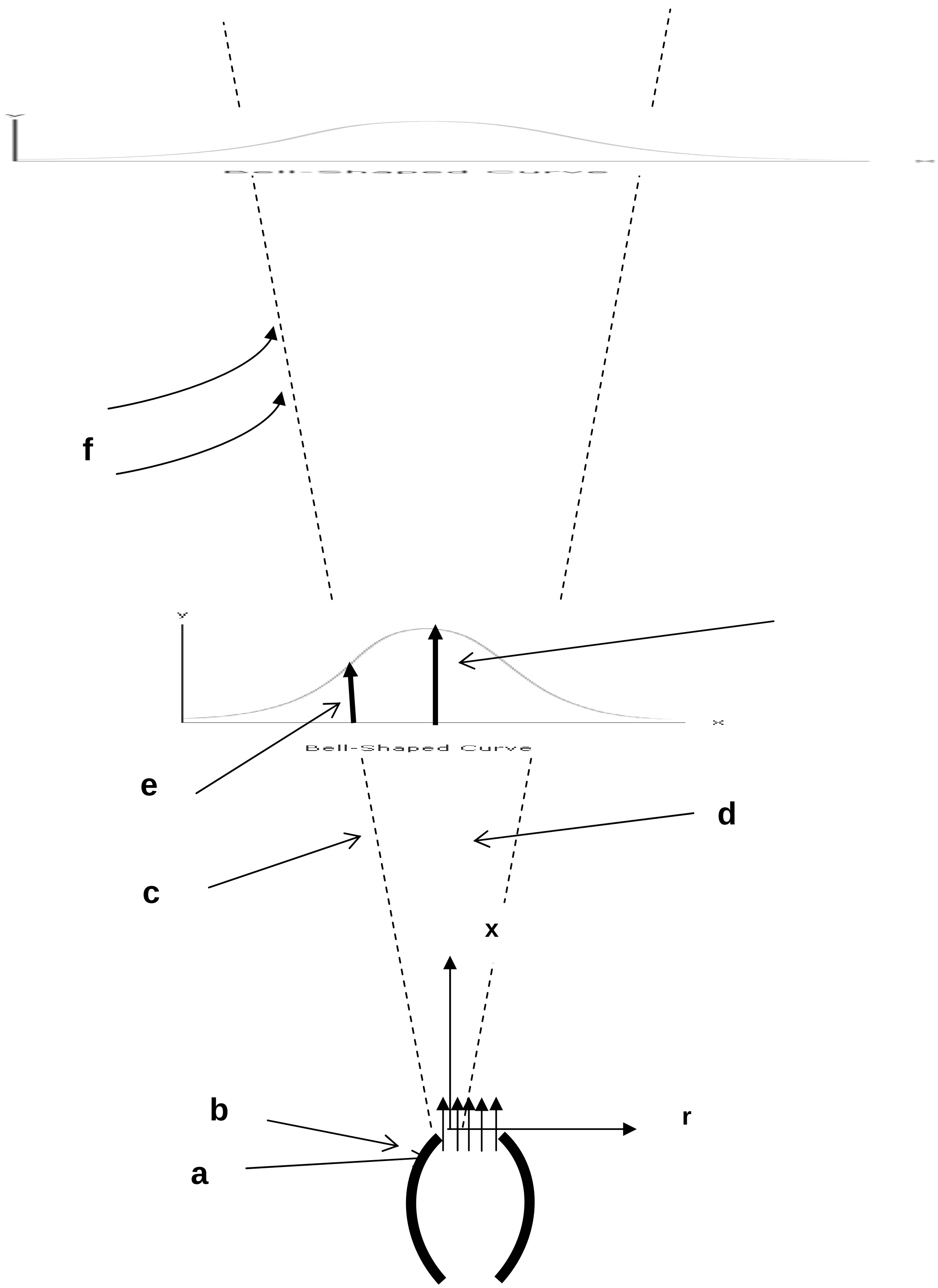

Figure A-1: Free jet schematics

For the vertical jet the cylindrical corrdinates are x and r where x is the height from the center of the nozzle of the jet engine. Assuming that the jet engine operates at sea level, x is also the elevation above sea level.

Using a control volume analysis on the jet that of any arbitrary height x from the jet origin, it is possible to show that the momentum flux of the jet is preserved at any distance from the jet origin. Therefore:

$$J = \rho_0 \ AU_0^2 = 2\pi\rho(x)\int_0^\infty rU^2(x,r)dr = const \tag{3}$$

for any value x.

In eq. (3) the density is a function of the height x and U(x,r) is the gas velocity which has a circular Gaussian velocity profile.

Description and equations of circular jet

The flow exiting from the jet engine nozzle has almost uniform velocity profile and therefore it is called “plug flow”. Upon ejection there is shear stress with the surrounding air and therefore its velocity profile changes to a Gaussian profile at a distance of approximately 6-10 of d_0 – diameter of the nozzle. Non-dimensional analysis provides the equations that approximate the subsequent flow:

$$\overline{U}_m(x) = c_2 \cdot \frac{\sqrt{J/\rho(x)}}{x} \tag{4}$$

Where $\overline{U}_m(x)$ is the jet maximum velocity at the centerline, J is the momentum flux defined in (3), $\rho(x)$ is the air density as a function of height x and c_2 is a constant.

The Gaussian velocity distribution is:

$$U(x,r) = \overline{U}_m(x) \cdot \exp\left(\frac{-r^2}{a^2(x)}\right) \tag{5}$$

For a circular jet:

$$a(x) = c_1 \cdot x \tag{6}$$

Ignoring eq. (4) we can derive the expression for $\overline{U}_m(x)$ through the use of equations (3), (5), and (6):

$$J = \rho_0 \ AU_0^2 = 2\pi\rho(x)\int_0^\infty rU^2(x,r)dr = 2\pi\rho(x)\int_0^\infty r\overline{U}_m{}^2 \exp\left(\frac{-2r^2}{c_1^2x^2}\right)dr =$$

$$= 2\pi\rho(x)\overline{U}_m^2(x)\int_0^\infty r\exp\left(\frac{-2r^2}{c_1^2x^2}\right)dr = 2\pi\rho(x)\overline{U}_m^2(x)\frac{c_1^2x^2}{4} = J \tag{7}$$

Rearranging:

$$\overline{U}_m(x) = \frac{1}{c_1}\sqrt{2/\pi}\,\frac{\sqrt{J/\rho(x)}}{x} \tag{8}$$

Let's define $c_2 = \frac{1}{c_1}\sqrt{2/\pi}$. c_1 has been found empirically to be 0.103 so $c_2 = 7.75$ (Rodi 1975).

Assumptions and a procedure for numerical calculations of circular jet

The assumptions and data used are for a specific single jet engine. The suggested procedure for numerical caculation is provided below.

Step 1

Calculate the initial momentum flux or thrust of the specific jet engine. Assume that the engine is a TF33-3 (that used to power the B-52 bomber and Boeing 707) for which $U_0 = 460\ m/\sec$. Also, assume that the jet produced by the engine is not of a combustion gas but air at the same ambient temperature and pressure as the ambient air at sea level. (These assumptions may be revised in a more rigorous analysis). For T=300 K, at specified barometric pressure and relative humidity we can calculate the density ρ_0 using the equation of state. For purposes of this calculation assume that $\rho_0 = 1.17\ \frac{Kg}{m^3}$. The nozzle diameter is $d_0 = 0.5\ m$. Substituting this into (1):

$$J = \rho_0\ AU_0^2 = 1.17\cdot\frac{\pi}{4}0.5^2\cdot 460^2 \cong 50{,}000\left[Kg\ m^{-3}\ m^2\ m^2\ s^{-2}\right] \cong 50{,}000\ N$$

Step 2

Assign a vertical profile of temperature, pressure, humidity and temperature lapse rate. From this, calculate the density of the air as a function of the height. The height is x_i . Steps can be at 1, 10 or 100 meters. This will be decided by the user.

Step 3

Assume that the jet engines are operated on a ship or a barge in the sea. Assume also that the jet becomes similar (or Gaussian) at x = 20 m. Substitute in eq. (3):

$$\overline{U}_m(x) = c_2\cdot\frac{\sqrt{J/\rho(x)}}{x} = 7.75\cdot\frac{\sqrt{50{,}000/\rho(20)}}{20} \cong 80.1\ m/\sec$$

The last result is significant. It shows that the jet speed has been reduced from 460 m/sec to a Gaussian profile when the maximum speed in the centerline is 80.1 m/sec where the flow becomes incompressible. The initial mass flow rate from the jet engine is:

$$\dot{m}_{engine} = \rho_0 A U_0 = 109 \frac{Kg}{\sec}$$

To calculate the mass flow rate of the Gaussian profile at **x = 20 m** using eq. (3), first calculate the velocity profile using eq. (5):

$$U(20,r) = \overline{U}_m(20)\cdot\exp\left(\frac{-r^2}{a^2(20)}\right) = 80.1\cdot\exp\left(\frac{-r^2}{0.103^2\cdot 20^2}\right) = 80.1\cdot\exp\left(\frac{-r^2}{4.244}\right)$$

The mass flow rate $x = 20\ m$ is:

$$\dot{m}(x=20) = 2\pi 80.1\rho(20)\int_0^\infty r\cdot\exp\left(\frac{-r^2}{4.244}\right)dr \cong 588.8\int_0^\infty r\cdot\exp\left(\frac{-r^2}{4.244}\right)dr$$

Use the identity $\int_0^\infty r\cdot\exp\left(\frac{-r^2}{a}\right)dr = \frac{a}{2}$

Therefore:

$$\dot{m}(x=20) \cong 588.8\int_0^\infty r\cdot\exp\left(\frac{-r^2}{4.244}\right)dr = 588.8\cdot\frac{4.244}{2} = 1{,}250\frac{Kg}{\sec}$$

The ratio of the mass flow rate of air at x = 20m to the mass flow rate from the jet engine is:
$\dot{m}(20) = 11.46\,\dot{m}_{engine}$

To check the the momerntum flux at x = 20 m:

$$J = 2\pi\rho(x)\int_0^\infty rU^2(20,r)dr = 2\pi\rho(x)\int_0^\infty r\overline{U}_m^2(20)\exp\left(\frac{-2r^2}{c_1^2 x^2}\right)dr =$$

$$= 2\pi\rho_0\overline{U}_m^2(20)\int_0^\infty r\exp\left(\frac{-2r^2}{c_1^2 x^2}\right)dr = 2\pi 1.17\cdot 80.1^2\int_0^\infty r\exp\left(\frac{-2r^2}{0.103^2 20^2}\right)dr =$$

$$47{,}162\int_0^\infty r\exp\left(\frac{-r^2}{2.122}\right)dr = 47{,}162\frac{2.122}{2} \cong 50{,}000\ N$$ As expected

Example B

Calculate of the speed of the jet and the total mass flow rate due to a single engine at **x** =1,000 m.

The density at x =1,000 m may be calculated as follows:

$$\frac{\rho(1{,}000)}{\rho_0} = \left(\frac{T(1{,}000}{T_0}\right)^{\frac{g}{R_{air}\cdot\mu}-1} \cong \left(\frac{300-6.5}{300}\right)^{\frac{9.81}{287\cdot 6.5 10^{-3}}-1} \cong 0.91$$

At this stage it is required to make assumptions about the necessary atmospheric conditions during cloud formation operation.

$$\rho(1{,}000) = 0.91\cdot\rho_0 = 1.066\frac{Kg}{m^{-3}}$$

$$\overline{U}_m(1{,}000) = c_2\cdot\frac{\sqrt{J/\rho(1{,}000)}}{1{,}000} = 7.75\frac{\sqrt{50{,}000/1.066}}{1{,}000} \cong 1.678\ m/\sec =$$

$$= 1.678\cdot\exp\left(\frac{-r^2}{0.103^2\cdot 1{,}000^2}\right) = 1.678\cdot\exp\left(\frac{-r^2}{10{,}609}\right)$$

The mass flow rate is:

$$\dot{m}(x=1{,}000) = 2\pi 1.678\cdot 1.066\int_0^\infty r\cdot\exp\left(\frac{-r^2}{10{,}609}\right)dr \cong 11.24\int_0^\infty r\cdot\exp\left(\frac{-r^2}{10{,}609}\right)dr$$

$$\dot{m}(1{,}000) \cong 11.24\cdot\frac{10{,}609}{2} = 59{,}622\frac{Kg}{\sec} = 547\dot{m}_{engine}$$

Checking the momentum flux:

$$J = 2\pi\rho(1{,}000)\int_0^\infty rU^2(1{,}000,r)dr = 2\pi 1.066\cdot 1.678^2\cdot\int_0^\infty r\exp\left(\frac{-r^2}{5304.5}\right)dr =$$

$$= 18.86\frac{5304.5}{2} \cong 50{,}000\ N \text{ as expected.}$$

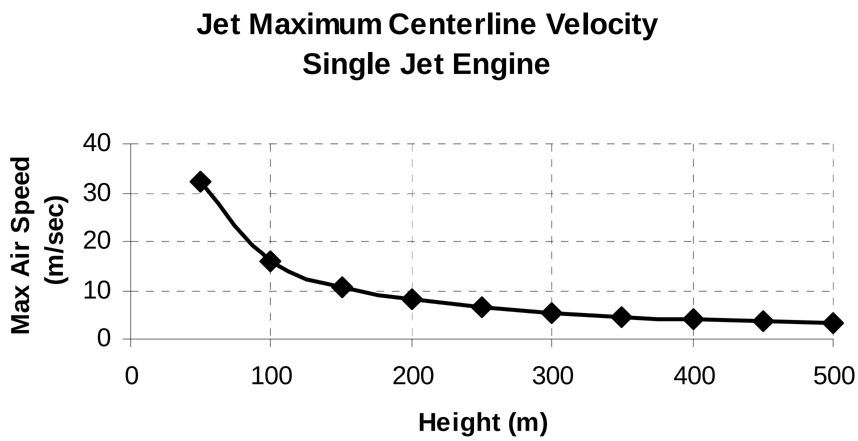

Figure A-2: Centerline maximum jet velocity. Initial speed 460 m s^{-1}.

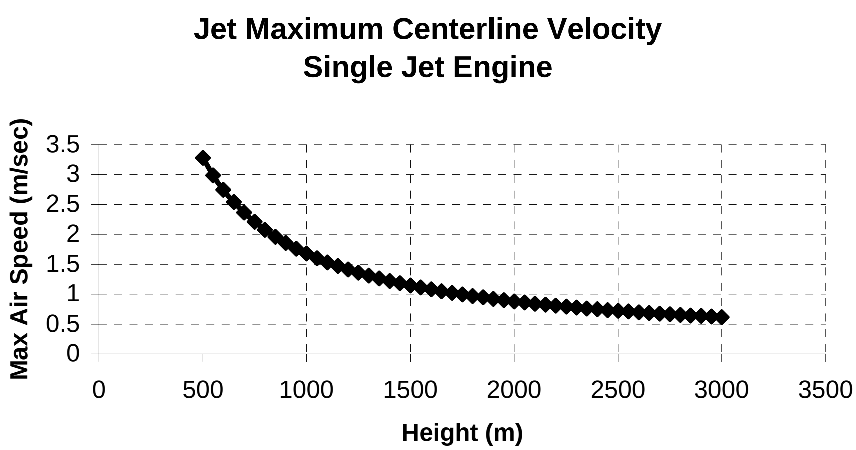

Figure A-3: Centerline maximum jet velocity. Initial speed 460 kg s^{-1}.

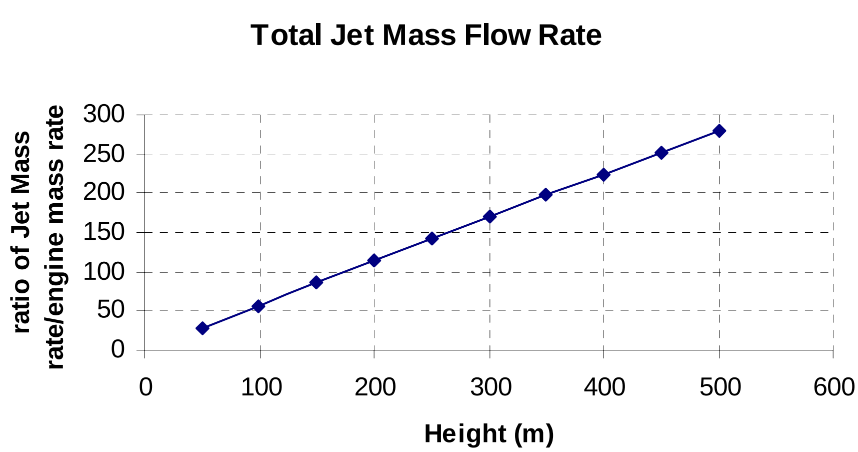

Figure A-4: Jet mass flow rate due to entrainment. Engine initial mass flow rate is 109 kg s^{-1} .

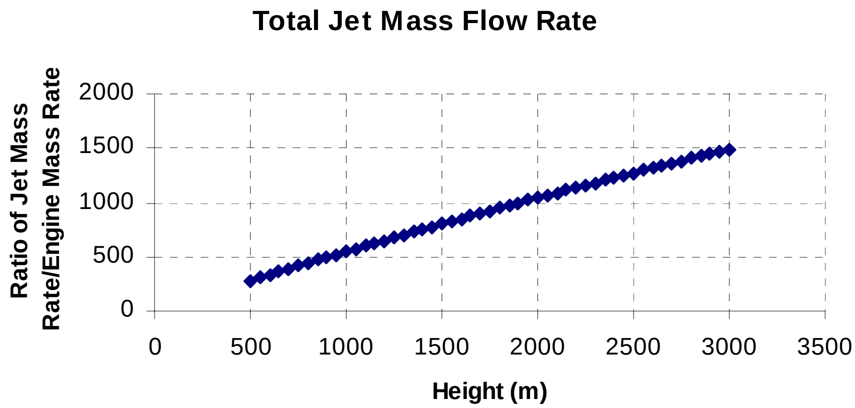

Figure A-5: Jet mass flow rate due to entrainment. Engine initial mass flow rate is 109 kg s^{-1} .

Planar Free jet

A planar jet has a rectangular cross section and an aspect ratio of at least 15:1. In a planar jet as in circular jet, the momentum flux is preserved. But in a planar jet the entrainment of air into the jet is slower than in a circular jer where the entrained air flows toward the jet radially. The result is that the jet speed for a planar jet is reducing with height slower than in a circular jet.

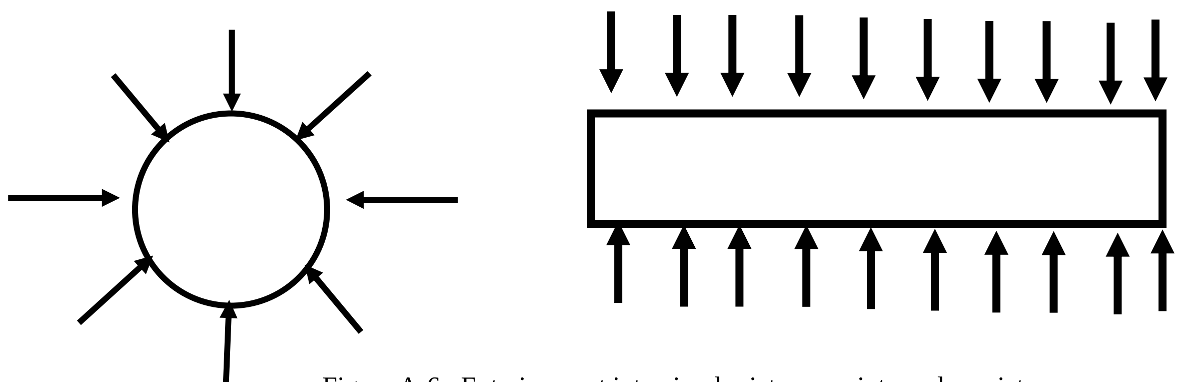

Figure A-6: Entrainnment into circular jet versus into a planar jet.

The equations governning the planar jet are:

$$\overline{U}_{mp}(x) = d_2 \cdot \frac{\sqrt{J'/\rho(x)}}{x^{0.5}} \tag{9}$$

In equation (9) J' is the momentum flux per unit lenth in [N m^{-1}], and d_2 is constant. The subnotation p is for “planar”.

The velocity profile for a planar jet is:

$$U(x,y) = \overline{U}_{mp}(x) \cdot \exp\left(\frac{-y^2}{d_1^2 x^2}\right) \tag{10}$$

Where d_1 is a constant. d_1 and d_2 were found in the same manner as for circular jet to be (Rodi 1975):

$$d_1 d_2^2 = \sqrt{2/\pi} \qquad d_1 = 0.132 \qquad d_2 = 2.46 \tag{11}$$

For a planar jet the divergence of the jet is:

$$y_{0.5} = 011 \cdot x \tag{12}$$

Arrangement of Multiple Jet Engines

The application of many jet engines at one site for cloud formation may be necessary. The physical arrangement of the engines has three potential configurations.

In the first configuration the jet engines are far away from each other and each jet does not influence each other up to a certain height as defined by the cloud modeler. For that eq. (1) can be applied. This configuration is difficult logistically since each engine will require its own floating platform.

The second possibility is to use the engines in a circular cluster. In this case the cluster can be viewed as one large engine that provides momentum flux of N engines.

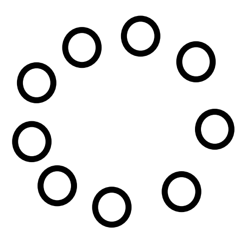

Figure A-7: Circular cluster of N jet engines

In this case:

$$\bar{U}_{mN}(x) = c_2 \cdot \frac{\sqrt{N \cdot J_{\sin gle}/\rho(x)}}{x} = c_2 \cdot \sqrt{N}\, \frac{\sqrt{J_{\sin gle}/\rho(x)}}{x} \tag{13}$$

It is possible to show that the air mass rate is also multiped by $\sqrt{N}$ in comparison to the mass flow rate of a single engine.

The third configuration is to have the N engines arranged in a straight row. In this case, the arrangement can be viewed as a planar jet where the momentum flux per unit depth is equal to the momentum flux of each engine divided by the distance L between the engines or:

$$J' = \frac{J_{\sin gle}}{L} \tag{14}$$

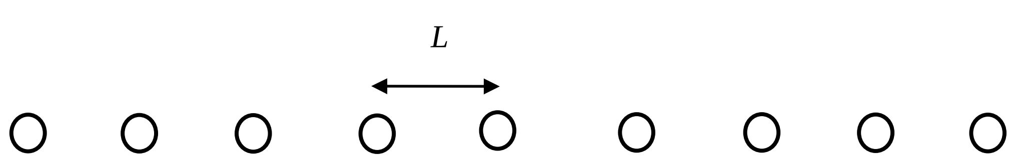

Figure 8: Planar configuration of N jet engines

Substituting (14) into (9):

$$\overline{U}_{mp}(x) = d_2 \cdot \frac{\sqrt{J_{single}/L \cdot \rho(x)}}{x^{0.5}} \tag{15}$$

The essential difference between a circular and a planar jet arrangement is the dependency of of the jet maximum velocity on the height. In the planar case the speed is proportional to $1/x^{0.5}$ while for a circular arrangement it is proportional to $\sqrt{N}/X$. In the planar case although the velocity of the jet may be higher (for a certain L), the total mass flow may be lower.

These calculations enable the cloud modeller to conduct optimization analysis for the best arrangement at various times during operation. If multiple floating platforms are used, it might be that at a certain time it will be better to use one configration while at a another time another configuration.

Summary

This outline provides a discussion of the mechanics of a compressible free jet produced by a single and multiple jet engines. It is important to note that the initial momentum of the jet is preserved under any atmospheric condition regardless of atmospheric stability.

The fundamental question concerning cloud formation is if the free jet will produce plumes and updafts of substantial proportions to cause or accelerate formation of a substantial cloud system. The jet is formed due to pressure difference in the nozzle of the jet engine, while plumes are generated by kinetic and then bouyant forces. The air mass flow rate generated by the jet engines is not enough to create a substantial cloud system, but perhaps to trigger its formation. Further investigation is required to determine the effects of condensation and on the necessary profile of the potential temperature in the atmosphere that may foster cloud formation.

Logistical considerations such as the availability of jet engines, load on the floating platform due to downward thrust, fuel weight, fuel cosumption, and corrosion impact on the engines will be covered in subsequent studies.

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COPING WITH PRECIPITATION VARIABILITY

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Abstract. The precipitation high variability and its intermittency suggest the use of percentiles to obtain a more detailed description of this variable. In general, the percentiles produce classes which allow a better comparison between correlated points. In our case the comparison is done using rain gage data from Midland and San Angelo, Texas. Apparent changes in precipitation associated with cloud seeding operations over the San Angelo area are estimated by regression analysis, but conditional probabilities are used to support potential positive increases in some years. This technique seems adequate to be used also in insurance claims. Spectral analysis is also used to detect weather modification signals.

1. Introduction

The natural variability of precipitation has been reported as the main problem against an accurate description of this variable. In addition, for the evaluation of Weather Modification programs this characteristic behaves like a noise, which may mask the effects of the seeding operations even in the cases where such effects are great. Three main difficulties can be quoted:

- The accuracy of the measurements (network density, data quality…)
- The seeding effect may be small in relation to the natural variability
- The natural complexity of the phenomena and operations

Together with high variability (Horinouchi, 2002), precipitation shows **intermittency** (the random alternation of wet and dry spells: **spatio-temporal clustered structured precipitation fields**). Both properties, high variability and intermittency, in combination with the aforementioned difficulties, lead to study the precipitation variables through aggregated values over time and space in an attempt to find regular patterns in accumulative values (usually monthly and annual values). The procedure allows simple descriptions of precipitation in terms of central and dispersion measures, but these descriptions have problems when they are used in weather modification evaluations: the noise due to the precipitation characteristics is not avoided. These problems suggest the need of a more detailed description of precipitation. Two Australian scientists proposed (Gibbs and Maher, 1967) one alternative which consists in arranging precipitation values in percentiles. The technique allows classifying the values into categories and avoids also some of the weakness of the mean description. As a matter of facts, it seems to export the high variability problem to only one of the categories, the upper one that does not have upper bounds. This paper presents briefly the application of this technique to detect possible impacts of cloud seeding operations at one point in West Texas Weather Modification target area (target point: San Angelo) by comparison with a point outside and upwind the target area (control point: Midland) (Bomar et al, 1999; Ruiz Columbié et al, 2003a) using rain gage data for the period 1948-2004 (NOAA National Data Centers, Information Service online).

Here is opportune to indicate that the technique has a potential use to characterize the behavior of precipitation for crop insurance purposes. Crop yield insurance by area consists in insurance taken out to recover financial losses due to poorly yielding crops. The estimation of losses clearly depends on the standard climatological measures used. The use of the mean as a standard for precipitation might hurt the insurance company during the very dry and dry years (averages are strongly affected by extreme values), whereas the aforementioned more complex characterization of precipitation might attenuate the claims to pay.

Back to evaluation, calculated potential increases of precipitation due to cloud seeding operations appeared to inherit the property of intermittency. This new situation led the authors to a spectral analysis of the data in an additional attempt to detect possible signals of modification. Fast Fourier Transforms of annual and monthly precipitation values were calculated for the target and control points.

2. Percentile Description

Monthly, seasonal and annual precipitation values can be classified according to table 1:

Table 1: Classes for precipitation values

Very Dry Class:	Precipitation < percentile 20^{th}
Dry Class:	percentile 20^{th} < Precipitation < percentile 40^{th}
Normal Class:	percentile 40^{th} < Precipitation < percentile 60^{th}
Wet Class:	percentile 60^{th} < Precipitation < percentile 80^{th}
Very Wet Class:	percentile 80^{th} < Precipitation

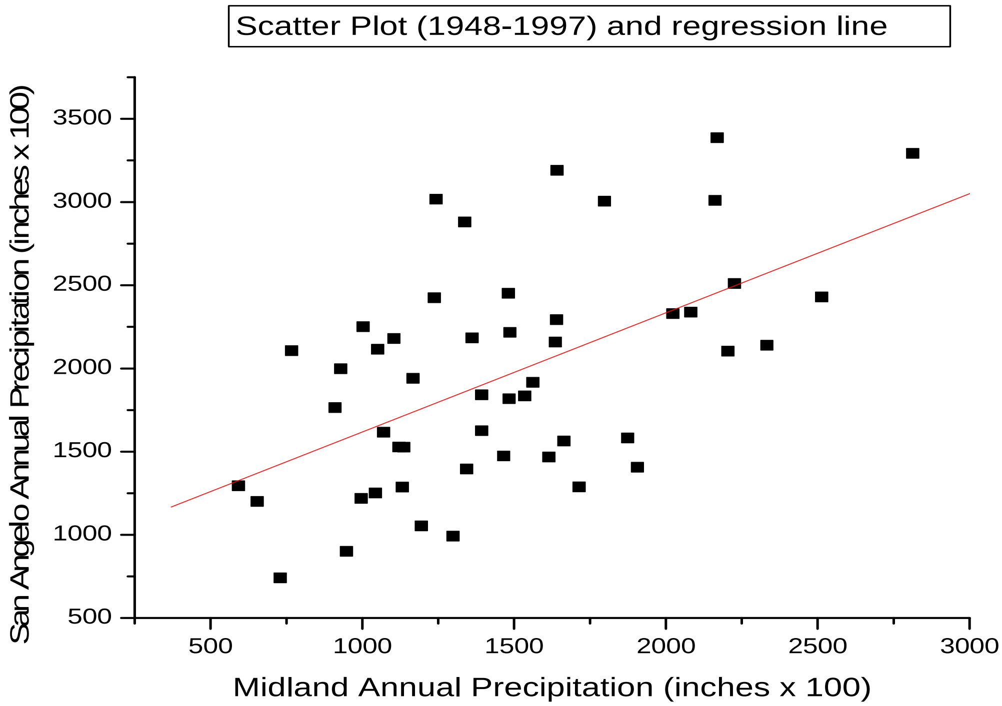
With these classes, months, seasons, and years can be classified and drought can be monitored. Drought is a complex phenomenon, but is mainly associated with relatively long periods when precipitation is below median values (very dry or dry periods). It is very important to determine when wetter periods can stop a drought. The answer should consider whether or not the embedded wet periods supplied enough precipitation to counteract the damages, and also determine the statistical distribution of the return period of very dry and dry precipitation values.

Table 2 shows the applications of this methodology for the annual values of precipitation at the control and target points during the period 1948-1997 (years with available data and previous to the West Texas Weather Modification Program redesigned to implement massive and dynamic cloud seeding operations all year along, but only on seedable convective conditions) (Ruiz Columbié et al, 2003b).

Table 2: Classes for annual precipitation at Midland and San Angelo

	Midland Annual Precipitation (1948-1997)	San Angelo Annual Precipitation (1948-1997)
20^{th} percentile:	**10.49 in**	**13.46 in**
40^{th} percentile:	**12.77 in**	**16.25 in**
60^{th} percentile:	**15.06 in**	**21.15 in**
80^{th} percentile:	**18.80 in**	**24.25 in**
Median:	13.93 in	19.16 in
Mean :	15.07 in	19.38 in
Standard deviation:	5.51 in	6.49 in

Values of annual precipitation at Midland and San Angelo show a significant linear correlation as the following Scatter Plot (Graphic 1 below) shows:



The correlation-regression analysis showed a correlation coefficient of **r = 0.54** (significant at $\alpha = 0.05$) and a regression equation:

$$\mathbf{Y} \text{ (San Angelo)} = 0.70\ \mathbf{X} \text{ (Midland)} + 9.32$$

The standard deviation of the regression is **S = 5.50 inches**, whereas its corresponding Working-Hotelling amplitude is **δ = 1.54 inches**. The equation allows calculating the predicted values of annual precipitation at San Angelo and later comparing them with the actual values to determine potential increases associated to the seeding operations. Table 3 shows these results together with the classification of operational years at both places:

Table 3: Annual Precipitation Actual Values, Predicted values for San Angelo and Differences (1998-2004)

	Midland	San Angelo	Predicted	**D** (= Actual – Predicted)
1998	5.40 in (**vd**)	12.98 in (**vd**)	13.10 in	**- 0.12 in**
1999	7.60 in (**vd**)	13.52 in (**d**)	14.64 in	**- 1.12 in**
2000	9.65 in (**vd**)	15.14 in (**d**)	16.08 in	**- 0.94 in**
2001	9.85 in (**vd**)	18.53 in (**n**)	16.22 in	**2.31 in**
2002	9.35 in (**vd**)	14.41 in (**d**)	15.87 in	**- 1.46 in**
2003	11.18 in (**d**)	19.76 in (**n**)	17.15 in	**2.61 in**
2004	21.46 in (**vw**)	30.48 in (**vw**)	24.34 in	**6.14 in**

(**vd** means very dry year, **d** means dry year, **n** means normal year, **vw** means very wet year)

The results indicate apparent decreases (negative values of D) during 1998, 1999, 2000, and 2002, but all these decreases are smaller than the Working-Hotelling amplitude (**δ = 1.54 inches)** and therefore are within the natural noise. However, the apparent increases during 2001, 2003, and 2004 appear to be significantly above the noise. **There is an intermittency pattern in D but its positive values seem to be significant.**

It is important to notice that between 1999 and 2002 the values of annual precipitation at Midland were always very dry (four years in a row), whereas the corresponding values of annual precipitation at San Angelo never fell into the very dry class. The matrix of conditional probability between Midland and San Angelo for the period 1948-1997 is showed below (table 4):

Table 4: Matrix of conditional probabilities for the classes (San Angelo/ Midland)

Midland	San Angelo vd	d	n	w	vw
vd	0.6	0.0	0.3	0.1	0.0
d	0.2	0.3	0.2	0.2	0.1
n	0.1	0.3	0.2	0.2	0.2
w	0.1	0.3	0.2	0.2	0.2
vw	0.0	0.1	0.1	0.3	0.5

Under the assumption that annual precipitation values are independent, the probability of the event "San Angelo non-very dry years four times in a row when Midland was very dry four times in a row" is equal to 0.4 x 0.4 x 0.4x 0.4 = **0.03**; a rare event that happened maybe due to the seeding operations.

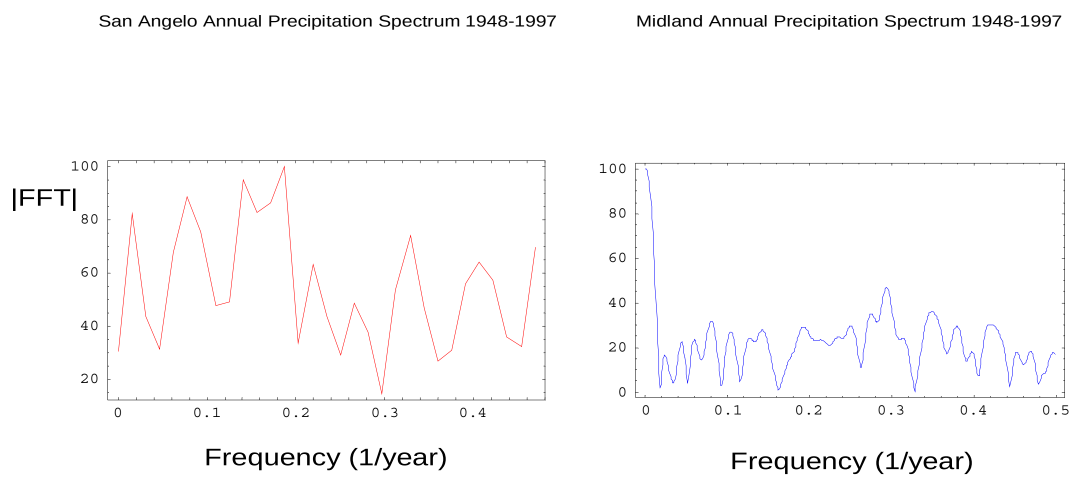
3. Spectral Analysis

The **F**ast **F**ourier **T**ransform (**FFT**) was used to detect cycles (quasi-oscillatory components) in the precipitation time series for Midland and San Angelo. Usually, cycles in a time series generates relative maximums in the spectrum. The mathematical expression for the absolute value of FFT is:

$$|(FFT)n| = \Sigma k \; fk \exp(-2\pi ink/N)$$

where the summation is in k = 0,1,2…N and fk are the corresponding time series values. A program written in Mathematica allowed to do fast calculations and graphics. The first application was done over annual precipitation values for the period 1948-1997 and the following graphic shows the results:

Graphic 2: Spectra of Annual Precipitation for San Angelo (red) and Midland (blue) (1948-1997)

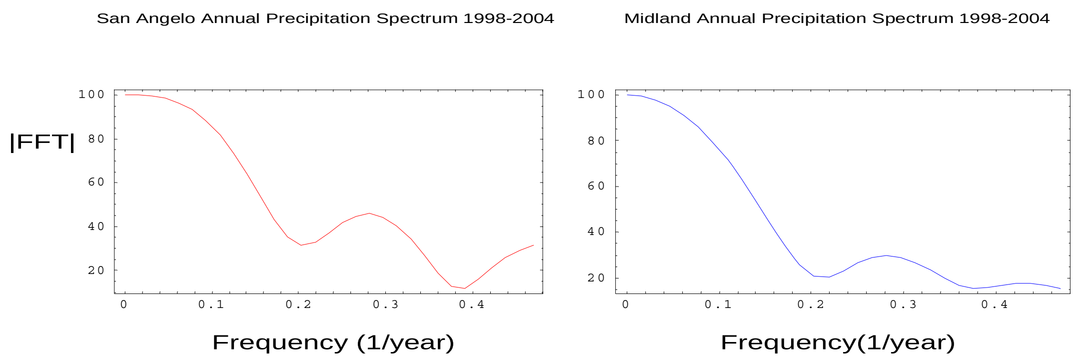


San Angelo Annual Precipitation Spectrum shows notable peaks at frequencies 0.016, 0.075, 0.14, 0.19, and 0.325 with respective approximate periods (the inverse of frequency) of 63 years, 13 years, 7 years, 5 years and 3 years. Midland Annual Precipitation Spectrum shows its peaks at frequencies 0.075, 0.16, 0.23, 0.36, and 0.43 with respective approximate periods of 13 years, 6 years, 4 years, 3 years, and 2 years.

Notice also that the differences in amplitude between both spectra.

Similar calculations were done for the period 1998-2004, when the operational program took place over the West Texas Weather Modification target area. The results are illustrated in Graphic 3 below:

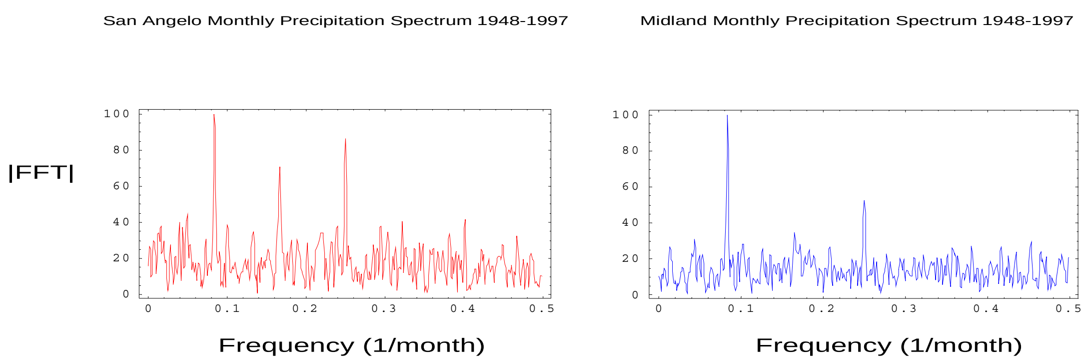
Graphic 3: Spectra of Annual Precipitation for San Angelo (red) and Midland (blue) (1998-2004)



Both spectra are very similar with peaks about the same frequency 0.28 (period 3.5 years). The annual precipitation spectra seem not to show any modification.

The analysis was extended to monthly data searching for a better resolution. Graphic 4 shows the spectra for these time series for the period 1948-1997:

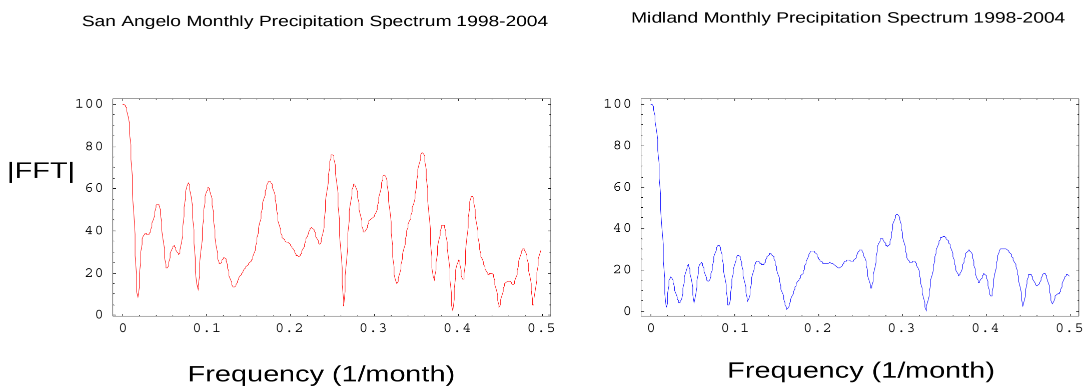
Graphic 4: Spectra of Monthly Precipitation for San Angelo (red) and Midland (blue) (1948-1997)



San Angelo Monthly Precipitation Spectrum 1948-1997 shows peaks at frequencies 0.08, 0.16, and 0.25 with respective approximate periods of 12 months, 6 months, and 4 months. The peaks for Midland Monthly Precipitation Spectrum 1948-1997 are at frequencies 0.08 and 0.25.

There is a slight peak at frequency 0.16 but it barely overcomes the noise. The corresponding analysis for the period 1998-2004 is showed in graphic 5 below:

Graphic 5: Spectra of Monthly Precipitation for San Angelo (red) and Midland (blue) (1998-2004)



The last graphic shows a notable difference about frequency 0.3 (approximate period 3 months) between San Angelo and Midland. The San Angelo Spectrum has four relative peaks near this frequency, whereas the Midland Spectrum has one peak at about 0.29 and another peak that barely overcomes the noise at about 0.35. A possible interpretation of the multiple peaks on the San Angelo Spectrum might be that **the seeding operations in place generated cycles that enhanced the spectral structure (a multi-frequency pattern, like a chord in music) while the Midland Spectrum kept a simpler structure (like a single note in music).** This interpretation should be considered heuristically as a hypothesis which should be confirmed (or refuted) analyzing other cases.

4. Conclusions

The obtained results seem to point out that cloud seeding operations may generate signals that are detectable with the proper mathematical tools. Some statements might be enounced:

1) **The use of percentiles** appears to cope well with the high variability of precipitation since values and all the classes but one obtained lower and upper bounds. For the case analyzed in this paper, the class of very wet years is the only one without upper bounds;
2) **Increases in precipitation** calculated by regression seem to inherit the natural precipitation intermittency, although in our case only the positive increases appear to be significant;
3) **The Spectral Analysis** for annual data did not show any signal of modification, but its extension to monthly values seems to indicate that cloud seeding operations are capable to generate quasi-oscillatory components in precipitation.

These conclusions should be considered as preliminary since the analysis was done only for a particular project and comparing only two fixed points. The search for similar patterns in other examples will empower or not these conclusions.

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TOWARDS A NEW PARADIGM FOR WEATHER MODIFICATION SCIENCE AND TECHNOLOGY*

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ABSTRACT

Weather modification science and technology development and implementation program plans have been created since 1946, and have collectively led to modern weather modification technologies. These modern weather modification technologies have helped the community at large for over 60 years. Recent technological and scientific advances, scientific community recommendations, and contemporary socioeconomic problems form the basis for constructing a new plan that facilitates the development and applications of modern weather modification technologies for more effectively benefiting society. Pending Congressional legislation adds urgency to a new approach for developing weather modification science and technology. This paper describes this new approach.

The proposed approach encompasses a comprehensive agenda of fundamental and applied research and development efforts directed toward optimizing existing technologies used to manage "treatable" atmospheric processes and conditions, and to allow the development of select relevant innovative technologies. It will require a permanent, national program that administers its resources and oversees its activities. High-level implementation guidelines are also provided.

1. Introduction

The scientific and operational communities generally agree that the recent advances in the relevant, general physical processes and technologies (e.g. Orville 2001; NRC 2003) need to be capitalized upon in the form of a concerted and sustained national program to carry out basic and applied research in weather modification (e.g. Garstang et al. 2005). They have not laid out the details describing such a program. Pending Congressional Legislation (e.g. Hutchison Bill in the Senate, S517 – 109th congress, and companion bill by Udall) adds a new urgency to establishing a new program. This paper describes such a weather modification program. Weather modification science and technology development plans have been constructed (e.g. Schaefer 1969, 1976; Juisto 1974) and subsequently implemented. Each implementation has yielded improved weather modification technologies and understanding of the hydrologic cycle, and has helped the community at large meet water resource requirements.

Weather modification technologies may be effectively applied to facilitate the water and energy cycles (e.g. Reinking & Martner, 1995; Smith et al., 1997; Silverman et al. 2001a,b; Woodley et al., 2003a,b). Nonetheless these results are tempered by a long-running issue concerning whether operational cloud seeding activities, especially associated with convective clouds, achieved the intended results claimed. Additional evaluations are required to address the aforementioned issue and before answering the question," are weather modification technologies ready to increase water resources and alleviate, or possibly prevent, drought."

Additional evaluations are planned as part of the Next Weather Modification Program (NWMP), partially since weather modification technologies are viewed as key to dealing with many present and potential future scientific, environmental, and socioeconomic issues, such as steadily increasing human suffering and property damage caused by hazardous weather (e.g., severe weather; supercooled fog, freezing rain), fire, and other environmental problems related to toxic wastes, ozone hole, "acid rain", biological or chemical warfare (CDC 2000). A socioeconomic issue relates to the effect from impending drought, predicted by modeling simulations to affect more than 40% of the world's population by the 2020's. A United Nations Water Development report (UN/WWAP 2003) notes that over the next 20 years the average global supply of water per person is expected to drop by one-third. This report also notes that by 2050, 2 billion to 7 billion people will be severely short of water. Precipitation accounts for roughly 1% (by volume) of the total global water budget, and its only input. Water usage is presently about 8% (by volume) of the total water budget and is projected to reach 12% by 2025 (Shiklomanov In Press). Anthropogenic air pollution, for example, may compound the water shortage (e.g. Givati and Rosenfeld, 2004). This emphasizes the need to develop cloud seeding technologies designed to enhance the efficiency of the hydrologic cycle.

The proposed Next Weather Modification Program (NWMP) would be built from current scientific base and implemented according to standard engineering practices. Modern weather modification technologies are effectively applied to disperse supercooled fog, augment the ice crystal process in cloud systems, especially orographic clouds. Thus implementing program objectives on such systems, especially winter orographic systems, would help maximize programmatic success. We agree with many of the suggestions and concepts for a weather modification scenario for the future recently promulgated by List (2004). He urged that "the study of the precipitation processes in all their forms is of greatest importance to the evolution of weather modification." Some technologies show great progress toward enhancing warm and cold cloud precipitation process efficiencies and even suppressing hail damage. However, they need to be further developed for successful application to mitigate hurricane and tornado damage, minimize the negative affects of anthropogenic air pollution on precipitation efficiency, or to neutralize negative effects from pollutant deposition. The near impossibility of obtaining statistical significance in random seeding trials, especially with respect to glaciogenic seeding of convective clouds complicates seeding evaluation confidence for these events. We also agree with List's (2004) assessment of the four WMO criteria for rain enchancement, i.e., that the criteria need to be overhauled and reformulated, and extended to hail.

The NWMP does not include less developed technologies (e.g. extraterrestrial mirrors-Muschinski 2001; ionization, chaos theory-related approaches; sonic initiation of precipitation, making hurricane disappear from conventional radar), based on insufficient scientific and engineering test results, which pose a significant risk to programmatic success. The existing technologies combined with lessons learned from the last 60 years, recent technological advances, science community recommendations, and societal need provide an impetus for developing systems and technologies that monitor and manage atmospheric events, as well as the creation of a new weather modification research program plan.

2. Program scope

The proposed NWMP would be a 10 to 20 year national program that would administer the resources and the activities for all research and development efforts directed toward optimizing the technologies used to manage atmospheric processes and their resultants (e.g., hurricanes, orographic and convective precipitation, frozen rain, drought). Its mission would be to develop the operational application of atmospheric modification (weather modification) technologies that help provide sustainable water supplies and reduce atmospheric hazards. This includes improving the understanding of the relevant processes and their simulations, as well as the evaluation methods (physical, chemical and statistical) for operational activities through cooperative multidisciplinary research and development arrangements and a well-designed outreach effort. Then to transfer these technologies to its customers, such as, farmers, crop insurance industry, water district managers, utility industry, relevant organizations (e.g., WMA), scientific community, and government agencies (e.g., National Oceanic and Atmospheric Administration-NOAA, Environmental Protection Agency-EPA, National Aeronautics & Space Administration-NASA, Department of Defense-DoD, Centers for Disease Control and Prevention-CDC).

The NWMP mission would concentrate on three areas; (1) monitoring atmospheric water resource management parameters, (2) fundamental and applied research (and development) of the science basis and seeding technologies, and (3) public outreach and professional development, fostering the cooperation between NOAA and other federal agencies, state agencies, relevant commercial organizations, private groups, as well as the general public. The latter follows List's (2004) urging that "the contributions of the engineers and operators to the science of weather modification also need to be acknowledged…Engineers, like the scientists, need to be on a learning curve; they have to be involved now, so that when we approach the next level of sophisticated experiments, they know how it is done."

There is a need to better simulate, and thereby identify and monitor atmospheric events, airborne pollutants, and select inadvertent weather modification signatures. This ability combined with improved seeding technologies will maximize the benefit and success of this program, since they contribute to the resolution of water-related issues (especially water scarcity). These improvements, when combined with improved scientific understanding, provide a more useful tool for determining when and where the atmosphere or cloud can most likely benefit from implementing the improved technologies.

There is a need to conduct research and development activities of our scientific understanding, operational seeding project evaluations, and seeding technologies. This includes documentation and mitigation of inadvertent effects of pollutants on hydrologic cycle efficiency, and physical, statistical, and chemical technology development, and the development of statistical analytical techniques. Statistical analytical techniques need to be improved, especially with respect to convective cloud seeding applications, in order that they may evolve into a statistical tool that is not data and/or process limited. The development of improved dispersion techniques and higher yield cloud seeding agents is needed for obvious reasons. Technologies to "treat" hazardous weather systems (e.g. freezing rain, hail formation, tornadoes, hurricanes) are more critically needed, and will benefit from past and ongoing research results, especially research using ground-, air-, and satellite-based remote sensing devices (radars including Doppler, lidars, radiometers). The aforementioned need is rather daunting, but necessary and attainable in time. Initial efforts to develop an understanding of how present day cloud seeding technologies can be applied and modified to lessen the socioeconomic impacts of hazardous weather events and materials might begin with the information gained from model perturbation experiments. Renewed emphasis on the modeling of seeding agent tracer study results would greatly improve seeding agent placement within cloud systems, and the models could form the basis for Homeland Security needs.

There is a need to develop state-of-the-art cloud seeding technologies for application toward mitigating the effects of freezing rain events. The knowledge base is not large enough to reliably and practically support tornado or hurricane reduction efforts. It may one day support these efforts *after* appropriately funded and directed cooperative research campaigns have been completed.

The existing cloud seeding technologies are operationally used to reduce hailstone size, and have the potential to reduce the intensity of rotational hurricane winds. The reductions in hurricane rotational wind speeds following cloud seeding ("Esther" in 1961, "Beulah" in 1963, and 30% for "Debbie" in 1969) were not statistically distinguishable from the range of natural variability, and thus not yet scientifically accepted. Consequently, initial activities must be directed toward adding seeding routines to the best physical and numerical models, and verifying its outputs, which should form the basis for transforming these models to operations and ultimate application.

Simulation and modeling studies will require verification through carefully designed cooperative efforts that will generate sufficient, adequate data for physical, chemical and statistical evaluation method developments. Cloud seeding program evaluations also need to be improved by revisiting whether measuring devices used for evaluations are primary standards; if not, does one exist, if so, is there a better device? For example, is the standard precipitation gauge, or the recent commercially introduced laser precipitation gauge, truly a primary standard for precipitation amount measurements? That is, could it provide the natural spatial and temporal precipitation amount field (e.g., DeFelice 1998) under all conditions at that point, versus alternative measuring devices? The answer is crucial to evaluating the success of precipitation enhancement projects, for example. Furthermore, if the existing precipitation gauges are not the best primary standards for precipitation amount measurements, then could the Z (reflectivity) – L (precipitation water content) relationship be used to estimate rainfall amount? The Z-L relationship would <u>not</u> require estimates of hydrometeor terminal velocity, and L could be verified using a dual wavelength microwave radiometer. It would require that the Z, L measurements are temporally and spatially concurrent, and 'normalized' to historical precipitation amount measuring devices.

Inadvertent modification studies need to be increased, and not solely from a climate change point of view. For example, an agricultural to urban land cover change over a modest area can introduce a climatic forcing similar in magnitude and direction to that from carbon dioxide (personal communication with R. Pielke Sr. 2001). Anthropogenic air pollutants have been reported to reduce precipitation process efficiency under some conditions (e.g. Givati and Rosenfeld, 2004). Here initial efforts should at least focus on strategies for minimizing the effect from such inadvertent modifications to the atmosphere, and neutralizing airborne pollutants within cloud systems or redirecting their air trajectories to settle on surfaces that have high buffering capability or which are less sensitive to environmental pollutant deposition.

3. Strategy

Recent technological and scientific advances, along with contemporary socioeconomic problems and lessons learned included in DeFelice (2002), make a case for seeking applications of modern weather modification technologies that could benefit society. This requires an organizational structure that optimizes the engineering and science disciplines that must work together to:

a) Develop and continually improve the ability to computationally identify and monitor all atmospheric environmental conditions that are good candidates for beneficial modification through its developed technologies.
b) Develop technologies to more efficiently execute traditional cold and warm cloud seeding applications, and targeting and delivery of seeding agents.
c) Develop computational simulations and strategies to mitigate atmospheric environmental hazards, including hazardous toxic clouds or plumes.
d) Improve evaluation protocols (includes verifying the models developed under a).
e) Develop strategies to minimize the effects from the inadvertent modification of atmospheric conditions (formerly termed inadvertent weather modification).
f) Create a proactive professional development and public outreach activity.

Any weather modification program plan, whether as described herein or otherwise, must pursue a comprehensive agenda of fundamental and applied research and development efforts directed toward the goal of optimizing the technologies used to manage atmospheric processes and conditions. It is also assumed that the resources stated below represent the amounts necessary to achieve stated deliverables, and that stated future needs are reasonable.

This plan addresses current and near future needs of the weather modification community and also outlines the high-level infrastructure that will address the recommendations from the parent science community (Table 1). Table 1 summarizes how the plan objectives align with recommendations from the National Research Council (NRC). This plan will benefit from using standard project management processes and updates from improvement exercises (e.g., DeFelice et al. 2005), and by having the depth and foresight to address the differences of perceptions between the science and operational communities as detailed in Garstang et al. (2005), i.e., 1) Interpretation of scientific proof, 2) Current status of cloud models as applied to weather modification, 3) Evidence of glaciogenic seeding in convective clouds, 4) Cold season orographic seeding, 5) Evidence for hail suppression, and 6) Support for specific purposes.

The cold season orographic seeding perceptual difference related to cold season orographic seeding (e.g. see Garstang et al., 2005 item 4) is not a significant difference in perspective, since the science community sees orographic cloud seeding as a particularly promising candidate for an intensive field program (Garstang et al. 2005). The sixth perceptual difference reflects differences between the individual cultures (i.e., scientific vs operational) than anything else. This program plan helps mitigate these perceptual differences by setting up an integrated team approach to its activities, and by insisting that the research and development component of this program be geared toward improving the effectiveness of operations.

Table 1. Next Weather Modification Program (NWMP) plan versus NRC (2003) recommendations

NWMP Plan	NRC Recommendations
1). *Assumes* a permanent, national (if not international) program that would administer the resources and the activities for all research and development efforts directed toward optimizing the technologies used to manage the efficiency of atmospheric hydrological processes.	1). "Because weather modification could potentially contribute to alleviating water resource stresses and severe weather hazards, … A renewed commitment to advancing our knowledge of fundamental atmospheric processes central to the issues of intentional and inadvertent weather modification ...."
2). Outlines a comprehensive agenda of fundamental and applied research and development efforts directed toward optimizing the technologies used to operationally manage the efficiency of atmospheric hydrological processes to help provide sustainable water supplies. See Resource Requirements	2). "Coordinated research program includes … Carry out exploratory and confirmatory experiments … Hygroscopic seeding … Orographic Seeding … Studies of specific seeding effects …". "Capitalizing on existing field facilities and developing partnerships among research groups and select operational programs."
3). Calls for developing: - better better monitoring capabilities for all atmospheric events, including frozen rain, hurricanes & tornadoes, airborne pollutants. - more effective dispersion techniques - higher yield seeding agents for warm and cold clouds - improved evaluation protocols. - strategies to minimize inadvertent weather modification.	3). "… coordinated national program be developed to conduct a sustained research effort in the areas of cloud and precipitation microphysics, cloud dynamics, cloud dynamics, cloud modeling, laboratory studies and field measurements designed to reduce key uncertainties…"

4. Organization

The proposed program would be organized into five functional areas as shown in Fig. 1, and their initial goals, based on lessons learned and recent scientific and technological advances, would be similar to the following:

- Weather Modification Event Monitoring/Analysis Prediction System Development Goals: (i) High resolution monitoring/analysis prototype systems able to identify the atmospheric conditions conducive to beneficial precipitation augmentation (e.g. orographic), hail suppression and other hazardous storm suppression (freezing rain, hurricanes, tornadoes, other). (ii) Transfer information to the Public Outreach/ Professional Development activity.
- Glaciogenic and Nonglaciogenic Seeding Technology Research/Development Goals: (i) Better nucleation efficiency of possible warm cloud, cold cloud, and other "cloud" seeding materials. (ii) More efficient delivery (dispersion) systems for a given application as identified under (i). (iii) Transfer results to Public Outreach/Professional Development activity.
- Applications Research/Development Goals: (i) Improved evaluation methodologies. (ii) Operational atmospheric management monitoring/analysis prediction systems. (iiia). Verified high resolution models with more sophisticated microphysics routines for understanding hazardous storms, inadvertent modification of atmospheric conditions (e.g. due to land cover

changes, air pollution, biomass burning) and other associated phenomenon (e.g. bioterrorist agent cloud transport). (iiib) Implement (iiia) with seeding material introduced. (iv) Improved targeting systems. (v) Improved applicability of evaluation technologies (e.g., dual, polarized, Doppler radars, tracer techniques). (vi) Transfer systems and results to public outreach/professional development activity for feedback on operational usefulness, and fine-tune them based on users' input.

- Public Outreach, Professional Development Goals: (i) Develop and present educational materials, demonstrations, workshops, and colloquia that emphasize the relevant appli-cations derived from this program's activities and related technologies. (ii) Coordinate the technology transfer to program customers. (iii) Conduct interactive open houses.

Plan Management Support Goals: (i) Provide an environment that facilitates the successful completion of all area goals and hence objectives. (ii) Provide overall programmatic metrics, guidance, and support during the life of the program. (iii) Participate in defining and developing future and related technology investigations. (iv) Administer seed grants for innovative or new applied research and applications.

The triangle in Fig. 1 symbolizes the interdependence of these functional plan areas. A core group consisting of the necessary skill mix to comprehensively address the underlying issue and a representative from the end user should be assigned to each objective.

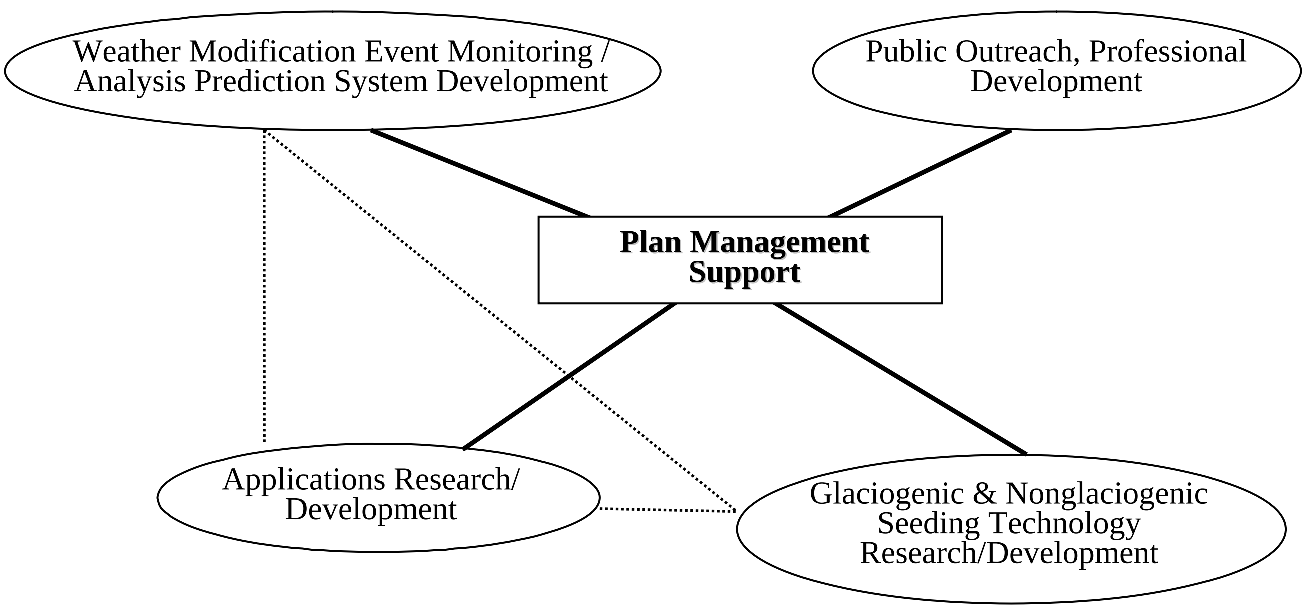

Figure 1. Next Weather Modification Program (NWMP) Organizational Chart. The triangle symbolizes the interdependence of these functional plan areas.

5. Resource Requirements (anticipated):

Resources are people, office and lab space, instrumentation, computers, money (herein budget). The Program Manager would use standard project management tools to track task schedules and cost metrics presented in the high-level tasking (i.e., primary activity) of work to be performed under this plan as summarized in Table 2.

Table 2. Suggested high-level tasking of work.

1. Weather Modification Event Monitor/Analysis Activity
   Prediction System Development
   a. Real-time monitoring component
      i. Orographic (winter)
      ii. Convective Systems (Summer)
      iii. Hailstorms
      iv. Other non-hazardous cloud systems (e.g freezing rain, etc)
      v. Hazardous 'cloud' systems
   b. Analytical component
2. Glaciogenic and Nonglaciogenic Seeding Technology Research/Development Activity
   a. Seeding material nucleation ability optimization
      i. Warm and Cold clouds
   b. Seeding material delivery system development
      Warm and Cold Clouds
3. Applications Research/Development Activity
   a. Evaluation methodologies
   b. Evaluation technologies (e.g. dual polarized Doppler radar, tracer techniques, Integrated Earth Observing Systems-IEOS)
   c. Model and prediction system development and verification
   d. Inadvertent weather modification/global climate change
   e. Targeting system development
   f. Extra-area and downwind effects
4. Public Outreach, Professional Development Activity
5. Program Management and Support Activity

Office and some laboratory space will be required, and should be capable of housing up to 500 employees. An east coast location would maximize the benefit of interaction with NOAA, DoD, DOE, DOI, NASA, other government centers and laboratories, and other relevant organizations. There should never be less than 70 to 80 FTEs for support and technical staff, 5 to 10 FTEs for student interns, and 15 to 20 FTEs for all program administrative staff. DeFelice (2002) provided a breakdown between FTEs and high-level activity (i.e., titles in Fig. 1 objects). The laboratory space could be used for archiving and processing large volumes (i.e., mega terabytes) of multi-disciplinary data, running multiple algorithms in near real time experimental cloud studies to develop modeling algorithms, nucleation experimentation with ice, water, and perhaps other substances, instrumentation development and storage, instrument calibration, sample prep for chemical analysis. This could include the development of 3 state-of-the-art cloud chambers to study ice, water and other species nucleation.

Budget *(anticipated based on fiscal year 2002 dollars, as exemplified in Table 3):* This program would require a budget adequate for successful fulfillment of its objectives, e.g., \$20+ M/yr. Precedent is set by successful medical and other science programs, wherein substantial, long-term, committed funding has led to overwhelming positive results after multiple decades. For example, making such an investment for this plan very soon and continuing it through the 2040s will most probably ensure that significantly less than 40% of the world's population will reside in water-stressed areas.

The fiscal internal funding requirements and anticipated programmatic expenditures would be aggregated to the main WBS activity (e.g. Table 2, 1. Weather Modification Event Monitor/Analysis Activity, 3. Applications Research and Development Activity), and tracked weekly compared to a baseline established at the beginning of the program. The budget amount categories will include loaded salary and non-salary (e.g. travel, benefits, equipment, supplies) and anticipated reimbursables (could include internal NOAA grants, NASA, NSF, EPA grants). The Applications Research and Development Area should have a budget that is no less than 10 to 20% of the total budget with nearly equivalent salary and non-salary amounts.

Anticipated Sources of Funding: NOAA, Congress, farmer groups, insurance industry, utility industry, state governments, water districts, and through **Cooperative Agreements.** This plan must contain cooperative agreements (or equivalent, i.e., MOUs - memorandum of understanding) with NOAA divisions, the National Center for Atmospheric Research Research Applications Program already dedicated to atmospheric modification activities, and relevant organizations throughout the cloud physics and weather modification research and operational communities. We suggest 40 to 50% of the total funds be set aside for reimbursables and MOUs.

Table 3. Next Weather Modification Program (NWMP) Summary Budget (for a 10 yr program)

WBS Activity	Salary ($M)	Non-salary ($M)	Total ($M-10 yr prgm)
1. Atmospheric Management Monitoring/Analysis Prediction System Development	42.0	10.8	52.8
2. Glaciogenic and Nonglaciogenic Seeding Technology Research/Development	40.0	10.8	50.8
3. Applications Research/Development	21.0	32.0	53.0
4. Program Management and Support	20.0	11.0	31.0
5. Atmospheric Modification Public Outreach	17.0	5.4	22.4
Professional Development			
Program Total	***140.0***	***70.0***	***210.0***
Anticipated Reimbursable			10.0
Anticipated Internal Requirement			***200.0***

6. Programmatic Success:

The likelihood of success is high, because the program is starting with some proven technologies, many of which have had more than 60 years to mature. The success of this program will be gauged by the development and transfer of demonstrated technologies to the operational sector. It is expected that there will be improved products, processes, and field procedures resulting in scientific publications and conference presentations. Success does not require new tools, demonstration of significant seeding signatures, or creation of new scientific disciplines. Consequently, future applications of this technology have a higher potential for success, and less risk than that of previous weather modification programs.

7. Risk Identification and Management:

The primary risks are likely to be losses of key personnel, funding, required data and technology, and systems, as follows:

- Loss of key personnel will be anticipated by management through open communication with government staff, unless a contractor is hired to handle the services contract. If a contractor is hired, then loss of key personnel will be anticipated through open communications with government and contract staff. The contractor will fill vacancies as quickly as possible. The contractor could be a particular government agency, an intergovernmental committee, or a non-government organization. We assumed that a non-government organization will handle the services contract since this is the current trend.
- Loss of internal agency funding allocation will be mitigated by (1) identifying and taking on reimbursed research that concerns similar interests and applications, for example, or by (2) re-scoping, postponing, or canceling the affected research endeavor.
- Loss of required data and systems will be anticipated in the planning process, and suitable proxy data or alternative systems will be identified for quick access if needed.
- Law Suits, while not likely, are possible and will be mitigated by (1) making sure the federal government does not conduct cloud seeding operations, (2) keeping the public informed about the activities associated with the NWMP.

8. Deliverables:

(Initial, anticipated programmatic, *not annual*, deliverables)

- ➢ Proven systems to monitor and analyze all atmospheric environmental conditions (e.g., frozen rain, hurricanes, tornadoes, air pollutants) that are favorable for the beneficial modification through technologies developed by its activities
- ➢ Improved evaluation protocols and technologies
- ➢ More effective weather modification technologies for traditional, weather and atmospheric environmental hazard applications. For example:
  - o Higher yield seeding agents for warm and cold cloud systems

    - More effective delivery techniques
    - Highly developed cloud and mesoscale numerical models
- ➢ An implementable strategy to minimize the possible negative effects resulting from the inadvertent modification of our atmosphere
- ➢ A proactive professional development, public outreach program.

9. High-level implementation plan

The aforementioned plan clearly contains scientific and engineering components. The engineering component is defined primarily by the monitoring system and its development as well as the seeding technology and sensor development. The organizational structure to address issues related to the integration of science and engineering disciplines features an integrated team that stays together throughout the life cycle of the project, and would include guidance with respect to project size, and the culture (science versus engineering) of the prime dependent.

It is important to make clear that the implementation of the Next Weather Modification Program (NWMP) plan calls for tackling all tasks, issues in a multidisciplinary, cross-component team environment that exists throughout the entire life cycle of the project. This is accomplished by:

- Starting with an organizational structure that supports the processes within this program and their interactions
- Specifying teams with multi-disciplinary skills and well-defined member roles and responsibilities at all levels within the plan at the plan's kickoff meeting.
- Developing carefully designed cooperative research and development efforts whose purpose is to enhance the understanding of the inherent multi-disciplinary processes for the good of the operational weather modification community. This has economic benefits to the program as well.
- Having somebody, i.e., the lead of the appropriate WBS Activity as noted in Table 3, dedicated to ensuring that matured plan products are transferred to stakeholders and end users in a timely fashion.

The ASCE/EWRI AWM SC Standard Practice Documents for hail suppression (ASCE/EWRI Standard 39-03, 2003), precipitation augmentation (ASCE/EWRI Standard 42-04, 2004), and supercooled fog dispersal (ASCE/EWRI Standard 44-05, 2005) provide details for implementing this program. The ASCE documents provide insights into the operational aspects for implementing respective programs, which will be most helpful in fine-tuning the relevant level 3 team activities (Fig. 2) under this program. They do not provide insight, for example, on how to implement hurricane weather modification component of this program. Initially, transform the best hurricane model into a hurricane observing system algorithm, verify performance, develop and insert seeding effect algorithms. Following subsequent verification, the latter would demonstrate the circumstances that lead to non-beneficial impacts from seeding. It could also help determine when the most effective time to seed the hurricane relative to minimizing wind damage and flooding likelihood, while maximizing rainfall amount on the mainland. Then verify the observing system algorithm results, etcetera in the manner outlined earlier in this section and as generally follows.

The following describes the high-level implementation team structure, and working guidelines for implementing each of the NWMP areas.

High-Level Implementation Team Structure: Implementing this program requires communication between the management and those carrying out the activities while allowing for a comprehensive approach at all vertical levels throughout the entire program. This is best accomplished by forming multiple, multi-discipline teams, whose leader reports to a similarly multi-disciplined team that is closer to the program level team, which is the core team. A program level team would be responsible for the overall program success and sets the strategic direction for the overall project. This team contains the leaders from the Atmospheric Modification Monitor/Analysis Prediction System Development (Monitoring systems) team, Glaciogenic and Non-glaciogenic Seeding Technology Research/ Development (Seeding Technologies R& D) team, Applications Research & Development team, and Public Outreach/ Professional Development team, which collectively make up the second level (or tier) teams. The customer is also part of this team. The program level team defines relevant objectives and corresponding deliverables. These objectives and corresponding deliverables become the focus of a team (often termed "second tiered" or level 2) tied to the respective area leader within the program level team The second tier teams devise their objectives necessary to create said deliverables, and contain the leaders from the next lower tiered teams. This structure enhances vertical integration within the program because each higher-tier team can optimize its higher-level product rather than allowing "sub-optimizing" of a lower-level product. Vertical integration is as important to programmatic success as is meeting the goals of each "tier" team. This mapping of teams to activity areas allows for a clear assignment of budget to the individual teams. Table 4 highlights some features of the NWMP interdisciplinary teams.

Table 4. Next Weather Modification Program (NWMP) Plan Multidisciplinary Team Features

- Led by a Team Leader who is also a member of the next higher tier team throughout program
- Multidisciplinary skill mix represented by its team members
- Has early and periodic involvement of customers and suppliers throughout lifecycle of project
- Given resources to enable success throughout the entire project (i.e., has its own budget and is empowered to act within its charter by its next higher tier team)
- Balances task, process and team relationships throughout the entire project
- Plans, performs, tracks and manages tasks and associated risks
- Maintains open communication both within the team and with other teams
- Plans integration with other teams toward overall product goals

10. High-Level Implementation Plan per Program Area:

Atmospheric Modification Monitor/Analysis Prediction System Development: Implementing this activity necessitates creating and empowering one multidisciplinary team for frozen rain monitoring, one for hail, one for supercooled fog monitoring, one for hurricanes, etcetera. Each team should include an engineering process representative who acts as interface to engineering processes throughout the life cycle of the project (i.e., a software engineer), a science programmer (not a software engineer), a science integrator (could be an applied scientist) who leads the team and acts as liaison to science process and attends engineering process meetings, subject matter expert(s) or SME(s) if necessary, and the customer. Here it is presumed that the science integrator must be tied to this plan, which implies that this plan is the owner of the team/process, but this does not necessarily have to be the case. Once the teams are formed at program start or shortly thereafter, each should agree upon and then work toward its immediate and long-term goals.

Glaciogenic and Non-glaciogenic Seeding Technology Research/Development:

Implementing this activity necessitates creating and empowering one multi-disciplinary team for research and development of hygroscopic seeding agents, glaciogenic seeding agents, and potentially fabricating better dispensing units. This team is primarily science driven, but does have an interface with customers, some of whom are engineers and possibly computer scientists, and personnel with appropriate skill mixes (i.e., a machinist instead of a lab technician). Each team should include a customer representative, scientist (from the plan), technician (from the plan), customer technician, a subject matter expert as necessary, quality assurance person. The scientist (from the program) leads the team and acts as liaison to management, Quality Assurance (QA), and customer. In this case, the scientist (from the plan) is responsible for ensuring that there is a team member from QA involved in this effort, and that the results exceed program standards.

Interaction of the Next Weather Modification Program with Commercial Partners: The contractual and program management aspects of this interaction are well established, but the implementation could make use of the following guidance:

➢ Implementation team must be set up to include representatives from the science team (scientist, technician, possibly other depending on application), and the commercial team (science point of contact-POC, technician, other depending on application)

➢ Science team does not direct the commercial operation

➢ The commercial team must go through a training session set up through the Next Weather Modification plan Public Outreach/Professional Development group.

➢ Science team directs the post commercial operation analysis, with priority given to the analysis required by the commercial team. Then subsequently to in-depth analyses and joint publications

➢ The science team installs and is responsible for maintaining instrumentation on commercial property, and sampling platforms

➢ Science Team and Commercial Team set up an operations friendly real-time display to guide commercial operations and a periodic direct-broadcast data download and archive system backup. This removes the burden on commercial priorities to use and provide information for optimal results required by its client(s).

Applications Research and Development: Implementing this activity necessitates creating and empowering one multi-disciplinary team for developing new and existing technologies and applications, and even to creating new technologies and products. The primary customer is probably the program activities themselves, which is not the case in the other program areas, except possibly for Outreach and Professional Development.

These activities might involve field sampling campaigns, which should be conducted as set forth in their plans. However, the program level team would have a representative of (a) this program (as person in charge), (b) customer, (c) ground instrumentation group, (d) airborne instrumentation group, (e) other instrumentation (satellite special instruments) group, and (f) the modelers. Once the teams are formed at program start or shortly thereafter, each team should work toward its immediate and long-term goals.

Outreach & Professional Development Program: An effective outreach activity should not only feed the scientific and engineering communities through publications and presentations, but also provide the public with a better understanding of its mission through the number of activities it sponsors or coordinates and the access it provides. It will coordinate the technology transfer to program customers. It is strongly recommended that this be done in a multi-discipline, vertically integrated programmatic team framework, and that no multi-disciplinary team should be lead by a person or entity that exists outside of the Program.

A strong outreach activity can *alleviate public misconceptions*, especially a proactive one that provides interested individuals an opportunity to participate by running an appropriate "simulator", or by setting up volunteer observation programs that allow them to help collect data needed for model verification and development. The outreach activity could also help concentrate the overwhelming collection of scientific, engineering, and technological knowledge gained since the 1940s.

11. Closing Remarks

The increasing need for water and the cost to society inflicted by severe weather further require that the intellectual, technical, and administrative resources of the nation be combined to resolve whether and to what degree humans can influence the weather (Garstang et al. 2005).

This paper describes a high-level plan for the "next phase" in weather modification science and technology development, made in response to recent technological and scientific advances, socioeconomic issues, and the findings expressed through Garstang et al. (2005). The program we propose will encompass a comprehensive agenda of fundamental and applied research and development efforts directed toward optimizing existing technologies used to manage "treatable" atmospheric processes and conditions, and to allow the development of relevant innovative technologies. It will require a permanent, national program that administers its resources and oversees its activities.

The proposed plan:

- ➢ is based on many lessons learned during the past 60 years
- ➢ has five functional components
  - Weather Modification Event Monitoring/Analysis Prediction System Development
  - Glaciogenic and Nonglaciogenic Seeding Technology Research/Development
  - Applications Research/Development including evaluation
  - Professional Development, Public Outreach
  - Management Support
- ➢ encompasses the recommendations of Garstang et al. (2005), an NRC (2003) report, Silverman et al. (2001a, b), Woodley et al. (2003a,b), Givati and Rosenfeld, (2004) and the near-term needs of the weather modification community.
- ➢ provides guidelines for implementation
- ➢ approaches tasks, issues within its components in a multidisciplinary, cross-component environment that exists throughout the entire life cycle of the plan. This is partially accomplished by specifying all plan member roles and responsibilities at the plan's kickoff meeting, cooperative agreements, and a well designed technology transfer activity.

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Testimony Before Joint Hearing By Sen. Subcommittee On Science & Space And Subcommittee On Disaster Prediction & Prevention, November 10, 2005:

By Dr. Joseph H. Golden

I am honored to appear before you today in regards to Senate Bill S.517, the Weather Modification Research and Technology Transfer Authorization Act of 2005. My name is Dr. Joseph H. Golden, retired from NOAA on September 2, 2005 after 41.5 years of Federal service in NOAA, both in severe weather research and NWS operations. I now work part-time as a Senior Research Scientist in the University of Colorado's Cooperative Institute for Research in the Environmental Sciences (CIRES) in Boulder,CO. My background in weather modification research relates to the fact that I was the last NOAA manager of the Atmospheric Modification Program (AMP) in NOAA Research, until its termination by the Congress in l995. I was never asked by anyone to defend the AMP Program, based on its merits and accomplishments. The AMP program was written into NOAA's budget by the Congress for many years, beginning in the late 1970's. I view the AMP program and its research productivity as a highlight of my NOAA career, especially due to the cooperative efforts among the six States in the program (Illinois, No. Dakota, Texas, Utah, Nevada and Arizona), the universities, private-sector operators, and NOAA research. None of the NOAA AMP funds were used to conduct any operational cloud seeding, and I feel that, at this time, funding under S517 should also not be used for operational cloud seeding efforts. I am pleased to see my colleague, George Bomar here from Texas: he was one of the State program managers in AMP, and his State was the first to utilize NWS NEXRAD Doppler radar data to estimate the rainfall increases from seeding convective clouds. One of my greatest career frustrations has been witnessing the adoption of new research results and technologies we developed under AMP by other countries, while Federal research and technology transfer in my own country has largely stagnated. For example, a chemical tracer technique developed by the Nevada-AMP program to quantify the amount of snow increase due to seeding over mountains is now being used by a new cloud seeding program in Australia. In China alone, their government is funding a greatly-expanded weather modification research and operations program at $100 million per year, as well as training over 1500 new weather modification scientists.

In the limited time I speak before you today, I want to address two types of natural disasters, and the potential for planned weather modification to alleviate them: **slow-onset disasters** over many years, such as the continuing drought in the West, and the **quick-onset disasters** such as the record-breaking Atlantic hurricane season this year and the massive Oklahoma City tornado outbreak of May, l999.

Federal funding for weather modification research in the U.S. reached its pinnacle in the l970's and early l980's, and has steadily declined ever since. During its heyday, weather modification research in the U.S. was at the cutting edge of worldwide efforts. For example, NOAA conducted large-scale seeding experiments in South Florida (called FACE) and collaborated with the Navy and university scientists in Project STORMFURY, to weaken hurricanes. I participated in STORMFURY while a PhD candidate, and found it to be one of most exhilarating experiences of my career. The National Center for Atmospheric Research (NCAR) also organized the National Hail Research Experiment, which attempted to test the validity of the Russian approach to artificially reduce hail by cloud seeding. Finally, the Bureau of Reclamation carried out the High Plains experiment, to seed convective clouds for rainfall increases over the Central U.S. While each of these programs, in my opinion, produced outstanding scientific results and new operational insights, they produced results that were inconclusive insofar as *statistical evaluation* is concerned. Nevertheless, I feel that our community was a good steward and used limited funding very wisely. I am also convinced that the atmospheric sciences have come a long way during the intervening years. The scientific foundation and underlying physics in purposeful weather modification, i.e., cloud seeding, is sound and well-established. We now have both the science and the technology to launch a new research attack on some of these other vexing problems.

The need for a renewed national commitment and funding for weather modification research has become more urgent. In recent years, we have seen severe drought in my home State of Colorado and the Pacific Northwest. New research results show unmistakable impacts of air pollution in reducing seasonal precipitation over mountainous areas of the Western U.S. during the past several decades. Pollution is systematically robbing the Western mountains of winter snowpack, and if the process continues, will lead to major losses of runoff water for hydroelectric power and agricultural crop productivity. However, research in Israel has demonstrated that their long-term cloud seeding programs have offset similar pollution-induced rainfall losses in their country. The new research has also developed new analysis techniques with NOAA satellite data to objectively identify and separate pollution episodes from affected neighboring clouds. The pollution effects on natural precipitation in our country and elsewhere is certainly a critical research issue for this Bill. Another issue needing more research attention is the question of extra-area effects: if we seed cloud systems in one area, and successfully produce increases of precipitation there, are we “robbing Peter to pay Paul” in downwind locations? Results supported by AMP suggested the answer is no, and that there is either no effect downwind, or a slight increase in precipitation.

Another weather modification research issue, and one that always elicits scientific controversy, is severe storms modification. This issue was not addressed much in the NAS/NRC weather modification report chaired by my distinguished colleague, Michael Garstang. These are the quick-onset disasters of which I spoke earlier, and include hailstorms, tornadoes and hurricanes like KATRINA and RITA this year. I should emphasize that AMP supported some outstanding hail modification research with the North Dakota Cloud Modification Program. This operational program is one of the longest-running hail suppression programs in the world. Positive results on the impact of cloud-seeding to reduce hail damage to crops, using insurance companies’ records of crop-loss ratios, were so impressive, that the Canadian insurance industry has supported a new multi-year effort in the province of Alberta, Canada to protect its largest cities from hail. The Alberta hail-suppression program uses many of the techniques that we used in the AMP-North Dakota program.

After the horrendous devastation and loss of life from Hurricanes KATRINA and RITA, I have been asked several times about the possibility of hurricane modification. And while I don’t have the time to fully address this issue today, I firmly believe that we are in a much better position, both with the science and the undergirding technology, than we were when Project STORMFURY was terminated in 1982. We now understand that both tornadoes and hurricanes exhibit a life-cycle, and both exhibit natural instabilities during their lifetimes. The key atmospheric condition leading to the decay of both destructive vortices is cooler, drier air, as well as cooling sea surface conditions for decaying hurricanes. Recent observational and modeling studies both suggest that there may be new approaches possible for future weakening or track-diversion of hurricanes threatening our shoreline. The key uncertainty, and one which requires enhanced observations, is more continuous and accurate monitoring of the natural fluctuations in hurricane intensity and path. For example, WILMA intensified in the western Caribbean overnight from a Category 1 to a Category 5 hurricane, resulting in the lowest pressure ever measured in the eye of an Atlantic-basin hurricane. There are now some very exciting computer models that reproduce both hurricane intensification and tornado behavior in remarkable detail. If we mount a sustained, adequately-funded national program of weather modification research and technology transfer, I believe that it may also be possible to successfully weaken tornadoes (or, alternatively, shorten their life-cycles). I would be pleased to elaborate details on promising approaches and testable hypotheses for tornado/hurricane amelioration at some future time. I am presently collaborating with w colleagues, Drs. Rosenfeld and Woodley, in testing a new technique for identifying storm systems with high threat of producing tornadoes. This technique utilizes NOAA satellite data at various wavelengths and shows promise in improving NWS lead-times for tornado watches and warnings.

Even after the demise of the AMP Program in l995, operational weather modification programs have continued to expand and flourish in the U.S. This is reflected in the annual reports of all such projects to NOAA, as required by law. Most of these projects are supported by the States, utilities or the private-sector. One of my private-sector colleagues recently noted his estimate *of total annual expenditures in the U.S. of $25-30 million* for weather modification operational projects. There is now very little Federally-supporting research to aid these operational programs in evaluation, or improving their technological base. We have some of the best cutting-edge science in NOAA research, NCAR and the universities that can help the private weather modification operators improve their evaluation of seeding effects, as well as improved targeting of seeding materials in suitable cloud systems. I like the idea of establishing the Weather Modification Advisory Board, with broad representation, which is needed to set the national agenda and priorities for these and other urgent water management issues facing the country. I have many close scientific colleagues in NOAA weather research who would welcome the opportunity to contribute to a reinvigorated national program of weather modification research and technology transfer, if support can be found. In fact, our Boulder laboratories won a Department of Commerce Gold Medal for our contributions to the recently-completed NWS Modernization and AWIPS computer workstations. I am one who has long believed, that to be successful in any form of purposeful weather modification, we must first do a very good job of predicting the natural phenomena.

In closing, I want to assure you that the U.S. has the technology and the best and brightest scientists who would welcome the opportunity to reinvigorate the weather modification field. These are very challenging issues and the worsening water crisis in the West and elsewhere demand our urgent attention.

Testimony Before Joint Hearing By Sen. Subcommittee On Science & Space And Subcommittee On Disaster Prediction & Prevention, November 10, 2005:

By Dr. Thomas P. DeFelice

I am honored to appear before you today in regards to Senate Bill S-517, the Weather Modification Research and Technology Transfer Authorization Act of 2005. My name is Dr. Thomas P. DeFelice. My background in weather modification began when I was 15 by reading books on the subject; I had many sessions with WMA forefathers Schaefer & Vonnegutt as an undergrad; my academic and subsequent professional career concentrated on learning the fundamentals of weather modification relevant sciences and its technologies; president of WMA (2000-2002), Chair WMA Public Information Committee (since 2004). I now work as the contractor program manager for 2 NOAA programs. I am here on my own behalf, expressing my own beliefs. I began this process, engaged John Leedom, who engaged Senator Hutchison & her staff, and here we are today.

Weather modification technologies are key to dealing with many present and potential future scientific, environmental, and socioeconomic issues like steadily increasing human suffering and property damage caused by hazardous weather (e.g., severe weather-Katrina, supercooled fog, freezing rain), fire, and other environmental problems related to "acid rain", biological or chemical warfare, for instance. Their application generally increases rainfall amount. Rain contributes 1% of the total global water budget. Global water consumption presently makes up 8% of the total global water budget. Models estimate about 40% of the world's population will live in water – stressed areas by the decade of the 2020's and consumption will increase. Further, air pollution (global warming) is (are) reported to reduce the amount of rainfall. Hence, a need to develop new technologies, while applying proven techniques. Water rationing and water management techniques are useful, they Do Not replenish the reduced rainwater amount. (They simply put a small band-aid on a wound that requires multiple stitches.) Therefore they fail to resolve the issues' root cause. Alternatively, weather modification technologies increase the rainfall amount (compared to normal) under certain conditions. (They simply put multiple stitches on a wound that requires multiple stitches.) Therefore weather modification technologies can resolve the issues' root cause, which *will be ensured through the research and development program set up by passing S-517 and its companion bill (HR 2995).*

Yet some retain an issue concerning whether operational cloud seeding activities, especially associated with convective clouds, achieved the intended results claimed. *Additional evaluations should pacify this issue, especially with the recent technological advances.* This would also help us answer, are weather modification technologies ready to increase water resources and alleviate, or possibly prevent, drought. *Yes they are ready to increase water resources under certain cases, based on the available 60 yr literature archive, and first hand information. S-517 provides a research and development infrastructure for a program that addresses and ultimately resolves these issues, while nurturing and developing these technologies to provide better returns on our investment.*

The *scientific* and *operational communities* generally *agree* that the recent advances in the relevant, general physical processes and technologies need to be capitalized upon in the form of a concerted and sustained national program to carry out basic and applied research in weather modification (e.g. Garstang report, Orville report, NRC). However, the *perceptions* between the science and operational communities *differ*, namely, 1) Interpretation of scientific proof, 2) Current status of cloud models as applied to weather modification, 3) Evidence of glaciogenic seeding in convective clouds, 4) Cold season orographic seeding, 5) Evidence for hail suppression, and 6) Support for specific purposes. The cold season orographic seeding perceptual difference (4) is not a significant difference in perspective, since the science community (post Garstang report) sees orographic cloud seeding as a particularly promising candidate for an intensive field program. Perceptual difference (6) reflects the differences between the individual cultures (i.e., scientific versus operational) than anything else. *Nonetheless, no implementation plans have been proposed.*

I summarize an implementation plan for S-517 for consideration by its Weather Modification Board, which addresses all issues. This implementation plan is born from sound scientific basis derived from 60 years of lessons learned exercises, recent technological advances, and science community recommendations (Garstang report, Orville report, NRC). Societal need provides an impetus for developing systems and technologies that monitor and manage atmospheric events, the creation of a new weather modification research program and implementation plan according to standard engineering practices. *This plan helps mitigate the perceptual differences by setting up an integrated team approach to its activities, and by insisting that its research and development component be geared toward improving the effectiveness of operations.*

It calls for administering the resources and the activities for all research and development efforts directed toward optimizing the technologies used to manage atmospheric processes and their resultants (e.g., collision-coalescence, hurricanes, orographic and convective precipitation, frozen rain). Its mission would be to develop the technologies used for operational activities that help provide sustainable water supplies and reduce airborne hazards. This includes improving the understanding of the relevant processes and their simulations, as well as the evaluation methods (physical; chemical; statistical-random, non-random) for operational activities through cooperative multidisciplinary research and development arrangements and a well-designed outreach effort. Further development is needed for successful application of weather modification technologies to mitigate hurricane and tornado damage, minimize the negative affects of anthropogenic air pollution on precipitation efficiency, or to neutralize negative effects from pollutant deposition. Such requires a modeling approach, then verification, and transition to operational use.

The modern weather modification technologies applied to disperse supercooled fog, augment the ice crystal process in cloud systems, especially orographic clouds, are very effective. Statistical reanalysis using 50+ years of Sierra data show strong signals that the seeding did produce seasonal snowpack increases of 5-10%; as measured by stream runoff data (a conservative surrogate for snowpack increases). Thus, orographic systems, especially winter orographic systems, would help maximize S-517 derived program success. Garstang's report apparently was unclear on this fact.

The implementation plan does not include less developed technologies (e.g. extraterrestrial mirrors; ionization, chaos theory-related approaches; sonic initiation of precipitation, making hurricane disappear from conventional radar), or technologies whose benefits fall short of justifying their cost (e.g., using vertical pointing jet engines, or mono-layer films to suppress moisture flow into hurricanes), based on insufficient scientific and engineering test results, which pose a significant risk to programmatic success. <u>The plan does not support funding for Federal Operational cloud seeding, except for small tests/experiments of new technologies</u>.

In closing, I urge that the joint committees send S-517 to appropriate committee hearings with the companion Udall Bill (HR 2995). We have an implementation plan for the program under this bill. We have the best technology, the brightest personnel to successfully carry out the implementation plan. The 60 years scientific and engineering basis helps assure success. *Passing S-517 now, helps avert adverse effects of desertification, Katrina-like hurricane destruction, and air pollution effect on the rain process, for example. This tax payer fully supports passage of Senate Bill S-517 with a sufficient budget and duration.*

Respectfully Submitted by Tom DeFelice, PhD.

CRITICAL ISSUES IN WEATHER MODIFICATION

Statement of Michael Garstang, Ph.D.
Professor, University of Virginia and Chair, Committee on Critical Issues in Weather Modification Research
Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, National Research Council,
The National Academies

before the Subcommittee on Disaster Prevention and Prediction and Subcommittee on Science and Space Committee on Commerce, Science, and Transportation, United States Senate

November 10, 2005

Good afternoon Chairmen Hutchison and DeMint, Ranking Members Bill Nelson and Ben Nelson, and members of the Subcommittees. My name is Michael Garstang, and I am a Distinguished Emeritus Research Professor in the Department of Environmental Sciences at the University of Virginia. I'm a fellow of the American Meteorological Society (AMS) and have served on numerous AMS committees. I was also the chair of the 2003 National Research Council's (NRC) Committee on Critical Issues in Weather Modification Research. The National Research Council is the operating arm of the National Academies, chartered by Congress in 1863 to advise the government on matters of science and technology.

This afternoon I will give you a brief summary of the status of weather modification research, as described in our NRC report, the major uncertainties that exist, and convey the committee's conclusions and recommendations. We will also provide an Executive Summary of the report which lists the key findings and recommendations in greater detail. (See http://www.nap.edu/catalog/10829.html for free access to the entire report, including the executive summary.

Efforts to minimize harmful weather impacts go back far in time. In the last 30 years, significant evidence has accumulated that human activities unintentionally affect the weather on scales ranging from local to global. Many of the same fundamental principles underlie both intentional and unintentional weather modification. Yet during this 30-year time period, there has been a progressive decline in weather modification research. Research support related to weather modification in the United States had dropped to less than $0.5M per year in 1999 from a high of $20M in the late 1970s. During the same period, there have been significant advances in technology. This has greatly improved our ability to observe, understand, and predict the weather. These advances, however, have not been either collectively or persistently applied to the problem of weather modification.

This decline in research is likely the result of a combination of factors, including early overly-optimistic claims, unrealistic expectations, and failure to provide scientifically demonstrable successes. But despite these limitations, and because of considerable pressures resulting from drought, hail, floods, and storm damage, private and state agencies actually spend significant resources on attempts to modify the weather. In 2001, there were 66 operational weather modification programs in 10 states and much more activity overseas.

How do we overcome this disparity between our willingness to attempt to modify weather and our reluctance to fund research to understand such activities? The 2003 National Academies committee that I chaired was charged to provide an updated assessment of the current state and the future of weather modification research, from new technologies to advances in numerical modeling and operations. A summary of our report is included in my written testimony. In my comments, I want to focus on our conclusions and recommendations.

First, with a few exceptions, the committee concluded that there still is no convincing scientific proof of the efficacy of intentional weather modification efforts. In some instances encouraging results have been observed, but this evidence has not been subjected to adequate testing.

Second, despite this lack of proof, the committee concluded that scientific understanding has progressed on many fronts. For instance, there have been substantial improvements in the ice-nucleating capabilities of new seeding materials. Also, new technologies such as satellite imagery are giving us tools to better understand the microphysical processes that lead to precipitation, and these advances, in time can help focus and optimize weather modification research.

Third, the committee stated that if progress in establishing our capability to modify the weather is to be made, intellectual and technical resources must be brought to bear on the key uncertainties that hamper progress. For example, there are critical gaps in our understanding of the complex chain of physical processes that lead to rain, snow, and hail.

Finally, and most importantly, the committee called for the establishment of a coordinated national program of weather modification research designed to reduce these and other key uncertainties. The program should consist of a sustained research effort that uses a balanced approach of modeling, laboratory studies, and field measurements. Instead of focusing on near-term operational applications of weather modification, the program should address fundamental research questions. It should take full advantage of recent related research and advances in observational, computational, and statistical technologies, by:

• Capitalizing on new remote and in situ observational tools to carry out exploratory and confirmatory experiments in a variety of cloud and storm systems;
• Improving model treatment of cloud and precipitation physics;
• Improving the use of current computational and data assimilation methods; and
• Capitalizing on existing field facilities and developing partnerships among research groups and select operational programs.

In the committee's opinion, it is premature to initiate large-scale operational weather modification programs. However, a great opportunity exists to coordiate research efforts to address the fundamental questions that will lead to credible scientific results. Focused investigation of atmospheric processes, cou pled with technological applications, will advance understanding and bring many unexpected benefits and results. In time, this research will place us in a position to determine whether, how, and to what extent weather and weather systems can be modified.

CLOSING THOUGHTS

The NRC Committee emphasizes that weather modification should be viewed as a fundamental and legitimate element of atmospheric and environmental science. Owing to the growing demand for fresh water, the increasing levels of damage and loss of life resulting from severe weather, the undertaking of operational activities without the guidance of a careful scientific foundation, and the reality of inadvertent atmospheric changes, the scientific community now has the opportunity, challenge, and responsibility to assess the potential efficacy and value of intentional weather modification technologies.

Thank you for the opportunity to testify. I would be happy to answer any questions the Subcommittees might have.

Correspondence

"America Can't Afford to Ignore Weather Modification Studies"

By Richard C. Jackson
Book Author and Song Writer

Tornadoes instead of tanks?

Tactical typhoons?

I don't know, but I hope not!

My family and my doctor told me that I am crazy if I think the weather can be controlled. When they asked me where I came up with such "silly ideas" about weather I said to them, "From the British rock group, 'The Moody Blues.' "

I explained in vain that one of their lead songs states, "Blasting, billowing, bursting forth with the power of ten billion butterfly sneezes, man, with his flaming pyre, has conquered the wayward breezes."

Now when I heard that I thought, "What are they blasting? Napalm in Vietnam?

Or is it something less sinister?" I later found out that it was a NASA spaceship which was blasting off and these vessels can rise above the winds and other elements of the earth.

The song continues on, "Climb to tranquility, finding its real worth," That was a reference to our landing on the Sea of Tranquility on the moon, the value of which may still be highly under rated."

I imagined a lot about controlling the weather. Years after that 1969 song release I found out that "The Moody Blues," were participating in a NASA experiment! What reassuring news this was!

I mentioned some of these ideas to my parents and to the doctor. They said, "You're obviously crazy if you think you can control the weather." I told him that I didn't have any dry ice nor a plane to deliver it with. "Still," I said, "I would be very concerned if weather modification technology was developed by enemies of the United States and used against us."

Other songs in American rock and roll music refer to weather. Don McLean, a favorite of President Bush, sings about "Swirling clouds reflecting Vincent's eyes that shine of blue." A blue eyed Vincent Van Gogh had painted similar clouds in his infamous "Starry Night" painting. I know of many persons with disabilities who absolutely adore the song, including many blind people. Would all of the pain and suffering cause Mother Nature to use retribution? Silly thought, but there are millions of people who love that song.

And Eric Clapton sings, "Mom, take this badge off of me. That long black cloud is coming down!" Countless other famous groups sing about the weather including the beautiful song "Seems it Never Rains in Southern California," by Albert Hammond. There are even entire compact discs dedicated to rain!

Regarding people who support weather modification being crazy, it must be remembered that when Marconi announced he could send sounds through the air, his family locked him in a mental hospital. Actually, he had invented the radio! And when the Wright Brothers said they would invent a machine that flies, they were rudely told that "If men were intended to fly, they would have wings, and therefore flying was against God's intentions."

Please, America needs to spend more money to gain weather modification technology before our enemies do. If a foreign power some day used massive storms against us, our only recourse might be nuclear weapons. I for one would like to avoid that.

A knowledgeable administrator said that weather modification has always been a desire. He added quickly though, that the liability from experiments has often been prohibitive.

While it is true that we can do considerably less with the weather than was hoped in the early years of modification, we can't afford to give up. We must pursue the technology with all scientific resources possible.

The opinions and views expressed in this section are not necessarily those of the *Journal of Weather Modification* or the Weather Modification Association, articles are published here to express independent viewpoints toward stimulation and discussion among members of the scientific community.

UNITED ARAB EMIRATES PRIZE FOR EXCELLENCE IN ADVANCING THE SCIENCE AND PRACTICE OF WEATHER MODIFICATION

On the recommendation of an evaluation committee comprising world-known prominent scientists from Canada, China, Russia, Serbia, South Africa, and the United States, the UAE Prize for Excellence in Advancing the Science and Practice of Weather Modification was conferred on the following winners:

- The South African National Precipitation Research and Rainfall Enhancement Programme (Graeme Mather, Deon Terblanche, Francois Steffens, Lizelle Fletcher and Andre Gorgens), received the UAE Prize ($200,000) for the design and execution of a successful weather modification experiment involving the revolutionizing concept based on hygroscopic nuclei injection and superb radar tracing software.
- Thomas J. Henderson (Atmospherics Incorporated, Fresno, California, USA) receives the UAE Prize ($40,000) in recognition of pioneering work of advancing the field of Weather Modification for more than 40 years, for many years advancing the cause and improving the technical basis and execution of weather modification projects
- Bernard Silverman (Englewood, Colorado, USA) receives the UAE Prize ($40,000) for many years of advancing and guiding the cause of weather modification and the assessment of rain enhancement projects.
- Magomet Abshaev , (High Mountain Geophysical Institute of ROSHYDROMET Nalchik, Russian Federation) with George Sulakvelidze, Ivan Burtzev, Lyudmila Fedchenko, Musabi Jekamuhov, Ali Abshaev, Boris Kuznetsov , Aminat Malkarova, Ahmat Terbuev, Pavel Nesmejanov , Ildar Shakirov and Georgy Shevela receive the UAE Prize ($40,000) for research of hail processes covering the mechanism of hail formation and the hail suppression concept of beneficial competition, and for developing radar and rocket technology applicable to different hailstorms.
- The Chinese Institute of Weather Modification (of Academy of Meteorological Sciences, China Meteorological Administration, Beijing) receives the UAE Prize ($20,000) for contributions to the rapid development of weather modification activities in China, for providing scientific guidance and for encouragement for further science based weather modification.
- Petjo Simeonov with Petar Konstantinov, Petko Boev , and Rangel Petrov (Cloud Physics and Weather Modification team of the National Institute for Meteorology and Hydrology with Bulgarian Academy of Sciences) receive the UAE Prize ($20,000) for developing a very efficient fast acting seeding agent and in recognition of more than 35 years of well planned research in weather modification
- William L. Woodley with Daniel Rosenfeld (Woodley Weather Consultants, Littleton , Colorado , USA) receive the UAE Prize ($20,000) for contributions to world-wide Weather Modification experiments and their advocacy of the aerosol pollution / precipitation link.
- Peter Hobbs with Arthur Rangno (Department of Atmospheric Science, University of Washington, Seattle, USA) receive the UAE Prize ($20,000) in recognition of their conscientious application of physical principles to weather modification.

The prize was sponsored by the Department of Atmospheric Sciences, successor of the Department of Water Resources Studies, UAE Ministry of Presidential Affairs which generously offered the Prize, which would stimulate international efforts for advancing the knowledge in the field important for satisfying the need for water under the increased shortage of fresh water in many regions of the world.

Congratulations to the award winners!

Athens 2005

The WMA Forum – Athens conference and associated social functions were held September 21-24, 2005, in Athens Greece. It was deemed to be a very successful event in terms of bringing people from around the world together for the exchange of ideas, information and experiences on multiple topics in the field of weather modification. Numerous European nations participated and, in all, there were 16 nations represented -- Austria, Australia, Burkina Faso, Canada, Czech Republic, Croatia, France, Germany, Greece, India, Italy, Morocco, Russia, Serbia, Spain and USA. There were 55 registered participants in the technical meeting, and 35 attendees stayed on into Friday afternoon to participate in the WMA-EWRI sponsored workshop.

Accommodations were superb and our wonderful Greek hosts from the Hellenic Agriculture Insurance Organization (EL.G.A.) and General Aviation Applications S.A., "3D", saw to it that the meeting and all social functions were handled perfectly. The Hotel St. George Lycabettus was a great choice for the meeting with excellent meeting rooms and facilities for the social events. The city of Athens and surrounding environs of southern Greece were fascinating – so much history and beauty.

During the introduction to the technical sessions we learned about the relationship between the national hail insurance program and the agricultural interests in Greece. The session participants were informed about the hail suppression programs in Greece, France, and Croatia. We also learned about precipitation enhancement studies in Greece, Italy, Morocco and the USA. Scientific studies on the nature of super cells, influence of geographical variation, giant aerosols, CCN, climate variation, measurement and weather modification technologies were presented to the audience. We also learned about experiences in some operational projects and some on-going research studies including hailfall studies in Serbia and the use of propane for snowfall enhancement in Utah. Topics on man's inadvertent impacts on aerosol load, the possible implications on project evaluation and suppression of natural precipitation underscored the need to reconcile this influence in our studies. Presentations on the challenges of evaluation, establishing economic value, and societal acceptance of value helped participants better appreciate the complexities in this area of weather modification science.

After the close of the technical session, WMA and EWRI sponsored a workshop on Friday afternoon. This was in keeping with the WMA charter to provide information and education on the topics in weather modification. Experts in the field led sessions on principles of cloud seeding technology, design of operational precipitation enhancement and hail suppression projects, statistical and physical evaluation techniques, and socioeconomic aspects of weather modification. Participants of the workshop received binders and CD's of the presentation materials, along with certificates of workshop completion.

At the close of the WMA Forum - Athens it was apparent that weather modification science is still young and that we have made some progress in our understanding of the principles. However, the more we learn the more we become aware of how incomplete our understanding is. Much remains to be learned. The problems, needs and challenges that face the science do not stop at borders or at the edges of continents. There is a continuing need for research, financial support, and education in order for the science and application of weather modification to achieve full potential in the world.

Byron Marler, Program Co-Chair
George Farazoulis, Program Co-Chair
WMA Forum Athens

WMA members and guests pose below the Lyon Gate, ancient Mycenea (BC 4000)

Maria Christodoulo;, Bruce Boe, Nikolaos Katsaros, Pres. of ELGA; Colonel Abraham Traore are enjoying the social hour.

Ted Karacostas, Jean-Francois Berthoumieu, Bruce Boe, and audience focused on the presentation.

Technical Session Co-chairs, Byron Marler and George Farazoulis, listen to interesting presentation

ELGA Interpreter Aspasia Chita, Aaron Gilstad presenting plaque to ELGA President Nikolaos Katsaros.

Roelof Bruintjes and Tommy Shearrer (background); Nikolaos Katsaros, Hilda Duckering, Aaron Gilstad,Colonel Traore are having a good time!

JOURNAL NOTES

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AUTHORS' GUIDE

INSTRUCTIONS AND FORMAT FOR PREPARATION OF CAMERA-READY MANUSCRIPTS ACCEPTED FOR PUBLICATION IN THE 2007 JOURNAL OF WEATHER MODIFICATION

Abstract. To give authors more control over the arrangement and format of their papers and reduce production costs, so as to avoid any increase in page charges, each author is asked to provide a final version of his paper electronically in Microsoft Word or Word Perfect format for Windows. The document should be typed in two columns on regular page size (8.5" x 11"), 1-inch margins (top, bottom, left and right), with 1/2-inch between the two columns, using **10-point** serif type (as shown here). This version will incorporate any changes suggested by the Editor or his referees after consideration of the original manuscript. Details of format and arrangement, and of style and referencing, are given in the following text and example.

1. LAYOUT

Upon acceptance, each article is to be formatted as a document with 8.5" x 11" page size, two- column format, with 1 inch margins (top, bottom, left and right) and ½ inch between columns using 10-point serif type. For authors who cannot arrange such final electronic document, the *JOURNAL* editorial staff can provide this service.

Line drawings and photographs with good contrast should be submitted as separate files, in one of the following formats: .gif, .bmp, or .tif. They should also be inserted electronically directly in the final document, with legends typed below them, preferably in *italics*. Tables and figures should be inserted into the papers at suitable places. Text will be in a normal two-column format, with 1/2-inch between columns, which can be broken for formulas, tables, and figures.

1.1 Style Details

Titles of papers should be informative but short (preferably less than 10 words) and should be centered at the top of the first page. Each author should be identified by affiliation, with a minimal postal address. Two authors should be listed in parallel boxes across the page.

An informative abstract of 50 to 200 words must precede each paper (formatted as shown above). It should contain numerical results and all conclusions, not just a description of the problem and methodology. Abstracts will not contain equations or acronyms.

The pages should be divided into sections of 300 to 1,000 words each, with an arabic-numbered heading, flush left, in capital letters. Subsection headings may be decimally numbered, capital and lower case, underlined, flush left. Leave one blank line before and after all headings, between paragraphs, and place one blank line between each of the references in the reference listing. [The layout of these instructions follows the WMA format rules.]

Acknowledgments. Acknowledgments (of financial support, provision of data, loan of equipment, advice, etc.) should be given in a final section, preceding references.

1.2 Units and Measures

In general, the International System of Units is standard in the *Journal Of Weather Modification*. SI units (m, kg, s, K) should be used throughout but not at the expense of clarity.

Since authors will be responsible for the final typing of any formulas or mathematical expressions, they must be prepared to present Greek letters or other symbols. Expressions should be properly arranged and spaced for ready comprehension. Formulas and equations may be numbered, at the extreme right end of the line, for further reference: "Substitution of Eq. (3) into Eq. (5) yields...." Formulas not mentioned should not be numbered.

1.3 References

Each reference should be generally available, as in the library of a large university. Contract reports, conference preprints, in-house publications, and similar material may be cited only if easily available from a public source, or if the author guarantees to supply copies.

Every reference should have been cited at least once in the text, table notes, or figure descriptions. References should give author (last name first for first author only), year, title, journal or publisher, volume and inclusive pages. [Note: **Last name first for first author only!**] Well-known journal titles may be abbreviated (*J. Wea. Mod.*, *J. Appl. Meteor.*, *Bull. Amer. Meteor. Soc.*, *Amer. Geophys. Union*, etc.), but others should be given in full.

For any reference in a foreign language, the title should be in the original language, with an English translation in parentheses. Place and year of first publication should be given, with any reprinting identified in parentheses.

For references to papers published in the non-reviewed section of the *Journal*, "(non-reviewed)" should be included after the reference.

3. PROCEDURES

To submit paper:

Draft papers for the reviewed section should be prepared electronically in Microsoft Word or Word Perfect format for Windows, double-spaced, and provided to the Editor by 15 November each year for adequate review prior to the next April publishing date. Draft papers or Notes for the non-reviewed section should be prepared electronically in Microsoft Word or Word Perfect format for Windows, double-spaced, and provided to the Editor by 15 January each year to appear in that year's volume. Please send all papers as an e-mail attachment to the Editor (Andrew.Detwiler@sdsmt.edu).

Upon acceptance by the Journal:

Only the **final** electronic version, in double columns, need be returned to the editorial staff, but authors should retain copies for safety. The final typed version must be single-spaced.

To implement these procedures and still publish by April, the final manuscripts should be sent, electronically, to reach the editor by **March 1.** This will permit orderly handling, preparation, printing, etc.

APPENDIX I: SAMPLE FOR PAPER TITLES AND AUTHORS

INTERCOMPARISON OF MEE AND NCAR ICE NUCLEUS COUNTERS AND THE CSU ISOTHERMAL CHAMBER

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Notice

Beginning with this issue (Vol. 38) of the *Journal of Weather Modification*, the following regular items will be placed on the Weather Modification Association website: www.weathermodification.org:

- Articles of Inc.
- Code of Ethics
- Qualifications and Procedures for Certification
- Operators/Managers/Honorary Members
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- Awards
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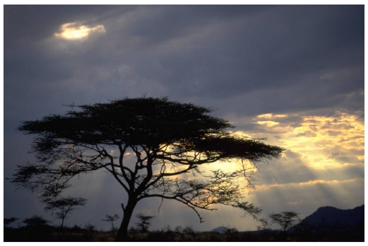

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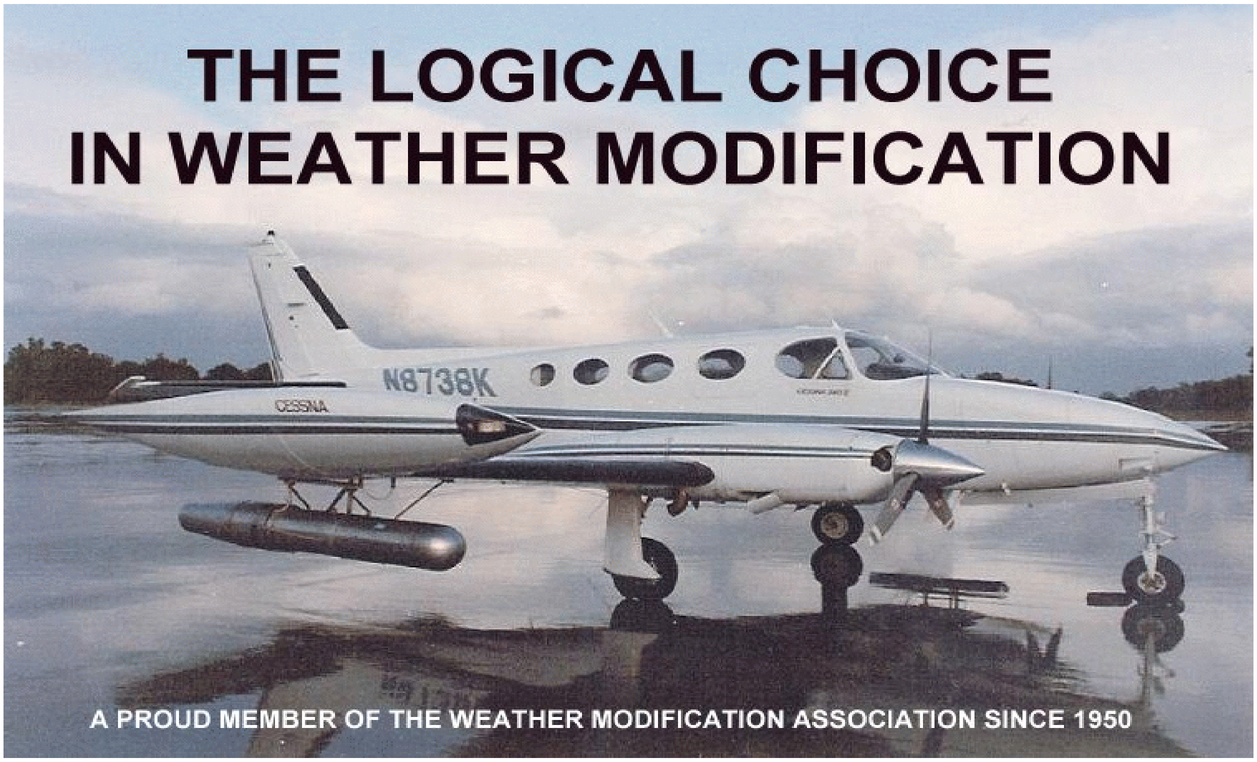

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