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ROGER TILBURY LOOKING FOR SUITABLE CLOUDS IN SAUDI ARABIA.

VIGOROUS CONVECTIVE TOP CAPPED BY PILEUS COMPOSED OF SMALL NEWLY NUCLEATED CLOUD DROPS.

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

THE JOURNAL OF WEATHER MODIFICATION

COVER PHOTOS: Roger Tilbury looking for suitable clouds in Saudi Arabia - Picture taken 4 August 2009 by Duncan Axisa (NCAR); Vigorous convective top capped by pileus composed of small newly nucleated cloud drops - Picture taken 11 August 2009 by Mike Chapman (NCAR).

PHOTO CREDITS FROM ANNUAL MEETING: Photos from the 2009 annual meeting in Anaheim, CA courtesy Darryl O'Dowd.

EDITED BY:

Andrew G. Detwiler, Editor
Connie K. Crandall, Editorial Assistant
Institute of Atmospheric Sciences
South Dakota School of Mines & Technology
501 East Saint Joseph Street
Rapid City, SD 57701
Phone: (605) 394-2291
Fax: (605) 394-6061

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Weather Modification Association
PO Box 26926
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Phone and FAX: (559) 434-3486
E-mail: wxmod@comcast.net

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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 42 volumes (44 issues).

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

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

The *Journal* is published annually and papers are always welcome for consideration in either the reviewed or non-reviewed sections. A nominal charge of $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.

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:

WEATHER MODIFICATION ASSOCIATION
P. O. Box 26926
Fresno, CA 93729-6926 USA
Phone and FAX: 559-434-3486
E-mail: wxmod@comcast.net
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President's Message

Dear WMA Members,

It has been a privilege and an honor to have served you as President. I am pleased about the accomplishments that have occurred over the last two years, although I certainly cannot take credit for them. This credit belongs to the talented, dedicated and hard-working Executive Board and Committees of the WMA.

During 2008, 2009 and 2010:

- The WMA has conducted two successful conferences. In addition to the 2009 Annual Meeting in Anaheim California, a semi-annual meeting was held in Mendoza, Argentina (1-3 October 2008).

- We have formed an 'International Committee' and recruited new committee members who have given us greater geographic and multi-disciplinary representation. This Committee is expanding our international membership and broadening the reach of the WMA to new countries.

- The WMA website is being revised with an updated organization and appearance. This process includes a journal management and publishing system that will expand and improve access to the *Journal of Weather Modification*.

- The Association has been represented at international conferences and meetings. For example, the WMA was an exhibitor at the International Commission on Clouds and Precipitation (ICCP) in Mexico and represented at the International Association of Agricultural Production Insurers (AIAG) International Congress in Italy.

As I move from the position of President to Past-President, I surely am glad this is not farewell, but just a change of roles. It is such a pleasure to work with the board and members that care deeply about the science of weather modification. We have many challenges and must continue pursuing scientific and educational efforts toward improving the understanding of weather modification technology.

Before concluding, I want to thank a number of people who contributed greatly to the WMA. Don Griffith has handled several tasks as an active Past-President. His vision for WMA is central to its organizational success. Tom DeFelice and Stephanie Beall worked very hard as members of the Public Information Committee. Tom's leadership in editing the 'Position Statement on the Environmental Impact of Using Silver Iodide as a Cloud Seeding Agent' is very much appreciated. Stephanie's role in keeping the WMA websites up-to-date has been a constant effort. I am very satisfied with the quality of papers that are being published in the *Journal of Weather Modification*. The excellent work of our Editor Andy Detwiler and Editorial Assistant Connie Crandall are to be highly commended. A note of great appreciation goes to our Executive Secretary and Treasurer, Hilda Duckering, who once again amazes me by her tireless and consistent dedication towards the Association. I consider her not only a hard working colleague of the WMA but a dear friend.

Finally, I would like to acknowledge the work of Todd Flanagan in reviewing meeting abstracts and planning the conference proceedings. Todd has attended all Association meetings during this period as President-elect in anticipation of accomplishing a smooth transition to his presidency. I know we have placed the direction of WMA in good hands, and I look forward to working with the Board as Past-President.

Duncan Axisa
President, WMA

Editor's Message

As we get Volume 42 of the *Journal of Weather Modification* ready to go to press, I look back on my five years as editor with a feeling of satisfaction for being able to serve the Association as editor of the *Journal*. Many authors from around the world have contributed manuscripts on a wide variety of topics, ranging from traditional studies of precipitation enhancement and hail suppression using glaciogenic and hygroscopic seeding techniques, to less traditional topics such as the role of lightning in tornadogenesis, and discussions of several mechanisms for mitigation of damage due to tropical storms. An even larger number of volunteer reviewers have provided comments on these manuscripts, helping the editor to assess the quality of these works, and helping authors sharpen their ideas and improve their presentations. We have had an active published correspondence section in which members comment in print on previously published work, and authors reply, with the exchange of views bringing into better focus some of the important ideas in our field.

It takes ideas to fill a journal, and it takes expert editorial assistance to produce a clean, crisp, well-edited, and attractive printed journal. Connie Crandall has worked with me for these past five years, 2006-2010, building on her record with the *Journal* as editorial assistant from 1996-2002, during the editorship of my colleague Jim Miller. Connie's experience in the publishing business spans early years spent with small town newspapers set via linotype to more recent years spent in scientific publishing using modern digital layout and publication software. She has continually adapted the latest in publishing technology to the production of the *Journal*. During two of these five years, I was working in Virginia while Connie worked from Rapid City, hardly ideal conditions, yet every year, through her efforts, the *Journal* was formatted, printed, and made its springtime appearance.

Exciting things lie ahead for the *Journal*. Software has been loaded onto the new Association web page that will allow distribution of the *Journal* in digital form via the internet, and allow on-line access to any paper ever published in the *Journal*. This software package will also assist the incoming editor in managing submitted manuscripts.

Although these are exciting times to be an editor, I find that I am not able to put the time into the *Journal* that is really necessary to properly serve the Association. I will be stepping aside as editor after this volume hits the streets, and look forward to helping with the transition to a new editor and toward instant worldwide access in the digital publishing age.

Andrew Detwiler
Editor

MAXIMUM HAIL SIZE PREDICTION

Evangelos Tsagalidis[1*], Kyriakos Tsitouridis[1], Georgios Evangelidis[2], and Dimitris Dervos[3]

(1) Hellenic Agricultural Insurance Organization, Meteorological Applications Centre,
International Airport Makedonia, 55103 Thessaloniki, GREECE,
{e.tsagalidis, k.tsitouridis}@elga.gr
2) Department of Applied Informatics, University of Macedonia,
156 Egnatia Street, 54006, Thessaloniki, GREECE, gevan@uom.gr
3) Information Technology Dept., T.E.I.,
P.O. BOX 141, 57400 Sindos, GREECE, dad@it.teithe.gr

ABSTRACT. We examine the possibility of building a meteorological prediction tool using data from the Greek National Hail Suppression Program. More specifically, we focus on maximum hail size prediction from operational meteorological radar and/or sounding data. Factor analysis and linear regression are applied in order to identify the optimum number of independent variables and the sequence to build the corresponding meteorological tool. A significant linear relationship is discovered for non-seeded storms relating hail size to various radar parameters, such as the Reflectivity or the group of Vertically integrated liquid density and Cloud top. A relationship for predicting hail size using radar parameters for seeded storms failed to be statistically significant.

1. INTRODUCTION

The Hellenic Agricultural Insurance Organization (ELGA) is a public organization and the main insurance carrier of the agricultural production in Greece. The Meteorological Applications Centre (KEME) is the section of ELGA that since 1981 conducts the Greek National Hail Suppression Program (GNHSP) using airborne seeding. The Program aims at reducing insurance payments due to hail damage and is being applied in Central Macedonia and Thessaly, covering an area of 5,000 square kilometres, during the April to September period. The cloud seeding is performed by three aircraft releasing AgI in developing hail-bearing clouds as indicated by radar (Tzoumaki *et al.* 2006).

In this study, we explore the possibility of building a prediction tool using the GNHSP data. More specifically, we focus on maximum hail size estimation and prediction from operational meteorological radar and/or sounding data. We apply factor analysis in a pre-processing phase to identify the optimum number of independent variables, and, subsequently, linear regression to build a simple, yet effective, meteorological tool. A meteorologist can easily use the tool to quickly map radar and atmospheric measurements to possible hail size on the ground.

The remainder of the paper is organized as follows: Section 2 describes the dataset we used to build the prediction tool, and Section 3 presents the adopted methodology. In Section 4, we present the results we obtained by experimenting with the chosen techniques, and, finally, Section 5 concludes the paper.

2. DATASET

The analysis utilizes radar data of the EEC S-band meteorological radar installed at Airport "Macedonia" of Thessaloniki. Data recorded by the Thunderstorm Identification, Tracking, Analysis and Nowcasting system (TITAN) (Dixon and Wiener 1993), are further analyzed to create a sample of Storm Cell Complexes (SCC) which is actually a structured form of the initial data and represents the storm characteristics data (Tsagalidis and Tsitouridis 2000, Tsagalidis et al. 2006). The data were recorded during the storm activity from April to September 1999, 2000, 2001 and 2005 in the protected area of Central Macedonia. The SCC structured data represent the values of each hailstorm attribute, and, more specifically, the type, reflectivity, cloud top, vertically integrated liquid water content (VIL) and vertically integrated liquid water density (VIL density).

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*Corresponding author address: Evangelos Tsagalidis, Hellenic Agricultural Insurance Organization, Meteorological Applications Centre, International Airport Makedonia, 55103 Thessaloniki, Greece; e-mail: e.tsagalidis@elga.gr

The structure of cloud systems and their classification in different categories follows the classification of SCC (Tsagalidis and Tsitouridis 2000, Tsagalidis et al. 2006). The classes are represented by the values of the Type attribute, where “S” is used for unicellular storms of a single ordinary cell, “SU” for Unicellular storms of a supercell, “M” for multicell storms, and, “L” for line storms. During the entire lifetime of the SCC, reflectivity in dBz is the maximum radar reflectivity at the -50ºC level or higher and the cloud top in km is the maximum height. The VIL in kg·m^{-2} is the integration from the echo base to the echo top of the liquid water content and is estimated using a mathematical function between liquid water content and radar reflectivity (Greene and Clark 1972). Our VIL parameter is the maximum value recorded during the entire lifetime of the SCC. The VIL Density is simply the VIL divided by the echo top (m) and multiplied by 1000 in order to express the result in g·m^{-3} (Amburn and Wolf 1997). In Table 1, we show the mean, standard deviation, minimum and maximum values of Reflectivity, Cloud top, VIL and VIL Density in our data.

Table 1: Mean, standard deviation, minimum and maximum values of Reflectivity, Cloud top, VIL and VIL Density.

	Refl. (dBz)	C. top (km)	VIL (kg·m^{-2})	VIL Density (g·m^{-3})
Mean	52.2	10.4	22	2.2
St.dev.	5.3	1.4	12.1	1.1
Min.	40	7	3.8	0.5
Max.	69	14.5	55.8	5.1

Furthermore, during the analysis, meteorological parameters are examined from the sounding data of the Upper Air Observation Station of Thessaloniki, which relate to the hail size on the ground too. The meteorological station is located close to the project area of Central Macedonia and the calculated values of the atmospheric parameters, such as wet bulb zero (WBZ) and mean temperature are associated with the SCC environment. The WBZ is the height in km of the wet bulb temperature 0ºC level, corresponding to the melting level of the hailstone during its fall to the ground, whereas, the mean temperature in Kelvin of the layer between that level and the ground is the mean temperature. These parameters were calculated using the most representative sounding related to the occurrence time of each SCC. In Table 2 we show the mean, standard deviation, minimum and maximum values of WBZ and Mean temperature in our data.

Table 2: Mean, standard deviation, minimum and maximum values of WBZ and Mean temperature.

	WBZ (m)	*Mean temp*. (K)
Mean	3123	288
St.dev.	419	2.1
Min.	2118	282
Max.	4182	293

The WBZ values associated with hail days are bounded in a specific range of values, because low WBZ values imply stable air conditions, not sufficient for hailstorms, and high values an increasing possibility that the hailstones will melt before reaching the ground (Tsagalidis 1996). During the preprocessing phase, we made the appropriate transformations of the WBZ values to ‘1’, ‘2’ and ‘3’ values using the method of Z-score normalization. The ‘2’ value corresponds to WBZ Z-scores between -1 and 1, the ‘1’ to less than -1 and the ‘3’ to greater than 1. Similarly, the mean temperature values have been transformed to ‘1’, ‘2’ and ‘3’ values, where the ‘1’ value represents a relatively cold air layer and the ‘3’ value a relatively warm air layer.

Each SCC is identified as a hailstorm using the data from the GNHSP hailpad network. These data include values of maximum hail diameter in mm, called hailsize, for each one hailstorm (SCC). In our sample, it was not the case that two or more SCC passed over a hailpad before changing the hailpad the next day with a new one.

In addition, due to potential seeding effect on hail size during the GNHSP operation, the insertion of the SCC seed attribute has been considered as crucial. Analyzing the operational radar data for each SCC, the value ‘yes’ or ‘no’ was given to the seed attribute. The ‘yes’ value represents an acceptable SCC seeding operation according to GNHSP seeding criteria, and the ‘no’ value a non-acceptable seeding operation or the case of a non-seeded SCC. During the preprocessing phase, we used the values ‘1’ and ‘0’ in the place of ‘yes’ and ‘no’ respectively. Examples of non-acceptable seeding operations were delayed or corrupted seeding, or the seeding far away from the targets, and, in general, cases where the experienced meteorologist analyst believed that there was not a seeding effect in a particular SCC.

The values of the above parameters belonging to the groups of radar, sounding, seeding and hailpad network data comprise for each one SCC one record. We obtained 74 records for the 74 SCCs that were identified on radar and had hail records on the hailpad network. According to the ‘yes’ and ‘no’ values of the seed variable our dataset is split into two subsets having 32 and 42 records respectively.

3. METHODOLOGY

A lot of research work deals with the problems of detecting hail or estimating the probability of hail and the hail size within the cloud or on the ground (Waldvogel et al. 1979, Witt et al. 1998, Foote et al. 2005, Auer 1994, Greene and Clark 1972, Amburn and Wolf 1997). In Waldvogel et al. (1979) the authors relate the height difference between the top of the 45 dBZ echo in the storm and the freezing level to the probability of hail, with S-band radar returns validated against a surface hailpad network. Witt et al. (1998) present an enhanced hail detection algorithm, which estimates the probability of hail (any size), probability of severe-size hail (diameter ≥ 19mm), and maximum expected hail size for each detected storm cell, and in addition the severe hail index (SHI) which is the primary predictor variable for severe-size hail. Foote et al. (2005) discuss the sensitivity and variation with time of several radar hail parameters computed using the TITAN system, including probability of hail, hail mass aloft, vertical integrated hail mass, hail kinetic energy flux, and the FOKR index. The FOKR index (Foote-Krauss) is a hail storm classification system that uses the maximum reflectivity in the storm and the difference between the height of the top of the 45 dBZ echo in the storm and the height of the 0ºC isotherm. Auer (1994) describes a technique whereby the radar reflectivity can be combined with cloud-top temperature, from either satellite imagery and/or sounding analysis, to provide a reliable discrimination between heavy rain and/or hail in convective clouds. In addition, hail sizing is also possible. Greene and Clark (1972) introduced the VIL, whereas, Amburn and Wolf (1997) propose VIL density as a useful indicator for assessing hail potential in thunderstorms.

The aim of this study is the estimation and prediction of maximum hail size associated with a SCC, using radar or/and sounding parameters. Our dataset has tuples consisting of the variables type, reflectivity, cloud top, VIL, VIL density, WBZ, mean temperature, seed and the values of the observed hailsize.

The problem of predicting hail size or the corresponding hail size classes from our database is a typical classification problem. In Tsagalidis et al. (2008), we attempted to predict the hail size class using supervised classification techniques, such as the decision tree-based algorithm of C4.5, a widely-used decision tree algorithm for classification in the field of data mining, and the Bayes classifier. In this study, we chose statistical linear regression to perform classification in our dataset having as dependent variable the numerical hail size (Hailsize).

Statistical regression is a supervised technique that generalizes a set of numeric data by creating a mathematical equation relating one or more input attributes to a single output attribute. A linear regression equation is of the form:

$$f(x_1,x_2,\ldots,x_n) = b_1x_1 + b_2x_2 + \cdots + b_nx_n + c$$

where $x_1,x_2,\ldots,x_n$ are independent variables and $b_1,b_2,\ldots,b_n$ and c are constants. $f(x_1,x_2,\ldots,x_n)$ represents the dependent variable. In general, linear regression is appropriate when the relationship between the dependent and independent variables is nearly linear.

4. ANALYSIS AND RESULTS

4.1 Data reduction

In a step prior to linear regression and in order to achieve data reduction by identifying representative variables from our dataset, we apply factor analysis (Hair et al. 2005). Factor analysis provides insight into the interrelationships among variables and the underlying structure of the data and is an excellent starting point for many other multivariate techniques, such as regression. For data reduction, we use the SPSS statistical software (SPSS) and we chose the principal component analysis extraction method with eigenvalues greater than 1 and the Varimax rotation method to construct a solution.

Table 3 shows the rotated component matrix that helps to determine what the 3 extracted components represent. The boldface cells show the significant loadings greater than the absolute value of 0.65. This threshold is chosen due to the dataset size consisting of 74 observations (Hair et al. 2005). We remark on the absence of cross-loadings and that the first component is most highly correlated to VIL, VIL density and reflectivity (group of SCC intensity variables), the second component to WBZ and mean temperature (group of atmospheric variables) and the third component to seed (operational variable). Additionally, the cloud top (SCC attribute) is correlated to both the first and third components in a remarkable level of 0.59 and 0.47 respectively.

Table 3: Factor analysis, rotated component matrix

	Component			*Comm.*
	1	2	3	
Type	0.57	-0.26	0.41	0.55
Cloud Top	0.59	0.28	0.47	0.65
Reflectivity	**0.84**	0.05	0.13	0.73
VIL	**0.91**	0.22	-0.13	0.89
VIL Density	**0.88**	0.10	-0.23	0.85
WBZ	0.07	**0.83**	-0.15	0.71
Mean temp.	0.14	**0.81**	0.30	0.76
Seed	0.10	-0.05	**-0.75**	0.57

The communalities, the estimation of the variance in each variable accounted for by the components, are all high, having values between 0.55 and 0.89. This indicates that the extracted components represent the variables well. Finally, we mention that in this procedure we used the values '1', '2' and '3' for both the WBZ and mean temperature variables. In addition, we experimented using their numerical values and we had the same results.

4.2 Hail size prediction

The factor analysis outcome during the data reduction procedure shed light on the dataset and highlighted the predictors. Interpreting the third component, where the operational variable *seed* is designated and taking into account the possible effect of seeding operations to hail size on the ground, we divide our sample based on the value 'yes' or 'no' of that variable. Similarly, the first component dictates the use of predictors from the group of SCC intensity variables, such as the *VIL Density*, *VIL* and *reflectivity*, whereas the second component is based on the group of atmospheric variables, such as *WBZ* and *mean temperature*.

The SPSS software package was used to apply linear regression on our dataset, where the dependent variable was hailsize (Hair et al. 2005, SPSS, Neter et al. 1996). Choosing different predictors, many trials were made in order to build an effective model, at least in the case of the non-seeded SCC. The results showed that the atmospheric variables *WBZ* and *mean temperature* do not contribute to the prediction. On the contrary, the *reflectivity* or the *VIL density*, especially when combining with cloud top, can give an acceptable model. The exploitation of *WBZ* or *mean temperature* variables that express the second component could be accomplished by furthermore dividing our already split dataset according to their values. Taking into account the small size of our dataset we prefer not to consider these atmospheric variables.

In the following, we use the notation regression (a) and regression (b) to refer to the two modes of the regression application, where in the first case the predictor is the *reflectivity* and in the second one the *VIL density* and *cloud top*. The assumptions of the linear regression model were checked and we can accept them as valid in the cases of the non-seeded hailstorms. Tables 4 and 5 show the corresponding coefficients of the regression lines.

Table 4: Coefficients of regression (a)

	B	S.Error	Beta	t	Sig.
Seed=no					
Const.	-24.93	5.46		-4.57	0.00
Refl.	0.738	0.10	0.75	7.07	0.00
Seed=yes					
Const.	2.35	8.72		0.27	0.79
Refl.	0.206	0.17	0.22	1.25	0.22

Table 5: Coefficients of regression (b)

	B	S.Error	Beta	t	Sig.
Seed=no					
Const.	-6.56	4.46		-1.47	0.15
VIL D.	1.876	0.57	0.41	3.29	0.002
C. top	1.53	0.43	0.43	3.49	0.001
Seed=yes					
Const.	-2.44	6.73		-0.363	0.719
VIL D.	0.273	0.86	0.06	0.316	0.754
C. top	1.463	0.71	0.39	2.075	0.047

In the case of non-seeded hailstorms, the hail size in mm is equal to

$$0.738{*}\mathit{Reflectivity} - 24.93 \qquad \text{Eq. (1)}$$

or

$$1.876{*}\mathit{VILDensity} + 1.53{*}\mathit{Cloudtop} - 6.56 \qquad \text{Eq. (2)}$$

For seeded hailstorms neither model is reasonable.

In Tables 6 and 7, we show the ANOVA for testing the acceptability of the models from a statistical perspective.

Table 6: ANOVA of Regression line (a)

	Sum of Squares	df	Mean Square	F	Sig.
Seed=no					
Regression	553.7	1	553.7	50.02	0.00
Residual	442.8	40	11.1		
Total	996.5	41			
Seed=yes					
Regression	42.7	1	42.7	1.55	0.22
Residual	823.5	30	27.5		
Total	866.2	31			

Table 7: ANOVA of Regression line (b)

	Sum of Squares	df	Mean Square	F	Sig.
Seed=no					
Regression	444	2	222	15.67	0.00
Residual	552.5	39	14.2		
Total	996.5	41			
Seed=yes					
Regression	147.4	2	73.7	2.97	0.067
Residual	718.8	29	24.8		
Total	866.2	31			

We notice that only for the case of non-seeded hailstorms the significance value of the F statistic is less than 0.05, which means that the variation explained by the model is not due to chance. Also, in the case of seeded hailstorms, the values of the sum of squares of the regression are low compared to the total.

In Table 8, we show the multiple correlation coefficient R, the coefficient of determination R square, the adjusted R square and the standard error of the estimate for the two regression application modes.

Table 8: Regression coefficients

	R	R Square	Adj. R Sq	S.Error
Regression (a)				
Seed=no	0.745	0.556	0.545	3.33
Seed=yes	0.222	0.049	0.018	5.24
Regression (b)				
Seed=no	0.668	0.446	0.417	3.76
Seed=yes	0.413	0.17	0.113	4.98

The values of the multiple correlation coefficient R for the cases of non seeded hailstorms are relatively large, especially for regression (a) (0.745). This indicates a strong relationship between the observed and model-predicted values of the *Hailsize*. The mean value of *hailsize* is equal to 13.5mm and the standard deviation to 4.93mm. Comparing the latter with the standard error of the estimate we observe that it is greater only in the cases of the non seeded hailstorms.

5. CONCLUSION

The present study refers to the specific system of GNHSP, where we examine the prediction of hail size that is associated with a SCC (hailstorm), using radar and /or sounding parameters. The factor analysis and the classification technique of statistical linear regression are used to build a meteorological prediction tool.

Applying linear regression, only in the case of non-seeded SCC (hailstorms) is there a strong relationship using as independent variables the *reflectivity* or the group of *VIL density* and *cloud top*. Hailsize from the non-seeded hailstorms shows a positive linear relationship with *reflectivity* or *VIL* or *VIL density*, whereas this relationship is violated in the case of seeded hailstorms.

Our study is a first attempt to build a meteorological prediction tool and it is limited by the hailstorm sample size. In the future, the examination of additional cases will improve the proposed tool as a robust element for decision-making during the GNHSP seeding operations.

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APPENDIX I: Acronyms definition

Hellenic Agricultural Insurance Organization	ELGA
Meteorological Applications Centre	KEME
Greek National Hail Suppression Program	GNHSP
Enterprise Electronics Corporation	EEC
Thunderstorm Identification, Tracking, Analysis and Nowcasting system	TITAN
Storm Cell Complexes	SCC
Vertically Integrated Liquid Water content	VIL
Vertically Integrated Liquid Water Density	VIL Density
Unicellular storms of a Single ordinary cell	S
Unicellular storms of a Supercell	SU
Multicell storms	M
Line storms	L
Wet Bulb Zero	WBZ
Severe Hail Index	SHI

STATISTICAL MODELING OF RAINFALL ENHANCEMENT

Stephen Beare[1*], Ray Chambers[2], Scott Peak[3]

[1]Analytecon, 4 Johnston Street, Narrabundah, ACT 2604, Australia

[2]Centre for Statistical and Survey Methodology, University of Wollongong, Wollongong, Australia

[3]Australian Rain Technologies, Pier 8/9, 232 Hickson Road, Millers Point, NSW 2000 Australia

ABSTRACT. Non-stationary spatial variation makes it difficult to establish real-time areas of control and effect in weather modification. Non-stationary temporal variation makes the comparison of long-term averages from limited climatic records open to question. Here we describe a statistical methodology which addresses both problems explicitly, in a trial of a ground-based ionization technology known as Atlant, and which could be applied to other weather modification technologies more generally. The approach adopted here is based on a statistical model for daily rainfall that achieves a high level of real-time control by the inclusion of both spatial and temporal components. In particular, it makes use of daily gauge level rainfall data, orographic and daily meteorological covariates, as well as dynamically defined downwind areas, to model the impact of Atlant operation on rainfall. Subject to the caveat that the trial was not randomized in any way, this type of dynamic control demonstrates a clear rainfall enhancement effect at both a simple observational level and when a spatial random effects model is used to control for covariates. Rainfall downwind of the Atlant test site was 15% higher than rainfall in the control (crosswind or upwind) areas. Based on these results, randomized trials with multiple sites are currently being conducted in the same area.

1. INTRODUCTION

With predicted climate change anticipated to have major impacts on the world's fresh water supply in the coming decades, it is imperative that new statistical models and techniques be developed to accurately quantify and evaluate a range of rainfall enhancement technologies in cost effective time frames. However, conclusive empirical evidence of weather modification – that is, persistent or recurring changes in local or regional weather patterns due to human intervention – is difficult to obtain because of the non-stationarity of meteorological conditions over space and time. The former, in particular, makes it difficult to establish real-time control and effect areas, while the latter makes comparison with long-term averages obtained from limited climatic records open to question. For decades major cloud seeding experiments have reported statistically significant increases in rainfall at high levels of confidence (e.g. CLIMAX I and II, Mielke *et al.* 1971; ISRAEL I and II, Grant and Neumann 1974, 1981). However, conclusive evidence that establishes various types of cloud seeding as an effective and viable means of rainfall enhancement remains elusive (WMO 2007; NRC 2003). Recent reviews of cloud seeding experiments to enhance precipitation detail a history of reported positive statistical results that have come under scrutiny and have been questioned, weakening their scientific credibility (Ryan and King 1997, Bruinjtes 1999). Most recently a comprehensive review of 45 years of cloud seeding in Tasmania, Australia, found consistent and credible statistical results but concluded that further field measurements of the cloud microphysics were needed to provide a physical basis for these statistical results (Morrison *et al.* 2009).

The problem is exacerbated where a causal link between the operation of a rainfall enhancement technology and increased rainfall has not been demonstrated. Establishing a physical link between ground-based ionization and rainfall would require an extensive multi-disciplinary research effort. Since the 1950's, various forms of ionization devices have been the focus of experiments involving the release of ions into the air from electrified wires (e.g. Vonnegut and Moore 1959, Vonnegut *et al.* 1961, Kauffman 2009). However, the general consensus of the scientific community is one of high skepticism (WMO 2007) despite current literature in the fields of cloud and aerosol microphysics suggesting that ions can influence the formation of clouds and raindrops at multiple stages throughout the process. Within the domain of physical experimentation, the need for statistical evidence is still inevitable (Haman 1976), and field trials appear to be the most effective means of initially establishing

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**Corresponding author address:* Scott Peak, Australian Rain Technologies, Pier 8/9, 232 Hickson Road, Millers Point, NSW 2000 Australia; e-mail: peak@australianrain.com.au

whether there is a statistical link between rainfall enhancement technologies and rainfall.

An experimental design and statistical method that explicitly addresses the problem of non-stationarity in space and time of meteorological conditions, in the context of a trial of a ground-based ionization technology, known as Atlant, in South Australia is presented in this paper. This effort focuses on the use of spatial statistics to exploit correlations in observed rainfall between individual gauges, on a daily or higher frequency basis, and the application of dynamic control areas defined on the basis of prevailing meteorological conditions. Specifically, the approach is based on a statistical model for daily rainfall during the trial that achieves a high level of real-time control by the inclusion of both spatial and temporal components. In particular, it makes use of daily gauge level rainfall data, orographic and daily meteorological covariates, as well as dynamically defined downwind areas, to model the impact of Atlant operation on rainfall in the trial area. More generally the method is intended for the purpose of measuring the effects, if any, of ion generation and other enhancement technologies on rainfall.

2. ATLANT

2.1 Background

Lord Rayleigh (1879) was the first to suggest that electrical effects in the atmosphere and rainfall are related. It has been hypothesized that the presence of electric forces enhances collision-coalescence and formation of larger raindrops. This aspect of rain formation has been intensely investigated, both experimentally (Sartor 1954, Goyer *et al.* 1960, Abbott 1975, Dayan and Gallily 1975, Smith 1972, Ochs and Czys 1987, Czys and Ochs 1988) and theoretically or with modeling studies (Sartor 1960, Lindblad and Semonin 1963, Plumlee and Semonin 1965, Paluch 1970, Schlamp *et al.* 1976). The current literature in the fields of cloud and aerosol microphysics suggests that ions can influence the formation of clouds and raindrops at multiple stages throughout the process (e.g. Harrison and Carslaw 2003 for an overview, Harrison 2000, Carslaw *et al.* 2002, Khain *et al.* 2004). In particular, there is evidence consistent with ions enhancing the coalescence efficiency of charged cloud droplets compared to the neutral case. Though electrical effects on cloud microphysics are not fully understood (see Ch. 10 of McGorman and Rust [1998] and Ch. 18 of Pruppacher and Klett [1997] for an overview), enhancement of the coalescence process may play an important role in explaining any effect on raindrop formation/enhancement attributable to the Atlant technology.

However, research attempting to link the micro-level effects of ions on the formation of raindrops and the macro-level application of ion generation to enhance rain has been limited. Bernard Vonnegut speculated that electrical charges in clouds could aid in the initiation of rainfall (Moore and Vonnegut 1960). Vonnegut carried out numerous experiments into the electrification of clouds, including the widespread release of ions into the air to test the effect of priming clouds with negative space charges (Vonnegut and Moore 1959). Vonnegut *et al.* (1961, 1962a, 1962b) showed that the electrical conditions in clouds could be modified with the release of ions of either polarity. These ions are released into the sub-cloud air using a high-voltage power supply which generates corona discharges from an extensive array of small diameter wires elevated above the ground and exposed to local winds and updrafts. These discoveries confirmed that anomalous polarity clouds developed over sources of negative charge and suggested the operation of an influencing electrification mechanism. It has also been reported (Moore *et al.* 1962, Vonnegut and Moore 1959; Vonnegut *et al.* 1961) that space charge released from an electrified fine wire produces large perturbations in the fair-weather potential gradient for distances of 10km or more downwind. Most recently Kauffman and Ruiz-Columbié (2005,2009) conducted field experiments on a DC corona antennae for the purpose of precipitation enhancement and also as a means of aerosol deposition.

2.2 Description of Atlant

Although these previous investigations were not conclusive, they do provide the basis for a plausible hypothesis for how the Atlant system may function to affect rainfall. This hypothesis was used to design key elements of the statistical analysis. Each Atlant ion-emitting device consists of a high-voltage generator connected to a large network of thin metal wires supported on a framework with a series of pyramids on top. The device's approximate dimensions are 12m x 3m x 5m (Figure 1). It consumes about 500W of power and generates voltages of 70kV.

2.3 Atlant Model

Assumptions about the operation of the Atlant relate to condensation nuclei and drop coalescence. As experiments detailed in section 2.1 have shown, the coalescence efficiency between colliding drops of opposite charge is enhanced, as it also is between charged drops and uncharged drops, and is significantly higher than the pure gravity and hydrodynamic induced values. At collision, the thin film of air between the drops and the surface tension of the

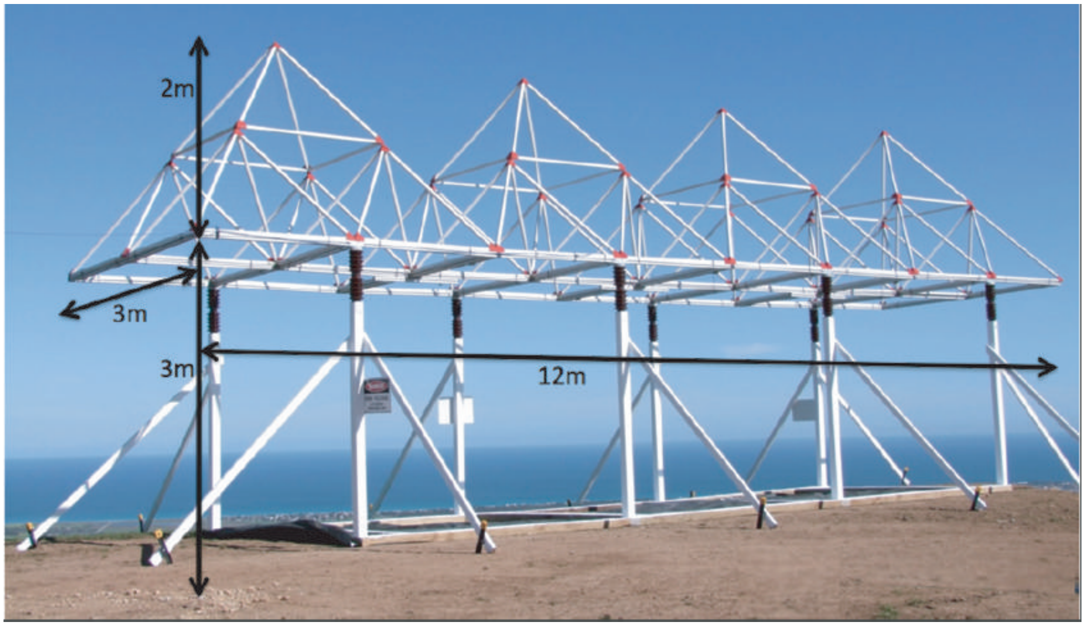

Figure 1. The Atlant Site in South Australia.

drop surfaces prevents coalescence. At small separation distances, the significance of electrostatic forces between the drops increase markedly. In the case of drops of opposite charge, or a charged and neutral drop, the electrostatic forces cause the viscous forces provided by surface tension and thin film of separating air to be overcome more readily, resulting in a higher portion of collisions resulting in coalescence and less bounce (Ochs and Czys 1988). Counterintuitively, this may also occur for drops of the same polarity. As two drops with same polarity of net charge get very close together, the drop with the largest charge can induce the opposite charge on the near surface of the other (Sartor and Abbot 1972). However, this requires very large charges on one of the drops, and must overcome initial repulsive electrostatic force.

Many questions remain to be answered about the underlying processes; however, based on current understanding, the working hypothesis is outlined below:

1. Initially, negative ions are generated from a high-voltage corona discharge wire array.
2. The ions will be conveyed to the higher atmosphere by wind, atmospheric convection and turbulence.
3. The ions become attached to particles in the atmosphere (especially soluble particles), which later act as cloud condensation nuclei (CCN).
4. The electric charges on these particles will be transferred to cloud droplets.
5. The increase in cloud droplet charge enhances coalescence, resulting in enhanced rain drop growth rate and ultimately increasing rainfall downwind from the Atlant.

Two key points relevant to a field evaluation under this model of the Atlant system are that the area of influence is:

- unique to orographic conditions at the site; and
- dynamically defined, depending primarily on wind speed and direction.

2.4 Summary of Previous Trials

2.4.1 Wivenhoe Dam

In May-June 2007, Australian Rain Technologies Pty. Ltd. funded a pilot study trial of the technology in southeast Queensland, closely monitored and evaluated by a team from the University of Queensland (UQ), led by Professor Jurg Keller, Head of the university's Advanced Water Management Centre. The area of influence was defined as the combined catchment area of the Wivenhoe, Somerset and North Pine dams. The control area was defined as that part of the wider study area outside the area of influence. The study used direct measurements of rainfall through official Bureau of Meteorology (BOM) stations and an additional 50 University of Queensland measurement stations installed in the area of hypothesized influence. Comparison of monthly rainfall amounts over the trial period inside and outside the area of influence were made and compared to historic values for the same month over the past 50 years. The results were positive and showed that average rainfall in the catchment area was increased by 28% (Keller *et al*. 2008). Also noted was unusual intensification of radar returns downwind of Atlant that appeared to be correlated with increases in rainfall.

2.4.2 Paradise Dam

From January 2008 until May 2008, the Atlant was trialed over the Wide Bay and Burnett district in Queensland, targeting a 70km circle centered on Paradise Dam, southwest of Bundaberg, again monitored by an evaluation team from the University of Queensland (UQ). Two external control areas, one to the north near Gladstone and the other to the south near Gympie, were selected as they were well outside any potential influence of the Atlant system but had similar historical rainfall patterns. Rainfall gauges were located uniformly in the target and control areas. In the target area 26% more rainfall was recorded than in control areas in 2008, whereas the long-term average rainfall difference only represents 3% of the value recorded in the control areas (Keller *et al*. 2008).

2.4.3 Initial Spatial Analysis

Beare and Chambers (2009) used data from the Paradise Dam trial to conduct an exploratory spatial analysis using daily rainfall data from individual rain gauges within the control and target areas. Random effects models were fitted to daily gauge data. Separate control and effects models were estimated to identify a potential effect of the Atlant (from here on, any potential effect of the Atlant will be referred to as the Atlant effect). The analysis also made use of dynamically specified partitions within the target area, determined by gauge location in relation to distance from the Atlant site and relative to wind direction (derived from daily vertical wind profiles). For example, a gauge 20km from the Atlant site may be directly downwind one day and at a crosswind angle the next. The directional analysis reflects the postulated downwind effect of the ion plume generated by the Atlant system.

The key findings from spatial analysis of the Paradise Dam trial data were that:

- the operation of Atlant was not associated with a significant increase or decrease in the probability of observing a rainfall event in the target area;
- given there was a rainfall event in the area of influence the operation of the Atlant system was associated with a significant and directional impact on rainfall. Within a 30° arc extending 70km downwind of the Atlant site, rainfall was estimated to be 17.6% higher. The effect was significant at the 99% confidence level. The effect was calculated as the predicted difference in rainfall between the control and effects model within and outside the downwind arc;
- the estimated Atlant effects in the areas upwind and crosswind of the site were not significant at the 90%-confidence level.

There were a number of issues raised with regard to the exploratory analysis. They included:

- the need to include an expanded set of meteorological and geographic covariates into the model, such as temperature, humidity and gauge elevation;
- eliminating the use of subjective criteria for determining when and for how long the system was operated; and
- explicitly accounting for spatial correlation between rain gauges when calculating standard errors of the estimated rainfall attributed to the Atlant system.

These issues were addressed in the 2008 Mount Lofty ranges trial.

3. DESIGN OF THE 2008 MOUNT LOFTY RANGES TRIAL

3.1 Site Location and Trial Area

The Atlant emitter was situated 44km south-southwest of Adelaide, South Australia, approximately 7km inland, on the first significant ridgeline of the southeast Mount Lofty Ranges (Figure 2). A successful trial had the potential to significantly augment supplies in this region, which had experienced an extended period of well below average rainfall, creating water shortages for commercial, urban users and the environment. The region has a Mediterranean climate, and generally experiences a dry and warmer period from November to April with prevailing trade wind from the southeast to east and a moderately wet and colder period from May to October with prevailing wind from the northwest to southwest with regular cold fronts (BOM 2008). The ranges are oriented northeast to southwest, and expose the Atlant to the prevailing weather during the trial period, typically from the west. The site was located at an elevation of 348m above sea level and has significant upslope valleys located to the west and northwest. The landform elevation rises from the coast travelling from west to east at a 1.1%

rise while the final 4.3km distance travelling east is a steeper 12.3% rise for 2.1km and the last 200m a very steep 21.7%. Typically, a moist marine onshore airflow from the west rises as it approaches the Atlant site due to orographic lifting.

In a previous trial, the University of Queensland estimated the probable area of influence of a single Atlant emitter to be within a range of 50-100km from the Atlant site, depending on the meteorological situation (Keller *et al.* 2007). However, prior to this trial the potential downwind extent of the Atlant footprint had not been statistically evaluated. Given the topography of the region, identifying an external control area would be difficult because the meteorological and topographic characteristics of neighboring areas are quite different from the trial area. When compared with the trial area, the land area to the north and east is relatively flat and dry, and the influence of offshore cold fronts on precipitation is not nearly as strong.

Figure 2. Land and water mass within a 100km radius about the trial site.

3.2 Trial Area Cloud

The incidence of cloud and rain in the trial area occur in association with frontal systems originating from low-pressure centres over ocean to the south of the trial area. On average they pass west to east approximately every 4-6 days during the trial period. Typically prefrontal altostratus moves in from the northwest and is replaced on the passage of the front by large cumulus degenerating to smaller cumulus coming from the west and southwest, stretching up to 200-300 km behind the boundary. The cumulus cloud bases average 500-1,000 meters with cloud top temperatures between 1 and -2°C. Eventually the weather clears from the west as the next high pressure system approaches. Freezing levels during August and September in the Adelaide Hills region will be in the 2,000-2,500 meter range rising to 4,000 meters and above in November. Typically post-frontal clouds are formed in a maritime air stream, below the freezing level and as such rain formed predominantly by the coalescence process. Based on the working hypothesis for how Atlant may modify the rain process, it was thought that cumulus and stratocumulus behind the frontal boundary would be most suitable for enhancement. However, as the technology is cheap to operate and suitable operating conditions not well defined, the operating protocol (described in section 3.3) was purposefully set to be very wide ranging to encompass the majority of cloud types including pre-frontal deep stratiform clouds which extend above the freezing level and likely produce rain by an ice-nucleation mechanism.

3.3 Operating Schedule

The trial ran for four months, from 9am on 1 August 2008 to 9am 1 December 2008, and was subject to an operating protocol. In particular, the operation of the Atlant technology was controlled by a team of meteorologists following a pre-described set of guidelines, which specified the meteorological parameters under which the Atlant system would be switched on. The main parameter for operation was forecast or observed significant cloud cover within the trial area (cloud depth of greater than 1km at any level in the atmosphere). The Atlant was operated three hours prior to the development or arrival of significant cloud cover within the trial area to ensure the Atlant-produced ions had sufficient time to disperse throughout the trial area through natural processes (wind, turbulence and convection). In some circumstances this lead-time was shorter than anticipated due to more rapid cloud development (on the order of 30 minutes). Significant cloud cover was typically inferred from model forecasts of wind, stability and moisture profiles as well as weather observations. Actual vertical profiles of the atmosphere taken at Adelaide Airport provided by the Australian Bureau of Meteorology (BOM) were used as a verification tool, as well as remotely sensed data from satellites. Operation of Atlant continued for a period of two hours after cloud had dissipated from the trial area. In the non-operating times, necessary system maintenance was conducted. Under some circumstances planned operation was not possible due to severe weather conditions or when the system was inoperable due to technical faults and damage.

3.4 Rainfall Data

The BOM maintains an extensive rain gauge and weather station network within the trial area. There were 159 BOM gauges that reported data during the trial period. Of these, 79 had daily rainfall data for the trial period (August to November) for the ten years 1999-2008. These gauges are referred to as historical BOM gauges in what follows. The BOM gauge data was supplemented by 54 ART weather stations that were programmed to record precipitation at 12-hourly intervals at 9am and 9pm daily. Figure 3 is a contour plot of gauge elevation for all 213 gauges that contributed data to the trial. The locations of the 79 historical gauges are identified in blue and the Atlant site location is shown as the intersection of the lines running north-south and east-west.

There were a substantial number of missing records as some gauges failed intermittently. The ART gauges were not in place until September 2008 and some were lost through the balance of the trial. On the basis of the records that were available, there were 7,915 'rain events' (gauge-days with rain) and 12,006 gauge-days with no rain recorded over the trial period. One of these, an isolated reading of 131.8mm on August 13 for the Inglewood Alert gauge, was excluded from the subsequent analysis. The distribution of daily rainfall observations in the trial area was strongly right skewed. Raw observations were therefore transformed using the natural logarithm. Since the logarithm of zero is not defined, this automatically resulted in the analysis being confined, for each gauge, to days when rainfall was recorded. In what follows, this transformed value is referred to as *LogRain*. The percentiles of distributions of *LogRain* from August though November 2008, is shown in Table 1.

It is reasonably clear that distributions of rainfall over the trial period for the historical and remaining gauges are not similar, highlighting the lack of geographic stationarity within the trial area. The mean and the median of the historical gauges are considerably higher than the corresponding mean and median of the remaining gauges and the inter-quartile range (25% to 75%) of the *LogRain* distribution for the historical gauges is wider than the corresponding range of the *LogRain* distribution for the remaining gauges. Consequently, we cannot use 1999-2007 rainfalls for the historical gauges as a temporal control for the 2008 rainfall observed in the trial.

Table 1. Percentiles of distributions of LogRain for the historical and the remaining trial rain gauges, August–November 2008.

Percentile	Historical gauges	Remaining gauges
100.0%	3.311	4.881
97.5%	2.653	2.625
90.0%	2.104	2.054
75.0%	1.569	1.435
50.0%	0.742	0.588
25.0%	-0.223	-0.511
10.0%	-0.916	-1.609
2.5%	-1.609	-1.609
0.0%	-2.708	-2.303
Mean	0.647	0.460
Std Dev	1.170	1.251
No. of Records	3399	4516

3.5 Secondary Data

Secondary data was obtained from the BOM. The data sets include daily meteorological observations from Adelaide airport and the location and elevation

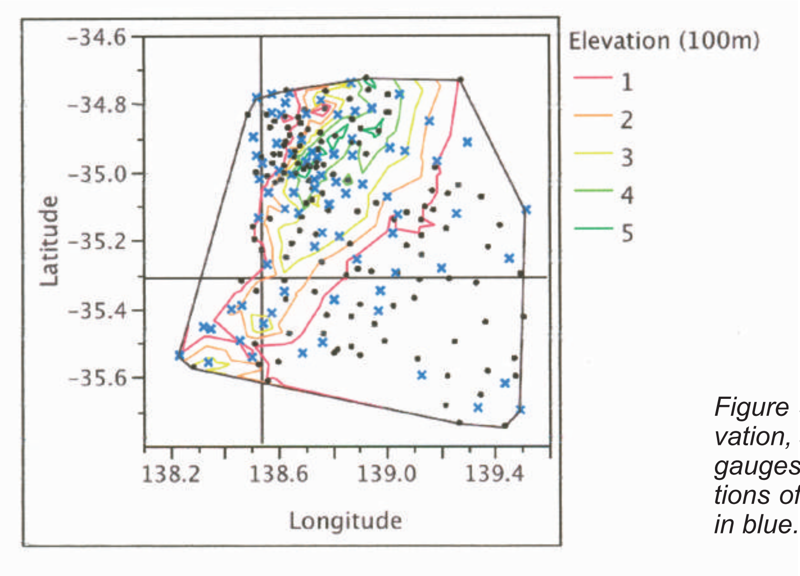

Figure 3. Contour plot of gauge elevation, showing spatial distribution of gauges across the trial area. Locations of historical gauges are shown in blue.

of BOM rainfall gauges. (The location and elevation of ART rain gauges were obtained using a handheld GPS receiver.) Observations from Adelaide airport were available from 1999 through 2008. The observations were calculated as daily averages and included:

- wind speed (km/h) with separate readings at 500hPa, 700hPa and 850hPa;
- wind direction (degrees from due north, clockwise) with separate readings at 500hPa, 700hPa and 850hPa;
- air temperature;
- dew point temperature;
- mean sea level pressure.

Steering winds are associated with the general direction and speed in which clouds are moving and will vary with the height of the cloud layer(s). Steering wind direction and speed were approximated by an average of the 500hPa, 700hPa and 850hPa readings. The distributions of daily steering wind direction and speed for August–November 2008 on rain days, i.e. days when rain was recorded for at least one of the gauges in the trial area, are shown in Figure 4. Note the small variation in the steering wind direction distribution, with virtually all the readings concentrated in the SW quadrant (180° - 270°).

Over the 24-hour period in which rainfall was measured, wind direction and speed will vary. Consequently, the boundaries of any downwind effect will be fuzzy. However, steering wind directions on rain days in the trial period did fall within a limited range (Figure 4) and variation in wind direction and speed would be expected to be less within a 24-hour period. As a consequence, the number of rainfall gauges which are downwind of the Atlant site for at least part of a day is likely to fall within an even more limited range. Observations of vertical wind profiles at Adelaide airport are available on a six-hourly basis. The adjusted daily ranges in wind direction (i.e. the range in the absolute values of wind direction minus 180°) were therefore calculated on a 9am to 9am basis. The distributions of these adjusted daily ranges of wind directions at 700hPa and 850hPa over the trial period are shown in Figure 5.

4. HISTORICAL OROGRAPHIC ANALYSIS

A historical orographic analysis was conducted by fitting a random intercepts linear model to *LogRain* values from August–November for each of the years 1999-2008 for the historical gauges. This is a model of the form:

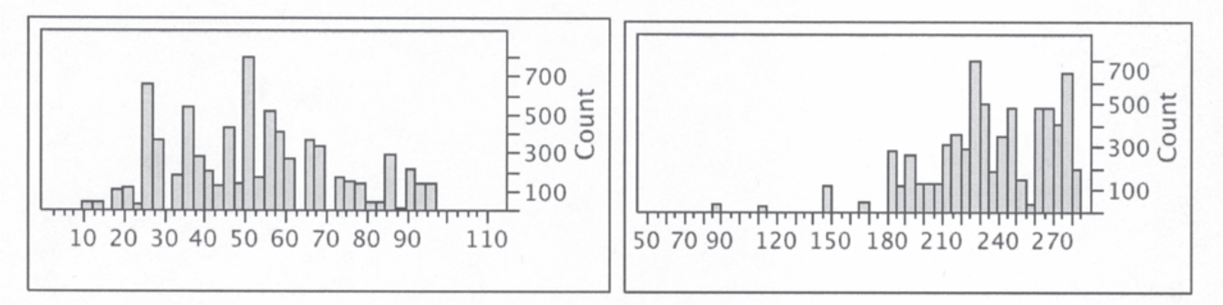

Figure 4. Gauge values of daily steering wind speed (left) and wind direction (right) on rain days.

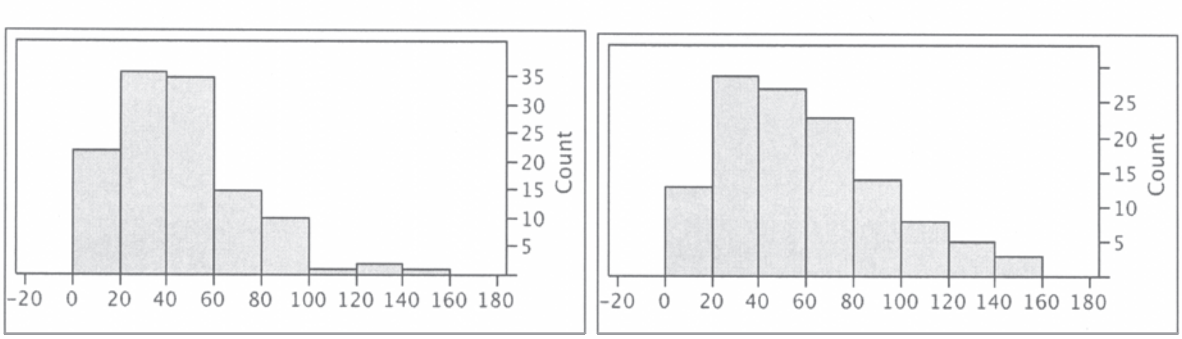

Figure 5. Distributions of the adjusted daily range in wind directions over the trial period at 700 hPa (left) and 850 hPa (right).

$$LogRain_{it} = \alpha^T x_i + \beta^T y_t + \gamma_i + \varepsilon_{it} \qquad (1)$$

where *i* denotes gauges and *t* denotes the day within a year, α and β are coefficient vectors, *x* is a vector of orographic covariates that are specific to gauge locations, *y* is vector of meteorological covariates that vary over time, γ is a vector of gauge specific random effects and ε is a random error that varies between gauges and over days. The choice of a random intercepts model allows for an unobserved or unmeasured time invariant independent of orographic effects at each gauge site. The overall orographic effect in the model is therefore a linear combination of what can be explained by the orographic covariates and this gauge specific random effect:

$$\alpha^T x_i + \gamma_i. \qquad (2)$$

Two issues arose when attempting to control for the influence of orographic effects on rainfall. These were:

- the predominant southwest wind direction and the topography of the Mount Lofty ranges, which gives rise to a strong declining rainfall gradient extending from west to east across the trial area; and
- the potential interaction between meteorological conditions, particularly wind speed and direction, topography and rainfall. That is, the distribution of gauge specific random effects in the model may vary from day to day.

While elevation is an obvious orographic covariate, the elevation of a gauge may not provide much information about the neighboring topography. Geographic location can also serve as proxy for orographic influences in the vicinity of a gauge. This can be controlled for by the inclusion of a factor in the rainfall model (1) that allows a different average rainfall to be observed in different parts of the trial area, though it leaves open questions concerning the shape and size of these sub-areas. In the results shown below we divided the trial area into nine sub-areas based on gauge locations. Figure 6 is a contour plot of gauge elevation for the 79 historical gauges, showing nine sub-areas (dotted lines) as well as the location of the Atlant site (intersection of the solid lines). The estimated orographic effect for a particular gauge is then a function of its elevation and the sub-area in which it is located. Operationally, the nine sub-areas shown in Figure 6 are defined in terms of the cross-classification of three latitude and three longitude zones:

- Southern Latitude Zone (SLaZ):
  Latitude < -35.3
- Middle Latitude Zone (MLaZ):
  -35.3 ≤ Latitude < -35.0
- Northern Latitude Zone (NLaZ):
  Latitude ≥ -35.0
- Western Longitude Zone (WLoZ):
  Longitude < 138.6

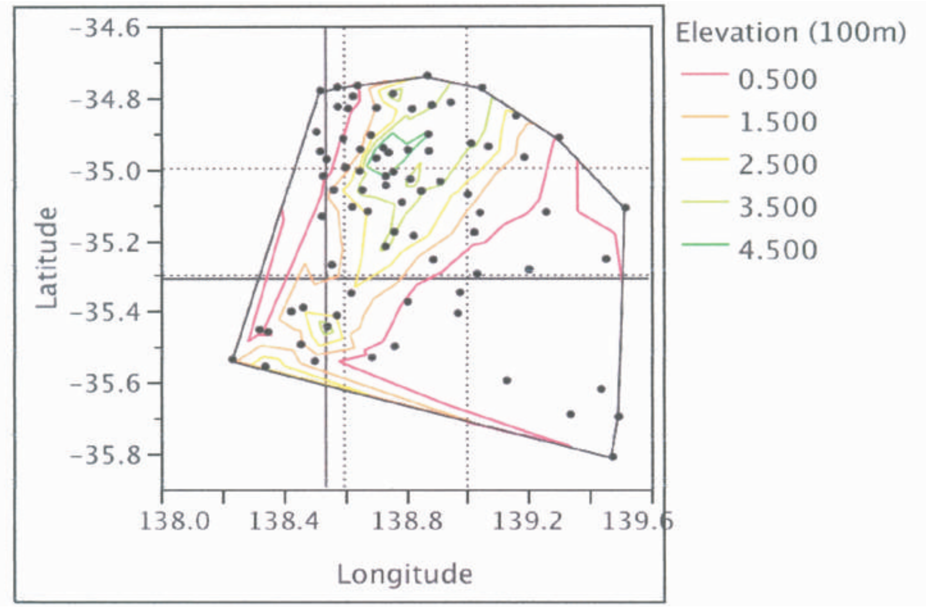

Figure 6. Contour plot of gauge elevation showing locations of 79 historical gauges within the nine sub-areas, as well as relation to the Atlant site (intersection of solid lines).

- Middle Longitude Zone (MLoZ):
  $138.6 \leq \text{Longitude} < 139.0$
- Eastern Longitude Zone (ELoZ):
  $\text{Longitude} \geq 139.0$.

The model was fitted for each year from 1999 though 2008 using rainfall and meteorological data for the months of August through November. The model-fitting method was Restricted Maximum Likelihood (REML) (Patterson and Thompson 1971) and the resulting fits are summarized in Table 2. Estimates that are significant at the 5% level are bolded. The variability in the significant coefficient estimates from year to year provides an indication of the lack of temporal stationarity in the data. Seasonal effects, which are represented by an indicator variable that takes on the value of one in a given month and zero otherwise, are significant in each year. The effects of elevation are also significant in each year. The majority of the metrological covariates are significant, including meteorological conditions on the previous day. The lagged meteorological covariates were included as a proxy for persistent conditions that were not measured directly. The sub-area effects are generally not significant at the 95% confidence level, indicating that at this level of spatial aggregation of gauge locations, elevation accounts for most of the variation in rainfall explained by the fixed orographic effects within the model.

Table 2. Parameter estimates for year-specific models for LogRain with random gauge effects (bolded text indicates significant at 5% level, L1 denotes a one day lag).

Term	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Intercept	**56.08**	**25.81**	**65.98**	**68.95**	**59.64**	**32.49**	**79.96**	**21.76**	**38.57**	**32.52**
August	**-0.498**	**0.230**	**-0.314**	**-0.137**	**-0.019**	**-0.329**	**-0.062**	**-0.262**	**-0.725**	**0.429**
September	**-0.173**	**-0.514**	**0.121**	**0.018**	**-0.273**	**-0.285**	**-0.332**	**0.261**	**-0.040**	**-0.034**
October	**0.126**	**0.283**	**-0.070**	**-0.349**	**0.060**	**0.135**	**0.067**	**-0.114**	**0.004**	**-0.457**
Elevation (100m)	**0.095**	**0.102**	**0.112**	**0.119**	**0.118**	**0.093**	**0.131**	**0.094**	**0.084**	**0.084**
Geographic Zone SLaZ	0.000	0.075	0.033	**0.164**	0.069	**0.080**	0.033	0.006	**0.237**	**0.141**
Geographic Zone MLaZ	-0.022	-0.015	-0.004	0.076	0.020	0.026	0.047	0.067	**-0.081**	0.014
Geographic Zone WLoZ	0.061	0.100	**0.119**	**0.118**	0.026	0.047	**0.161**	0.063	0.057	0.005
Geographic Zone MLoZ	0.011	-0.007	0.074	**0.132**	0.030	0.068	0.075	**0.117**	**0.118**	0.068
SLaZ & WLoZ	-0.027	0.005	0.008	-0.051	-0.040	**-0.126**	-0.004	0.060	-0.046	-0.014
SLaZ & MLoZ	0.026	**-0.152**	-0.108	-0.128	-0.012	-0.099	-0.042	0.016	**-0.133**	0.007
MLaZ & WLoZ	0.061	0.137	0.093	0.013	0.148	0.081	0.033	0.014	0.105	0.059
MLaZ & MLoZ	-0.081	0.035	0.002	-0.020	-0.043	-0.052	-0.007	-0.034	0.027	-0.051
Wind Speed 500	**0.011**	**-0.012**	0.002	-0.002	**0.004**	**0.009**	**-0.010**	**0.006**	**-0.010**	-0.002
Wind Speed 500 L1	0.001	**-0.005**	**-0.008**	0.001	0.000	0.012	**0.009**	**0.007**	**0.018**	**0.004**
Wind Direction 500	**-0.007**	**0.003**	**-0.006**	-0.002	**0.006**	**0.006**	**-0.002**	**-0.007**	**0.029**	**-0.006**
Wind Direction 500 L1	**0.003**	**0.003**	**0.004**	0.011	**0.007**	-0.001	0.001	**-0.005**	**-0.005**	**0.007**
Wind Speed 700	**-0.030**	**0.034**	**0.005**	-0.022	**-0.009**	**-0.017**	**0.010**	**-0.019**	0.002	0.002
Wind Speed 700 L1	**-0.023**	**-0.013**	**-0.015**	0.003	**-0.005**	**-0.034**	**-0.014**	**-0.008**	**-0.039**	**-0.016**
Wind Direction 700	**-0.004**	0.000	-0.002	-0.001	**-0.010w**	**-0.010**	**-0.007**	0.004	**-0.031**	0.001
Wind Direction 700 L1	0.001	**-0.006**	**0.005**	**-0.002**	**-0.004**	**0.011**	**0.009**	**0.010**	**0.013**	**0.004**
Wind Speed 850	**0.037**	**0.008**	**-0.004**	**0.037**	**0.011**	**0.021**	0.003	**0.032**	**0.028**	-0.001
Wind Speed 850 L1	**0.048**	**0.042**	**0.053**	**0.013**	**0.019**	**0.041**	**0.030**	**0.016**	**0.023**	**0.024**
Wind Direction 850	**-0.002**	**-0.011**	**-0.002**	**-0.007**	**-0.002**	**0.001**	0.000	-0.001	0.000	**0.001**
Wind Direction 850 L1	**0.001**	**0.007**	**-0.001**	**0.003**	0.000	-0.004	**-0.009**	-0.001	**0.001**	**-0.002**
Air Temperature	**-0.207**	**-0.093**	**-0.200**	**-0.175**	**-0.189**	**-0.250**	**-0.237**	**-0.144**	**-0.306**	**-0.145**
Dew Point	**0.132**	**0.082**	**0.072**	**0.084**	**0.126**	**0.071**	**0.181**	**0.092**	**0.085**	0.017
Sea Level Pressure	**-0.052**	**-0.026**	**-0.063**	**-0.067**	**-0.057**	**-0.031**	**-0.075**	**-0.021**	**-0.037**	**-0.032**
R-Squared	49.4%	48.2%	44.4%	44.8%	33.1%	50.0%	46.5%	39.0%	47.4%	33.9%
Random Effects	3.1%	2.9%	2.9%	4.9%	3.4%	1.8%	2.1%	3.7%	1.5%	2.3%
Residual Effects	96.9%	97.1%	97.1%	95.1%	96.4%	98.2%	97.9%	96.3%	98.5%	97.7%

The summary statistics include the percentage of variation in rainfall accounted for by all the covariates in the model (R-Squared). The unexplained variation is decomposed into the percentage attributed to random gauge effects and a residual balance. On average the model explains over 43.7% of the gauge level variation in *LogRain*. The random gauge effects (estimated via REML) account for approximately 3% of the unexplained variation in gauge level rainfall, on average. This indicates that any fixed independent orographic effects that are not captured by the orographic covariates included in the model are relatively small. It also suggests that elevation captures the majority of the fixed orographic effects and that a finer regional resolution would not greatly improve the model specification.

Non-fixed orographic effects

By fitting the model each year we can see how stable the estimated orographic effects are. This is important because the distributions of wind speed, wind direction and other meteorological variables vary from year to year. A lack of stability would suggest that orographic effects are dependent on prevailing meteorological conditions. The order of magnitude of the estimated elevation coefficient in the model is stable over time but the estimates do range from a low of 0.084 to a high of 0.131 with an average over the 10 years of 0.103. The individual coefficient estimates for the sub-area covariate vary significantly between years. This was confirmed by fitting a model in which the estimates of the orographic effects were constrained to be the same in each year. This model was clearly rejected in favor of a model that allowed the effects to vary between years.

As the estimated orographic effects, assumed to be fixed within a year, vary over time, the random effects model does not fully control for potential orographic influences. This does imply a significant increase in rainfall could be observed relative to an arbitrary location due to unaccounted-for orographic effects. That is, the choice of the Atlant site could matter. Looking at the variation in the random effects provides some insight about the strength of these effects. By construction the random gauge effects have a mean of zero in any given year. The variance of the random effects is not constant and, while the variance of the random effects is a small proportion of the total variance in *LogRain*, it is still related to the mean as well as the variance of actual rainfall. In standard mean and variance notation:

$$\mu_{Rain} = \exp\{\mu_{LogRain} + 1/2(\sigma^2_{RandomEffect} + \sigma^2_{Residual})\} \quad (3)$$

The mean level effect on rainfall of the variance of the random effects for *LogRain*, expressed in percentage terms, is simply:

$$mean\ effect = 100\,\{\exp(1/2\sigma^2_{RandomEffect}) - 1\} \quad (4)$$

Over the 10-year period the mean effect on observed rain ranged from 0.7% to 2.2%. Again the range of these effects is small.

5. ANALYSIS OF THE ATLANT TRIAL

The analysis of the trial data was carried out in three stages. First, a descriptive analysis was used to investigate marginal relationships between observed rainfall and wind direction, elevation, location and distance from the Atlant site. The purpose of this analysis was to examine evidence for an apparent Atlant effect in the raw data. Second, a statistical model for *LogRain* that simultaneously controlled for gauge-to-gauge and day-to-day variation in meteorological and orographic covariates was fitted to gauge-day data in order to estimate the influence of the Atlant system on rainfall after accounting for these factors. In the final stage, the level of Atlant-induced rainfall enhancement achieved during the trial was estimated.

5.1 Descriptive Analysis

The Atlant system generates a passive plume of ions that relies on the uplift at the site and low-level atmospheric turbulence to carry charged particles to the cloud layer. The conveyance model is analogous to a cold plume emitted from a point source. This leads to the following hypotheses regarding the enhancement effect:

- the primary effect will be downwind of the Atlant site;
- the effect will dissipate laterally and in the downwind direction as the concentration of the particles or aerosols within the plume declines; and
- the rate of lateral versus downwind dissipation is likely to be influenced by wind speed.

The adjusted daily range in wind direction tends to be 120° or less, particularly in the higher elevation winds. We therefore took a 120° arc centered about the average daily steering wind direction and extending downwind from the Atlant site as defining the extent of the downwind area of Atlant effect within the trial area. We defined for any day that rain was recorded at any gauge:

- Downwind Rain = recorded daily rain for gauge when it is within this 120° arc on the day, otherwise missing;

- Cross/Upwind Rain = recorded daily rain for gauge when it is not within this 120° arc on the day, otherwise missing.

Averages and medians of non-missing gauge-day values of Downwind Rain and Cross/Upwind Rain over both a 24h and a 48h period were then calculated for four different levels of intensity of Atlant operation over the preceding 48h, defined by allocating each rain day of the trial to one of the following groups:

- Atlant operational between 0 and 12h in the preceding 48h;
- Atlant operational between 12 and 24h in the preceding 48h;
- Atlant operational between 24 and 36h in the preceding 48h;
- Atlant operational between 36 and 48h in the preceding 48h.

Values of these averages and medians are shown in Table 3. In general, increased hours of Atlant operation are associated with an increase in Downwind Rain relative to Cross/Upwind Rain. The pattern is reasonably consistent for rainfall values measured over both 24h and 48h periods. The median level differences in Downwind Rain versus Cross/Upwind Rain are larger, in percentage terms, than the mean level differences. This suggests that the observed differences are not simply due to a few large outlying observations.

In the previous table, the set of downwind gauges (i.e. those inside the 120° arc centered about the average daily steering wind direction and extending downwind from the Atlant site) changes from day to day; a downwind gauge one day can be a cross/upwind gauge on another day. In what follows we therefore compare a fixed set of gauges based on the percentage of rain days that they are downwind gauges. A contour plot showing the spatial distribution of these downwind percentages for all 213 of the gauges involved in the trial is shown in Figure 7. This is consistent with the location of Atlant and the general SW to NE wind directions observed over the trial period.

Each gauge in the trial area was classified into one of three groups based on the frequency with which it was downwind of the Atlant site on rain days:

- less than 30%;
- greater than or equal to 30% but less than or equal to 70%; and
- greater than 70%.

Average and median levels of Downwind Rain and Cross/Upwind Rain over the preceding 24h and 48h were calculated for gauges in each group. These results are summarized in Table 4. Higher rainfall levels are associated with a greater frequency of days that a gauge is located downwind of the Atlant site.

Table 3. Average and median values of 24h and 48h Downwind Rain and Cross/Upwind Rain classified by hours of Atlant system operation in the preceding 48 hours.

Operating Hours	***Obs***	***Average Rainfall (mm)***			***Median Rainfall (mm)***		
		Downwind	***Cross/ Upwind***	***Δ%***	***Downwind***	***Cross/ Upwind***	***Δ%***
Over Preceding 24 hours (9am – 9am)							
0 - 12	732	2.85	3.17	-10.1	2.2	2.6	-15.4
12 - 24	1917	3.04	2.13	42.7	2.0	1.0	100.0
24 - 36	3637	3.64	2.90	25.5	2.2	1.6	37.5
36 - 48	1219	3.75	2.76	35.9	2.2	1.0	120.0
Over Preceding 48 hours (9am – 9am)							
0 - 12	732	4.43	3.96	11.9	2.8	3.4	-17.6
12 - 24	1917	3.92	3.06	28.1	2.2	1.6	37.5
24 - 36	3637	5.57	3.79	47.0	4.0	2.0	100.0
36 - 48	1219	7.78	5.26	47.9	6.2	2.8	121.4

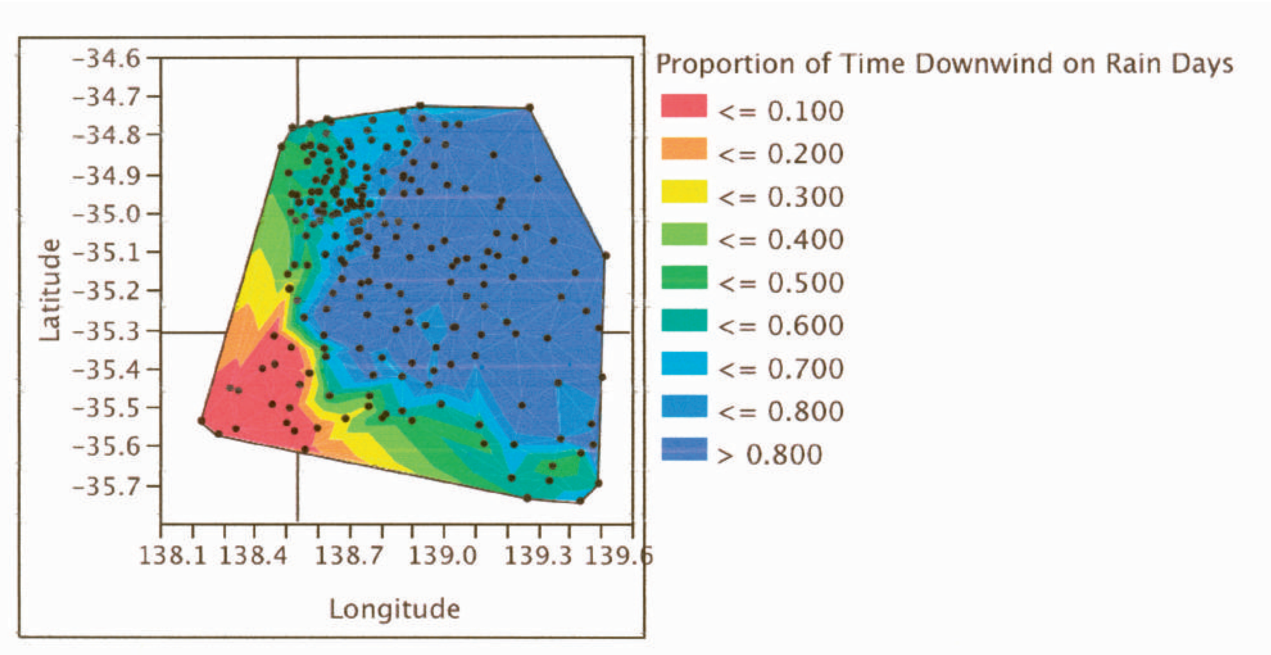

Figure 7. The distribution of gauge locations showing the proportion of rain days that a location was downwind of the Atlant site (identified by intersection of solid lines).

Table 4. Average and median Downwind Rain versus Cross/Upwind Rain for gauges classified by the frequency of rain days that they are downwind of the Atlant site.

Downwind Frequency		***Average Rainfall (mm)***			***Median Rainfall (mm)***		
	Obs	***Downwind***	***Cross/ Upwind***	***Δ%***	***Downwind***	***Cross Upwind***	***Δ%***
24 hours (9am – 9am)							
<30%	20	3.12	3.64	-14.3	2.2	2.07	6.3
30% - 70%	91	3.42	2.44	40.2	2.2	1.35	63.0
>70%	102	3.33	2.28	46.1	2.05	1.55	32.3
48 hours (9am – 9am)							
<30%	20	3.27	6.48	-49.5	2.4	4.68	-48.7
30% - 70%	91	5.06	3.07	64.8	3.38	1.6	111.3
>70%	102	5.28	2.68	97.0	3.4	1.8	88.9

The results displayed in Table 3 and Table 4 can be extended to show how average values of Downwind Rain and Cross/Upwind Rain vary as a continuously distributed variable. Similarly, the distance of the gauge from the Atlant site also varies. In this case we used spline scatterplot smoothers to show how the average values of Downwind Rain and Cross/Upwind Rain vary with this distance. We restrict the analysis to gauges that were downwind of the Atlant site between 30% and 70% of the time. Spline smoothes based on the data for average 24h and 48h rainfall are shown in Figure 8. Note that in both plots the left axis is rainfall in mm and the bottom axis is distance from the Atlant site in degrees (1° = 91km).

Rainfall levels are substantially higher downwind of the site but only over a limited range. The downwind and cross/upwind curves begin to diverge at distances of around 12km downwind. The curves re-converge at about 82km downwind. The effect is more pronounced with 48h rainfall compared with 24h rainfall.

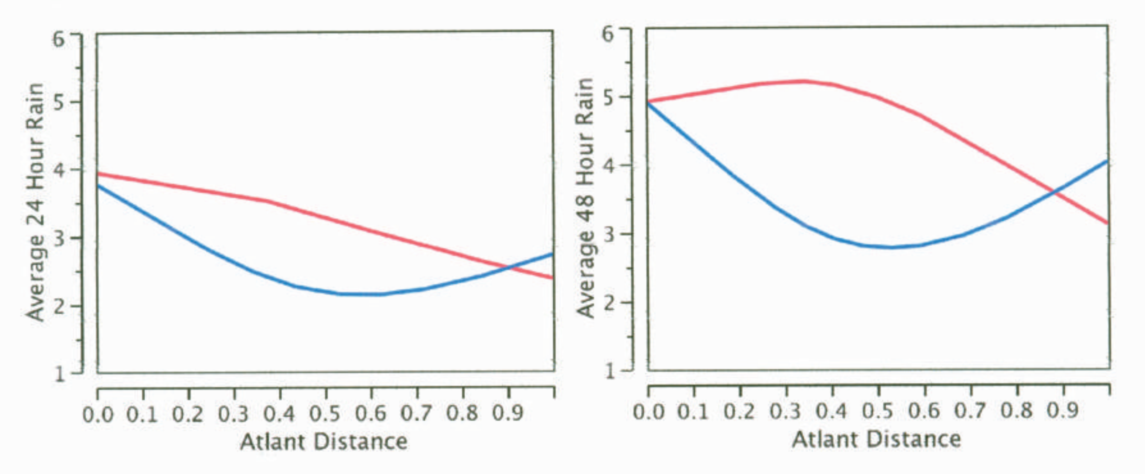

Figure 8. Spline smoothes of average 24h (left) and 48h (right) Downwind Rain and Cross/Upwind Rain as functions of distance from the Atlant site, restricted to gauges that are downwind between 30% and 70% of the time on rain days: Downwind (Cross/Upwind) Rain smooth is in red (blue).

On the basis of the preceding analysis, there appears to be evidence for an association between operation of the Atlant and elevated levels of rainfall. Further, the potential range of the Atlant effect appears to end at around 0.9° or just over 82km. However, we cannot ascribe the differences between Downwind Rain and Cross/Upwind Rain that are evident in our results so far purely to the operation of Atlant. This is because most gauges are downwind of Atlant more than 50% of the time and the orographic effects due to the changing topography of the trial area are from west to east, which was also the most prevalent wind direction. Consequently, before ascribing any differences in rainfall to the operation of Atlant, we must first control for meteorological and orographic effects (particularly gauge elevation, wind direction and wind speed) that also influence the spatial distribution of rainfall. A model for *LogRain* that includes these controls is the focus of the analysis described in the following sub-section.

5.2 Model-based Evaluation

The model (1) for *LogRain* only needs to be modified slightly for the purpose of evaluating the trial data. In particular, we model these data using a random intercepts specification of the form:

$$LogRain_{it} = \alpha^T x_i + \beta^T y_t + \lambda^T z_{it} + \delta^T s_{it} + \gamma_i + \varepsilon_{it} \quad (5)$$

where λ and δ are vectors of coefficients, z is a vector of Atlant covariates and s is vector of dynamically specified gauge locations.

The Atlant covariates included:

- the duration, in hours, that the system was operational in a 24h period, starting at 9am. This corresponds with the daily rainfall measurement period used by the BOM. This covariate was used in lagged form in the model, with values ranging from L0 (operating hours in the 24h period up to 9am on the day) to L6 (operating hours in the 24h period up to 9am six days previously);
- the distance in degrees from a rainfall gauge to the Atlant site.

The dynamic specification of gauge locations was done on the basis of the average daily steering wind direction, and corresponded to a categorical variable that identified the dynamic orientation of each gauge relative to the direction of steering wind flow on the day:

- Wind Flow Sector 1–downwind–the gauge is 30° or less away from the steering wind direction;
- Wind Flow Sector 2–downwind–the gauge is between 30° and 60° away from the steering wind direction;
- Wind Flow Sector 3–crosswind–the gauge is between 60° to 90° away from the steering wind direction;
- Wind Flow Sector 4–crosswind–the gauge is between 90° and 135° away from the steering wind direction; and

- Wind Flow Sector 5–upwind–the gauge is more than 135° away from the steering wind direction.

Note that a gauge is classified as being downwind on a particular day if it is in either in Wind Flow Sector 1 or Wind Flow Sector 2 on the day. The random effects model (1) was then fitted via REML, with results summarized in Table 5.

Overall, the model accounts for nearly 50% of the daily gauge variation in *LogRain*. Consistent with the historical orographic analysis the random effects are small, accounting for only around 4% of the residual variation in *LogRain*. The monthly or seasonal effects are highly significant. As with the historical orographic analysis, gauge elevation is highly significant but the fixed sub-area effects are mainly not significant, and are small compared to the overall average. In general the meteorological covariates are highly significant. The exceptions are the higher-level wind speeds at 500hPa and 700hPa.

The Atlant covariates are generally significant. The effect due to distance from Atlant is negative and significant at the 95% confidence level. The main effects for the first two dynamically defined Wind Flow Sectors, i.e. for the downwind gauge-days, are positive and significant at the 99% level. The main effects for the two sectors corresponding to crosswind gauge-days (Wind Flow Sectors 3 and 4) are not significant. Note that Wind Flow Sector 5 (upwind gauge-days) is the reference group for these estimates, so the coefficient for its main effect (-0.301) is obtained as the negative of the sum of the estimated coefficients of the main effects for the other sectors. Note also that a number of the interactions of distance from the Atlant site (Atlant Distance, measured in degrees) with Wind Flow Sector are significant. These interactions are based on mean corrected Atlant Distance, so the positive signs for their coefficients indicate enhanced rainfall further away from the Atlant site.

The main effects for the Atlant hours of operation (Atlant Hours) are highly significant and exhibit a very pronounced lag structure. This phenomenon was also observed in the second Atlant trial at Paradise Dam (Beare and Chambers 2008). A number of the interactions of Atlant Hours with Atlant Distance are also significant. Since both variables are mean corrected in these interactions, we can see that gauges closer to Atlant benefit more from extended hours of operation of Atlant in the last few days. These lagged effects may be due to the operating rules used to switch the system on and off. These rules were based on forecast and observed cloud cover. To the extent that cloud cover and the conditions on which forecasts are based are linked to cyclical conditions affecting rainfall, a lag effect could be generated. Such effects might also be captured by lagged rainfall. However, the inclusion of lagged rainfall in the model did not substantially improve the model fit or change the Atlant operating hours lag structure.

Lagged operating hours as well as the distance from the Atlant site could serve as a proxy variable for relevant but excluded factors influencing rainfall. The coefficient estimates for the lag and distance covariates may therefore in part capture these proxy effects. The extent of this excluded variable bias is unknown and may be positive or negative. As a check, an alternative model for *LogRain* was fitted which did not include lagged operating hours or distance effects. While this alternative model accounts for less variation in *LogRain*, inferences about the extent of Atlant rain enhancement based on it are not substantially different from corresponding inferences based on the model specified in Table 5.

As gauge-level rainfall is spatially correlated it is reasonable to expect that the residual variation in *LogRain* will also be spatially correlated. As a consequence the '*t*' ratios reported in Table 5 may be overstated. This issue is discussed in more detail below, where we discuss how the model fit specified in Table 5 can be used to estimate the level of Atlant-induced rain enhancement.

5.2.1 Measuring rainfall enhancement

Our aim is to decompose the observed rainfall for a gauge *i* on day *t* when rainfall is observed at the gauge as:

$$\mathit{Observed\ Rainfall}_{it} = \mathit{Latent\ Rainfall}_{it}\,(1 + \mathit{Enhancement\ Effect}_{it}) \qquad (6)$$

Here $\mathit{Latent\ Rainfall}_{it}$ is the natural rainfall that would have been observed at gauge *i* if Atlant had not been operating when rain fell at the gauge on day *t*. Since we cannot observe latent rainfall while the Atlant system is operating, we derive estimates of the log scale values of the components of the decomposition (6) using the model (5). In order to do so we note that (6) implies an additive relationship on the log scale:

$$\mathit{LogRain}_{it} = \mathit{LatentLogRain}_{it} + \mathit{LogAtlantEffect}_{it}. \qquad (7)$$

Here $\mathit{LatentLogRain}_{it}$ is the logarithm of $\mathit{Latent\ Rainfall}_{it}$ and $\mathit{LogAtlantEffect}_{it}$ is the logarithm of 1 + $\mathit{EnhancementEffect}_{it}$. Given that (1) is an appropriate model for log scale latent rainfall, $\mathit{LatentLogRain}_{it}$ is then obtained by eliminating (1) from (5). Equivalently

$$\mathit{LogAtlantEffect}_{it} = \lambda^{T} z_{it} + \delta^{T} s_{it}. \qquad (8)$$

Table 5. Estimated coefficients defining fit of model (5) to the 2008 trial data.

Term	Estimate	t Ratio	Prob>|t|	F Ratio	Prob > F
Intercept	16.982	4.71	<.0001		
Month[8]	0.947	24.20	<.0001	234.07	<.0001
Month[9]	-0.076	-3.23	0.0012		
Month[10]	-0.549	-18.42	<.0001		
SLaZ	0.254	7.85	<.0001	32.96	<.0001
MLaZ	-0.050	-1.57	0.1171		
WLoZ	-0.032	-0.67	0.5011	0.25	0.7810
MLoZ	0.006	0.20	0.8434		
SLaZ & WLoZ	0.034	0.67	0.5041	0.24	0.9202
SLaZ & MLoZ	-0.009	-0.20	0.8419		
MLaZ & WLoZ	-0.004	-0.08	0.9394		
MLaZ & MLoZ	-0.013	-0.34	0.7378		
Elevation (100m)	0.082	5.85	<.0001		
Wind Speed 500	0.000	0.20	0.8388		
Wind Speed 750	-0.001	-0.60	0.5459		
Wind Speed 850	-0.008	-4.37	<.0001		
Wind Speed 500 L1	0.011	11.94	<.0001		
Wind Speed 750 L1	-0.018	-10.26	<.0001		
Wind Speed 850 L1	0.022	14.44	<.0001		
Wind Direction 500	-0.008	-17.50	<.0001		
Wind Direction 750	0.002	4.37	<.0001		
Wind Direction 850	0.002	4.58	<.0001		
Wind Direction 500 L1	0.006	9.96	<.0001		
Wind Direction 750 L1	0.006	9.28	<.0001		
Wind Direction 850 L1	-0.005	-14.59	<.0001		
Air Temperature	-0.098	-10.86	<.0001		
Dew Point Temperature	0.051	6.73	<.0001		
Sea Level Pressure	-0.017	-4.84	<.0001		
Atlant Distance	-0.426	-2.27	0.0239		
Wind Flow Sector 1	0.137	4.63	<.0001	11.17	<.0001
Wind Flow Sector 2	0.174	6.07	<.0001		
Wind Flow Sector 3	0.030	0.99	0.323		
Wind Flow Sector 4	-0.040	-1.15	0.2499		
Atlant Distance * Wind Flow Sector 1	0.016	0.12	0.9052	5.31	0.003
Atlant Distance * Wind Flow Sector 2	0.390	2.92	0.0035		
Atlant Distance * Wind Flow Sector 3	0.493	3.58	0.0003		
Atlant Distance * Wind Flow Sector 4	0.089	0.53	0.5966		

*Note that a highly a significant p-value indicates a low Standard Error. These can be calculated by the ratio of the estimate and the t-ratio.

Table 5 cont. Estimated coefficients defining fit of model (5) to the 2008 trial data.

Term	Estimate	t Ratio	Prob>|t|	F Ratio	Prob > F
Atlant Hours L0	0.030	19.05	<.0001		
Atlant Hours L1	-0.033	-18.57	<.0001		
Atlant Hours L2	-0.016	-10.35	<.0001		
Atlant Hours L3	0.030	19.33	<.0001		
Atlant Hours L4	-0.010	-6.51	<.0001		
Atlant Hours L5	-0.015	-11.27	<.0001		
Atlant Hours L6	-0.008	-4.73	<.0001		
Atlant Hours L0 * Atlant Distance	0.024	3.36	0.0008		
Atlant Hours L1 * Atlant Distance	-0.029	-4.61	<.0001		
Atlant Hours L2 * Atlant Distance	-0.005	-0.75	0.454		
Atlant Hours L3 * Atlant Distance	-0.026	-3.94	<.0001		
Atlant Hours L4 * Atlant Distance	0.010	1.54	0.1243		
Atlant Hours L5 * Atlant Distance	0.019	3.04	0.0023		
Atlant Hours L6 * Atlant Distance	0.007	1.07	0.2825		

Table 5 cont. Estimated coefficients defining fit of model (5) to the 2008 trial data.

Random Effect	**Variance Component**	**Per Cent of Total**
Gauge Location	0.038	4.76
Residual	0.772	95.23

Summary Statistic	**Value**
R-Squared	0.4952
Adjusted R-Squared	0.4916
Root Mean Square Error	0.8785
Observations	7138

We can estimate $LogAtlantEffect_{i,t}$ from the 2008 trial data, by substituting the coefficient values displayed in Table 5 into (8). Since the expected values of $LatentLogRain_{i,t}$ and $LogAtlantEffect_{i,t}$ are not separately identifiable under (7), we force the average value of the estimated log scale Atlant effects defined by (8) to be zero by mean correcting them. This has the effect of moving the expected value of the log scale Atlant effects into the corresponding expected value of the log scale latent rainfall, which is a conservative approach to dealing with this issue. Estimated values of $1+EnhancementEffect_{i,t}$ are then obtained by exponentiation. That is, our estimate of the Atlant enhancement for a particular gauge on a day when rainfall is observed is:

$$Enhancement\ Effect_{it} = k \exp\left(LogAtlantEffect_{it}\right) - 1 \tag{9}$$

The corresponding estimate of Latent Rainfall is obtained from (6) as:

$$LatentRainfall_{it} = k^{-1} \exp\left(-LogAtlantEffect_{it}\right) \times Observed\ Rainfall_{it}. \tag{10}$$

Finally, the estimated increase (or decrease) in rainfall attributed to Atlant at a gauge on a day when rainfall is observed is:

$$Atlant\ Attribution_{it} = Observed\ Rainfall_{it} - Latent\ Rainfall_{it}. \tag{11}$$

The constant *k* in (9) above corrects for the bias that is inherent in using exponentiation to move from log scale rainfall to raw scale rainfall. This bias arises because an effect that changes the mean on the log scale has an asymmetric effect on the variance at the raw scale, understating positive residuals and overstating negative residuals. To make the correction, a simple mean adjustment (*k*) is made so that the mean of the regression predictions when back-transformed from logarithm, equals the mean of the observed rainfall.

The last methodological issue is determining the precision of the total estimated Atlant attribution (11) for domains defined by specified gauge-days. To estimate proper confidence intervals we need to take into account the gauge level correlation in latent rainfall, which includes the variation in rainfall that is not explained by the model. The current procedure used to calculate standard errors is based on an assumption of spatial independence, however. In an attempt to define conservative estimates of the true standard errors, these naïve standard errors were therefore inflated by 100%. Confidence intervals were then calculated on the basis that errors associated with the estimated Atlant attribution are normally distributed. Subsequent bootstrap analysis indicated that the adjustment was conservative, in the sense that the bootstrapped standard errors that took into account spatial correlation, were uniformly smaller than those implicit in Table 5 and stated in Table 6.

5.2.2 The estimated enhancement effect

The estimated enhancement effects described in the previous section were calculated on a gauge by day basis. Table 6 summarizes the corresponding estimates of latent rainfall (10) as well as rainfall attributable to operation of the Atlant system (11) for all gauge-days for which model (6) can be fitted, as well as for those gauge-days corresponding to the downwind and cross/upwind parts of these data. The overall estimated Atlant attribution within the trial area over the trial period is 10.3%. More importantly, nearly all of this is due to enhanced rainfall for gauge-days that are downwind of the Atlant site, which is consistent with the hypothesized wind driven model for how the Atlant system operates. It is also consistent with results of the descriptive analysis presented in section 5.1. The estimated overall downwind attribution (i.e. for a downwind arc of 120°) is 15.8%, with approximate confidence intervals as shown in Figure 9. The 80% confidence bounds range from a low of 13.2% to a high of 18.4%. A contour plot showing the geographic distribution of the enhancement effect is shown in Figure 9. Comparing this with Figure 6, we see that the enhancement effects are reasonably well correlated with the predominant wind direction over the entire trial.

Table 6. The estimated contributioni of Atlant System to rainfall in the trial area.

Scope (No. of Gauge-Days with Rainfall)	Total Observed Rainfall (mm)	Total Latent Rainfall (mm)	Total Atlant Attribution (mm)	Attribution %	Standard Error on Attribution %
All (7138)	22008	19951	2058	10.3	1.6
60º Downwind Arc (2472)	8003	6997	1006	14.4	2.6
120º Downwind Arc (4458)	14792	12771	2021	15.8	2.0
Upwind-Crosswind (2680)	7216	7179	37	0.5	2.4

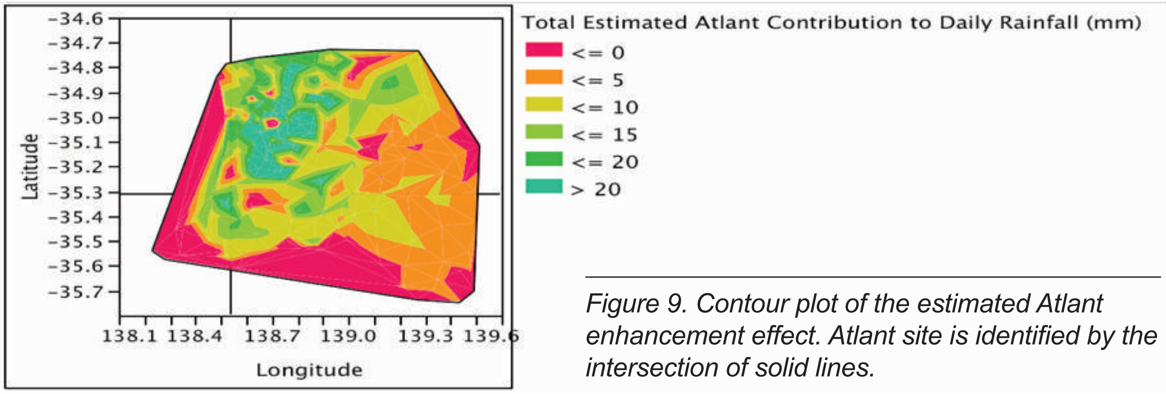

Figure 9. Contour plot of the estimated Atlant enhancement effect. Atlant site is identified by the intersection of solid lines.

6. CONCLUDING COMMENTS

Subject to the caveat that the trial was not randomized in any way, rainfall over the trial period was significantly higher downwind of the Atlant site over periods when the site was in operation. The estimated 15.8% downwind enhancement effect translates into 2,021mm (Table 6). This is the equivalent of an average of 0.4533mm per downwind gauge day.

Comparison of crosswind and downwind rainfall suggests that the observed Atlant effect had a range of approximately 80km. The 120° downwind area, on any given day, was 10,000km^2 or 1,000,000ha. One hundred mm of rainfall falling on one hectare equates to a volume of one megalitre. Given the average of 0.4533mm per downwind gauge day, this equates to 4,588ML per rainfall day. There were 65 days during the trial period where greater than 1mm fell in the trial area. This gives an approximate yield in the downwind area of 298GL for the trial. The corresponding estimate for a 60° downwind arc is a total of 132GL for the trial. This is slightly less than half of the 120° effect as estimated Atlant contribution for this area is slightly lower. However, the difference is not statistically significant (as can be seen in Table 6).

The statistical approach taken reflects two underlying objectives. The first was to establish whether the trial data supported the conclusion that the operation of the Atlant system was associated with a significant increase in rainfall in the trial area. The second was to measure the rainfall that could be attributed to the operation of the Atlant system. The latter objective imposed an important restriction on the analysis as this required interactive effects between the Atlant and meteorological covariates to be excluded. By definition, interactive effects generate joint attribution. It would be reasonable to expect such interactions to exist since the same number of Atlant operating hours should have a different rainfall impact depending on the weather conditions, but this impact should vary depending on the actual number of Atlant operating hours. The inclusion of interactive effects may not only improve the fit of the model but would help to better understand the conditions under which the system operates most effectively. However, by not including interactive effects it was possible to partition the rainfall data into latent rainfall and enhanced rainfall and thus more clearly identify any Atlant effect. If interactive effects were included, then the data would have to be broken into latent, enhanced and mixed rainfall.

In general, the results indicate that operating the Atlant for longer periods (>24hrs) is associated with a larger effect. However, this is only indicative as we had only a small number of observations at shorter operating intervals. While operating the Atlant system and determining when it would be operational at any given time were decided from a set of prescribed guidelines, the fact that they were related to meteorological conditions still generated a sub-optimal experimental design. This may have been justified given the trial had an underlying objective of generating rainfall during a period when there was a critical shortage in the local availability of water resources. Nevertheless, it reduced the extent to which an Atlant Effect could be accurately identified. This trial design issue was addressed in the second South Australian trial, run from August to December 2009.

A randomized trial design was applied to the 2009 trial, where the 2008 Atlant site and a second Atlant site, suitably separated and similar in terms of meteorological and topographic conditions, were operated on a randomly predetermined rotation basis throughout the trial with no breaks. The operation schedule chosen was followed irrespective of any predicted rainfall or meteorological events. The two sites were operated in a randomized asynchronous alternating schedule. One Atlant site was operated on a randomized alternate day on/day off sequence, while the other was operated on a randomized 2-day on/2-day off sequence. The advantage of this approach was to ensure that each combination was scheduled for an equal number of days. Similar statistical modeling analysis to that presented in this paper will be carried out. As in the 2008 trial, the aim of the 2009 trial is not to establish a causal link between operation of Atlant and enhanced rainfall, but rather to concentrate on a more rigorous statistical assessment of any effect of Atlant on rainfall quantity, which will add significant confidence to any results.

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Copies of reports that are not generally available can be obtained by request from the corresponding author.

APPENDIX:
DETERMINING DOWNWIND SECTOR

Each Wind Flow Sector is defined in terms of two distinct arcs of a circle centered at the Atlant site and including all gauges in the trial area. The two arcs that correspond to a particular Wind Flow Sector are of the same length and are symmetrically placed on opposite sides of the radial vector defined by the downwind direction of the daily steering wind flow at the Atlant site. Thus, the arcs defining Wind Flow Sector 1 lie on either side of this vector, those that define Wind Flow Sector 2 lie further along the circle on either side and so on. By combining these arcs sequentially on either side of the radial vector we define a set of increasing segments (wedges), each uniquely defined by an angle θ (measured in radians) relative to the steering wind flow or wind direction, which is itself defined by an angle ω (also measured in radians) relative to due north. A rainfall gauge at a location (*lat*, *long*) is then at an angle θ relative to the direction of wind flow on the day if θ is the angle defining the smallest such wedge that includes the location of the gauge. That is, θ is the smallest value between 0 and π such that both the following conditions hold:

$$\sin(\theta - \omega)\,(lat - lat_A) + \cos(\theta - \omega)\,(long - long_A) < 0$$

$$\sin(\theta + \omega)\,(lat - lat_A) - \cos(\theta + \omega)\,(long - long_A) < 0$$

where lat_A and $long_A$ denote the latitude and longitude respectively of the Atlant site. Note that θ can take any value between 0 and π, so a gauge does not need to be downwind of the Atlant site in a literal sense. For values of θ greater than 135° the gauge is in fact upwind of the Atlant site, while for values of θ between 60° and 135° it can be considered to be located crosswind relative to the Atlant site.

OVERVIEW OF THE QUEENSLAND CLOUD SEEDING RESEARCH PROGRAM

Sarah A. Tessendorf[1*], Roelof T. Bruintjes[1], Courtney E. Weeks[1], Michael Dixon[1],
Matthew Pocernich[1], James W. Wilson[1], Rita D. Roberts[1], Edward A. Brandes[1], Kyoko Ikeda[1],
Charles A. Knight[1], Louise Wilson[2], Justin R. Peter[2,3], Nicole Torosin[1]

[1]National Center for Atmospheric Research, Boulder, CO
[2]Monash University, Melbourne, VIC, Australia
[3]Queensland Climate Change Centre of Excellence, Indooroopilly, QLD, Australia

ABSTRACT. As a response to water shortages in Southeast Queensland brought about by reduced rainfall and increasing population, the Queensland government decided to explore the potential for cloud seeding to enhance rainfall. A cloud seeding feasibility study was conducted in the Southeast Queensland region December 2007–March 2008 and again from October 2008–February 2009. In both seasons of the field effort, radar measurements and in situ aircraft microphysical data were collected and an exploratory randomized seeding study was initiated. Climatology analyses established the weather regimes responsible for the regional rainfall. Results indicate that most deep convection in the region has a strong warm rain formation component, except for early summer storms with higher cloud bases. Initial statistical analyses of the randomized seeding experiment suggest that hygroscopic seeding may potentially increase rainfall, consistent with previous experiments; however, the robustness of the results is limited by the small sample size.

1. INTRODUCTION

Water shortages in Southeast Queensland (SEQ), Australia prompted the Queensland government to seek ways to create more water resources. As a response, the Queensland Cloud Seeding Research Program (CSRP) was conducted to investigate the feasibility of precipitation enhancement via cloud seeding.

Scientists from the National Center for Atmospheric Research (NCAR), the South African Weather Service (SAWS), the University of Witwatersrand (WITS), and Weather Modification Inc. (WMI), in collaboration with the Australian Bureau of Meteorology (BoM), Monash University, the University of Southern Queensland (USQ), the Centre for Australian Weather and Climate Research (CAWCR), and MIPD Pty Ltd, conducted the feasibility study for rainfall enhancement via cloud seeding during the summer rainfall regime. The CSRP feasibility study included a variety of measurement systems, some using novel technologies. A unique component of this study was a dual-polarization, dual-wavelength Doppler weather research radar (CP2). This multi-parameter radar also contributed to dual-Doppler radar coverage. This is noteworthy in that the evolution of microphysical precipitation characteristics, such as particle type, number, and size, within a seeded cloud can be related to the airflow patterns within the cloud.

The potential for man-made increases in precipitation strongly depends on the natural microphysics and dynamics of the clouds that are seeded. Further, these factors can differ significantly from one geographical region to another, as well as during and between seasons in the same region. Hence, an evaluation of the climatology of clouds and precipitation in the SEQ region was a necessary part of this feasibility study. For example, in some instances clouds may not be amenable to seeding, or the frequency of occurrence of suitable clouds may be too low to warrant the investment in an operational cloud seeding program.

Another important part of this feasibility study was to obtain high-quality measurements that pertain to cloud and precipitation processes. Aerosol and microphysical measurements, in particular, help determine if seeding could be beneficial and also what the optimal seeding method would be with regard to enhancing precipitation in local clouds. Thus, microphysical and dynamical studies of naturally forming clouds were an integral part of the study.

Cloud seeding techniques also need to be evaluated using a randomization procedure to demonstrate statistically if the seeding method works to enhance rainfall and to quantify any potential enhancement. The randomized experiment conducted in the Queensland CSRP was exploratory; if the CSRP results indicate that cloud seeding is feasible, then a confirmatory randomized statistical experiment should become the next phase of a future program.

**Corresponding Author*: S.A. Tessendorf, Research Applications Laboratory, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307. saraht@ucar.edu

Typically, the statistical evaluation of cloud seeding experiments has relied on radar-derived precipitation flux, storm water mass, duration, and size. However, the very large natural variability in storms can mask cloud seeding effects. Consequently, a large sample size of randomized seeded and unseeded cases is required to obtain statistical significance at a high confidence level. Even then, in the absence of physical measurements, there is uncertainty in the true understanding of physical mechanisms that were responsible for any seeding effect suggested by the statistical analysis. This project was undertaken in the hopes that through the use of physical measurements, such as from aircraft and a multi-parameter radar, microphysical processes could be more directly observed, making it possible to understand cause and effect seeding relationships, thus not having to solely rely on statistical means that have often generated controversy.

Analysis efforts for the Queensland CSRP were therefore focused on three issues: understanding the weather and climate, characterizing the atmospheric aerosol and its relation to cloud microphysics, and assessing the impact of cloud seeding on microphysical and dynamical processes in clouds to enhance rainfall. The data sets collected in the two field seasons are vast and unique for cloud seeding research, and thus will support a variety of research efforts. The purpose of this paper is to present an overview of the Queensland CSRP experiment. The program design describes the facilities and research goals of the project, as well as some initial climatology results, in Section 2. A summary of the field operations is provided in Section 3, and includes some results from the aircraft measurements and statistical analysis. Section 4 outlines some unique opportunities that utilize the dual-polarization and dual-Doppler radar data, but analysis of these data is still ongoing. Conclusions and future work are summarized in Section 5.

2. PROGRAM DESIGN

The region of Southeast Queensland (SEQ), which includes the city of Brisbane and the Sunshine and Gold Coast regions north and south of the city, was targeted for the field effort (Fig. 1). Two seasons of field operations were conducted to assess the feasibility of both hygroscopic (Mather et al. 1997, Foote and Bruintjes 2000) and glaciogenic (e.g., Rosenfeld and Woodley 1993, Levi and Rosenfeld 1996) cloud seeding methods. Operations took place from December 2007–March 2008 in season one, and from November 2008–February 2009 in season two.

2.1 Facilities

Facilities employed during the Queensland CSRP are key to what made this cloud seeding experiment different from previous experiments. In addition to traditional radar measurements, the Queensland CSRP included dual-polarization, dual-wavelength, and dual-Doppler radar capabilities. Furthermore, an extensive suite of aircraft instrumentation was used to collect in situ cloud microphysical and aerosol measurements, and disdrometers were deployed at the surface to aid in radar calibration. Each element of the field effort is described in more detail in the following sections.

Figure 1. Map of Southeast Queensland region targeted for the Queensland CSRP field effort and associated facilities and landmarks. The 30-degree beam crossing angle dual-Doppler lobes are overlaid in black.

2.1.1 Radar

The Australian Bureau of Meteorology (BoM) operates a network of surveillance weather radars in the SEQ region (Table 1). Most of these weather radars operate at 10 cm (S-band) wavelength and complete a volume scan every 10 min. The Marburg and Mt Stapylton radars are the two radars closest to the CSRP operations (Fig. 1). The Mt Stapylton radar also has Doppler capabilities and is the only network radar that operates on a 6-min volume scan cycle. Data from the five BoM network radars described in Table 1 were merged into a mosaic reflectivity product, which provided coverage over the full SEQ region.

The CP2 radar, originally developed and owned by NCAR, was obtained by the BoM in 2007 and installed at Redbank Plains to the southwest of

Brisbane (Fig. 1; Keenan et al. 2006). CP2 is actually two co-located radars, the main radar being an S-band (10 cm) unit and the smaller radar being an X-band (3 cm) unit. The X-band antenna piggybacks on the main S-band antenna (Fig. 2b) and is designed to view the same sample volume as the S-band radar. The technical characteristics of CP2 are described by Bringi and Hendry (1990).

The CP2 radar scanning strategies for the Queensland CSRP were designed to meet three main objectives: (1) obtain statistics of rainfall in SEQ storms, (2) monitor storm microphysical characteristics in support of in situ observations, and (3) gather sufficient observations of precipitation initiation in both seeded and unseeded storms to document the evolution of microphysical precipitation formation processes in these storms. The BoM network radars operated in a regular volume scanning mode (full 360 degree azimuth scans) and as such provided adequate data for statistical rainfall studies (Objective 1). Special CP2 scanning strategies were designed to meet the remaining radar objectives.

Table 1. General specifications for the Bureau of Meteorology radars located in/near the Southeast Queensland region.

Site	Latitude (deg)	Longitude (deg)	Type	Wavelength	Scan interval
Grafton	29.620 S	152.970 E	WSR 74S	10 cm	10 min
Moree	29.500 S	149.850 E	WF100C	5 cm	10 min
Mt Stapylton	27.718 S	153.240 E	Gematronik Doppler	10 cm	6 min
Marburg	27.610 S	152.540 E	EEC WSR 74S	10 cm	10 min
Mt Kanigan	25.957 S	152.577 E	EEC DWSR 8502S	10 cm	10 min

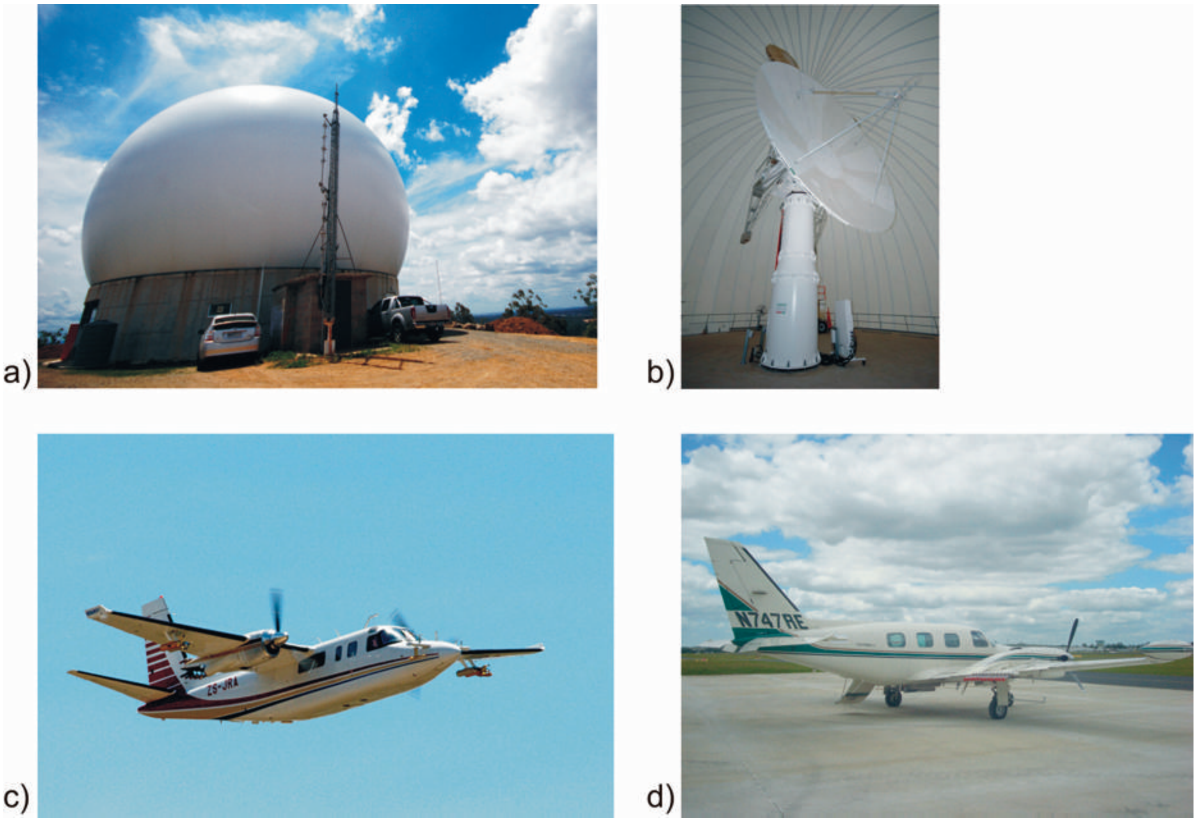

Figure 2. CP2 site infrastructure at Redbank Plains: (a) Antenna and pedestal are within an inflated radome mounted over housing for office, storage and transceiver, and (b) CP2 S-band and X-band antennae (right) [Photos courtesy Scott Collis/CAWCR], and photos of the (c) the SAWS Aerocommander research/seeding aircraft in flight on a research mission [Photo courtesy Scott Collis/CAWCR], and (d) WMI Piper Cheyenne II seeding aircraft highlighting the wing-mounted flare racks [Photo courtesy Sarah Tessendorf/NCAR].

When unattended, CP2 operated in a volume-scan mode, synchronized with Mt Stapylton for dual-Doppler analysis capabilities, which produced a volume of Plan Position Indicator (PPI) sweeps once every six minutes. During field operations, CP2 was operated in a PPI or Range Height Indicator (RHI) sector-scan mode, in which designated azimuth sectors were scanned with PPI sweeps or RHI scans. Sector scanning allowed high resolution of designated storms. When seeding operations were underway, the CP2 radar scans followed the targeted cell for at least 20 minutes after seeding ended to capture any initial microphysical responses before scanning another declared case. If the targeted cell was within the dual-Doppler lobes, then CP2 aimed to scan it for an additional hour after seeding ended to capture any dynamic responses (see Fig. 1). If no other cells were declared in the interim, CP2 would scan the most recently targeted cell through its dissipation. Other scanning strategies employed by the CP2 radar included vertically pointing scan sequences during light rain and low-level (0.5 and 1.0 degree elevation) small sector scans over the disdrometer site. These scans were used to evaluate the radar hardware calibration and to verify radar-derived rain drop size distributions.

2.1.2 Aircraft

Two aircraft were used during the first season of the project: one was primarily a research aircraft, but also served as a secondary seeding aircraft if conditions warranted; the second aircraft was the primary seeding aircraft. In season two, only the research aircraft was available and it also served as the seeding aircraft. The research aircraft was the South African Weather Service (SAWS) Aerocommander (ZS-JRA; Fig. 2c). It carried flare racks on each wing (10 burn-in-place hygroscopic or silver iodide flare capacity each) and had a full suite of atmospheric instrumentation described in detail below. In season one, the Weather Modification Inc (WMI)/MIPD Piper Cheyenne II (N747RE; Fig. 2d) served as the primary seeding aircraft. It carried flare racks on each wing (12 burn-in-place hygroscopic or silver iodide flare capacity each) and an undercarriage ejectable silver iodide flare rack (306 flare capacity).

The research aircraft had a suite of instruments capable of taking trace gas, aerosol, and microphysical measurements in seeded and unseeded clouds (see Table 2 for a list of instrumentation on board in each season). All instruments were monitored by an in-flight scientist and maintained by a technician to ensure proper function. Data quality checks were routinely performed to assess instrument performance and diagnose maintenance needs. The full suite of instruments provided multiple measurements of key microphysical parameters and allowed for intercomparison measurements to assess instrument performance and data quality.

Aircraft operations were based at Archerfield Airport, where daily weather and flight planning briefings were held for the pilots (see Fig. 1). During flights, operations were coordinated via radio communications between the pilots and the Operations Director at the CP2 radar facility, which served as the Operations Center (see Fig. 1). Both the Operations Center and the airport hangar office had phone and high speed internet connections to enable communications and data transfer/archival between the two sites, as well as off site (i.e., NCAR).

2.1.3 Surface measurements

Raindrop measurements were made with disdrometers installed at a ground site roughly 16 km from the CP2 radar. In season one, a two-dimensional video disdrometer (2DVD), owned and operated by NCAR, was deployed. Three disdrometers were available for season two: a 2DVD and an impact disdrometer owned by the BoM and a Particle Video Imager developed by NASA. The ground-based raindrop measurements were used to help calibrate the CP2 radar, establish drop size distribution (DSD) characteristics of stratiform and convective rains and radar-derived microphysical relationships, and to develop procedures for monitoring drop size distributions in seeded and unseeded clouds with polarimetric radar.

2.2 Research goals and procedures

2.2.1 Climatology analyses

The first objective in this feasibility study was to understand the local precipitation climatology, including weather patterns and conditions that drive convection, in order to put the cloud seeding and precipitation process analyses into context, as well as to determine the frequency of clouds suitable for seeding. These analysis efforts include building climatologies of radar and rain gauge data, synoptic weather patterns, thermodynamic soundings, and relationships of climate indices (i.e., Southern Oscillation Index) with precipitation in the region. Five years of Marburg radar data were examined to determine the climatology of storm initiation location, size, storm top height, and duration (Peter et al. 2010). This was combined with a k-means statistical clustering analysis (Hartigan and Wong 1979) that used thermodynamic sounding data (i.e., instability, wind, and moisture flux parameters) to characterize the synoptic regimes that accounted for the observed rainfall (from radar and rain gauge data).

Table 2. List of instrumentation on SEEDA1 in each season of the Queensland CSRP.

Instrument	Purpose/Comment	Range	Season
	State Variables		
Rosemount Temperature, Static and Dynamic Pressure, and GPS	Temperature, pressure, altitude, TAS, and location (SAWS)	*multiple*	Both
Edgetech Dew point sensor	Moisture content (NCAR)	−40° to 60°C	2
Vaisala Temperature and Relative Humidity	Secondary temperature and moisture content (SAWS)	−50° to 50°C, 0–100%	Both
AIMMS-20 probe	Temperature, relative humidity, pressure, three-dimensional wind components	*multiple*	Both
	Cloud Physics		
PMS FSSP	Cloud droplet spectra (SAWS)	0.5–47 µm	1
DMT SPP-100 FSSP	Cloud droplet spectra (SAWS)	0.5–47 µm	Both
PMS 2D-C	Small precipitation particle size, concentration and shape (SAWS)	25–800 µm	1
PMS 2D-P	Large precipitation particle size, concentration and shape (SAWS)	200–6400 µm	1
DMT CIP	Small precipitation particle size, concentration and shape (NCAR; part of CAPS probe listed below)	25–1550 µm	Both
DMT PIP	Large precipitation particle size, concentration and shape (NCAR)	100–6200 µm	2
PMS Hot-wire (King) Liquid Water Content (LWC) Probe	Liquid water content (SAWS)	0.01–3 g m^{-3}	Both
DMT CAPS probe	Aerosol through precipitation size spectrometer; LWC; CIP; static and dynamic pressure; temperature (NCAR)	*multiple*	Both
	Aerosols		
DMT CCN Counter	Cloud condensation nuclei concentration and spectra (WITS)	Depends on supersaturation	Both
Texas A&M DMA	Fine mode aerosol spectra and concentration (NCAR)	0.01 to 1 µm	Both
PCASP	Aerosol concentration and spectra (WITS)	0.1 to 3 µm	1
DMT SPP-200 PCASP	Aerosol concentration and spectra (WITS)	0.1 to 3 µm	2
ASU Aerosol Particle Sampler	Aerosol chemical composition (NCAR)	N/A	Both
	Trace Gases		
TECO SO_2 (43c)	Sulfur dioxide (WITS)	0–100 ppm	Both
TECO O_3 (49i)	Ozone (WITS)	0–200 ppm	Both
TECO NO_y (42c)	Nitrogen oxides (NCAR)	0–100 ppm	Both
TECO CO (48c)	Carbon monoxide (WITS)	0–10,000 ppm	1
	Cloud and Situation Imagery		
Digital still camera	To show development of clouds and treatment situations for historical purposes	N/A	Both

A cluster analysis was performed using 00Z radiosonde data from the Brisbane Airport for the period 1 January 1990 to 31 December 2008. Seven regimes were identified: three separate southeasterly regimes, three westerly regimes, and an easterly regime. The analysis clearly illustrates the seasonality of rainfall regimes. The seasonal rainfall cycle has low monthly totals in the winter months and high totals in the summer months, as expected, with November–February being the wettest months (Fig. 3). During the summer, the easterly and westerly regimes contribute much of the monthly rainfall (E and W, respectively, in Fig. 3), and combined yield nearly half of the annual rainfall (Table 3). The northwesterly regime (NW, in Fig. 3) also makes important contributions to annual rainfall (22%), mostly during the summer, despite only occurring 6% of the time. The southeasterly 'dry' and southwesterly regimes occur most exclusively during winter and do not make any sizeable contributions to rainfall in any month (SE (d) and SW, respectively, in Fig. 3).

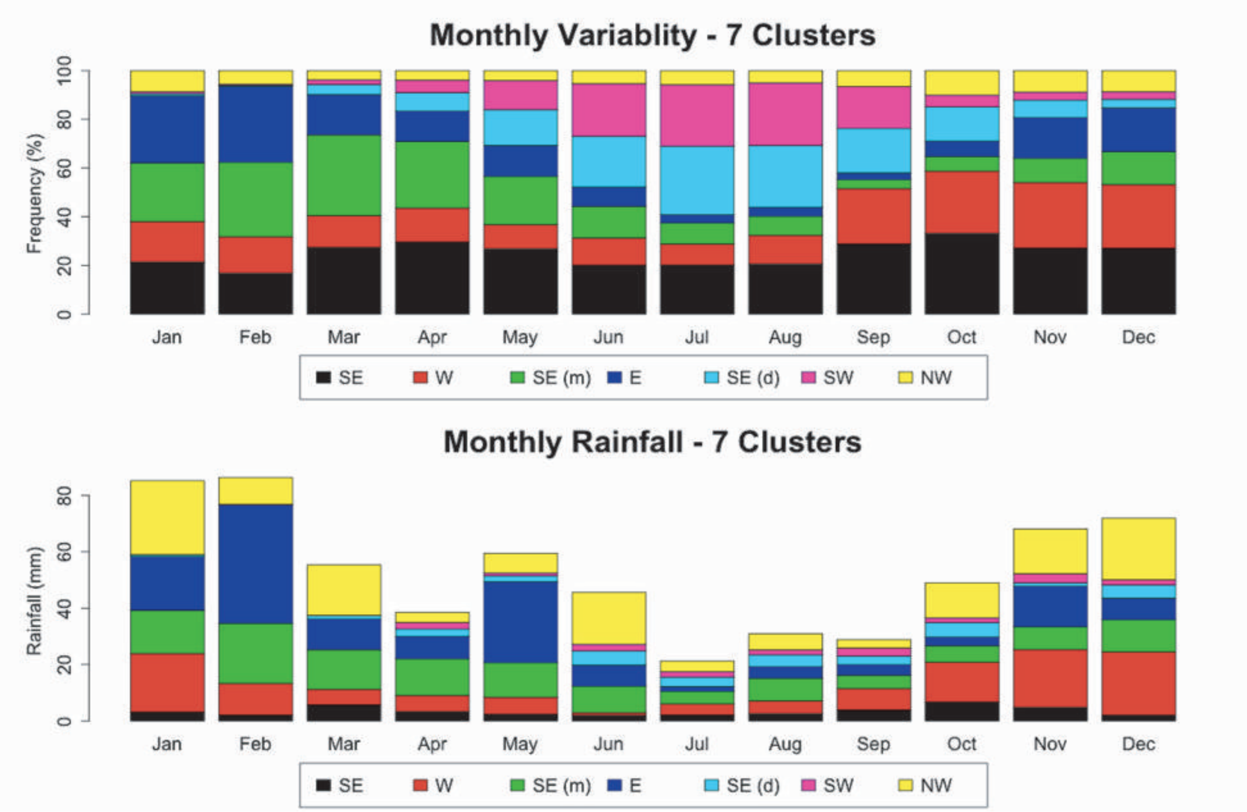

Figure 3. Monthly distributions of the 7-cluster synoptic regimes' (top) frequency of occurrence and (bottom) contribution to annual rainfall.

Table 3. Abbreviation (Abbr.), annual frequency (rounded to nearest whole percentage), contribution to rainfall, and a brief description for each of the seven synoptic clusters.

Regime	Abbr.	Frequency (%)	Rainfall (%)	Description
Southeasterly	SE	25	6	SEly, low moisture flux (mflux); all months
Southeasterly moist	SE (m)	16	21	SEly, high mflux; summer
Southeasterly dry	SE (d)	13	5	SEly, low mflux, high shear; winter
Easterly	E	13	23	Ely, moderate mflux, high total water; summer
Westerly	W	17	20	Wly, high mflux; all months
Southwesterly	SW	11	3	SWly, low mflux, low total totals; winter
Northwesterly	NW	6	22	NWly, high mflux; summer

The most frequent regime, accounting for roughly a quarter of all days (Table 3) and regularly occurring throughout the year, is southeasterly (SE, in Fig. 3). The SE regime is characterized by a southeasterly moisture flux and moderate instability and shear, and does not contribute significantly to the total rainfall in any month. A 'moist' southeasterly trade regime (SE (m), in Fig. 3) accounts for 16% of all days and occurs most frequently during the late summer, although it still accounts for approximately 10% of days during the winter months. This regime contributes 21% of rainfall during all months of the year and is characterized by strong southeasterly moisture flux and moderate atmospheric moisture and instability (Table 3). A key feature of the sounding in this regime is the trade inversion at about 800 hPa and high moisture up to approximately 500 hPa.

2.2.2 Aerosol and microphysics studies

Since the primary goal of this project was to ascertain if cloud seeding is a feasible means for enhancing rainfall in the SEQ region, analyses to study the effects of cloud seeding are paramount. While the effects of seeding are often mostly based on randomized seeding statistical analyses, it is also important to gain a good *physical* understanding of natural cloud microphysical and precipitation processes and potential seeding effects to be able to explain and support the statistics. Therefore, in order to fully understand the effects of cloud seeding, a working knowledge of the natural precipitation processes in the region is vital, including the environmental conditions that influence cloud microphysics (such as sub-cloud aerosol particles). Specific analysis efforts include characterizing the ambient aerosol conditions and initial cloud base DSDs in natural and seeded clouds and studying the evolution of drop growth and ice crystal formation through the mixed-phase region in deep convection via in situ cloud microphysics measurements.

In order to collect measurements for the aerosol and microphysical studies, several standardized research flight plans were implemented. In season one, when there were two aircraft, the seeding aircraft spent its flight time at cloud base searching for hygroscopic seeding candidate clouds and burning flares on declared cases, while the research aircraft spent time in cloud above the seeding aircraft penetrating key levels of interest or collecting sub-cloud aerosol measurements. Such aerosol measurements included surveys in the sub-cloud layer to look for any gradients in aerosol from the coastline to further inland, and aerosol and cloud condensation nuclei (CCN) measurements at cloud base. In season two, the standardized research flight plans were modified slightly due to having a single aircraft for both seeding and research. In this vein, every flight aimed to collect cloud base aerosol (just below cloud base) and cloud base droplet spectra measurements (1000 ft above cloud base) before attempting other flight objectives. If the flight was declared a randomized seeding mission, then immediately after each randomized case (seed or no seed), cloud base penetrations (1000 ft above cloud base) were performed to measure the initial droplet spectra before continuing to the next case or research objective. If the flight was a cloud microphysics research mission, then cloud base aerosol measurements and cloud penetrations at key levels were conducted including 1000 ft above cloud base, the freezing level, and −5°C and −10°C levels. Often flights had both seeding and research objectives. We attempted to collect a large sample of cloud base droplet spectra in seeded and unseeded clouds for a statistical comparison of the initial DSDs and to understand mixed-phase microphysical processes.

The goals of the aerosol and microphysics studies are to determine the naturally occurring aerosol and droplet size spectra and how they affect precipitation processes, such as warm rain formation and mixed phase processes. From these studies we hope to determine whether hygroscopic or glaciogenic seeding would make these clouds more efficient.

2.2.3 Cloud seeding assessment studies

Statistical analysis provides a first glance at potential effects of seeding and offers guidance for important physical analysis of the data to interpret the statistical results. The SEQ CSRP statistical randomized seeding experiment was very similar to those conducted previously in South Africa and Mexico (Foote and Bruintjes 2000). As in the earlier experiments, the selection criteria for the Queensland CSRP statistical analysis required that randomized cases have a 35 dBZ threshold TITAN track (Dixon and Weiner 1993) for greater than two volume scans and a maximum storm volume (defined as the volume of the storm with reflectivity greater than the 35 dBZ TITAN threshold) less than 750 km^3 (Mather et al. 1997). The Mt Stapylton radar was used for the TITAN tracking of the randomized cases and determination of whether each case met the criteria for inclusion in the statistical analysis.

For the Queensland CSRP randomized experiment, only hygroscopic seeding was conducted; however, some non-randomized trials with glaciogenic seeding were performed during the project. Randomized cases were declared by the pilots of the seeding aircraft when a rain-free, uniform, and dark cloud base at least roughly 2 km in diameter was located optimally within 100 km of the CP2 radar and within the Mt Stapylton domain, with an approximate updraft of at least 200 ft/min. We also required a minimum of 20 km separation between randomized cases in order to avoid contamination among the cases. A 35-dBZ TITAN track was not a requirement for declaring a randomized case in the CSRP, but as was mentioned above was required at some point during its evolution for the case to be included in the statistical analysis. A pseudo-random sequence of decision envelopes was created by joining together blocks of evenly balanced random sets of decisions. This was done to prevent excessively long strings of identical decisions, which will occur in a truly random series of binomial events (Cleveland 1978). For each case declaration, the next sequential randomized envelope was opened at the CP2 Operations Center and the decision was communicated to the pilots via radio. For seed decisions, three to four sets of 2 flares (one on each wing) were burned consecutively depending on the length of each burn to achieve roughly 15 minutes of consecutive flare burn time. In cases where the updraft diminished during seeding, the seeding was stopped after the current set of flares completed burning. For no seed decisions, the seeding aircraft circled at cloud base for 5 minutes to mark the case location before undertaking the next mission objective.

The goal of the randomized seeding statistical analysis is to quantify the effects of hygroscopic cloud seeding on storm properties (size, duration) and rainfall production. Furthermore, these cloud seeding assessment studies aim to understand the microphysical effects that seeding with hygroscopic or glaciogenic material has on clouds in Southeast Queensland. A key part of this objective is to establish new methods to study the physical effects of seeding, especially those that utilize advanced radar and measurement technologies. This topic will be further explored in Section 4.

3. SUMMARY OF FIELD OPERATIONS

3.1 Aircraft research

Aircraft-based research operations began in earnest on 12 January 2008 in season one and 4 November 2008 in season two. The two seasons had a total of 108 flight operation days with 164 total flights. Of the total flights, there were 142 research flights. In season one, 49 research flights were flown by the research aircraft and 39 by the seeding aircraft, while in season two, all operations were conducted by the research aircraft and they flew 54 research flights. These flights comprised 386 total flight hours. In each season the research aircraft flew 150 hours and in season one the seeding aircraft flew 86 hours.

Out of the total research flight segments in each season, there were relatively more cloud base aerosol measurements in season two, while season one operations were more dominated by warm cloud penetrations (above cloud base yet below the freezing level; Fig. 4). Season two had relatively more penetrations in the freezing and mixed-phase levels, instead of focusing on the warm cloud region. This was partially due to the type of convection that occurred predominantly in each season (more deep mixed-phase convection occurred in season two) and a shift in the flight mission objectives (see Section 2.2.2). Furthermore, since the research aircraft also performed hygroscopic cloud seeding in season two, it resulted in more flight time spent at cloud base, whereas in season one it spent more time in cloud above the seeding aircraft that was seeding at cloud base.

From the frequent and regular cloud base measurements collected by the research aircraft in season two, a summary of the cloud base aerosol

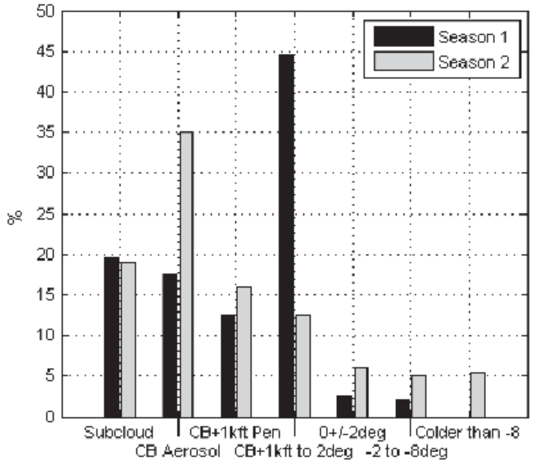

Figure 4. Frequency of SEEDA1 flight heights relative to cloud base (CB) for both seasons. The percentage is the fraction of all flights for each season that fell into the given height range: "Subcloud" = any height below cloud base, "CB Aerosol" = at (but just below) cloud base (out of cloud) for aerosol and CCN measurements, "CB + 1kft Pen." = cloud base penetrations made around 1000 ft above cloud base, "CB+1kft to 2deg" = warm cloud penetrations above the initial cloud base penetration yet warmer than the freezing level, "0 +/− 2deg" = penetrations taken within 2°C of the freezing level, "−2 to −8deg" = penetrations taken between −2° and −8°C, "Colder than −8deg" = penetrations taken at temperatures less than −8°C.

conditions has been compiled, and studies to characterize the various aerosol conditions are underway. One effort has focused on how the aerosol varies by source region, and thus back trajectories were calculated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess 1998). The Global Data Assimilation System (GDAS) archived data, with a temporal resolution of three hours and gridded to 1 degree x 1 degree in latitude and longitude, was used to calculate the back trajectories. The GDAS data set is the only one available that covers the CSRP project domain for the entire duration of the measurements; however, comparisons between trajectories calculated using GDAS and other data sets for the same region in past years yielded similar results (not shown). The back trajectories were calculated for 48 hours ending at every cloud base measurement location, altitude, and time. The trajectories were then grouped into regimes with similar paths based on the time each trajectory spent in quadrants relative to Brisbane: ocean (or land) north or south of the city. The regimes were grouped by first determining if each trajectory spent the majority of its time over ocean or land, then it was assigned to which of the two ocean (or land) quadrants it spent the most time within (Fig. 5a).

The PCASP (Passive Cavity Aerosol Spectrometer Probe; see Table 2) aerosol concentrations at cloud base were observed to vary from clean (100 cm^{-3}) to more polluted (1500 cm^{-3}), with the maritime HYSPLIT trajectory regimes (easterly, E, and northeasterly, NE) being the cleanest (Fig. 5b). Likewise, the maritime regimes exhibited the lowest 0.3% supersaturation CCN concentrations, often less than 300 cm^{-3}, while the CCN concentrations in the continental flow regimes (westerly, W, and northwesterly, NW) ranged from 200-600 cm^{-3}, still relatively clean compared to CCN concentrations measured in highly polluted regions (Andreae 2008).

The cloud base temperatures from the aircraft measurements for the two seasons when the aircraft

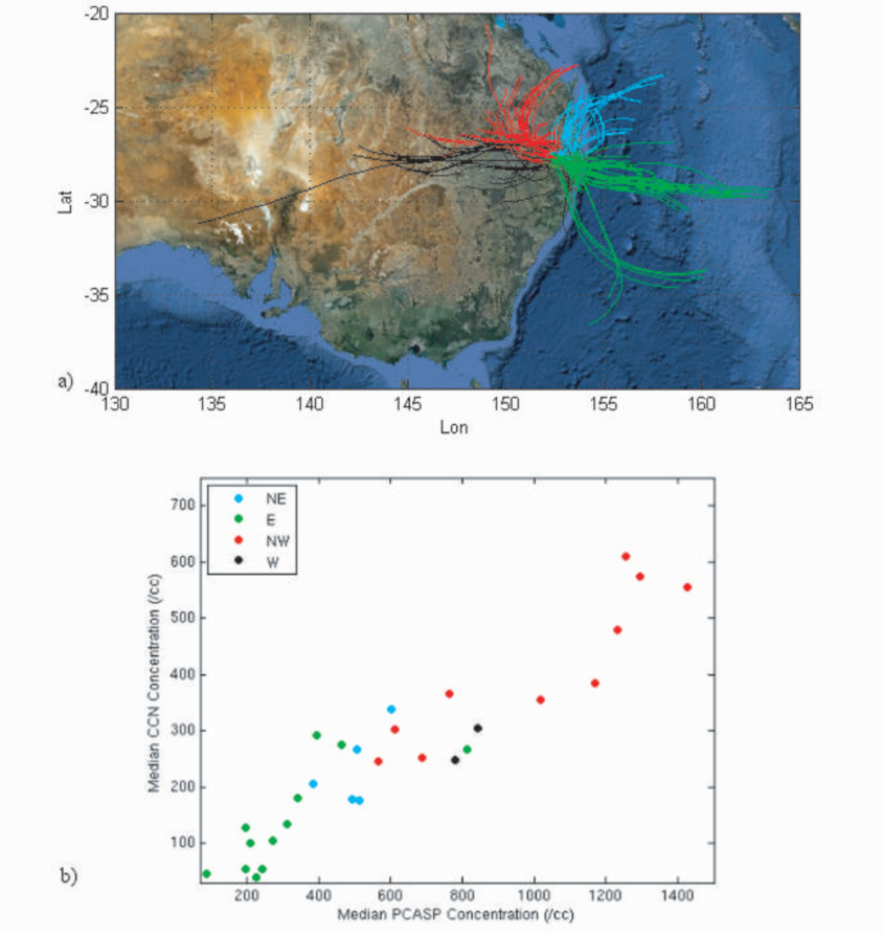

Figure 5. a) Map of HYSPLIT back trajectories colored by the quadrant (or HYSPLIT regime) it spent the most time in, and b) scatter plot of the median PCASP concentration versus the median 0.3% supersaturation CCN concentration per cloud base segment with colors corresponding to the HYSPLIT regime the measurement was assigned to (see legend).

were flying are displayed in Figure 6. Although there are large variations, there is a general tendency for cloud bases to be higher, at cooler temperatures, during the early part of the summer season and for lower and warmer bases as the season progresses. The lower cloud bases in the latter part of the season also provide for a deeper layer of the cloud warmer than 0°C (not shown). The depth of the "warm" cloud layer is important because this will determine in many instances if coalescence will be active and large drops present before the cloud top reaches temperatures colder than 0°C. This certainly impacts the efficiency of the ice processes in the cloud and could also affect precipitation production.

During the second season of the Queensland CSRP, the aircraft took measurements in the tops of newly developing turrets of deep convective mixed-phase clouds on at least 18 different days. To date, we have studied the in situ measurements on six of these days in detail. On four of the studied days, in natural (unseeded) clouds, the aircraft measured large drizzle-sized drops (diameters >300 μm) in the growing cloud turret tops near the 0°C level. The cloud bases in these cases ranged from 700 to 1200 m MSL. The natural clouds on two of these days showed evidence that graupel had formed around the −5°C level, and subsequently a secondary ice process (ice multiplication; Hallet and Mossop 1974) evolved. The microphysical cloud data from a case in which ice multiplication was observed (27 January 2009) is shown in Figure 7, while the same for a case (20 November 2008) without the presence of large drops at the freezing level (and thus no subsequent ice formation at temperatures warmer than −12°C) is presented in Figure 8. The two days studied with clouds that did not exhibit large drops at the freezing level were both observed in November 2008, in the early part of the season when cloud bases were generally higher (Fig. 6). The cloud bases in those cases ranged from 1500 to 2400 m MSL. It is possible that during the early part of the season, when cloud bases are generally higher (and thus colder), coalescence does not occur before reaching mixed-phase conditions, ice multiplication may not occur, and first ice may only form at temperatures colder than −12°C. Hygroscopic seeding may be more effective in these clouds providing for earlier coalescence and possibly the onset of a more efficient ice process. Future analyses will study the remainder of the mixed-phase in situ measurements in more detail and also focus on the ice formation processes in seeded clouds to investigate if there is evidence of more efficient warm rain and ice formation processes in such cases.

At times, deep stratiform systems are observed in the region and in those that we collected in situ measurements the natural precipitation processes were very efficient, with very little (if any) supercooled liquid water and much ice evident at subfreezing temperatures (not shown). This suggests that neither hygroscopic nor silver iodide seeding would have a precipitation enhancement effect in such highly efficient systems.

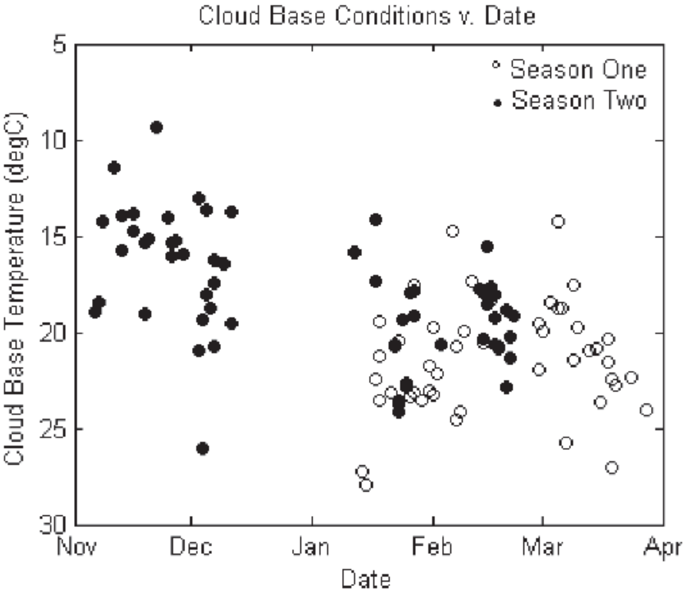

Figure 6. Cloud base temperatures as a function of the date during the field season (2007–2008 and 2008–2009 seasons).

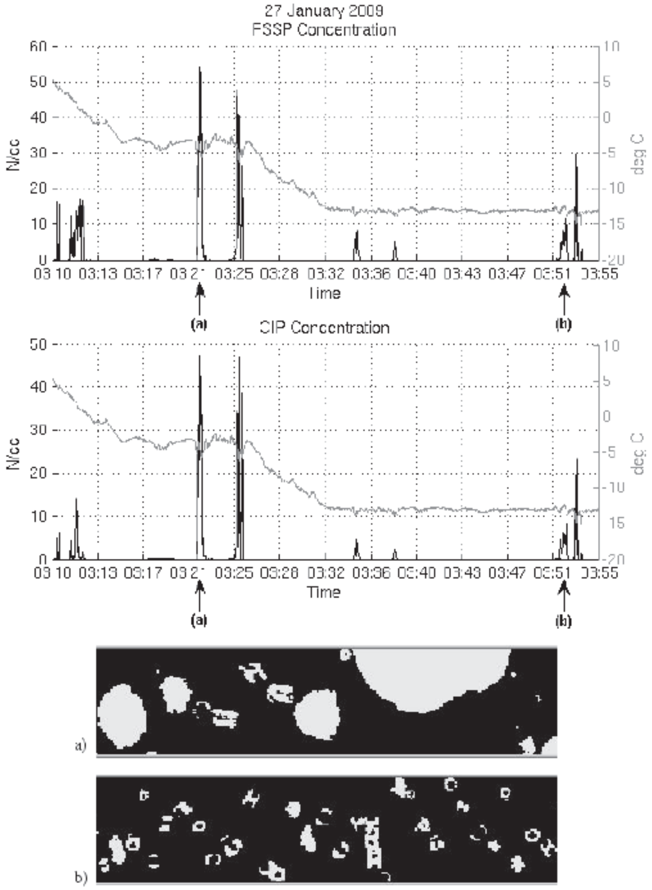

Figure 7. Time histories for FSSP droplet concentration (cm^{-3}) and CIP particle (larger than 40 μm diameter) concentrations (cm^{-3}) with temperature (°C) overlaid in gray for several cloud top mixed-phase penetrations through a growing deep convective cloud on 27 January 2009 (top). Bottom panels illustrate CIP particle images for penetrations at (a) −5°, and (b) −13°C. The vertical axis of a CIP image panel represents 1.55 mm.

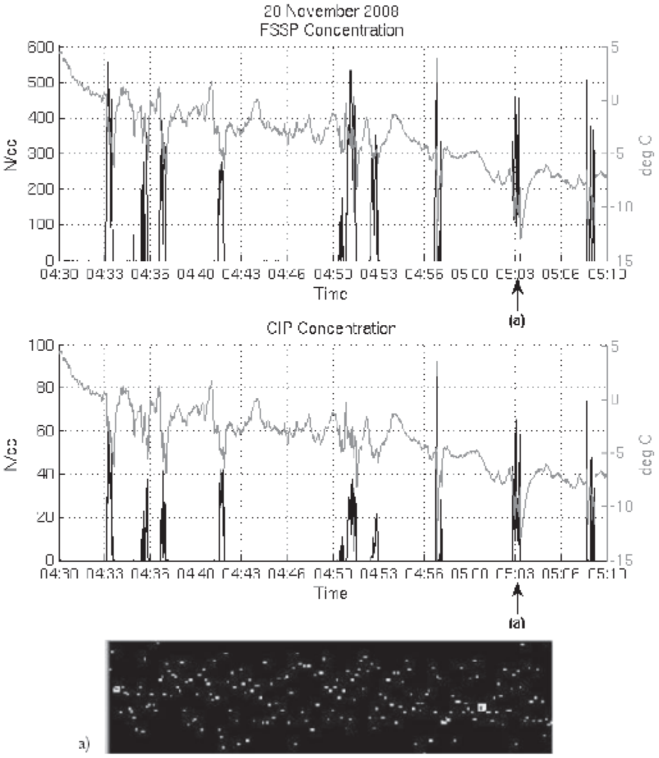

Figure 8. Same as Figure 7, except for 20 November 2008. CIP image shown in (a) is from a convective cloud top penetration at −9°C.

3.2 Randomized seeding experiment

Sixty-two randomized cases were declared in season one and 65 in season two. A map of the location for all randomized cases declared between the two seasons is shown in Figure 9.

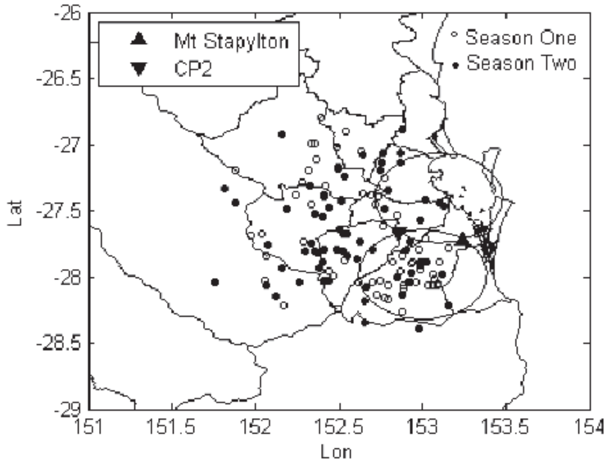

Figure 9. Map of the locations of all randomized seeding cases declared in season one (open circles) and season two (closed circles). Mt Stapylton and CP2 radar locations are overlaid (see legend) along with the 30-degree dual-Doppler lobes that intersect at each radar.

Based on the statistical analysis criteria (set to match that used for the South African and Mexican experiments; see Section 2.2.3), 39 (19 seeded and 20 unseeded) of the 127 total randomized cases were included in the statistical analysis. The first season was dominated by days with shallow trade-wind cumulus clouds, and many of those randomized cases never developed a 35 dBZ echo that lived long enough (>2 volume scans) for inclusion in the statistical analysis. From our climatology analysis (see Section 2.2.1) and field experience from season one, we learned that less precipitation, especially from deep mixed-phase convection, occurs in March, while more deep convection can occur earlier in the season (beginning as early as October). Therefore, we shifted our field season up a month for season two, beginning in November and ending in February. As a result, we encountered more deep convection, increasing both the number of randomized cases meeting the statistical analysis criteria and in situ mixed-phase microphysical measurements. Furthermore, from our experiences in season one (and reinforced by our analysis from season two presented briefly in Section 3.1), we observed a lack of supercooled liquid water in the deep stratiform and most deep convective clouds in the region due to naturally efficient ice formation processes. Hence, there is little opportunity for glaciogenic seeding in these situations. Therefore, we focused solely on randomized hygroscopic seeding in season two, whereas we had pursued some experimental (non-randomized) glaciogenic seeding in season one.

One of the major obstacles in the statistical analysis of rainfall enhancement experiments, such as the Queensland CSRP, has always been the effect of initial biases and outliers (large storms) that could easily overwhelm and dominate the statistical results. In addition, the effects of merging or splitting storms can influence and complicate the analysis substantially. Several such cases of storm mergers into large outliers were observed in the Queensland CSRP data set.

To study the effects of such large storms on the analysis, we stratified the storms by maximum volume. It is clear that most of the storms attained maximum volumes less than 1000 km^3 and that the seeded and unseeded storms were nearly equally represented in this sample (Fig. 10). For storms with maximum volumes between 1000 and 2000 km^3, however, more seeded cases were observed while virtually no unseeded were. Conversely, more unseeded storms were observed with maximum volumes larger than 2000 km^3 than seeded clouds. This bias in not having equal representation of seeded and unseeded storms at larger volumes can impact the statistical analysis and emphasizes the importance of choosing appropriate statistical techniques to analyze the differences between seeded and unseeded storms. Our preliminary statistical analyses indicate that it is extremely important to take these effects into account when interpreting the results. In addition, it is important to note that for most storms larger than 1000 km^3, mergers and splits introduce unrealistic storm tracks into the analysis. Consistent with the findings of Mather et al. (1997), we conclude that the statistical analysis and interpretation should focus on the storms that are less than 750 km^3 in volume because they exclude large merged complexes and line storms.

The analyses are still in progress, but initial results for the 39 cases that satisfied the statistical analysis criteria seem to indicate similar tendencies (although not statistically significant) for the radar-derived[1] rain mass, area, precipitation flux, and integrated precipitation mass to what was found in the South African and Mexican experiments (see rain mass results in Fig. 11; Mather et al. 1997, Foote and Bruintjes 2000). At first glance one could easily interpret these results to suggest that hygroscopic seeding has a positive effect on rain mass,

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[1] Single-polarization radar data (Mt Stapylton) was used to derive these parameters, as was done in the South African and Mexican experiments.

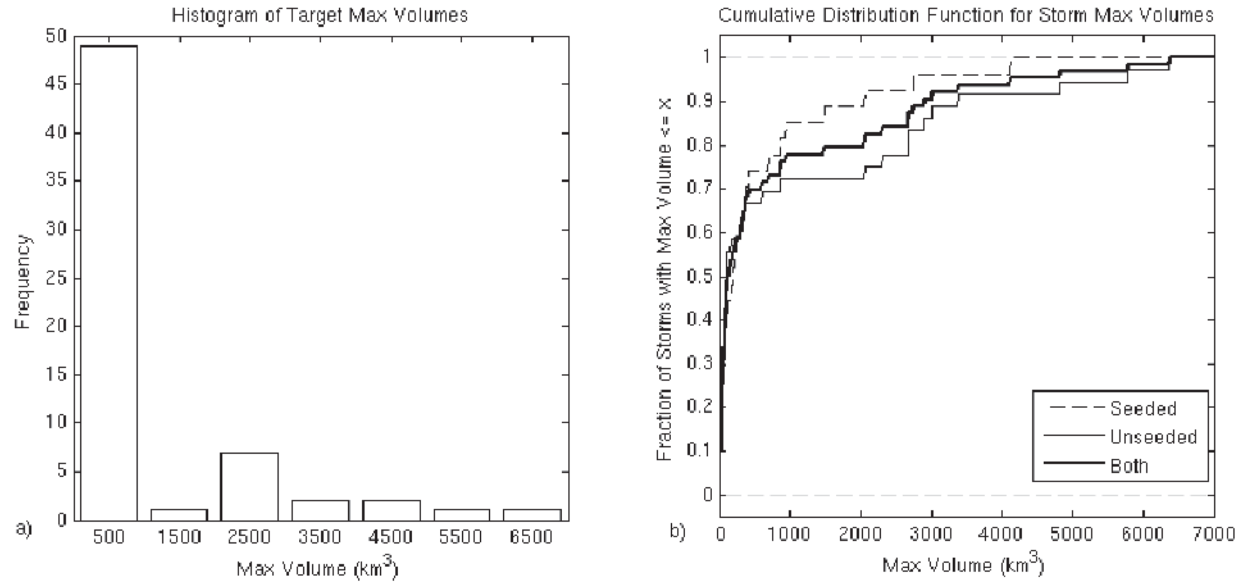

Figure 10. (a) Frequency histogram of TITAN tracks >35 dBZ, and (b) normalized frequency distribution of seeded, unseeded and total storm tracks as a function of maximum volume of tracks.

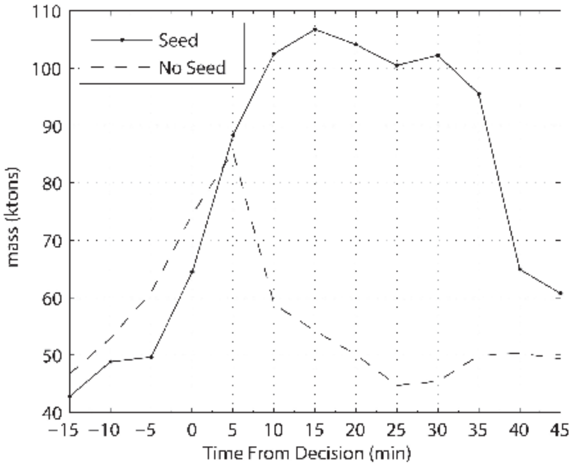

Figure 11. Radar-derived rain mass of the 35-dBZ echo as a function of time from 15 minutes prior to seeding decision time to 45 minutes after decision time for seeded (solid) and unseeded (dashed) cases.

but in some re-analyses we found that with such a small sample set, including or excluding cases by changing the selection criteria changed the results dramatically (not shown). The p-values (determined by the re-randomization test; not shown) should also be interpreted with caution because of multiplicity effects and the small sample size.

The only significant difference between the seeded and unseeded clouds in the re-randomization tests was for the duration of the clouds after seeding, with the seeded clouds living significantly longer than the unseeded clouds (p-value of 0.04; not shown). This is also a similar result as to what was found in the South African and Mexican experiments.

4. UNIQUE OPPORTUNITIES AND ONGOING ANALYSIS

4.1 Dual-polarization and dual-wavelength radar studies

Dual-polarization and dual-wavelength measurements from the CP2 radar can offer unique insight into the microphysical properties and evolution of seeded and unseeded clouds. For example, the differential radar reflectivity (Z_{DR}) is a polarimetric variable related to the size of raindrops (Bringi et al. 1986, Wakimoto and Bringi 1988, Brandes et al. 2004). In addition, particle identification in mixed phase processes is possible with dual-polarization radar (Vivekanandan et al. 1999). Furthermore, utilizing the ground-based disdrometer measurements, microphysical properties within the storms—such as drop median volume diameter (D_0) and maximum drop diameter (D_{max})—can be estimated using relationships derived from the radar reflectivity and differential reflectivity data (see Fig. 12). Such relationships have been calculated using the NCAR 2DVD disdrometer measurements from season one for convective and stratiform rains over the disdrometer (not shown). These measurements could provide new insights in the difference of microphysical processes between seeded and unseeded clouds.

Polarimetric radar measurements from CP2 are expected to be especially sensitive to the development of warm rain, and hence to hygroscopic seeding effects. If seeding significantly alters the raindrop size distribution, it should be detectable with polarimetric radar. Another possible radar-detectable response to cloud microphysical processes related to cloud seeding is the time to the development of precipitation. Here, the dual-wavelength capability of CP2 may play an important role. At 10 cm (S-band), the radar reflectivity needs to be above about 5 dBZ (occasionally as high as 10 dBZ) before one can be sure that it is caused by precipitation (Knight and Miller 1993). This is because Bragg scattering from turbulent mixing inside the clouds also produces radar echoes of this magnitude. However, at X-band (3 cm), this threshold is 20 dB lower such that when the reflectivity is above −15 to −10 dBZ it can be relied upon to be from water drops. Thus the X-band radar echo can be used to estimate cloud lifetime, while the S-band can be used to estimate a time when precipitation starts forming. If hygroscopic seeding is done early enough in a cloud's life cycle, there is the potential to see its effect with radar, both through the time required for precipitation formation and the early comparison of Z and Z_{DR}.

Another possible analysis technique to utilize the dual-polarization radar data is to statistically compare polarimetric characteristics of seeded cells with nearby similar unseeded cells (here we refer to them as "sister cells"). For this type of analysis, it would be important to select convective clouds that were fairly isolated, at a similar stage in their life cycle, and in which the seeding occurred at a similar stage of growth. By choosing single cell storms containing primarily one updraft, it should maximize the chance to observe any seeding modifications by reducing the likelihood that raindrops from nearby updrafts would mask events in the seeded updraft. This kind of effort could also utilize dual-Doppler analyses to ascertain the portions of the seeded cells that are more likely influenced by the seeding material (see following section).

4.2 Dual-Doppler analysis

Having multiple Doppler radars scanning the same area allows for the radial velocities from each radar to be combined to estimate the three-dimensional winds within storms in the area (see Fig. 12). These overlapping coverage areas are often called dual-Doppler lobes, and such lobes (highlighting the area of 30 degree minimum beam crossing angles between the CP2 and Mt Stapylton radars) are illustrated in Fig. 1. Several storms were observed during the Queensland CSRP within the dual-Doppler lobes. Detailed polarimetric and dual-Doppler radar and aircraft-based analyses of these storms will allow trajectories of seeding material to be determined and evaluation of the storms' microphysical and dynamical responses. The dual-Doppler analyses could also be used to initialize a cloud parcel model to study aerosol uptake in precipitating systems (both background and flare produced), as well as study the dynamical evolution (e.g., updraft intensity with time) of seeded and unseeded clouds. It may be possible to conduct a statistical study comparing updraft and downdraft intensities in seeded and unseeded storms and look for evidence of dynamical seeding effects that may contribute to the initiation and/or enhancement of secondary convection.

5. CONCLUSIONS

Two seasons of field operations were conducted for the Queensland Cloud Seeding Research Program (CSRP), with the first season taking place between December 2007 and March 2008, and the second season between November 2008 and February 2009. Analysis efforts for the Queensland CSRP were focused on three major issues for the greater Brisbane region: understanding the weather and climate, characterizing the atmospheric aerosol and cloud microphysics, and assessing the impact of cloud seeding on rainfall. The data sets collected in the two field seasons are vast and unprecedented for a cloud seeding research project, and thus many varied research efforts can continue to utilize the Queensland CSRP data sets. The purpose of this paper was to present an initial overview of the Queensland CSRP field experiment and the research and analyses that are being pursued.

The wet season in Southeast Queensland occurs generally from November–February. Climatology clustering analysis quantified that Southeast Queensland can be divided into 'wet' and 'dry' weather regimes, with the 'wet' regimes occurring most in summer and the 'dry' regimes more in winter. The 'wet' regimes are as such responsible for the majority of the region's rainfall and include the northwesterly, 'moist' southeasterly, easterly, and westerly regimes.

During the early part of the summer season, when cloud bases are generally higher, our results suggest that coalescence is not active at heights below the freezing level, and as such ice multiplication may not occur and first ice may only form at temperatures colder than −12°C. Hygroscopic seeding may be more effective in these clouds by providing earlier coalescence and possibly the onset of a more efficient ice process. Otherwise, clouds in Southeast Queensland generally seem to develop precipitation initially via the "warm rain" process that then results in a more efficient mixed-phase process in deeper convective systems that extend above the freezing level. Seeding with hygroscopic flares could potentially enhance the "warm rain" process, but glaciogenic seeding would not be advised in these conditions because of sufficient concentrations of natural ice particles at temperatures below −5°C. Our observations indicate that natural precipitation processes are very efficient in deep stratiform systems. Thus, neither hygroscopic nor glaciogenic seeding may have a positive effect in these systems.

The randomized seeding statistical results seem to show the same tendencies that were observed in previous experiments in South Africa and Mexico, which used the same hygroscopic seeding techniques. Nonetheless, the sample size is still too small to make any meaningful conclusions. Efforts

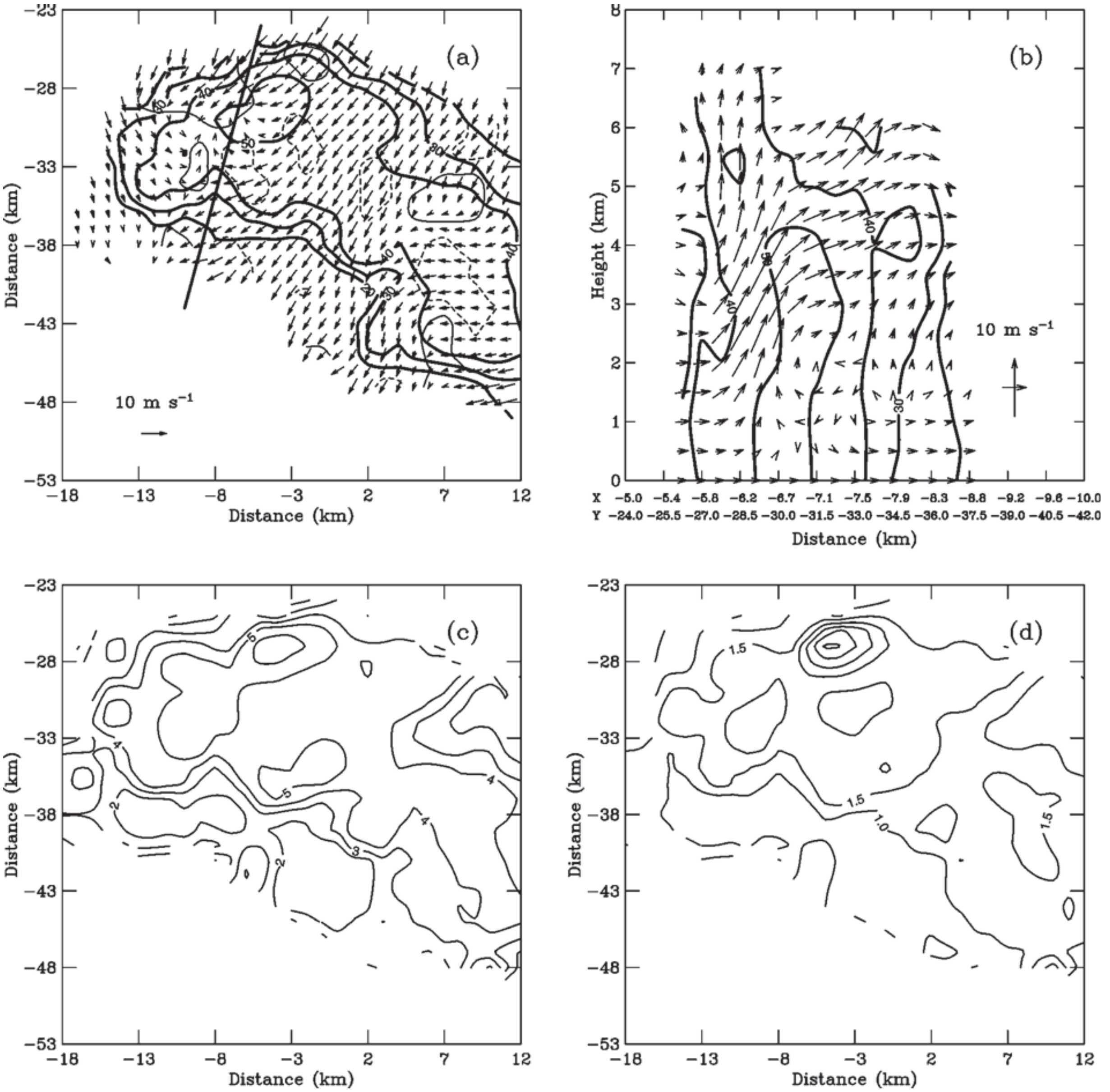

Figure 12. Example of multi-parameter radar analysis for a case observed in the 30-degree dual-Doppler lobes on 21 February 2009. (a) Horizontal cross section at 1 km and (b) vertical cross section through the plane highlighted in (a) of radar reflectivity contoured (thick black) with a 10-dBZ contour interval, and black arrows illustrate the wind vectors in the cross sectional plane from the dual-Doppler analysis. Thin black contours in (a) denote updrafts of 1 m s^{-1} (solid) and downdrafts of 0.5 m s^{-1} (dashed). Horizontal cross sections at 1 km of estimated (c) maximum drop diameter (D_{max}; mm) and (d) median volume diameter (D_0; mm) are also shown using relationships derived from disdrometer measurements (not shown).

are being made to use appropriate analysis techniques to interpret and understand the data and results. Future operations should focus on increasing the randomized sample size or attempt to design (a priori) a new confirmatory randomized experiment.

5.1 Future work

Given the vast amount of data collected in the two seasons of the Queensland CSRP, there is a lot of analysis to be done. Efforts to utilize the polarimetric and dual-Doppler radar data for assessing the effects of cloud seeding are one of the key areas of future work, and will include developing innovative methods for this type of analysis. Furthermore, we plan to incorporate cloud resolving and parcel modeling into the analyses in order to corroborate and help explain the physical observations.

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COMPARISON OF SILVER IODIDE OUTPUTS FROM TWO DIFFERENT GENERATORS AND SOLUTIONS MEASURED BY ACOUSTIC ICE NUCLEUS COUNTERS

Arlen B. Super*
St. Cloud, Minnesota

Bruce A. Boe
Weather Modification, Inc.
Fargo, North Dakota

James A. Heimbach, Jr.
Springvale, Maine

Jack T. McPartland
Evergreen, Colorado

Gerhard Langer
Boulder, Colorado

ABSTRACT. Field testing in late September 2009 permitted comparisons of the output of a WMI remote-controlled seeding generator burning a modern solution with an older style AgI generator and solution previously calibrated in the Colorado State University (CSU) Cloud Simulation Laboratory. That facility is no longer available for seeding generator calibrations. Acoustical Ice Nucleus Counters (AINCs), usually operated at -20°C, were used to monitor ice nucleus concentrations from passage of AgI lines released upwind by mobile generators towed approximately perpendicular to the prevailing wind direction. Considerable variability existed for total ice nuclei per AgI plume passage as could be anticipated given variations in atmospheric conditions. However, examination of all tests with useable data revealed no major difference between the outputs of the two generator types using different solutions. The WMI generator uses a newer solution, expected to produce ice nuclei which operate primarily by condensation-freezing in winter orographic clouds. It had yields in the -15 to -20°C range similar to the Montana State University Skyfire generator producing a relatively pure AgI aerosol likely to operate by contact nucleation. However, AINCs with standard configurations as used in this investigation cannot differentiate between ice nucleation processes. The observations also documented that a newly-manufactured AINC compares favorably with previously tested units. Recommendations are made for future testing expanded to warmer temperatures than practical with the standard configurations of the AINCs available for this study.

1. INTRODUCTION

Remote-controlled silver iodide (AgI) generators manufactured by Weather Modification, Inc. (WMI) are being operated at mountain locations as part of the randomized Wyoming Weather Modification Pilot Project (NCAR 2008). These units have not been calibrated for yield of ice nuclei (IN) per gram of AgI due to the unavailability of a suitable US facility such as the CSU Isothermal Cloud Chamber (ICC) previously used for this purpose (e.g., DeMott *et al.* 1995). During the past two winters, one of the AINCs used in this comparison has been operated at high elevation in Wyoming's Medicine Bow Range to detect IN produced by WMI ground-based generators as part of the randomized project.

The primary purpose of this paper is to compare WMI AgI ice nucleation activity with an older, calibrated generator, the Montana State University Skyfire (hereafter Skyfire) described by Super *et al.* (1972). Both the Skyfire, using a 2% AgI-NH_4I-acetone seeding solution, and one of the three acoustical ice nucleus counters AINCs used in this study was calibrated at the CSU Isothermal Cloud Chamber (ICC) as discussed by DeMott et al. (1995). These previous observations provide a quasi-standard with which the output of the newer equipment and solutions can be compared.

The field approach discussed in this paper obviously lacks the repeatability and accuracy of earlier CSU laboratory results. Moreover, observations were made primarily at -20°C, the normal AINC cloud chamber operating temperature. Construction of a fixed dilution and testing facility even crudely approximating the ICC would require resources well in excess of those available for this study. While a large capacity fan was used by the ICC, natural wind and turbulence over miles diluted AgI aerosol to concentrations sufficiently low for observation by AINCs. Useful comparisons were obtained by the simpler field approach.

A secondary purpose of this paper is to compare three AINCs (a.k.a. NCAR counters). The oldest was built during 1976 under the supervision of the instrument's inventor, G. Langer. It is herein referred to as Unit 1, in order of production. Detailed

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**Corresponding author address:* Dr. A.B. Super, 621 19th Ave. S.E. St. Cloud, MN 56304-1365; e-mail: amsuper@charter.net

discussions of the AINC have been provided by Langer *et al.* (1967) and Langer (1973). An improved AINC was built by J. Heimbach during 2006, which herein is called Unit 2. These two units were previously compared in the laboratory as discussed by Heimbach *et al.* (2008), therein called Unit 3-2 and the WMI unit, respectively. A third AINC, designated Unit 3 herein, was recently built by Heimbach for future use by Snowy Hydro in Australia (Huggins et al. 2008). All three AINCs were compared under field conditions during late September, 2009, near Fargo, ND, at the same time the IN sources were compared.

2. SPECIFICATIONS

Detailed specifications of Units 1 and 2 are presented in Table 1 of Heimbach et al. (2008). Unit 3 is similar to 2 except that its cloud chamber diameter is 17.8 cm (7 inches) rather than 20.3 cm (8 inches). Also, the Unit 3 sample intake is centered on the cloud chamber lid (as in Unit 1) rather than being offset 5.1 cm (2 inches) from the chamber wall in Unit 2. All 3 AINCs began counting ice crystals less than 30 sec after AgI input from a common manifold. Count rates rapidly increased after first detection and peak values were typically reached within 5-10 minutes depending upon AgI pass characteristics, especially concentration. Unit 3 always flushed out AgI plume remnants a little before the other AINCs.

Unit 1 was made for use in small aircraft. Accordingly, it has the smallest refrigeration compressor, smallest "footprint," and, more importantly, lacks a glycol pre-cooler and uses a smaller humidifier than the newer units. Observations presented by Heimbach *et al.* (2008) show that only about 50% of the Unit 1 cloud chamber volume was less than -6°C compared with 77% for Unit 2. In that study the latter unit measured greater AgI IN concentrations depending upon the AgI solution being burned, with the observed difference being greater when contact nucleation was presumed to occur, rather than condensation-freezing nucleation. It will be shown that total observed IN per AgI plume passage was consistently greatest from Unit 2 with the largest cloud chamber volume.

Each ice crystal exiting the base of an AINC cloud chamber is rapidly accelerated then decelerated when passing through a Venturi tube glass sensor. This results in an audible "click" detected by a microphone connected to an electronic signal processor. Three nearly identical electronics units discriminated the respective acoustic signals. Each legitimate count triggered a TTL signal which was sent to a M300 data system for real-time display and archiving at 1 Hz. The electronics used with Unit 1 had a fixed delay of 7.0 msec and that used with Unit 2 was fixed at 8.2 msec. The adjustable delay of the package used with Unit 3 was set to 7.3 msec. These delays eliminated counting the first (loudest) echoes from the flat Plexiglas lid atop each chamber. Signal sensitivity is adjusted to eliminate "double counts" from much weaker second echoes and background noise. Given the delay times, maximum count rates ranged from 122 to 143 sec^{-1}. The true count rate is unknown when such high rates are encountered, so such periods must be rejected. The greatest unadjusted rate detected by any AINC during the 12 passes to be discussed in Tables 1 and 2 was 106 sec^{-1}, below allowed maximums.

It should be recognized that neither the ICC nor the AINCs mimic typical winter orographic clouds. Liquid water content (LWC) within the ICC was set to 0.5 g m^{-3} for the experiments reported by Garvey (1975), corresponding to about 2100 droplets cm^{-3} in the cloud chamber. Other reported experiments had generator yields also provided for a LWC of 1.5 g m^{-3}. New cloud droplets were continuously introduced to maintain LWC and ice crystals were frequently collected on microscope slides for up to 50 min after aerosol introduction. The ICC droplet concentration and LWC values were well above most winter measurements within orographic clouds of the Intermountain West (e.g., Rauber and Grant 1986).

Even higher droplet concentrations are required within AINC cloud chambers to enhance the probability of nucleation and ice crystal growth to detectable sizes (~ 20 μm) within the limited time available, typically about 1 min, before introduced aerosol and cloud exit the chamber. Table 2 of Langer (1973) indicated that for cloud and humidifier temperatures typically used in this paper, LWC varied from about 15 g m^{-3} at the cloud chamber top inlet to about 2 g m^{-3} by the bottom exit. Calculations and observations suggested typical droplet concentrations in the range 3 to 8 X 10^4 cm^{-3}. The purpose of the AINC was to force nucleation by whatever process in order to maximize detection of AgI aerosol concentrations.

These and other differences from natural clouds suggest considerable caution in directly applying ICC or AINC results to winter orographic clouds. As noted by Boe and DeMott (1999), "It has long been recognized that results from the CSU isothermal cloud chamber may not be entirely relevant to the behavior of ice nucleus aerosols in real clouds." But whatever the differences in cloud characteristics and nucleation modes, the ICC was the AgI generator and flare calibration standard for decades, providing the only comprehensive data base for comparisons among several AgI seeding devices and solutions. Comparisons between the ICC and two AINCs reported by DeMott et al. (1995) showed the latter sampled ice nucleus aerosols at about one-third of the ICC efficiency after dilution airflow corrections were made to the ICC. Agreement was closer (two-thirds) for raw ICC results commonly reported over the years.

3. EXPERIMENTAL DESIGN

All three AINCs were installed in close proximity (see Fig. 1) at the northeast corner of the Ice Crystal Engineering (ICE) manufacturing plant, located at 46.679° N latitude and 97.009° W longitude, 3.2 km (two miles) north of Kindred, ND, and 29 km (18 miles) southwest of Fargo, ND. Outside air was continually drawn through all-metal tubing, to minimize AgI wall losses, from a 3.4 m (11 ft) tower located about 6 m (20 ft) east of the northeast building corner. Sample air was drawn to each AINC from the common manifold by each unit's own vacuum pump, and the excess air was exhausted outside.

Silver iodide particles were released from a towed open flatbed trailer upon which were mounted two Skyfire generators with separate stainless steel solution tanks (see Fig. 2). One tank was for the 2% $AgI\text{-}NH_4I$-acetone seeding solution, historically used with these generators. The other tank contained a solution of 2% $AgI\text{-}NH_4I\text{-}C_6H_4Cl_2\text{-}NaClO_4$ in acetone, expected to produce condensation-freezing IN (DeMott 1997). The latter solution is used with WMI generators in the Wyoming project. For simplicity these will hereafter be referred to as Solutions S (for Skyfire) and W (for WMI), respectively. Also mounted on the trailer was a single WMI generator with separate stainless tanks for the respective solutions. All but a few successful plume releases used either the Skyfire generator with Solution S or the WMI generator burning Solution W.

With few exceptions the ICE facility is surrounded by a grid network of north-south and east-west roads with one mile (1.6 km) spacing. The terrain is flat and mostly covered by cropland with tree cover usually limited to local windbreaks for farms. No tree cover or other buildings exist near the ICE facility.

The experimental approach was to release AgI particles from between about 3.2-6.4 km (2-4 miles) upwind of ICE in a line as near to crosswind as practical. Ideally, similar plume characteristics would exist among the population of plume passages, and

Figure 1. The three AINCs. from left to right are: Unit 1 tested at the CSU ICC during 1994; Unit 3, newly constructed for the Snowy Hydro program in Australia by J. Heimbach (pictured); and Unit 2, the WMI counter. (Photograph by A. Super)

AgI IN totals could readily be compared for different configurations of generator and solution types. In reality, differences in wind speed and direction as well as atmospheric stability could be expected to result in substantial differences among plumes. While photo-deactivation has been shown to be minor with the Skyfire and Solution S (Super *et al.* 1975) its importance with Solution W is unknown. Sky conditions during AgI particle releases ranged from clear to overcast and both wind speeds and directions were wide-ranging. Consequently, substantial variability might be expected among the field observations as was observed.

In spite of the known shortcomings this was a practical approach to provide at least approximate comparisons between the previously calibrated Skyfire generator using Solution S and the much newer WMI generator with Solution W. A superior approach would have calculated AgI fluxes using an aircraft-mounted AINC flown across the wind at different altitudes from near ground level to above plume tops. That approach, used by Super *et al.* (1975), was impractical with existing time and resources. With the exception of construction of the two Skyfire generators using original blueprints, all equipment used in these tests was already available, most provided by WMI. That availability combined with considerable volunteer time and reduced fees by the authors made this investigation possible with limited available resources. More sophisticated and longer-duration testing was not feasible.

The usual experimental procedure was to make north-south or east-west passes with a pickup truck towing the seeding generator trailer upwind of ICE. Each pass was of sufficient length, typically 10 km (6 miles), to ensure that a portion of the released AgI line passed by ICE even with moderate wind direction changes. To maximize uniformity, passes were planned with the intention of placing the central portion of the AgI line plume at the ICE facility where the sampling occurred. The truck was driven as near to 8 m s^{-1} (18 mi h^{-1}) as practical, slow enough to avoid generator flameout but fast enough to accomplish multiple passes. This approach usually worked well

Figure 2. The flatbed trailer used for mobile releases of AgI during generator and solution comparison tests parked by the ICE facility. Two black MSU Skyfire generators are in the foreground with seeding solution being poured into a stainless steel tank by A. Super (left) and J. McPartland. The dark green WMI generator is mounted at trailer's rear. A silver wind shield used with a Skyfire is in front of the WMI unit. The extreme flatness of the terrain is evident; note the corn field in the background (right) of the photo. (Photograph by A. Super.)

except with light and variable winds. Frequent radio communication between the vehicle navigator and an AINC operator permitted real-time decisions for pass start and stop times and adjustments to pass locations to accommodate wind changes. Periodic wind estimates were made well upwind of the ICE building. These were supplemented by hourly data from the two nearest automatic weather stations operated by the North Dakota Agricultural Weather Network. These are "Leonard 5N" located 18.7 km (11.6 mi) at 289 degrees true from ICE and "Ekre" sited 20.0 km (12.4 mi) at 209 degrees from the AINCs.

4. TESTING SOLUTIONS AND AINC RESPONSES

A total of 13 plume passages were successfully detected on September 25, 26, 27 and 29, 2009. Observations from several other attempts were rejected because of generator problems or winds becoming too light and variable for AgI IN detection at ICE. Strong winds on the 27th precluded use of the Skyfires because of flame blowouts, but the WMI generator functioned well. Field sampling was not conducted on the 28th, which had continued strong winds.

Figure 3 illustrates the "classic" shape of an AgI plume (line passage) as observed by AINCs. In this case, Pass #4 (of Table 1), onset of plume detection was rapid and intense for all three AINCs which peaked simultaneously. Gradual decays followed as the plume of AgI aerosol passed the sampling input and then the cloud chambers flushed. This fast response, with rapid increase after initial AgI IN input, followed by holdup time in the cloud chamber is characteristic of AINCs as discussed by Heimbach et al. (1977).

The passage of a more complex plume is illustrated in Figure 4. In this case, Solution S was burned in a Skyfire generator. Dispersion and passage was more complex than that shown in Figure 3, with "shoulders" apparent during both onset and decay. Agreement in the maximum observed values was unusually close between Units 2 and 3 on this pass, for reasons not fully understood. The broader, apparently well-mixed plume likely resulted in part due to significantly lighter winds. Mean wind speed for this passage was only 7 miles per hour (3.0 m sec-1), compared to 17 mph (7.6 m sec-1) and 16 mph (7.2 m sec-1) for Passes 4 and 7, respectively. Final decay seems to be prolonged by persistence

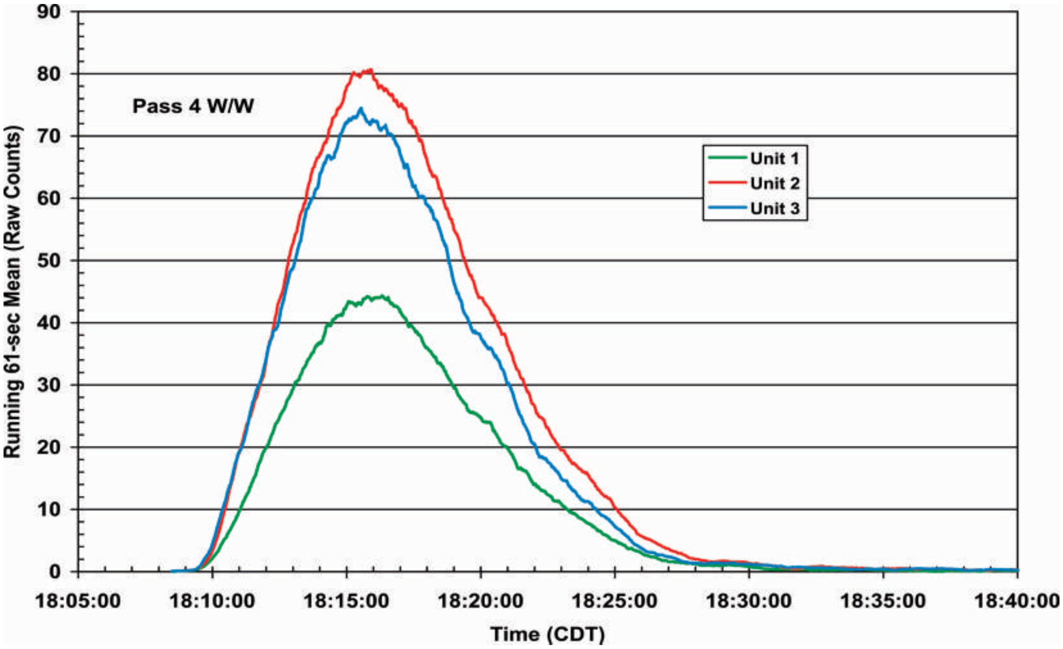

Figure 3. Running 61s means calculated from 1 Hz data (recorded acoustic counts) are shown from each AINC for Pass #4, the passage of an AgI line produced by combustion of Solution W in the WMI generator. Each AINC responded rapidly to AgI arrival at the sampling site. This rather dense but compact plume showed atypically close agreement between Unit 2 (Red), with largest cloud chamber, and Unit 3 (Blue). Unit 1 (Green), the oldest AINC, consistently measured lowest total counts in all passes. Maximum count rates were achieved about 7 minutes after plume arrival and more than 10 additional minutes were required to totally flush AgI remnants from AINC cloud chambers.

of a low but elevated background after passage of the primary plume.

Units 2 and 3 tracked unusually closely on this pass. Unit 1, with the smallest cloud chamber and no glycol pre-cooling, monitored the plume at lower concentrations by less than a factor of two.

Figure 5 shows a plume passage using Solution W in the WMI generator. Once again each AINC responded rapidly to AgI plume arrival and then required several minutes to totally flush out the seeding material and resulting ice crystals.

Table 1 summarizes the 12 successful field experiments. One pass on the 26th was excluded because the ice crystal count rate reached the maximum allowed by the associated electronics. Silver iodide IN arrival and departure (start and stop) times at ICE were estimated by reference to field notes, one minute count totals and raw second by second data. Arrival times are accurate because AINCs react to AgI IN presence in 1/2 minute or less. Departure times are much later than ends of AgI passage because of cloud chamber holdup times and the subjective nature of determining them, especially when new plumes occasionally arrived before natural background IN levels again existed. But in all cases indicated AgI IN concentrations were far below peak levels before arrival of the next plume and any errors in total counts should be minor. Further discussion of AINC response to sampled AgI particles is presented by Heimbach *et al.* (2008).

"Peak" in Table 1 refers to the minute (00~59 sec) with maximum counts detected by Unit 2 for each AgI line passage, minus 1 minute to allow for typical chamber holdup times before detection of high IN concentrations. Unit 2 always produced the greatest total counts per pass and is used as the standard in Tables 1 and 2 (but not Table 3). Peak minutes for the other AINCs were generally the same and never differed by more than a minute.

The nearest time and distance in Table 1 are estimates for when and where the mobile generators were closest to ICE based on local wind direction observations and assuming straight-line plume transport. In reality, plumes meandered, especially during lighter winds, and AgI IN from higher levels with stronger winds may have mixed to ground level. During Pass 1 the generator was upwind of ICE while in a rain shower, and other showers were nearby, so that plume trajectory is particularly uncertain.

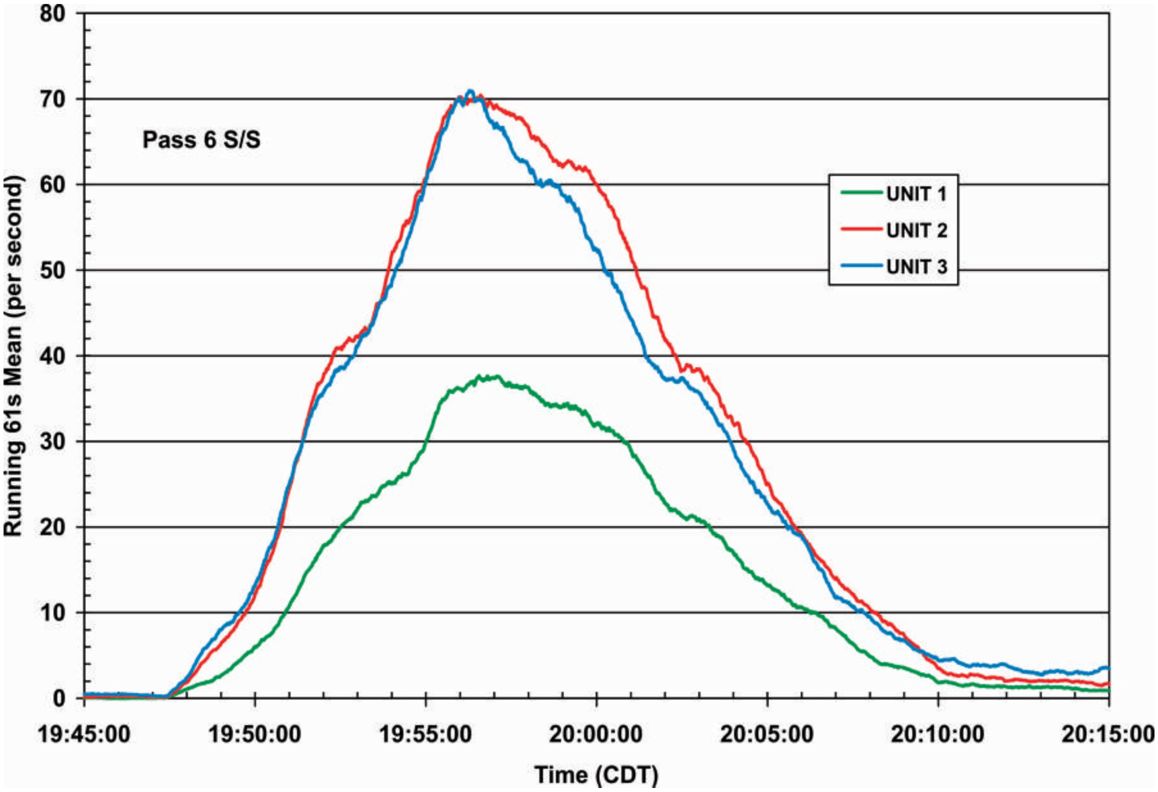

Figure 4. Similar to Fig. 3 but for Pass #6 showing plume passage produced by combustion of Solution S in the Skyfire generator. A broad plume resulted requiring about 10 minutes to reach peak count rates.

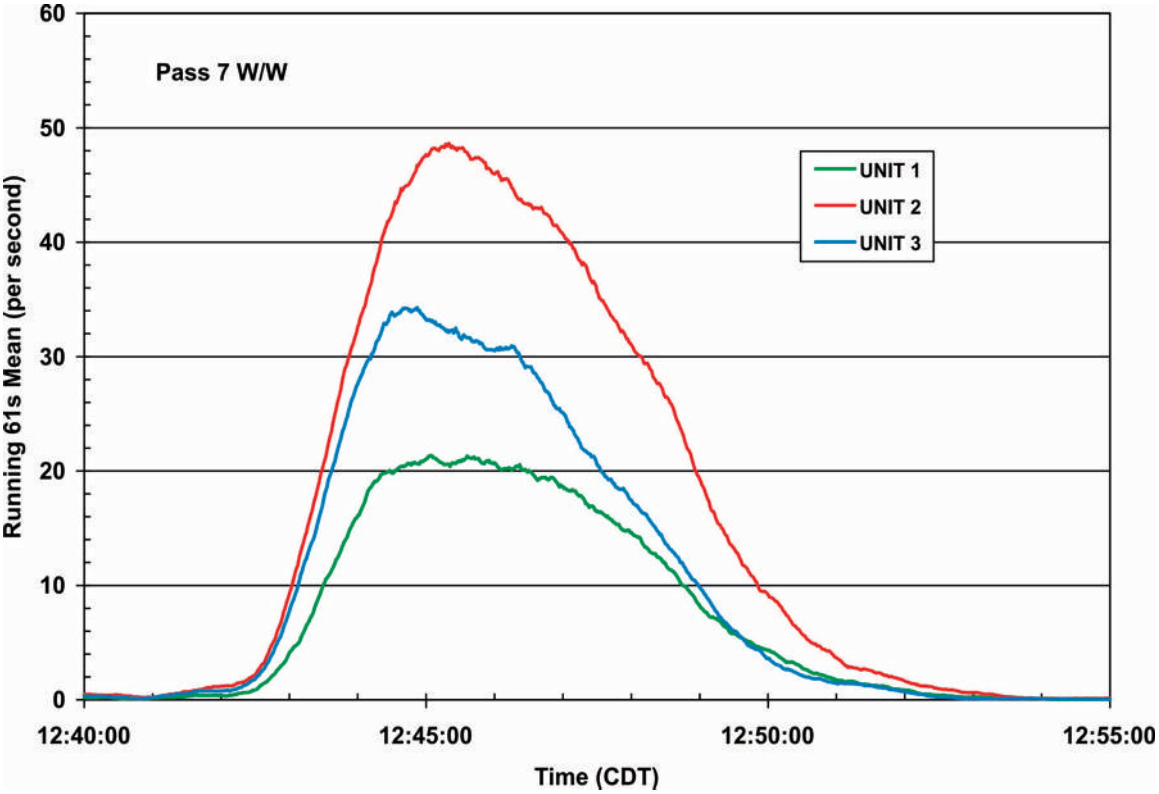

Figure 5. Similar to Figures 3 and 4 but for Pass # 7 produced by burning Solution W in the WMI generator. Each AINC responded rapidly to AgI arrival at the sampling site with peak count rates within ~3 minutes.

Table 1. Summary of mobile AgI generator passes, and generator and solution types during 25-29 September 2009. Generators are noted by S for Skyfire and W for WMI with the same letters used to denote solution types used. Other variables are discussed above. Wind directions are noted by SW for southwest, etc. Distance is in statute miles matching the road network spacing.

No.	Day	Start/Stop (CDT)	Heading	Gen./ Soln.	Nearest Time/Dist.	Peak (CDT)	Speed (mph)	Dir./Spd. (mph)
1	25	1639-1704	East	W/W	1651/2.2	1738	3	S/<5
2	26	1438-1452	West	S/S	1446/2.6	1457	14	SSW/10
3	26	1701-1716	East	S/W	1707/3.2	1726	10	SW/10+
4	26	1757-1813	West	W/W	1804/3.2	1815	17	SW/10
5	26	1817-1835	East	W/W	1826/3.2	1852	7	SW/5-10
6	26	1922-1935	East	S/S	1927/3.2	1956	7	SW/<5
7	27	1229-1249	North	W/W	1233/3.1	1245	16	WNW/18
8	27	1253-1318	South	W/W	1303/4.2	1317	18	NW/20
9	27	1338-1404	North	W/S	1351/4.2	1405	18	NW/20+
10	27	1411-1435	South	W/S	1421/4.2	1436	17	NW/20+
11	29	1133-1155	South	S/S	1146/2.1	1207	6	ESE/5+
12	29	1215-1238	North	S/S	1227/2.0	1254	4	E/<5

The right-most column of Table 1 contains local wind direction and speed estimates except that speeds on the 27th are based on hourly averages from the nearest upwind weather station (Leonard 5N) which showed some gusts in excess of 40 mph. These estimates are usually in reasonable agreement with “Speed” calculated from estimated time and distance when generators were nearest ICE, given uncertainties in actual trajectories.

Table 2 lists the passes in a different order, sorted by generator and solution type. Contrary to Figs. 3, 4 and 5, raw recorded counts for each second were corrected for coincidence losses caused by the electronic count integrators having a delay after each count; 7.0, 8.2 and 7.3 msec for Units 1, 2 and 3, respectively. Equation 1 was used:

$$X_{true} = X_{obs}/(1-[X_{obs}\,Y/1000]) \qquad (1)$$

where X_{obs} is the counts (ice crystals) recorded in any given second and Y is the AINC-specific delay in msec. This is similar to equation (1) of DeMott *et al.* (1995) which was applied to one minute totals. In addition, summations of adjusted counts for each pass were normalized to 10 liters min^{-1} by equation 2:

$$\sum X_{normal} = \sum X_{true}\,(10.0/Q) \qquad (2)$$

where Q is the sample flow for the particular AINC in liters min^{-1}. Sample flows were measured with a precision flowmeter and depended on the specific glass sensor flow, each hand-blown, less the filtered atomizer flow used to produce abundant cloud condensation nuclei for the moistened sample air. Sample flows were 10.3, 8.6 and 7.6 liters min^{-1} for Units 1, 2 and 3, respectively. Average AgI IN concentrations, effective at -20°C, are listed for Unit 2 by dividing total adjusted counts per pass by the minutes required for AgI nucleation and ice crystal transport through the AINC cloud chamber including flush time. This assumes the standard correction factor of 10 for ice crystals which do not reach the glass sensor because of losses to glycol-wetted chamber walls and bottom cone (Langer 1973).

Total adjusted Unit 2 counts for all passes are shown to range between 4339 and 109,743, a factor of 25, with a median near 23,000. A large range might be anticipated given the variability in transport and dispersion conditions among the passes. Excluding the lowest value, an obvious outlier, reduces the range to a factor of 7 with median of 24,722.

Table 2. Summary of Unit 2 total counts per pass by grouping of generator and solution types. Duration is the time from first AgI detection to return to background concentrations for each AINC. Average IN per liter is explained above. Total counts have been adjusted by equations 1 and 2. Total counts for Units 1 and 3 are presented as percentages of Unit 2. Mean values for the first two sets are in parentheses. Passes 10 and 12 began after first AgI detection once Unit 3 data were available (see footnotes).

Pass	Gen./ Soln.	Duration (min)	Ave IN Liter^{-1}	Total Counts Unit 2	Unit 1 (%)	Unit 3 (%)
01	W/W	21.52	698	15,029	34	77
04	W/W	33.45	3083	103,141	28	82
05	W/W	17.93	6120	109,743	29	79
07	W/W	9.73	2541	24,722	30	63
08	W/W	6.57	660	4339	36	73
		(17.84)	(2620)	(51,395)	(31)	(75)
02	S/S	11.72	1680	19,695	50	82
06	S/S	31.58	3305	104,379	30	95
11	S/S	12.35	4855	59,956	39	71
12*	S/S	14.57	1422	20,724	51	70
		(17.56)	(2816)	(51,189)	(43)	(80)
09	W/S	9.52	1882	17,918	43	93
10#	W/S	7.11	3516	25,000	46	98#
03	S/W	19.72	1057	20,839	35	89

* Unit 3 data unavailable until 7 min after AgI detected.

Unit 3 data unavailable until 2 min after AgI detected and different prototype electronics used with that unit only on this pass which had the highest Unit 3 percentage.

The average value for the passes using the WMI generator with Solution W is quite similar to that from the Skyfire generator with Solution S. The three passes (3, 9 and 10) using other combinations of generators and solutions are all within a factor of 3 of the other averages and similar to individual values within the aforementioned sample populations.

Comparison of average AgI concentrations (IN liter^{-1}) among all 12 plume passages reveals a range from 660 to 6120. All values are within a factor of 3 of the median of 2212. Averages are very similar for the two sets with more than two values.

The results can be considered encouraging in view of the wide range of encountered atmospheric conditions plus differences in generator design and seeding solution. To summarize the Unit 2 observations from Table 2, there appears to be little difference in -20°C yield between the generators tested whatever solution was used which cannot be explained by natural variability in atmospheric conditions.

Based on available AINC data it is concluded that combustion products from the WMI generator with Solution W, used by the Wyoming project, provides a similar yield of effective AgI IN to the older Skyfire unit burning Solution S. The latter produced a yield (effectiveness) of 8 X 10^{15} ice crystals per gram of AgI at -20°C for maximum tunnel flow (about 20 knots across the burner head) according to its most recent CSU ICC calibration (DeMott *et al.* 1995). This is a respectable yield judged against maximum draft calibrations for several ground generators presented by Garvey (1975) which included the Skyfire. DeMott *et al.* (1995) noted that the CSU calibration of the Skyfire generator over two decades later was in excellent agreement with the Garvey (1975) results.

5. COMPARISONS AMONG THE THREE AINCs

Table 2 provides comparisons of the oldest Unit 1 and newest Unit 3 AINCs with the consistently highest counting Unit 2. It will be recalled that Units 2 and 3 are similar regarding components, glycol precooling and cloud chamber dimensions except that Unit 2 has an 8 inch diameter chamber and that of Unit 3 is 7 inches. All three AINCs chambers have similar heights. Therefore, chamber volume is a primarily a function of the square of the radius so Unit 2 has a chamber volume approximately 31% larger than Units 1 and 3 (in inches, 16.0/12.25). Actual measurements including the bottom cones revealed Unit 2 was 41% larger in volume than Unit 3. The latter typically counted about 80% of the adjusted totals of Unit 2, or, in other words, Unit 2's observations averaged about 25% higher than those of Unit 3. It seems likely that much of the difference between these two otherwise similar units can be attributed to the larger chamber size of Unit 2 although differences in cloud condensation nuclei production, humidifier output and glass sensor characteristics may have also played roles. None of these factors can be precisely controlled with an AINC.

Unit 1's adjusted counts per plume passage averaged 37% of Unit 2's for all cases (median 36%). In addition to the smaller chamber volume than Unit 2, Unit 1 uses a smaller humidifier and lacks a glycol pre-cooler unlike the other two units. Unit 1's chamber cloud is visibly less dense than in the other units and, as previously noted, a substantially smaller portion of the chamber is cold enough for rapid ice nucleation and growth.

DeMott *et al.* (1995) noted that Unit 1 and a sister unit showed linear correlation coefficients usually above 0.90 during 1994 CSU ICC experiments, with differences usually less than 15%, so some scatter was experienced as seen in Table 2's percentages for Unit 1. It was also noted that those units detected about two-thirds of the raw ICC results commonly reported by the CSU facility over the years, but had about one-third of the efficiency of the ICC after dilution airflow corrections were applied to the ICC raw data. This suggests that Unit 2, which counted about 3 times the AgI-seeded ice crystals detected by Unit 1, would be in close agreement with corrected CSU ICC results if the latter were still available.

6. TEMPERATURE DEPENDENCE OF AINC RESPONSE

Continued strong northwest winds on 28 September precluded use of the Skyfire generators. Attempts were made to test AgI IN activity (yield) vs. cloud chamber temperature by maintaining Unit 3 at -20.0°C (all reported temperatures were measured near the chamber bottom) while operating the other two units at warmer temperatures. Generators were lit outside near the southeast corner of the ICE building (position shown in Fig. 2) for few minute periods and a 60 cc metal syringe was used to collect an AgI aerosol sample just above the burner head. The sample was immediately injected into a 5-gallon metal container and capped off. Although the generators were operated just downwind of the building, local turbulent mixing caused each burn to overwhelm Unit 3's capacity so usable data were not available. Good data were obtained from several tests by taking a metal syringe sample from the 5-gallon container and releasing the AgI-air mix just below the sample intake tube over about 15 seconds. A number of these attempts also exceeded Unit 3's capacity so those data were rejected.

Table 3 summarizes results of the 5 tests with usable data. Only Unit 3 was operated at -20°C so it provided the highest total counts, contrary to the results of Table 2. Consequently, Unit 3 is used as the standard for Table 3 whereas Unit 2 is the Table 2 standard. Start times were obvious from dramatic increases in the Unit 3 count rate and stop times indicate a return to background-level IN concentrations. Unit 2 and 1 were operated at -16°C and -15°C, respectively. Total counts per test were again adjusted using equations (1) and (2).

Additional adjustments were needed for Units 2 and 1 to compensate for AINC differences revealed in Table 2. On average, Unit 3 and Unit 1 counted 80 and 43% of Unit 2 totals for the Skyfire generator with Solution S. Corresponding values were 75 and 31% for the WMI generator with Solution W. Accordingly, adjusted Unit 2 values were decreased by multiplying by 0.80 or 0.75, depending upon generator and solution, and Unit 1 values were increased by factors of either 2.33 (100/43) or 3.23 (100/31). These adjusted values, listed in Table 3 as percentages of Unit 3 totals, are admittedly approximations given the scatter of individual comparisons in Table 2.

Unit 2's percentages ranged from 22 to 51% with a median of 39% and no obvious difference between generator and solution type. This suggests a yield near 3 X 10^{15} ice crystals per gram of AgI effective at -16°C. Unit 1 values at -15°C suggest better yields for the WMI generator with Solution W but only two data points exist.

The Skyfire generator calibration reported by DeMott *et al.* (1995) had values only for -6, -12 and -20°C for maximum tunnel draft. The -12°C value was 13% of the -20°C yield so the Unit 3 and 2 comparisons appear reasonable, suggesting a reduction to approximately 39% at 16°C. An earlier 1972 Skyfire calibration using 3% Solution S rather than 2% had observations at -15°C, -16°C and -20°C as well as warmer temperatures (Super *et al.* 1972; summary results in Garvey 1975). The -15°C value was 15% of that at -20°C, while the -16°C observations were near 35%. The results of Table 3 are in reasonable agreement with the CSU ICC calibrations. This agreement may be fortuitous given the limited data and variability among individual passes and tests.

A few attempts were made to compare Unit 3 at -20°C with Units 1 and 2 operated at -12°C. It was discovered that Unit 1 could not detect any AgI if warmer than -13°C. A single test provided useable Unit 3 data, not reaching its maximum count rate. The Unit 2 adjusted total count was only 1% that of Unit 3. Past ICC calibrations indicated -12°C values were about 10% those at -20°C. AINC cloud densities were very likely too low at -12°C for accurate IN observations. Special modifications would be required for adequate AINC operation at such warmer temperatures, not practical during these tests.

Langer *et al.* (1978) used AINCs to investigate AgI yield as functions of temperature and aerosol size between -14 and -20°C. AINCs can provide useful data to temperatures at least as warm as -8°C (Langer 1973) if modifications are made to maintain cloud density. One of the authors (Langer) noted necessary changes would include increasing humidifier temperature as cloud temperature increases. The glycol-water mixture specific gravity can be carefully maintained within a narrow range to minimize water vapor absorption. Larger AINCs than used in this study can eliminate the 90° glass elbow between chamber bottom cone and glass, thereby reducing ice crystal losses to impact and melt.

It would obviously be desirable to compare IN yields from the WMI and other generators burning modern solutions at moderately supercooled temperatures, especially in the -6°C to -12°C range. Supercooled liquid water is frequently found at such temperatures, near western mountain crests at temperatures sufficiently cold for AgI nucleation

Table 3. Summary of 28 September tests with Unit 3, 2 and 1 operated at -20°C, -16°C and -15°C, respectively. Total counts per test were adjusted by equations (1) and (2). In addition, Unit 1 and 2 totals were further corrected for differences among the AINCs discussed above.

Test	Gen./ Soln.	Duration (min)	Ave IN Liter^{-1} Unit 3	Total Counts Unit 3	Unit 2/ Unit 3 (%)	Unit 1/ Unit 3 (%)
A	S/S	8.51	7837	66,696	22	7
B	S/S	9.02	2578	23,257	40	11
C	S/S	8.52	2509	21,375	39	12
D	W/W	8.20	6952	57,004	33	37
E	W/W	8.52	3314	28,233	51	62

while seedable with ground-based generators. Future work should include such testing with modified AINCs. Size distributions of AgI aerosol should also be investigated given their importance in nucleation (Langer *et al.* 1978).

7. DISCUSSION

Silver iodide cloud seeding generators were calibrated over many years at special facilities, most commonly the Colorado State University CC. Such facilities are no longer available for that purpose in the US. This paper describes an affordable method of comparing a modern WMI generator and solution against an older Skyfire generator and solution last calibrated at the ICC during 1994 (DeMott *et al.* 1995).

Three AINCs were connected to a common source of outside air while sited in a building surrounded by a wide expanse of flat, open countryside in eastern North Dakota. They were used to monitor passages of AgI lines laid out about 3 to 6 km upwind by mobile generators towed approximately perpendicular to the prevailing wind direction. Most tests used either a Skyfire generator burning the 2% $AgI\text{-}NH_4I$-acetone seeding solution historically used with those units, or a solution of 2% $AgI\text{-}NH_4I\text{-}C_6H_4Cl_2\text{-}NaClO_4$ in acetone being used with WMI remote-controlled generators in a Wyoming randomized winter orographic experiment. Three AINCs were operated at their normal cloud chamber temperature of -20°C during AgI line passages. This allowed them to be inter-compared including a newly-manufactured AINC to be used in Australia. One of the AINCs was compared with the ICC with good results at the same time as the last Skyfire calibration.

Four sampling days had substantial variations in wind speed, direction, atmospheric stability and cloud cover. As would be expected, this resulted in a wide range of AgI IN totals per plume passage, and average concentrations, as observed during twelve tests with acceptable observations. However, average results were similar between the Skyfire generator and its usual solution and the WMI generator burning the newer solution used in Wyoming. Three tests used other combinations of generator and solution type and these were also in reasonable agreement with the other experiments. It is concluded that the available data set indicates no marked difference between the older ICC-calibrated Skyfire and solution and the WMI generator burning a modern solution as measured by AINCs with cloud temperatures maintained at -20°C.

Limited laboratory-type testing was done with the three AINCs operated at temperatures of -15, -16 and -20°C, respectively. These indicated warmer temperature yield decreases, relative to -20°C, for both generator and solution types in reasonable agreement with earlier ICC Skyfire tests. Attempts to compare yields at -12°C failed because special modifications are needed to operate AINCs at warmer temperatures in order to maintain an adequate cloud density. Past work has shown that reasonable results are possible with modified AINCs but such efforts were beyond the scope of this study.

Comparisons among the three AINCs document that the newest unit is in very good agreement with the WMI AINC when the difference in cloud volume (chamber diameter) is considered. The WMI and oldest (1976 vintage) AINC were recently compared (Heimbach *et al.* 2008) and the latter was previously tested at the ICC facility with good results (DeMott *et al.* 1995). The oldest unit lacks the glycol pre-cooler and larger humidifier of the two newer units and, consequently, consistently recorded lowest total AgI IN per plume passage. But any of the units are adequate for detecting AgI presence and approximate concentration effective at -20°C.

It is recommended that future testing be done at warmer cloud temperatures to provide yield verses cloud temperature curves between about -8°C (warmer if possible) and -20°C. At least one modified AINC would be used at warmer temperatures along with a standard AINC operated at -20°C for reference. These tests could be conducted in a laboratory setting with well-downwind generators briefly operated to provide AgI IN samples for storage in a large metal container to minimize coagulation losses. Diluted samples would later be injected into the AINCs. This approach is similar to that previously used at the ICC except AINCs would be substituted for the large Isothermal Cloud Chamber. While lacking ICC sophistication and reproducibility, the multiple AINC approach offers an affordable and practical alternative in the absence of available ICC-type facilities. Monitoring the size distribution of AgI aerosols should be part of future testing because of the importance of particle size in nucleation effectiveness.

Newer IN instruments exist which could be used in similar testing instead of AINCs if resources permitted. For example, Rogers *et al.* (2001) discuss a more sophisticated instrument with better controls. Whatever approach is used, future generator testing is needed, given the loss of CSU facilities for this purpose.

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PRECIPITATION CHARACTERISTICS OF NATURAL AND SEEDED CUMULUS CLOUDS IN THE ASIR REGION OF SAUDI ARABIA

Terrence W. Krauss[1], Andre A. Sinkevich[1], and Ayman S. Ghulam[2]

[1]Weather Modification Inc., Fargo ND, USA
[2]Presidency of Meteorology and Environment
Jeddah, Kingdom of Saudi Arabia

ABSTRACT. This study presents the typical meteorological conditions and radar-derived precipitation characteristics of developing cumulus congestus clouds over the Asir region of southwest Saudi Arabia. Radar response variables were analyzed to see if there were differences between clouds seeded using AgI at various stages of development, and carefully selected similar natural clouds that formed nearby and at approximately the same time.

Three groups of seeded clouds were studied: Group I consisted of 28 clouds seeded at a time without any radar echo, and 43 natural clouds for comparison purposes. Group II consisted of 21 clouds seeded when the radar echo was >0 dBZ but <20 dBZ, and 44 natural clouds for comparison purposes. Group III consisted of 13 clouds seeded when the initial radar echo was >30 dBZ, and 19 natural clouds for comparison purposes.

In all three groups, there was a positive association between the seeding and greater maximum radar reflectivity (ZMAX) and maximum precipitation flux (MAX FLUX). The biggest differences between groups was for clouds with ZMAX >50 dBZ and MAX FLUX >100 m^3/s. The greatest seeding effects were observed for clouds that were seeded prior to the appearance of a radar echo. Further research is required to determine the effects on precipitation when seeding clouds that merge with a pre-existing cell.

1. INTRODUCTION

The Kingdom of Saudi Arabia (KSA) has an area of about 2.25 million km^2, most of which is located in arid regions. The available surface water and groundwater resources are limited, precipitation rates are low, and evaporation is high. The Kingdom does not have permanent rivers or significant bodies of water, therefore, rainfall, groundwater, desalinated seawater, and very scarce surface water must supply the country's needs. The vast majority of Saudi Arabia's water needs are met by two sources that are absent in most other countries: water desalination and fossil water. Saudi Arabia is the largest producer of desalinized water in the world, but this is very expensive. Groundwater is stored in more than twenty layered principal and secondary aquifers of different geological ages (MAW 1984). Isotopic analyses show that the fossil groundwater in these aquifers is ten to thirty-two thousand years old. The estimated groundwater reserves to a depth of three hundred metres below ground surface have an estimated total annual recharge rate of 0.13% (Al Alawi and Abdulrazzak 1994; Dabbagh and Abderrahman 1997). The renewable groundwater resources are mainly stored in shallow alluvial aquifers and in basalt layers of varying thickness and width, which are found mostly in the southwest Asir region. These aquifers store about 84 billion cubic metres with an estimated average annual recharge rate of 1.4%. According to the United Nations Environmental Program, the present rate of groundwater withdrawal from the region threatens the Saudi aquifers, and with increased development and population growth, groundwater contamination becomes an additional concern.

Several feasibility studies have been conducted previously in the KSA in order to determine if cloud seeding is able to increase the precipitation. The Saudi Arabia Cloud Physics Experiment (SACPEX) was conducted in 1990 by the University of Wyoming, and they reported a limited potential for provoking significant rain enhancement (Vali 1991). Weather Modification Inc. (WMI) and the National

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Corresponding author address: Dr. Terry Krauss, Weather Modification Inc., 3802 20th St. North, Fargo, ND 58102 USA; e-mail: twkrauss@gmail.com

Center for Atmospheric Research (NCAR) conducted a feasibility study in 2004 in the southwest Asir region of the KSA, and documented clouds that appeared suitable for hygroscopic and glaciogenic seeding (NCAR 2004). Starting in November 2006, cloud seeding trials and cloud physics research studies have been conducted in Saudi Arabia by WMI for the Presidency of Meteorology and Environment (PME) in both the central region around Riyadh and the southwest Asir region around Abha. The most recent studies have examined cloud and aerosol properties in the two regions to determine if the environmental conditions are favorable for cloud seeding.

Many similar assessment studies have been conducted around the World. For example: in Alberta, Canada (Krauss and Santos 2004), South Africa (Krauss et al. 1987; Hudak and List 1988), the United States (e.g. Dennis *et al.* 1975), Russia (Dovgaluk *et al.* 1991) and Thailand (Woodley *et al.* 2003). The review articles by Bruntjes (1999) and Silverman (2001) discuss the challenges of obtaining the necessary physical evidence, and statistical analyses using unbiased measures to determine sufficient proof that any increases in rainfall were the result of seeding induced causes and effects.

Randomization is the recommended procedure to get statistical seeding results, but natural variability of clouds, especially convective clouds, demands many carefully conducted experiments with no guarantee that there still won't be a bias in sample groups due to natural variability, luck of the draw, or unforeseen circumstances. In many cases, to get statistically significant results one needs to carry out these seeding experiments for many years. Usually, this is difficult to accomplish since most cloud seeding projects are operational in nature. Here, we try to carry out an assessment of seeding results based on data obtained during an operational project, with the latest available radar software, to get statistical results, although the authors clearly understand the inherent shortcomings in this approach.

This paper examines precipitation characteristics of natural clouds and clouds seeded with silver-iodide in the Asir region of Saudi Arabia, and observed by weather radar. A variety of radar derived precipitation parameters have been examined, primarily maximum radar reflectivity, precipitation flux, and rain volume. A summary of the storm characteristics and an exploratory statistical analysis of the response variables are presented.

2. BRIEF CLIMATOLOGY OF THE STUDY REGION

The prevailing climate of the KSA can be classified as hot desert, except in the southwest Asir region. The southwestern Asir region exends from 16.5º to 22º North latitude, and from 40º to 43.5º East longitude. The area is bounded by the Red Sea on the west, and the Najd Plateau and Ar Rub Al Khali desert on the east. The Hijaz plateau bounds the region on the North and the Yemen border to the South.

Rainfall in most of the Kingdom is <200 mm annually, highly irregular with large natural variability and sporadic. The geographic distribution of annual rainfall across Saudi Arabia is shown in Fig. 1 (Ghulam 2007), based on observational data from the PME for the period 1985-2003. Much of the rainfall falls from thunderstorms. The geographic distribution of the annual number of thunderstorm days is shown in Fig. 2 (Ghulam 2007).

The central Kingdom of Saudi Arabia rain season is in the winter and runs from late October through early May and produces an average rainfall of about 110 mm near Riyadh to a maximum of about 250 mm northeast of Qassim during that period. The summer is almost completely dry.

The Asir (southwest) region receives annual rainfall > 300 mm, primarily due to the interaction of the nearby escarpment and the advection of warm, humid conditionally unstable air in the lower atmospheric layer from the Red Sea, a trough of low pressure in Sudan, and the extension of the Indian monsoon low centered over Asia (Abdullah and Al-Mazroui 1998). The precipitation in summer has a strong diurnal cycle due to a sea breeze circulation from the Red Sea and the rapidly rising terrain of the escarpment. The escarpment starts south of Makkah, and consists of a rugged western face with mountains exceeding 2,400 meters in several places with some peaks topping 3,000 meters to the west of Abha. The rugged western face of the escarpment drops steeply to a coastal plain along the Red Sea, whose width averages only sixty-five kilometers. The relatively well-watered and fertile upper slopes and the mountains behind are extensively terraced to allow maximum land use. The eastern slope of the mountain range east of Abha is gentle, melding into a plateau region that drops gradually into the desert Ar Rub al Khali.

The Asir region has a much longer rainfall season, and rain can occur at any month of the year. The mean number of thunderstorm days in the Asir region, over the escarpment west of Abha, is >100 days as shown in Fig. 2, according to Ghulam (2007). March through April are the wettest months of the year, followed by August, December, and January. The driest months of the Asir region are in June, October, and November.

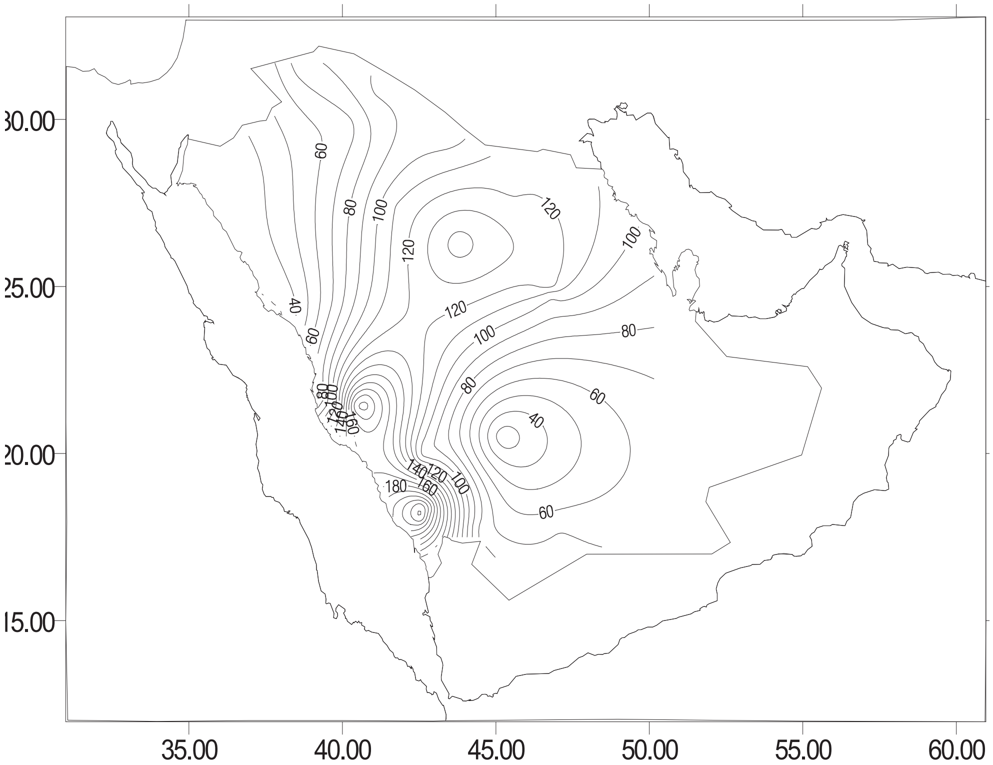

Figure 1: The geographic distribution of annual rainfall (mm) across Saudi Arabia, based on observational data from the PME for the period 1985-2003 (from Ghulam, 2007).

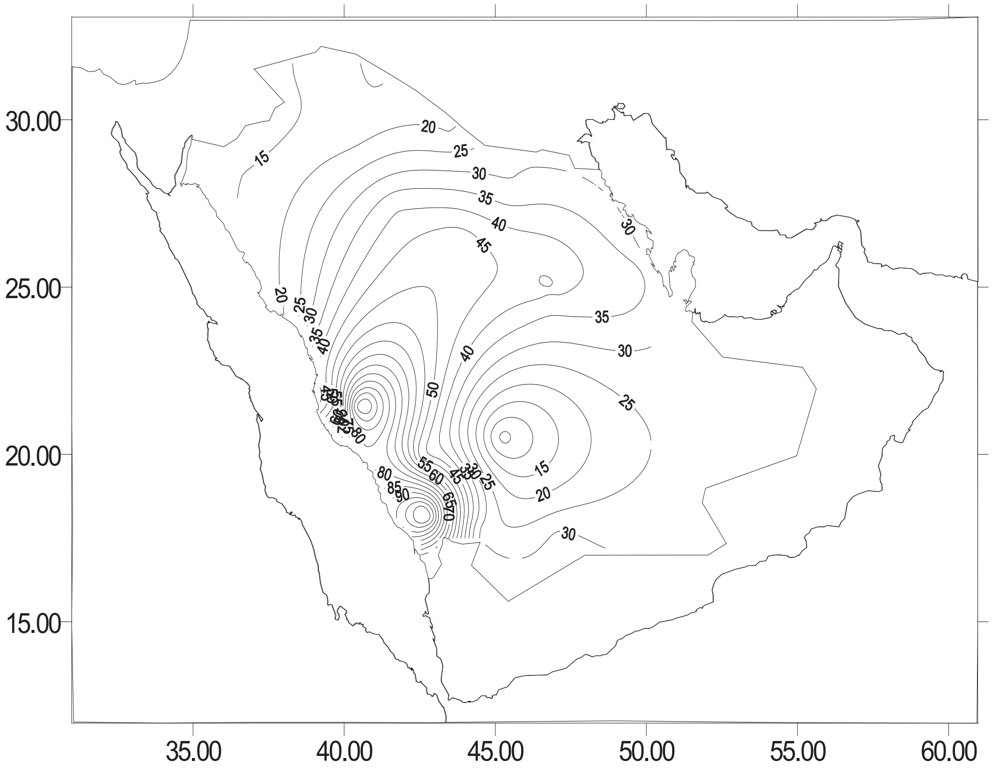

Figure 2: The geographic distribution of the annual number of thunderstorm days (Ghulam 2007).

2.1 Typical Meteorological conditions

A typical atmospheric sounding at Abha during August is shown in Fig. 3. A parcel of air at the surface with temperature 29ºC and dew point 13ºC, produces a lifted condensation level (cloud base) at 4.1 km MSL with temperature 9.5ºC, and CAPE of 2546 J/kg.

The atmosphere is typically conditionally unstable. It is usually very dry above about 6 km MSL due to the presence of a quasi-stationary sub-tropical High. The upper winds are prevailing easterlies. An afternoon southwesterly or westerly wind in the lower atmosphere forms due to a sea breeze circulation between the Red Sea and the escarpment. The sea breeze increases the humidity in the lower atmosphere and triggers or releases the instability, causing tall cumulonimbus clouds to form along the escarpment. All the clouds in this study formed by this process.

Easterly winds prevail at higher levels during the Summer-Autumn period. Hence the sea-breeze convergence zone is enhanced over the escarpment which is an additional dynamic factor for thunderstorm development. Moreover, the directional and speed wind shear with altitude contributes to the formation of long-lived storms and the possibility to form hail (Marwitz 1972, Bibilashvili *et al.* 1981). Hail is a common phenomena during the summer in the Asir region, and the project aircraft of WMI have encountered hail during research and seeding missions.

The lifted condensation level (LCL) can be used to approximate the cloud base level. The distribution of lifted condensation level (LCL) temperatures for all soundings during the month of August 2009 is given in Fig. 4. The mean LCL temperature is 5.9ºC, however, there clearly exists a bi-modal distribution with peaks at approximately 12ºC and another peak near -4ºC. This shows the difference between cloud base height and temperature with and without the presence of the sea breeze. The sea breeze corresponds to the warm, lower cloud bases created by the maritime-tropical air from the Red Sea. Clouds with very low bases with temperatures near 20ºC are sometimes observed in the region. This results in large liquid water contents within clouds and very intense precipitation during some rain events. The higher, cooler cloud bases correspond to air originating from the continental airmass over the interior of the KSA. The clouds in this study formed in the maritime tropical air masses.

The studies by Johnson (1982a, 1982b), based on theoretical calculations and observations for different geographical areas, suggested that the cloud base temperature separating the ice phase and warm-rain-coalescence precipitation formation mechanisms is between 10º and 15ºC. Cloud base temperatures >15ºC had a much greater

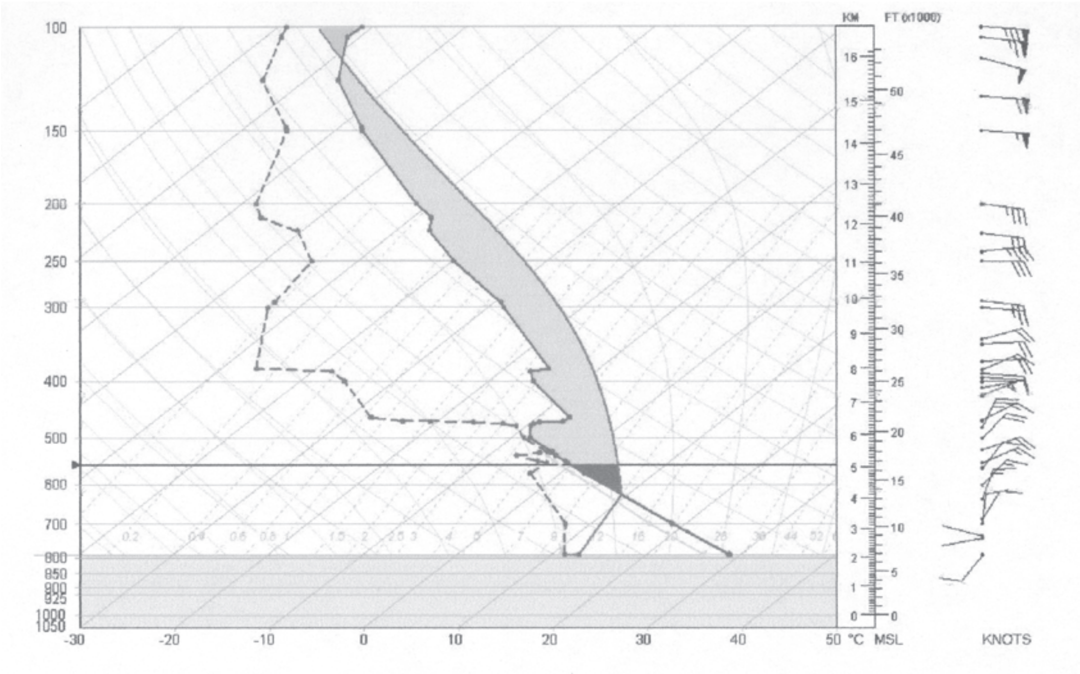

Figure 3: A typical SKEWT vertical profile of temperature, humidity, and wind at Abha on August 17, 2008 at 12Z (1500 local time). The shading represents a CAPE of 2546 J/kg. Cloud base is at 4.1 km and 9.5 C.

propensity to develop precipitation via the liquid coalescence process. The Asir cloud base temperatures are mostly characteristic of continental cumulus clouds. Airborne cloud physics measurements indicate continental type cloud droplet concentrations in the hundreds per cubic centimeter (Vali 1991, NCAR 2008) and an active ice phase precipitation process. However, the role of a liquid coalescence precipitation process and large liquid drops cannot be completely ruled out for cloud base temperatures >15ºC due to an unknown contribution by large aerosol particles, especially for clouds triggered by the warm, moist sea breeze, as discussed by Johnson (1982a and 1982b).

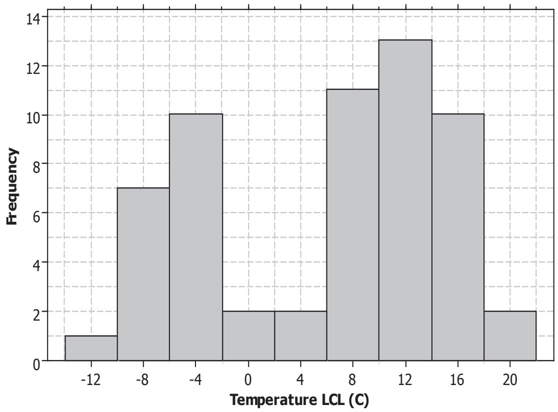

Figure 4: The distribution of lifted condensation level (LCL) temperatures for the month of August 2009 computed using the Abha radiosonde soundings. The bi-modal distribution shows the difference between continental air masses (cold cloud bases) and maritime air masses (warm cloud bases).

3. WEATHER RADAR CHARACTERISTICS

The radar used in this study is located at Abha (18.2286 N, 42.6607 E, elevation 2105 m). It is a C-band (5.35 cm wavelength) radar, manufactured by Gematronik, upgraded in 2008 to include a Vaisala-Sigmet RVP8 signal processor receiver. The nominal output power is 250 kW and the beam width is 0.9 deg. The minimum detectable signal equals approximately 0 dBZ at 100-km. The radar was operated 24 hr per day during the operational period. A complete volume scan was performed every 5 min.

3.1 TITAN Radar Software

The radar data for this study was processed using the software system called TITAN (Thunderstorm, Identification, Tracking, Analysis and Nowcasting). The program ingests radar data, converts it into Cartesian coordinates, identifies storms, tracks them and displays the tracks and forecasts (Dixon and Wiener 1993). TITAN makes it possible to compute a number of relatively sophisticated storm and track parameters very easily in real time and for post analyses (as detailed in Mather *et al.* 1996).

The radar reflectivity data were transformed into rainfall amounts using the Marshall–Palmer (M-P) relationship: $Z = 200R^{1.6}$ where Z is in mm^6/m^3 and R is in mm/h (Marshall and Palmer 1948). To avoid hail contamination, the maximum Z for the rain calculation was truncated at 50 dBZ. The ability of single polarization radar to measure rainfall has been well documented in the literature (e.g., Wilson and Brandes 1979). Empirical values of radar reflectivity vs. rain intensity relations and their variations for geographical location, storm to storm, or even within individual storms, have been the subject of many studies (a list of empirical Z–R relations can be found in Battan 1973). The Marshall and Palmer relation is the most widely used description of the size distribution of raindrops and fits measured raindrop spectra typical for a wide range of rainfalls reasonably well (Joss and Waldvogel 1990). Attempts to optimize Z–R relationships for a specific region between gage and radar estimates have not yielded substantial improvement and are generally not the major issue in radar rainfall measurements (Smith *et al.* 1975). The measurement of raindrop spectra using disdrometers began in the Asir region during August 2009. Ongoing analyses (Kucera, private communication) indicate the Z-R relationship for the Asir region is approximately $Z=300R^{1.44}$. Any differences with the M-P relation are not thought to be significant for the purposes of this paper.

The TITAN system objectively computes cell statistics for all storms within the radar viewing area. This feature allows the comparison of seeded storm cells with many natural (non-seeded) storm cells in an objective manner. The only difference between the seeded and non-seeded cells is their location. Otherwise, the geographical and meteorological conditions were the same.

3.2 Cell Identification and Tracking Criteria

The TITAN package was set to objectively identify and track cells defined by radar reflectivity >30 dBZ, with volume >10 km^3, above 2 km MSL. Furthermore, only storm cells that existed longer than 10 min were chosen to eliminate the very many small cells that pulse up and down for only one or two radar scans, which generally would not be seeded.

4. CLOUD SEEDING METHODOLOGY

Cloud top seeding was conducted by Beechcraft King Air turbo-prop aircraft flying at an altitude corresponding to the -10ºC level, typically between 6 and 7 km MSL. The seeding aircraft penetrate the tops of the developing cumulus towers as they grow through the -10ºC altitude and seed them using 20-g ejectable silver-iodide flares (described at www.ice-flares.com). The flares fall approximately 1200 m during their 37 s burn time. The fall zone covers a temperature range of approximately 8ºC; therefore, the seeding material is dispensed in a vertical curtain covering the temperature range at which the glaciogenic nuclei first become active. The seeding aircraft penetrate the center of single convective cells in most cases. For multi-cell storms, or storms with feeder clouds, the seeding aircraft seed the tops of the developing cumulus towers on the upwind sides of the more mature convective cells, as they grow up through the -10ºC altitude.

4.1 Seeding Rates and Amounts

The ejectable flares are typically dropped at a rate of one 20-g flare every 5 s (500m) during a cloud penetration. This translates to a seeding rate of approximately 240 g of seeding material per minute. The flares produce $3x10^{13}$ ice nuclei per gram of material at –10ºC, based on cloud chamber tests (Demott 1999). Seeding continued as long as new developing convective clouds with updrafts and super-cooled liquid water were observed during seeding penetrations at approximately 3-5 min intervals. Seeding stopped if there were visual signs of glaciation and high ice concentrations.

5. DATA ANALYSIS

5.1 Cloud Selection Criteria

Several groups of seeded clouds were chosen for the investigation of seeding effects. These were all cumulus congestus clouds; however, the seeding was carried out at different stages of cloud development dependent on proximity of the seeding aircraft to the cloud.

The first group of clouds was seeded without an existing radar echo (minimum detectable signal is approximately 0 dBZ inside 100 km range), but a radar echo formed on the next volume scan (time between scans is 5 minutes). The second group of clouds was seeded when there was a radar echo > 0 dBZ but less than 20 dBZ at time of seeding. The third group of clouds studied was seeded at a stage when a TITAN cell (reflectivity >30 dBZ) had already formed. All clouds chosen for this analysis formed TITAN cells that persisted for more than two radar scans (>10 min of TITAN cell duration).

Naturally developing clouds were chosen for comparison. Clouds were chosen that developed in the close proximity to the seeded clouds in space and time. These clouds were chosen for comparison analysis if they produced a TITAN cell that lasted more than two scans (>10 min duration), similar to the seeded clouds. Their position was within +/- 25 km from the seeded clouds in most cases, though in some cases they were located slightly further. We also tried to choose more or less equal number of naturally developing clouds with the number of seeded clouds, but sometimes there were slight differences on a given day.

Cumulus congestus clouds that merged with larger cells (usually called feeder cells) and further develop as a part of larger thunderstorm complexes, commonly observed in the Asir region, were not included in the first part of the study.

A common criticism in this type of non-randomized study is that the pilots choose the best cloud candidates for seeding, and so there is bias against the naturally developing clouds being initially weaker. In the case of the Asir region, we do not believe this is a problem, and often it is definitely not the case. In many cases the developing convection in the Asir region is so intense that the pilots select less intense, developing clouds due to comfort and safety reasons. Whether a cloud is seeded or not is mostly determined by the proximity of the aircraft to the cloud, at the time the growing cloud top passes through the altitude of the -10ºC level. The authors believe that the seeded clouds are a representative, independent sample of the overall population of clouds, and care was taken to not bias the sampling in any way. In many ways the seeded clouds were selected randomly by the pilots, but not in a formal manner.

6. CHARACTERISTICS OF CONVECTIVE CLOUDS EARLY IN THEIR DEVELOPMENT

A total of 136 single cumulus congestus cells were selected for analysis from 2008 and 2009 in the Asir region, within 100 km range of the Abha radar, during the months of June (9 days), July (9 days), August (15 days), and September (9 days). All clouds under consideration formed due to day-time heating and the sea breeze, between 09:40 and 14:45 UTC. The most intense development was observed between 11:30 and 13:00 UTC (14:30 to 16:00 local time), and 73% of the clouds in this study formed during this period of time

6.1 Clouds Seeded With No Echo

Of the 136 clouds, 28 were seeded when they did not have a radar echo. Forty-three (43) nearby natural clouds were chosen for comparison. All 71 of these clouds produced a radar echo on the next radar scan (5 min later). The time of the previous scan was accepted as the zero time for reference purposes and subsequent analysis.

The radar variables chosen for analysis were maximum radar reflectivity (ZMAX) and maximum precipitation flux (MAX FLUX). The probability plots of ZMAX for the 43 natural and 28 seeded clouds are shown in Fig. 5, and a statistical summary of ZMAX is given in Table 1. The maximum values of ZMAX were in the range from 34 dBZ to 64 dBZ. Figure 5 shows a tendency for seeded clouds to have greater maximum reflectivity in comparison with naturally developing clouds. The 95% confidence intervals for the corresponding normal distributions are also shown in Fig. 5. The Student's t-test was used to test the difference between the means. The assumptions of the t-test are that both groups are independent of one another and that the distributions are normal. The ZMAX values are distributed sufficiently normally (as shown in Fig. 5) to test the difference in the means. The seeded clouds had a mean maximum reflectivity 3.3 dBZ greater than the natural cases and the difference is significant at the 94% level.

The probability plots of MAX FLUX for the natural and seeded clouds are shown in Fig. 6 and a statistical summary of MAX FLUX is included in Table 1. The observed MAX FLUX varied between 7 and 5011 m^3/s. The distribution of MAX FLUX is observed to be log-normal (shown in Fig. 6). There is a tendency for seeded clouds to have greater MAX FLUX in comparison with the natural clouds. The median MAX FLUX for the seeded (S) clouds was 193 m^3/s and 148 m^3/s for naturally (N) developing clouds. The S/N ratio of the median values is 1.3. We have applied the t-test on the log-transformed values to meet the requirement that they have normal distributions with similar variances. The seeded clouds had greater mean MAX FLUX, significant at the 93% level.

Although not statistically significant at the usually accepted level of 95% confidence, there is a strong positive association between the seeding and increases of ZMAX and MAXFLUX.

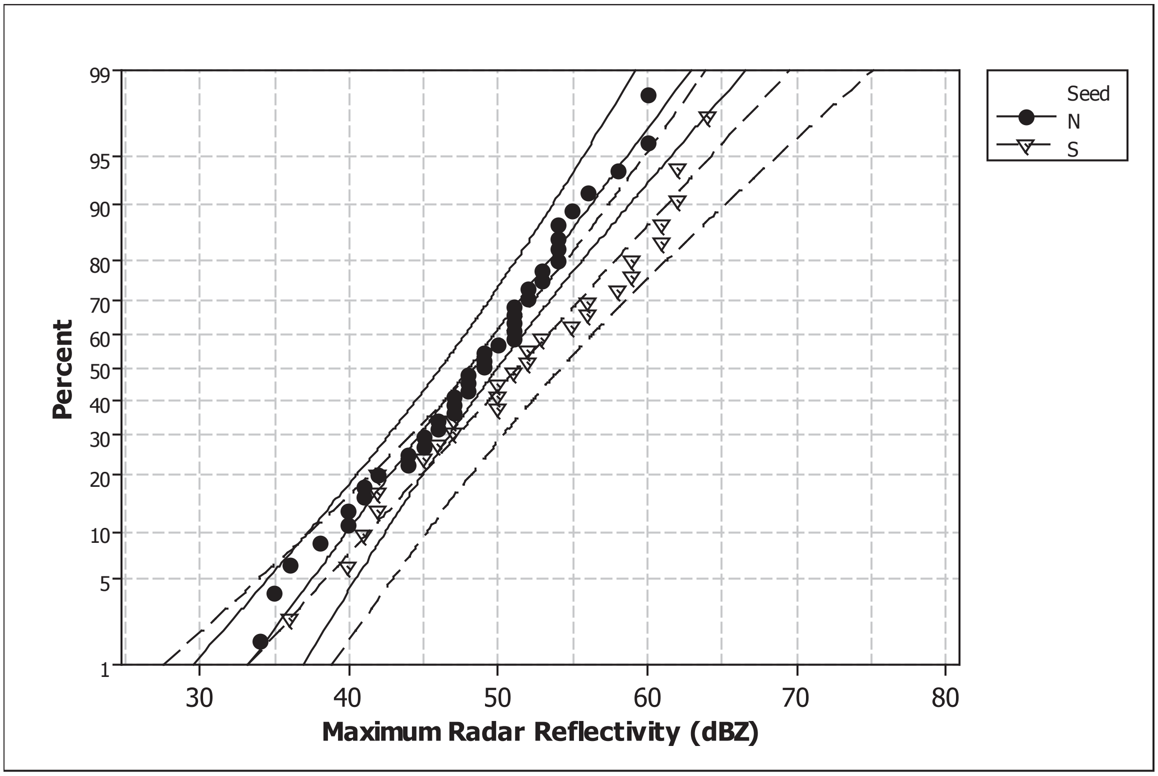

Figure 5: Probability plot of maximum radar reflectivity for 43 natural clouds (N) and 28 seeded clouds (S) that had no-echo at time of selection. The 95% confidence intervals for the corresponding normal distributions are also shown.

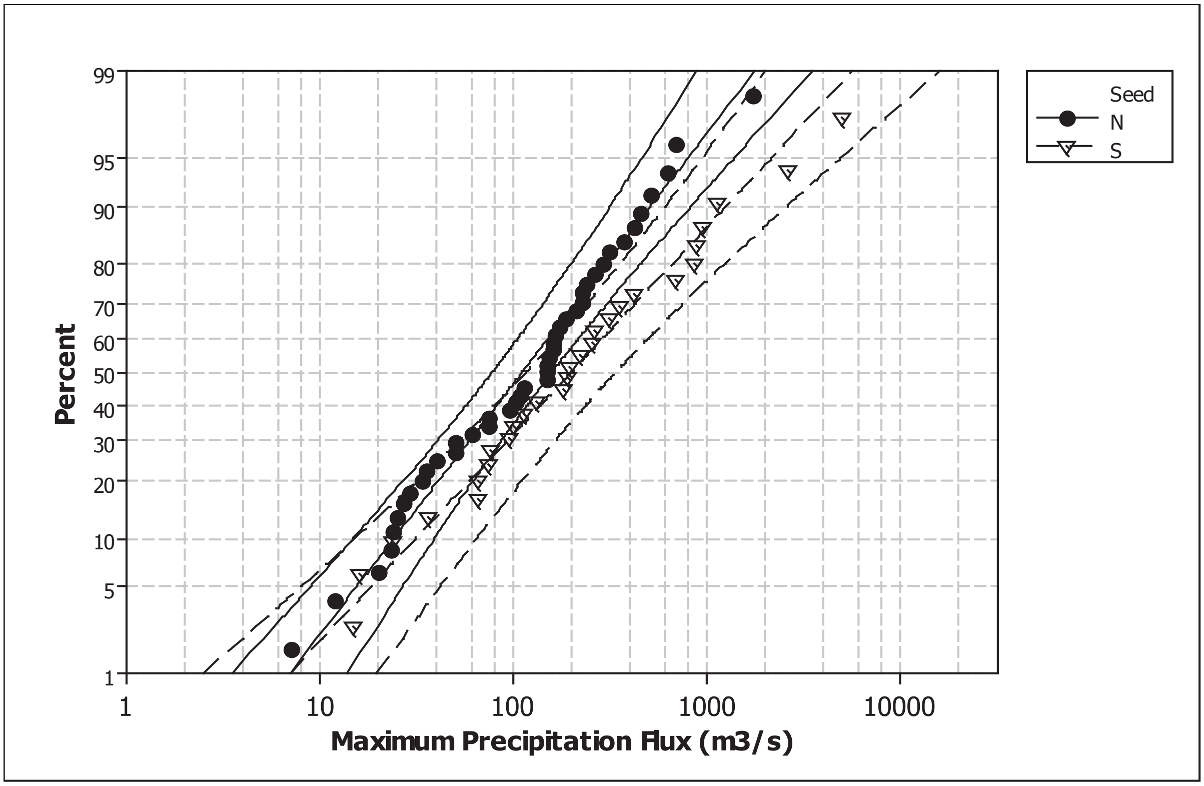

Figure 6: Probability plot of maximum precipitation flux for 43 natural clouds (N) and 28 seeded clouds (S) that had no-echo at time of selection. The 95% confidence intervals for the corresponding log-normal distributions are also shown.

Table 1: A statistical summary of ZMAX, Log MAX FLUX, MAX FLUX, Time to ZMAX, and Time to MAX FLUX for the 43 Natural cells and 28 Seeded cells with no radar echo at time of selection.

Variable	Seed	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Zmax(dBZ)	N	43	48.1	6.4	34.0	44.0	49.0	53.0	60.0
	S	28	51.4	7.8	36.0	45.3	51.5	58.8	64.0
Log Max Flux (m3)	N	43	2.0	0.5	0.8	1.6	2.2	2.4	3.2
	S	28	2.3	0.6	1.2	1.9	2.3	2.8	3.7
Max Flux (m3/s)	N	43	210.2	290.2	7.0	40.0	148.0	239.0	1737.0
	S	28	549.0	1026.0	15.0	74.8	193.0	625.0	5011.0
Time to Zmax	N	43	26.9	11.8	10.0	20.0	25.0	35.0	60.0
(min)	S	28	25.9	10.5	15.0	20.0	25.0	30.0	65.0
Time to Max Flux	N	43	27.9	13.4	10.0	20.0	25.0	35.0	60.0
(min)	S	28	26.1	13.2	15.0	16.3	22.5	30.0	65.0

Another important parameter which can be expected to have changes due to seeding is *Time to reach Maximum Radar Reflectivity.* Time zero for both the natural and seeded cases is 5 min before appearance of the first echo. A statistical summary for *Time to Maximum Radar Reflectivity* and *Time to Maximum Precipitation Flux* is given in Table 1. The mean time to reach ZMAX for the Natural and Seeded groups is 26.9 and 25.9 minutes respectively. The seeded clouds achieved their ZMAX more quickly, but the difference is 1 minute and not statistically significant. The mean time to reach MAX FLUX for the Natural and Seeded groups is 27.9 and 26.1 minutes respectively. The seeded clouds achieved their MAX FLUX more quickly, but the difference is 1.8 minutes and not statistically significant. The median times to reach ZMAX were 25 min in both cases. The third-quartile values of ZMAX and MAX FLUX were 5 min less for the seeded cases. The maximum times of ZMAX and MAX FLUX were 5 min greater for the seeded cases, but this may be due to ZMAX being 4 dBZ greater in the seeded cases, and MAX FLUX was also substantially greater for the seeded cases, therefore, it is reasonable to expect these maximum values to require additional time. Overall, these observations do not indicate any significant differences in times to achieve ZMAX or MAX FLUX.

The *Height of Maximum Reflectivity* at 5, 10, and 15 min was investigated to see if there were differences that could be attributed to seeding, and a statistical summary of the *Heights of Maximum Reflectivity* are given in Table 2. The heights of maximum reflectivity versus time were very similar for the seeded and natural clouds. These heights correspond to the cloud layer between -10ºC and 0ºC (i.e., melting level). This is consistent with a precipitation formation process involving the ice phase as reported by Vali (1991) and NCAR (2008), for both the seeded and natural clouds, whereby the first precipitation sized particles form near the -10ºC level, and then begin to descend in the cloud. These statistics do not preclude some role of liquid coalescence and large drops, although 15 min is generally insufficient time for coalescence to produce precipitation size drops that could fall in the cloud.

6.2 Clouds Seeded With Radar Reflectivity >0 dBZ but < 20 dBZ.

Twenty-one (21) clouds were seeded when they had a radar echo >0 dBZ but < 20 dBZ. Forty-four (44) nearby natural clouds were chosen for comparison, also with initial radar reflectivity >0 dBZ, but <20 dBZ.

A statistical summary of the initial radar reflectivity (*Zinitial*), ZMAX, and MAX FLUX for the 44 natural cells and 21 seeded cells is given in Table 2. There was a 0.5 dBZ difference in the mean and 2 dBZ difference in the median initial radar reflectivity between groups at the time of seeding, with the seeded group having a slight advantage at the outset.

Table 2: A statistical summary of the Maximum Radar Reflectivity Heights (km) at 5 min, 10 min, and 15 min, for the 43 Natural cells and 28 Seeded cells with no radar echo at time of selection.

Variable	Seed	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
HZm(5min), km	N	43	6.8	1.1	4.0	6.0	7.0	8.0	9.2
	S	28	7.0	1.4	4.0	6.0	7.0	8.0	9.0
HZm(10 min), km	N	43	6.2	1.2	4.0	5.4	6.1	7.0	8.0
	S	28	6.3	1.4	4.5	5.1	6.0	7.4	11.0
HZm(15min), km	N	43	5.5	1.5	1.6	4.0	5.5	6.8	8.9
	S	28	5.4	1.8	1.7	4.0	5.7	6.2	10.0

Table 3: A statistical summary of the distribution of initial radar reflectivity, ZMAX, and MAX FLUX for the 44 Natural cells and 21 cells Seeded when the radar reflectivity was >0 dBZ but <20 dBZ.

Variable	Seed	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Zinitial (dBZ)	N	44	11.1	5.4	1.0	6.3	12.0	15.0	20.0
	S	21	11.6	5.8	0.5	7.0	14.0	15.5	20.0
Zmax(dBZ)	N	44	45.9	5.9	35.0	41.5	46.0	50.0	59.0
	S	21	47.6	8.1	34.0	40.0	47.0	53.0	62.0
Max Flux (m3/s)	N	44	114.0	117.7	10.0	31.5	61.5	139.3	457.0
	S	21	181.1	177.3	7.00	30.0	134.0	317.0	537.0

The probability plots of ZMAX for the 44 natural and 21 seeded clouds are shown in Fig. 7, along with the 95% confidence intervals for the corresponding normal distributions. The ZMAX values ranged from 35 to 59 dBZ in the natural clouds, and 34 to 62 dBZ in the seeded clouds. The difference between groups lies in the number of cases with high reflectivity values >50 dBZ. Half of the seeded clouds achieved greater ZMAX than the natural clouds, but the difference is not statistically significant.

The distributions of the MAX FLUX for the natural and seeded clouds are shown in Fig. 8. The MAX FLUX values ranged from 10 to 457 m^3/s in the natural clouds, and 7 to 537 m^3/s in the seeded clouds. The MAX FLUX values follow the log-normal

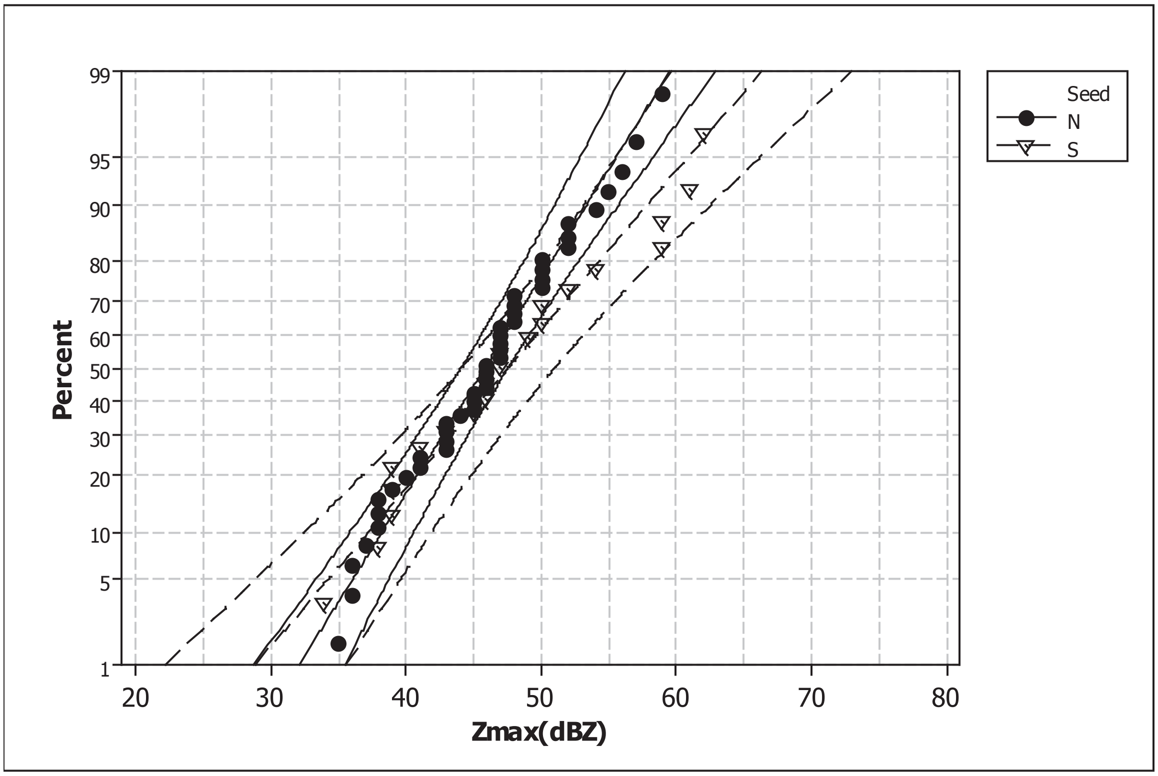

Figure 7: Probability plot of maximum radar reflectivity for 44 natural clouds (N) and 21 seeded clouds (S) that had a radar echo > 0 dBZ but < 20 dBZ at time of selection. The 95% confidence intervals for the corresponding normal distributions are also shown.

distribution as shown in Fig. 8. The median MAX FLUX equaled 61.5 m^3/s for the natural clouds, and 134 m^3/s and for seeded clouds. There is a shift in the distribution to greater values for the median, Q3, and maximum seeded MAX FLUX, compared with the natural clouds. This is another indication that seeding increases the precipitation, but the differences are once again not statistically significant. The biggest difference is indicated for clouds with maximum precipitation fluxes > 100 m^3/s. These clouds represent heavy rainfalls, consistent with the ZMAX values >50 dBZ.

7. CHARACTERISTICS OF CLOUDS SEEDED WITH RADAR REFLECTIVITY >30 DBZ AT TIME OF SEEDING

Microphysical effects of glaciogenic seeding have been shown in previous studies of simple clouds, early in their development (Cooper and Lawson 1984, Krauss et al. 1987, Sinkevich 2001). Simple clouds usually account for a small fraction of the total rainfall, and the scientific challenge is to determine the effects of seeding more mature clouds, at a later time in their life cycle. This section examines the radar characteristics of cells that were seeded after they already had radar reflectivity > 30 dBZ. The data set consists of 19 natural cells and 13 seeded cells from 8 days during August 2009.

7.1 TITAN Track Matching Results

The natural cells, used for comparison purposes with the seeded cells, were selected using the TITAN track-matching algorithms. TITAN computes the initial conditions as averages for various important parameters for the first three radar scans (15 min) of the cell lifetime. Firstly, radar cells were only chosen if they occurred between 10Z and 16Z (1300 to 1900 local time) since all seeded cells were between these times. Secondly, only cells that tracked within 150 km range of the radar were selected. Total cell mass (calculated by TITAN using the radar reflectivity, area, and height) was chosen as the primary selection parameter. Only cells that had a positive change in mass during the first 3 volume scans (i.e. growth during the first 15 min) were selected. All cells for the day were ranked according to mass, and then the natural cells that ranked immediately before and after each seeded cell were chosen for the comparison analysis.

A statistical summary of the initial Mass and Precipitation Flux for the 19 natural clouds and 13 seeded clouds are shown in Table 4. The mean, median, minimum and maximum values are all very similar; therefore, there were no significant differences or biases between the natural and seeded clouds during the first 15 min of their lifetimes.

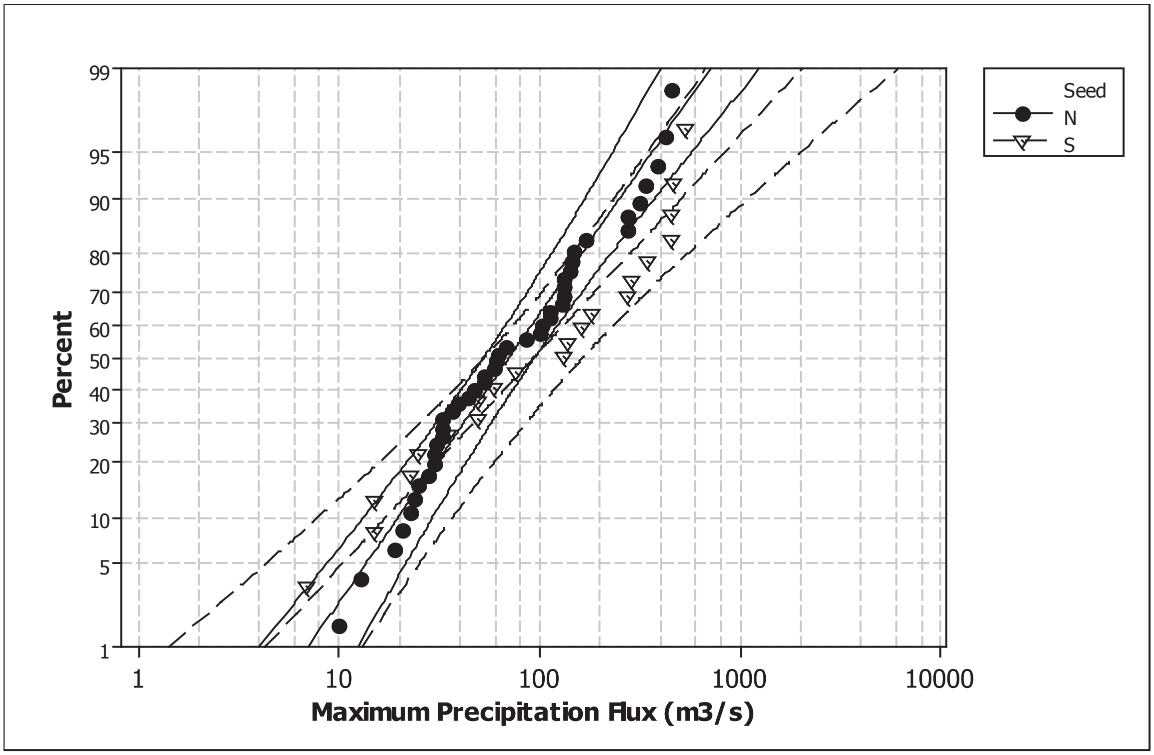

Figure 8: Probability plot of maximum precipitation flux for 44 natural clouds (N) and 21 seeded clouds (S) that had a radar echo > 0 dBZ but < 20 dBZ at time of selection. The 95% confidence intervals for the corresponding log-normal distributions are also shown.

Table 4: A statistical summary of the initial Mass and Precipitation Flux for 13 cells Seeded when their initial radar reflectivity was >30 dBZ and the corresponding matched 19 Natural cells.

Variable	SEED	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Mass(ktons)	N	19	23.7	20.3	3.5	5.9	19.2	37.5	75.4
	S	13	25.7	22.9	3.2	5.7	18.5	37.3	79.4
Precip_flux(m3/s)	N	19	48.8	43.8	10.5	13.9	36.7	70.9	184.8
	S	13	50.3	42.1	11.2	14.2	36.7	68.5	157.8

7.2 Radar Response Variables

Total Rain Volume (RVOL) is a parameter calculated by TITAN for the entire storm lifetime that can be used for assessment of the seeding. In fact, increasing RVOL is the ultimate goal of seeding. RVOL is computed by accumulating the rain volume from each radar scan over the lifetime of the storm. It is also the product of the Mean Precipitation Flux and the total storm Duration. The cumulative distributions of the log-transformed total Rain Volume for the 19 natural clouds and 13 clouds seeded with echo >30 dBZ are shown in Fig. 9. The RVOL values for the clouds in Group III were within the limits $1.1x10^4$ to $6.2x10^7$ m^3 for the natural clouds, and $6.9x10^4$ to $4.2x10^7$ m^3 for the seeded clouds. There is a shift in the distribution of seeded RVOL to greater values than the natural clouds.

The cause of the greater RVOL was investigated further. The relationship between cell duration and mean precipitation flux (MEAN FLUX) for the natural and seeded cells is shown in Fig. 10. For a given cell duration, seeded cells tended to have greater MEAN FLUX in most cases, and therefore, greater RVOL. Sixteen of the natural cells and 8 seeded cells lived < 1.5 hr and had MEAN FLUX values in the 10 to 200 m^3/s range. However, there were

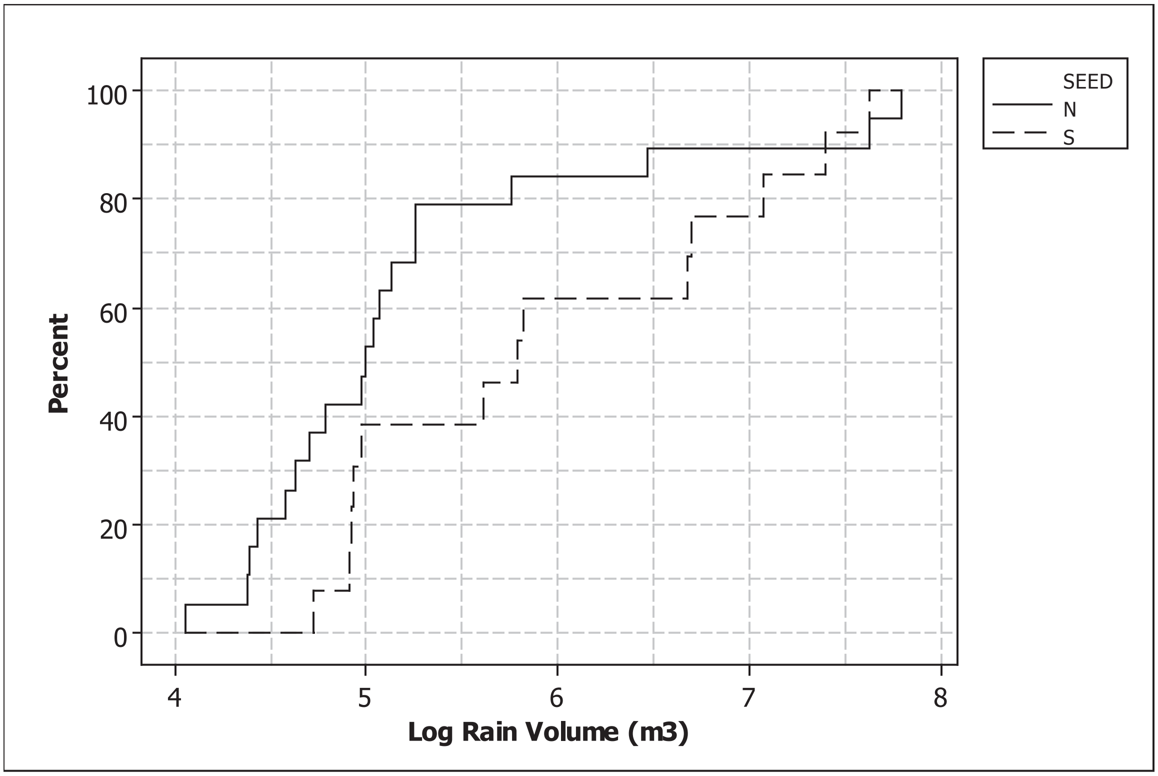

Figure 9: The empirical cumulative distributions of the log-transformed Rain Volumes for the 13 cells seeded with pre-existing echo >30 dBZ, and their corresponding, matched 19 natural cells, including the merged complexes.

5 seeded cells and only 3 natural cells that lived > 2 hr and these shifted the distribution as a whole towards greater precipitation fluxes for the seeded cases. There is a bias in the number of long-lived cells, favoring the seeded group, which cannot necessarily be attributed to the seeding.

The TITAN program keeps track of cell mergers for multi-cell storms. All of the natural and seeded storms with durations >2 hrs had multiple mergers. Storms with durations between 2 and 3 hrs had between 13 and 26 cell mergers. The seeded storm that had 3.25 hr duration had 30 mergers. The storms that had >4 hr durations had between 67 and 128 mergers, and the natural storm that lived for 6 hrs had 123 cell mergers.

Five of the seeded cells and three of the matched natural cells lived >2 hrs. Further examination of the aircraft seeding logs showed that these 5 seeded cells merged with other cells that had already existed for 40 min to 1:40 hr. TITAN then included the rain volume from the earlier cells into the resultant merged complex. After the merger, it is not possible to determine the contribution of the seeding to the resulting merged complex. The cells that were seeded and then merged, continued to live for 1 to 3 hrs after seeding, and had the greatest mean precipitation fluxes, and therefore, produced the greatest RVOL. Although the cells started out similarly (initial conditions for first 15 min were similar), some became merged complexes and others did not. Furthermore, it is not valid to attribute all of the rain from the merged-complex to the seeding. This selection bias issue is also not resolved by randomization. Further research is required into the effect of seeding feeder clouds and the effect on precipitation for the resulting convective complex.

7.3 Removal of Large Merged-Complexes

A sub-set of cells was selected for analysis by removing all cells that lived >2 hrs, and only including cells that were seeded during the first 15 min, thereby removing all the large merged complexes. The corresponding natural TITAN cell track matches were included for comparison. This reduced the sample to 18 cells (6 seeded cells and 12 natural cells) on four days (Aug, 21, 24, 26, and 31, 2009).

The cumulative distributions of the log-transformed RVOL for the reduced set of cells seeded with preexisting echo >30 dBZ, and their corresponding matched natural cells are shown in Fig. 11.

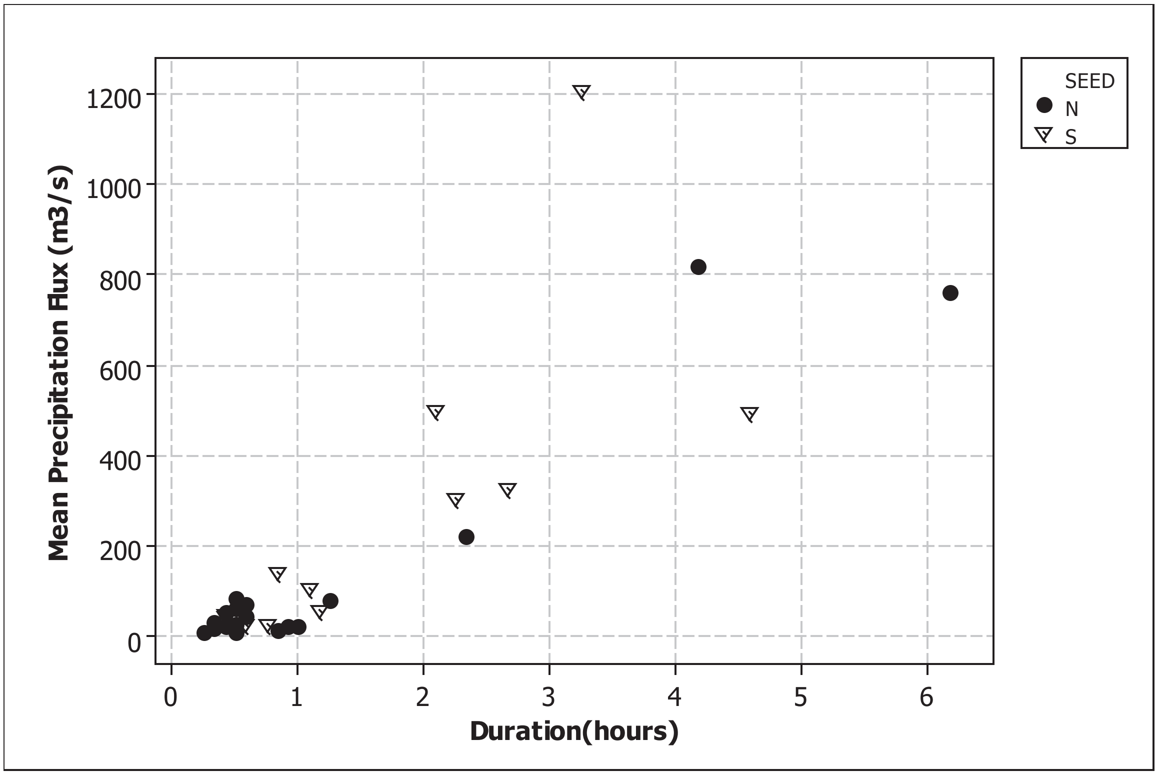

Figure 10: Scatter plot between the Cell Duration and Mean Precipitation Flux.

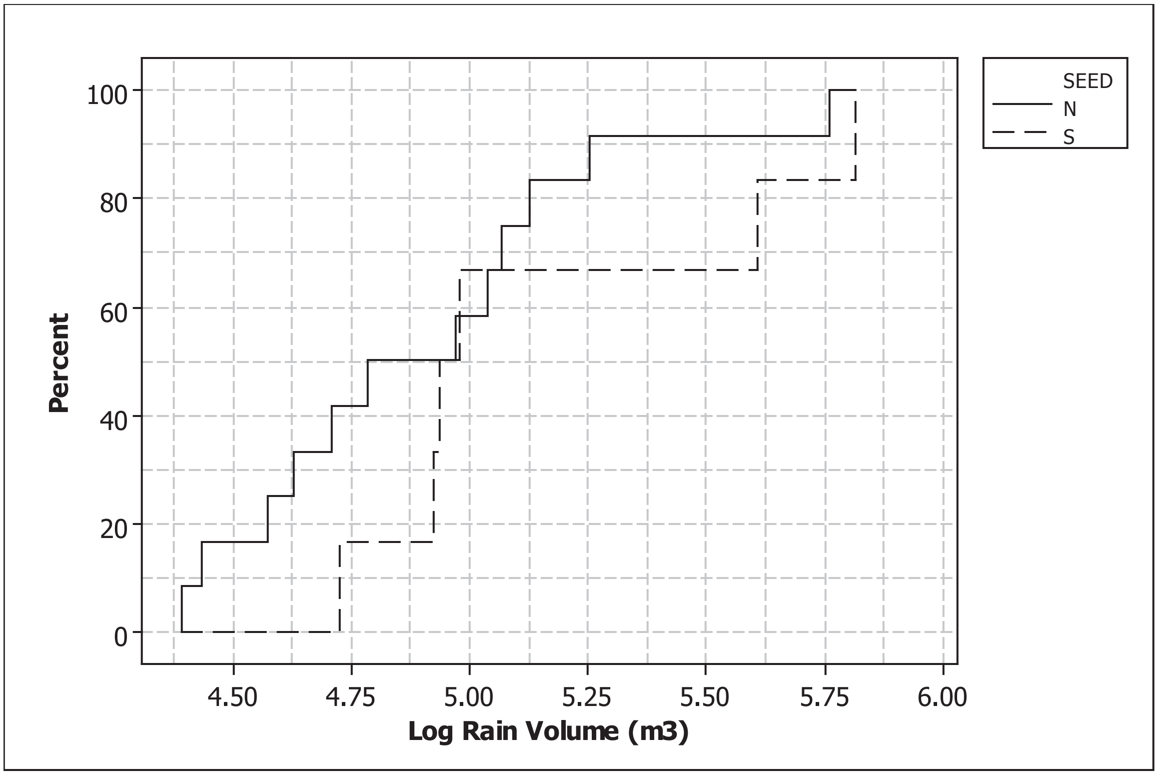

Figure 11: Cumulative distributions of the log-transformed Rain Volumes for the 6 cells seeded with pre-existing echo >30 dBZ, and their corresponding, matched 12 natural cells.

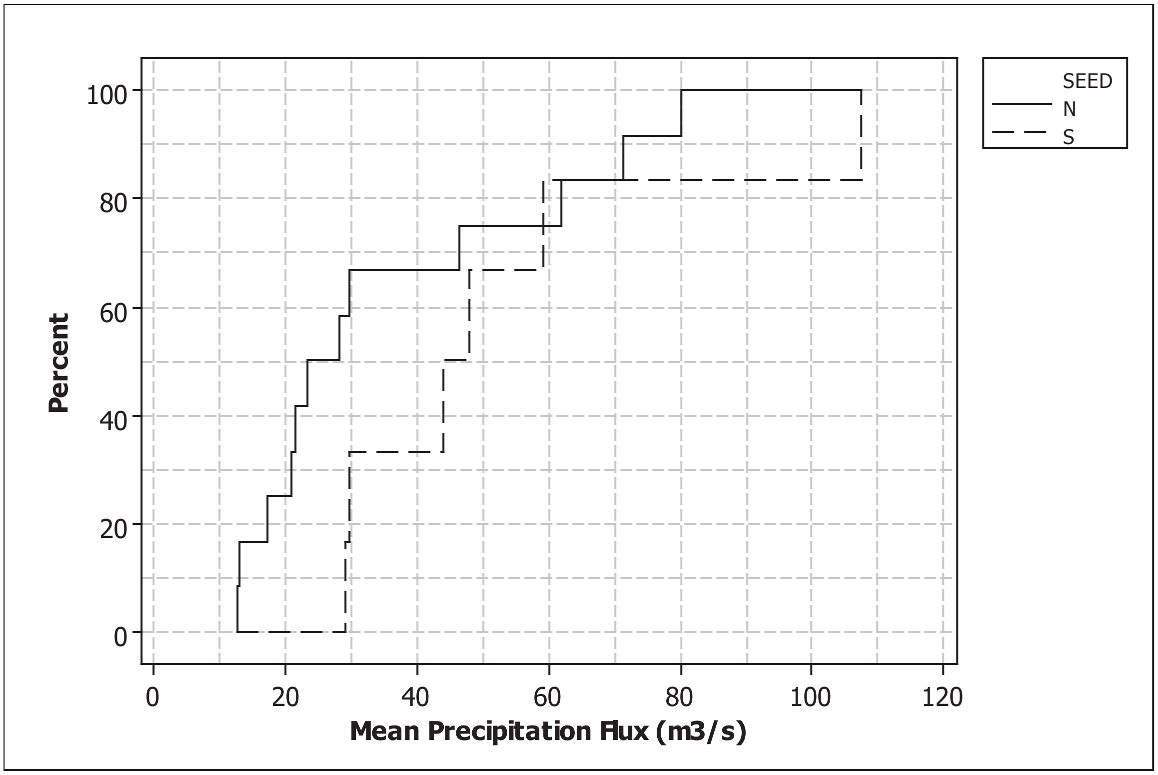

Figure 12: The empirical cumulative distributions of the Mean Precipitation Flux for the 6 cells seeded with pre-existing echo >30 dBZ, and their corresponding, matched 12 natural cells.

The cumulative distributions of MEAN FLUX for the reduced set of cells seeded with pre-existing echo >30 dBZ, and their corresponding matched natural cells are shown in Fig. 12.

There is a positive association between the seeding and greater RVOL evident in the cumulative distribution plots of Fig. 11, although the median values are similar and we must remember that the sample size is small. The positive seeding effect is a result of increased MEAN FLUX for the seeded cases as shown in Fig. 12. There were no significant differences in the storm durations and all storms had durations < 1.2 hrs. The mean ZMAX was 43.4 dBZ for the natural clouds, and 49.3 dBZ for the seeded clouds. The median values for MAX FLUX for the natural and seeded clouds were 50.2 m^3/s and 95.5 m^3/s respectively. The median values for MEAN FLUX for the natural and seeded clouds were 25.7 m^3/s and 46.0 m^3/s respectively (shown in Fig. 12). The positive association with seeding is consistent with the findings for the cells in Group I and Group II. These findings must be viewed with caution because of the small sample size, and there is need for further investigations of this type before any definite conclusions can be made.

8. DISCUSSION AND CONCLUSIONS

This study has documented the radar derived precipitation characteristics of new, developing cumulus congestus clouds both in their natural state, and those that were seeded using AgI at various stages of development, over the Asir region of southwest Saudi Arabia. These clouds represent a valuable source of water for the KSA. Radar response variables were analyzed to see if there were differences between the seeded clouds and natural clouds. Special attention was given to select similar clouds at the same time and location to those that were seeded.

Three groups of seeded clouds were studied: Group I consisted of 28 clouds seeded at a time without any radar echo, and 43 natural clouds for comparison purposes. Group II consisted of 21 clouds seeded when the radar echo was >0 dBZ but <20 dBZ, and 44 natural clouds for comparison purposes. Group III consisted of 13 clouds seeded when the initial radar echo was >30 dBZ, and 19 natural clouds for comparison purposes.

The Group I seeded clouds produced greater maximum reflectivity (ZMAX) and greater precipitation flux (MAX FLUX) than their natural counterparts. The difference in the ZMAX means was 3.3 dBZ. The median MAX FLUX for the natural clouds was 148 m^3/s and for the seeded clouds was 193 m^3/s. The differences in the mean for ZMAX and MAX FLUX were significant at the 94% and 93% level respectively. Although not significant at the 95% level, there is a very positive association between the seeding and greater ZMAX and greater MAX FLUX. The mean times to reach MAX FLUX for the natural and seeded clouds were very similar; 27.9 min and 26.1 min respectively.

The Group II seeded clouds also produced greater ZMAX and greater MAX FLUX than their natural counterparts. The difference in the mean ZMAX was 1.7 dBZ. The median MAX FLUX for the natural clouds was 61.5 m^3/s and for the seeded clouds was 134.0 m^3/s. The biggest differences between groups was for clouds with ZMAX >50 dBZ and MAX FLUX >100 m^3/s. The positive association with seeding persisted, but the statistical significance was less.

The results of the Group III clouds was dominated by a few large merged-complex storms. Five of the seeded clouds and three of the natural clouds formed large, merged complexes that dominated the radar statistics in favor of the seeded group. The seeded clouds merged with older cells and the effects of seeding could not be determined after merger. A sub-set of cells was selected for further analysis, which was seeded during the first 15 min and did not merge with older cells. This removed all of the large merged complexes and removed the bias in favor of the seeded group. Unfortunately this reduced the sample size substantially to 6 seeded cells and 12 natural cells. The positive association with seeding persisted, but the statistical significance was low, and must be considered to be very preliminary because the sample size is very small. Further research into the effects on precipitation when seeding clouds that merge with a pre-existing cell is required.

The differences between MAX FLUX for the seeded and natural clouds became less as the radar reflectivity at the time of seeding increased. The greatest seeding effects were observed for clouds that were seeded prior to the appearance of a radar echo. These statistical evaluations were not significant at the 95% confidence level; however, there is a positive association between seeded clouds and greater ZMAX, MAX FLUX and RVOL. The distributions of the response variables to seeding overlap; however, there is a consistent shift to larger values for the seeded cases. The overlap is not surprising because the responses to seeding are highly variable and fall within the range of natural variability. The authors do not believe that a blind, random selection process would necessarily account for all of the natural variability that exists. This variability is caused by seeding at slightly different times in the cloud development, with slightly different initial conditions, with slightly different seeding amounts, at slightly different locations, with slightly different topography, and slightly different forcing conditions and so on. Therefore, it is not surprising that the differences are not statistically significant at the 95% confidence level. However, this also does not mean that the differences are not positive and sufficient to warrant further assessment and considerations. The results to date have been sufficiently encouraging for the PME to continue with the cloud seeding program.

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FEATURES OF THE WEATHER MODIFICATION ASSESSMENT PROJECT IN THE SOUTHWEST REGION OF SAUDI ARABIA

Paul A. Kucera[1*], Duncan Axisa[1], Roelof P. Burger[2], Don R. Collins[3], Runjun Li[3], Michael Chapman[1],
Rafael Posada[4], Terry W. Krauss[5], and Ayman S. Ghulam[6]

[1]National Center for Atmospheric Research, Boulder, CO, USA
[2]University of the Witwatersrand, Johannesburg, South Africa
[3]Texas A&M University, College Station, TX, USA
[4]University of León, León, Spain
[5]Weather Modification Incorporated, Fargo, ND, USA
[6]Presidency of Meteorology and Environment, Jeddah, Saudi Arabia

ABSTRACT. This paper provides an overview of an ongoing rainfall assessment program that has been conducted in the southwest region of Saudi Arabia in the summers of 2008 and 2009 in conjunction with an intensive airborne measurement program. The goal of the study is to examine summertime convection that is observed over the mountainous region (often referred to as the "escarpment") that is adjacent to the Red Sea. The escarpment provides a focus for orographic precipitation as a result of complex interactions with the sea breeze and upper level thermodynamics.

The main interest in the study is to examine clouds that are observed on top of the escarpment. Seasonal precipitation results show two distinct peaks in this region: March-April and August. Evaluation of radar observations during these two peaks indicates the area has distinct characteristics in terms of the diurnal cycle and cell structure. Climatological evaluation indicates there are several distinct precipitation zones in the southwest region.

We have initially focused our airborne research program on summer clouds observed over the escarpment. This paper presents observations of clouds measured by aircraft during an intensive study carried out in the summer of 2009 in the southwest region of Saudi Arabia. A total of 35 research flights were flown during the intensive field campaign during the period 5 August 2009 to 31 August 2009. These flights were conducted under the direction of a flight scientist that assisted the pilot in flight planning and in performing the necessary profiles to accomplish the measurement objectives. Research aircraft operations focused primarily on conducting measurements in clouds that are targeted for cloud top-seeding. Cloud measurements describing the evolution of droplet coalescence, supercooled liquid water, cloud ice and precipitation hydrometeors are necessary to the understanding of precipitation formation.

From this study, we describe the large annual variability in precipitation in the southwest region of Saudi Arabia. Based on our analysis, we have developed a new conceptual model that summarizes the mechanisms for summer precipitation formation in the southwest region. Observations indicate that convective cells tend to be short-lived with complicated microphysics; the presence and concentration of large cloud droplets suggest that GCCN broaden the cloud droplet spectrum; and ice-phase microphysics is important and seems to be efficient. These results have important ramifications for cloud seeding operations.

1. INTRODUCTION

Water stresses often occur in Saudi Arabia. For example, in the absence of permanent surface water, agriculture is largely dependent on irrigation from pumped groundwater, as well as desalination. As stated in a recent United Nations Environment Programme (UNEP) report (http://www.unep.org/geo/geo4/report/06_Regional_Perspectives.pdf), the present rate of groundwater withdrawal threatens near-term depletion of Saudi Arabia's aquifers. Furthermore, with increasing development as well as the increase in population, groundwater contamination has become an additional concern.

Government officials in the Kingdom of Saudi Arabia began a feasibility study to assess the possibility of augmenting rainfall in response to the growing scarcity of freshwater. Scientists from the National Center for Atmospheric Research (NCAR), Texas

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Corresponding author address: Dr. Paul Kucera, National Center of Atmospheric Research/Research Applications Laboratory, PO Box 3000, Boulder, CO 80307; e-mail: pkucera@ucar.edu; phone 1-303-497-2807; fax 1-303-497-8401

A&M University (TAMU), Arizona State University (ASU), University of Witwatersrand (WITS), The University of North Dakota (UND), and Weather Modification, Inc. (WMI) collaborated with scientists from the Presidency of Meteorology and Environment (PME) in Saudi Arabia to carry out the study.

The potential for man-made increases in rainfall using cloud seeding is strongly dependent on the natural microphysics and dynamics of the clouds that are being seeded. The microphysics is dependent on background aerosol levels, because it is the aerosol particles that attract water vapor to form cloud droplets, and in cold clouds, ice particles. In addition, the types and concentrations of aerosol particles can be influenced by trace gases (i.e., air pollution). Given these dependencies, the microphysics of clouds can differ significantly from one geographical region to another, and even between seasons in the same region. In some instances, clouds may not be suitable for seeding, or the frequency of occurrence of suitable clouds may be too low to warrant the investment in a cloud seeding program.

These factors need to be evaluated in a climatological sense or at least over a sufficient period of time to account for natural variations. This requires the conduct of preliminary studies on atmospheric aerosols, cloud microphysics, and dynamics prior to commencing a large cloud seeding effort. If the targeted measurements and additional data show sufficient evidence for clouds to be positively affected by cloud seeding, the cloud seeding technique(s) should then be evaluated using a randomization procedure to statistically demonstrate that the seeding method is effective and measurable. Such a randomized statistical experiment would become the second phase of a future program, which would build on other randomized statistical experiments performed under similar conditions.

Using a combination of radar, aircraft, and surface observations of aerosol, cloud, and precipitation, this project attempts to determine if cloud seeding is a viable option for augmenting freshwater resources in Saudi Arabia. In this project, we are attempting to answer three grand questions:

1. Can seeding clouds in Saudi Arabia increase rainfall at the surface?
2. Under what conditions are seeding techniques viable for increasing rainfall?
3. If rainfall increases are possible, what is the magnitude of the increase attainable over an area, and is the technology cost-effective in serving the water resource needs of Saudi Arabia?

Initially, the assessment program (2006-2007, 2007-2008) was focused on the central region of Saudi Arabia during the winter and spring seasons (November – May). In the summer of 2008, the assessment study shifted to the southwest region of Saudi Arabia. Intensive airborne field programs were conducted in the summer of 2008 and 2009. Because of the vast amount of data collected in Saudi Arabia, only a snapshot of the project can be presented. Therefore, we narrow the focus of the overview to the field programs conducted in the southwest region, with a particular focus on the 2009 observations.

2. PROJECT AREA AND INSTRUMENT OVERVIEW

2.1 Study Region

The Kingdom of Saudi Arabia occupies about 80% of the Arabian Peninsula with an area of approximately 2,250,200 km^2. The Kingdom is bounded by the Red Sea to the west; the Arabian Gulf, UAE, Qatar, and Bahrain to the east; Kuwait, Iraq, and Jordan to the north; Yemen and Oman to the south.

Saudi Arabia comprises several distinct physiographic regions. Eastward from the coastal plain, the Red Sea escarpment rises steeply to the great interior plateaus: the crystalline Najd, the Hismah, and the Hijaz Asir. These highland areas include local mesas, buttes, lava fields, and large and small wadi (e.g., watersheds) systems. Continuing eastward through the sedimentary Najd, to the north of the central region, is the Nafud Basin. The Great Nafud Desert is connected by a long narrow belt of sand (the Dahna) to the largest sand dunes in the world – those of the Ar Rub' Al Khali. Further eastward, in the eastern Province, the downward sloping land surface continues on an even gentler slope to the eastern edge of the Kingdom at the Arabian Gulf.

The project study area is located in the southwestern region in Saudi Arabia (Fig. 1a,b). This region is bounded by the Red Sea to the west, Jeddah to the north, desert highlands to the east, and the Yemen border to the south (see Fig. 1b). As described above, this region is mountainous, composed of mesa, buttes, deep valleys and plateaus. The high elevation is often referred to as the "escarpment". The escarpment rises abruptly from the Red Sea to a maximum elevation of around 2800 m (cyan to white colors on the map, respectively) over horizontal distances of 100 km. This abrupt change in elevation provides the orographic lift for convective storm development, which is the focus of the study.

Figure 1(b) shows a zoomed in view of the southwest region, which was the focal area for the radar study. This region has radar coverage from five radars. The radars are located (from north to south): Jeddah, Taif, Baha, Abha, and Jizan. The radars will be described in more detail in the next section. The final map (Fig. 1c) shows the region of the airborne field study in more detail, which was centered on the Abha radar.

2.2 Radar Network

Five C-band weather radars were utilized during the study. As described above, the radars were located near the cities of Jeddah, Taif, Baha, Abha, and Jizan (e.g., see Fig. 1). Photos of the radar installations are shown in Fig. 2. The radar systems were developed or upgraded by a variety of manufacturers (e.g., Gematronik, Vaisala, and Advanced Radar Corporation [ARC]). They all have Doppler capability. However, the radar located in Baha has the capability to scan in dual-polarimetric mode. For polarimetric scanning, the Baha radar is configured to transmit in a simultaneous horizontal (H) and vertical (V) mode. In this mode, the observed parameters include horizontal radar reflectivity (dBZ_h), differential reflectivity (ZDR), Doppler velocity (VR), spectrum width (SW), differential phase (PhiDP), specific differential phase (KDP), and correlation between H and V polarizations (RhoHV). The readers should refer to Bringi and Chandrasekar (2001) for a detailed description of polarimetric parameters. Analysis of the polarimetric fields is outside the scope of our study. A summary of radar characteristics is provided in Table 1.

The radars continuously scan at a temporal resolution of 5 min and spatial resolution of 0.25 km in range and 1° in azimuth. In volume scan mode, the radars' range in elevation is from 0.5° to 45°. The radars are networked and provide real time information.

For analysis and display of radar observations we used the TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) software system, which is described by Dixon and Weiner (1993). In addition to TITAN, a new Configurable Interactive Data Display (CIDD) system was also used for

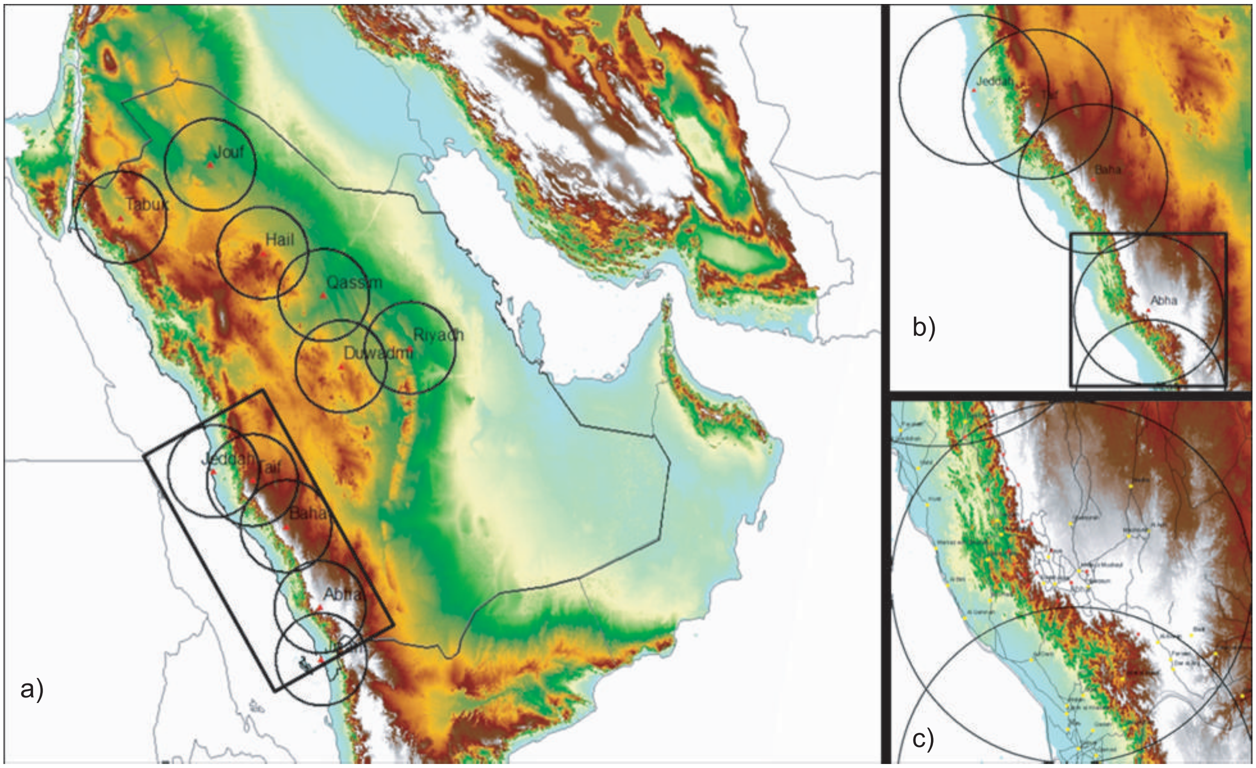


Figure 1: Map showing the project area. Map a) shows the study region (area indicated in the rectangle box) located in the southwest region of Saudi Arabia. Map b) shows the study region in more detail. This region was used in the radar climatology study. Map c) shows the region centered over Abha, which was the focus area for the aircraft sampling studies. In each map, the circles indicate the 150 km range ring for each radar and color background shows terrain features, which ranges from sea level (cyan) to 2800 m (white).

operations and analysis. The TITAN software can display radar data and aircraft position in real-time for the purpose of directing the operations. The CIDD system is routinely set to display an animated 1-hour movie loop of the high resolution polar radar data.

Figure 2: Five radars located in the southwest region of Saudi Arabia: a) Abha, b) Baha, c) Jizan, d) Jeddah, e) Taif. The specifications of the radar are given in Table 1.

Table 1: Radar characteristics for Abha, Baha, Jizan, Jeddah, and Taif.

	Abha	Baha	Jeddah	Jizan	Taif
Description	Gematronik	Vaisala	Gematronik	Gematronik	Gematronik
Frequency	C-Band	C-Band	C-Band	C-Band	C-Band
Type	Doppler	Dual-Pol	Doppler	Doppler	Doppler
Receiver	Vaisala RVP8	ARC HiQ	ARC HiQ	ARC HiQ	Vaisala RVP8
Latitude	18.2287	20.2952	21.7108	16.8963	21.4799
Longitude	42.6607	41.6430	39.1853	42.5835	40.5607

For this study, we used TITAN to determine the diurnal cycle and statistical properties of typical lifetimes, sizes, intensities, and storm movements of the cells. These data will be used to determine if the clouds have the potential to be seeded. This is important in order to understand the number of cells that occur naturally, the length of time that might be necessary in order to perform a later randomized experiment that would quantitatively describe the potential rainfall increase from seeding, to assess the operational aircraft needs in treating these storms in a timely manner, and to estimate the overall area rainfall increases that might be possible from seeding.

2.3 Aerosol Surface Site

Continuous aerosol measurements were made at a surface site located just to the east of the escarpment. The surface and airborne measurements were linked through a repeatedly employed flight pattern that included multiple low-level orbits around the site. Submicron and supermicron size distributions were measured at the surface using a differential mobility analyzer and a TSI, Inc. Aerodynamic Particle Sizer (APS), respectively. A Droplet Measurement Technologies (DMT) CCN counter (CCNc; Roberts and Nenes 2005) was operated together with a tandem differential mobility analyzer (TDMA) to measure supersaturation-resolved CCN concentration and hygroscopic growth of size-resolved particles as the RH to which they are exposed is raised from <15% to 85%.

2.4 Airborne Platform

The WMI Beechcraft King Air B200, hereafter referred to as the WMI King Air, was used as the research aircraft since it was equipped to make cloud microphysical and liquid water content measurements. These measurements are required to address the research objective to study the life cycle of supercooled liquid water content and cloud microphysical properties present in convective towers. The instruments included the Particle Measuring Systems (PMS) Forward Scatter Spectrometer Probe (FSSP-100: Dye and Baumgardner 1984), the DMT Cloud Droplet Probe (CDP), the DMT Cloud Imaging Probe (CIP), the DMT Liquid Water Content (LWC) hot-wire probe and the Stratton Park Engineering Company (SPEC) two dimensional stereo probe (2D-S: Lawson et al. 2006) probe. The cloud physics instrumentation is shown in Figs. 3 and 4. The cloud physics instrumentation payload for the intensive field campaign is listed in Table 2. In addition to the cloud physics instruments, a PMS Passive Cavity Aerosol Spectrometer Probe (PCASP) and a DMA were operated on the aircraft to characterize the below-cloud aerosol size distribution. A pair of DMT CCN counters were operated on board the aircraft in order to provide 1 Hz measurement of CCN concentration at a single supersaturation and slower (~0.002 Hz) measurement of CCN spectra over a range in supersaturation.

The duplication in cloud physics instrumentation proved to be a very important aspect in this project. Since most of the measurements were done in mixed phase convective clouds, shattering of ice crystals at the probe inlets caused by the collision of ice hydrometeors with probe tips forward of the sampling volume (Field *et al*. 2006) complicated the analysis of supercooled cloud droplet and ice crystal size, concentration, and mass that is needed for cloud modification studies and single cloud model

Figure 3: FSSP (left) and 2D-S (right) mounted under the right wing.

Figure 4: PCASP (left) and CIP/CDP/LWC combination probe (right) mounted under the left wing.

Table 2: Cloud physics measurements made by the WMI King Air research aircraft.

Property Measured	Diameter Size Range	Instrument
Cloud droplet particle size	3 to 47 μm, 20 channels	PMS FSSP-100
Cloud droplet particle size	2 to 50 μm, 30 channels	DMT CDP
Cloud hydrometeor size and image	25 to 1550 μm, 62 channels	DMT CIP
Cloud hydrometeor size and image	10 to 1280 μm, 128 channels in horizontal 10 to 1280 μm, 128 channels in vertical	SPEC 2D-S

simulations. Hydrometeor shattering appeared to be most pronounced in the FSSP particle size distribution (PSD) in mixed-phase clouds. The shattering of ice particles on the FSSP sampling inlet and the effect on measurements has raised concerns on the use of FSSP in ice and mixed-phase clouds (Korolev and Isaac 2005). In the presence of irregular large ice crystals FSSP sizing is inaccurate and may detect concentrations an order of magnitude higher than what is believed to be the actual ice particle concentration (Gayet *et al.* 1996). Figure 5 shows the conceptual diagram of the mechanism of particle shattering during sampling by the FSSP. To overcome this issue, measurements with the 2D-S (Lawson *et al.* 2006) were considered alongside the CDP, FSSP and CIP probes. The 2D-S data were processed using criteria-related particle inter-arrival time. Shattering effects on the 2D-S are minimized by removing closely spaced particle images (Baker *et al.* 2009). Shattered fragments have different initial velocities and the distance between them are also different (Korolev and Isaac 2005). The interarrival time between such frames is smaller than the average interarrival time, and it is used as an indicator of shattering events. In the 2D-S, algorithms are used to reject shattered fragments by comparing the particle's inter-particle time to the average inter-particle time for every 10,000 particles. Since the 2D-S has two optical paths (these are labeled as "vertical" and "horizontal" or 2DSV and 2DSH respectively), the particle-by-particle processing algorithms were run independently for the vertical and horizontal path. Figure 6 shows an example of a splashing event and noisy diode data intermixed with 'accepted' data for the vertical optical path. Figure 7 gives an example of particle size distributions (PSDs) calculated using particle-by-particle processing of all particles with no artifact removal (blue trace) and splashing events and noisy photodiodes removed (green trace). In this example the vertical channel has less noisy diodes in the first 5 bins than the horizontal channel. The 2D-S "accepted" data are believed to represent the "actual" particle size distribution and any deviation from the shape of the 2DSV and 2DSH PSD is assumed to be due to shattering artifacts. The orientation of the vertical and horizontal laser beams do not correspond to a horizontal frame of reference. This is due to the probe being installed on a pylon that is perpendicular to the wing dihedral angle. This is also shown in Fig. 3.

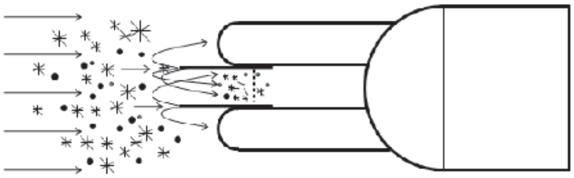


Figure 5: Conceptual diagram adapted from Fig. 16 of Korolev and Isaac (2005) of the mechanism of particle shattering by the FSSP due to the mechanical impact of particles with the FSSP shroud inlet upstream of the sample area. The sample area axis is indicated by the dotted line inside the shroud.

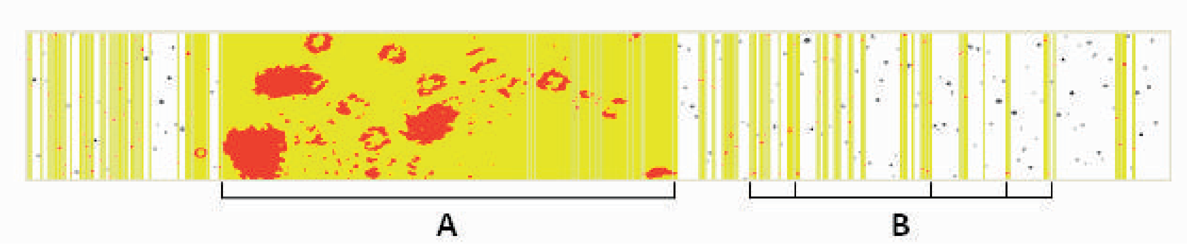


Figure 6: Example of 2D-S splashing event (A) and noisy diode data (B) intermixed with "accepted" particle data for the vertical channel on 11 August 2009 from 11:56:50.151.903.301 to 11:56:50.171.646.603 UTC. The yellow highlighting identifies the "rejected" particles. The height of an image frame is 1280 μm.

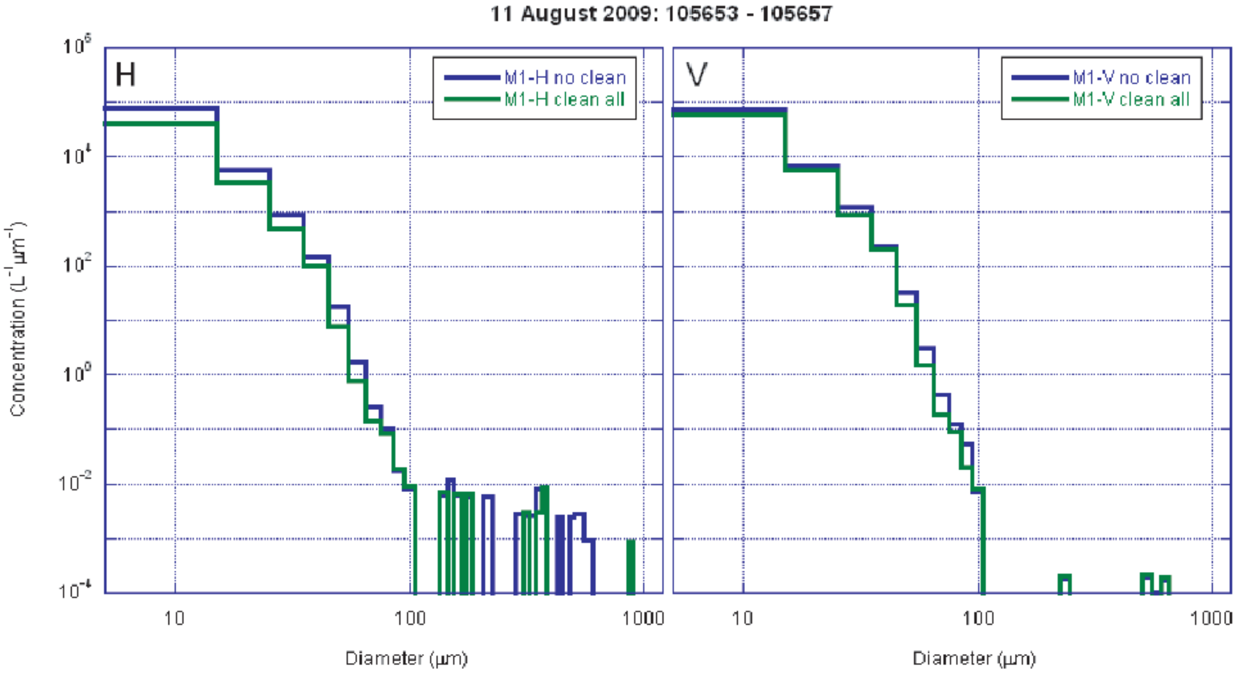


Figure 7: Example of 2D-S mean particle size distribution on 11 August 2009 from 11:56:53 to 11:56:57 UTC. The blue trace ("no clean") includes no artifact removal while the green trace ("clean all") removes splashing events and noisy diode data for the horizontal channel (H) and vertical channel (V).

3. Regional Climatology

The Arabian Peninsula is in many respects a crossroads of the world. Apart from being the cradle of civilization, it also is a crossroads with respect to aerosols in the atmosphere. Large areas of sandy deserts and exposed soil characterize the Arabian Peninsula and surrounding regions, and desert dust lifted aloft in the atmosphere is thus a common feature in the region. Pollution from Europe, especially in the form of sulfates and nitrogen oxides, commonly penetrates the region during the winters and pollution from southwest Asia is very common during the summer. In addition, smoke produced by biomass burning in Africa can also penetrate the region during the summer. Finally, due to the extensive oil industry in the region vast amounts of local pollution are also produced in the form of sulfates that can also affect cloud processes. In addition to the unique dynamic and thermodynamic conditions observed over the Arabian Peninsula, these conditions could either inhibit or enhance natural precipitation processes. This complex interaction between the synoptic scale forcing to the microscale interactions need to be understood and evaluated before a final assessment of cloud seeding to enhance precipitation can be made.

A review of rainfall climatology is an important component in relating the observations from the field campaigns in context of the larger scale, seasonal forcing. Climatologically, Saudi Arabia has a link to the neighboring eastern Mediterranean area. Mid-latitude air masses come predominantly from the north and west, and are occasionally deep enough to produce cool weather with scattered rain showers. There is a potential for tropical air masses from the south to influence conditions along the mountains from Yemen and along the Red Sea coast of Saudi Arabia.

Dryness is the prevailing climatic character in Saudi Arabia except in the southwest region. The geographic distribution of rainfall in Saudi Arabia based on a 50-year climatology of rainfall derived from a study by Hijmans *et al.* (2005) is shown in Fig. 8. The precipitation patterns observed in our study are in agreement with the long-term climatology described in Hijmans *et al.* (2005). The southwest region receives annual rainfall > 300 mm due to its unique geographical configuration and interactions of the sea breeze with the escarpment. Rainfall in most of Saudi Arabia is < 200 mm, highly irregular (i.e., large natural variability), and sporadic. In our analysis, we focus on describing the seasonal variability in the southwest region. The goal was to determine when storms occurred and if there were unique sub-regions that have similar precipitation characteristics. This analysis will give valuable insight on when conditions might be viable for

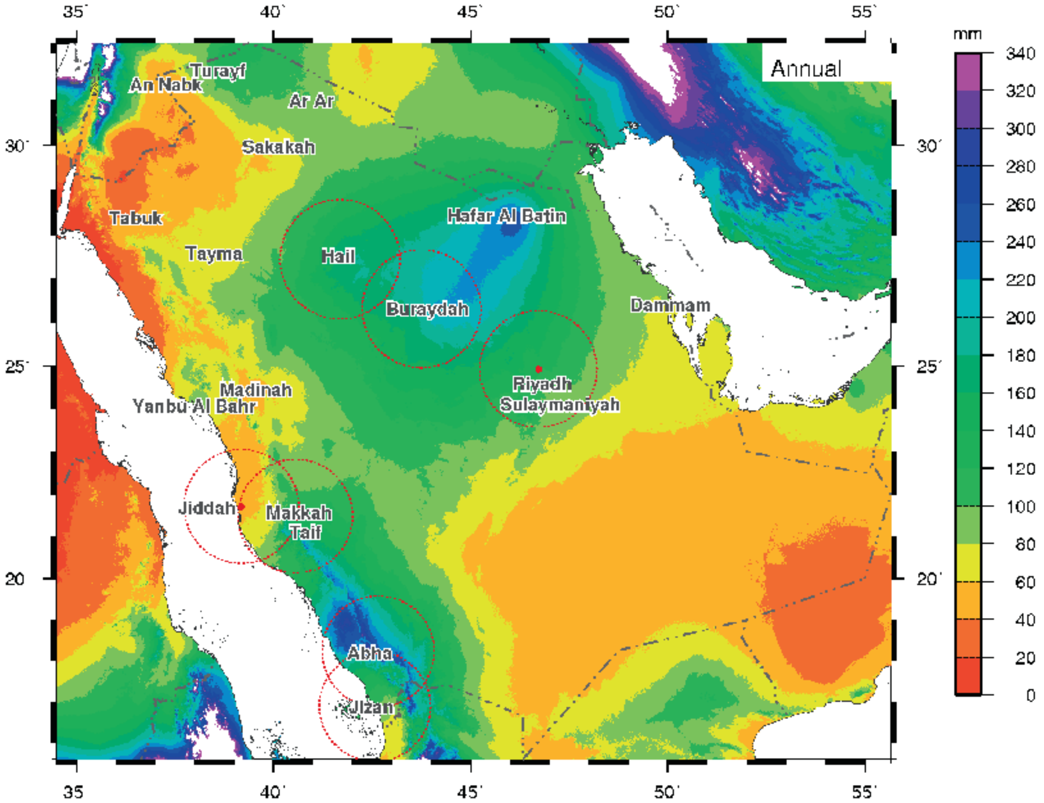


Figure 8: Map of Saudi Arabia showing the distribution of annual rainfall (mm) over Saudi Arabia based on a 50-year surface rainfall climatological record (Hijmans et al. 2005).

seeding and provide regional boundaries that have similar precipitation characteristics. Presumably, in these sub-regions, aerosol, clouds, and forcing mechanisms have similar characteristics for a given season and targeting criteria would be the same.

To determine regions with similar characteristics, we use the precipitation climatology dataset presented in Hijmans *et al.* (2005) and apply a self-organizing map (SOM) technique. The SOM technique uses a neural network algorithm that learns to cluster groups of similar input patterns from high dimensional input fields (e.g., two or three dimensional rainfall fields) in a non-linear fashion into a low dimensional output field (Kalteh *et al.* 2008). The output field is a discrete index that identifies and groups regions that have similar input patterns. The SOM technique has been used successfully to link common circulation patterns in the United States (Hewitson and Crane 2002) and rainfall patterns in Spain (de Luis *et al.* 2000).

Our SOM analysis of the precipitation fields in the southwest region of Saudi Arabia is shown in Fig. 9a. Based on the SOM stratification, there are nine distinct sub-regions or areas that have similar precipitation features that were identified within our study area. The seasonal trend in precipitation for these nine regions is shown in Fig. 9b. It is interesting that the unique precipitation areas have an association with the location of the escarpment (e.g., below to the west, directly on top, to the east). For illustration, the following discussion focuses on the four sub-regions that are observed within the range of the Abha radar. One region is composed of a narrow band that is located on top of the escarpment. Figure 9b indicates this region has two distinct peaks in rainfall. The first peak and maximum peak occur in the months of March and April. A secondary peak is observed in August. Also, the region is associated with some of the largest amounts of rainfall in the southwest regions (and in all of Saudi Arabia). The region that is adjacent to the escarpment located to the east (dark red) covers a much broader area. This area also has a bimodal distribution in the seasonal precipitation analysis. Again, there is a maximum peak in March-April and a secondary peak in August. This region also has observed extreme rainfall events.

The other two regions within the range of the Abha radar is the land adjacent to the Red Sea (purple) and the desert highlands (cyan) to the west. Both have distinct rainfall distributions in comparison to those on top of the escarpment. The region near the Red Sea (below the escarpment) receives most

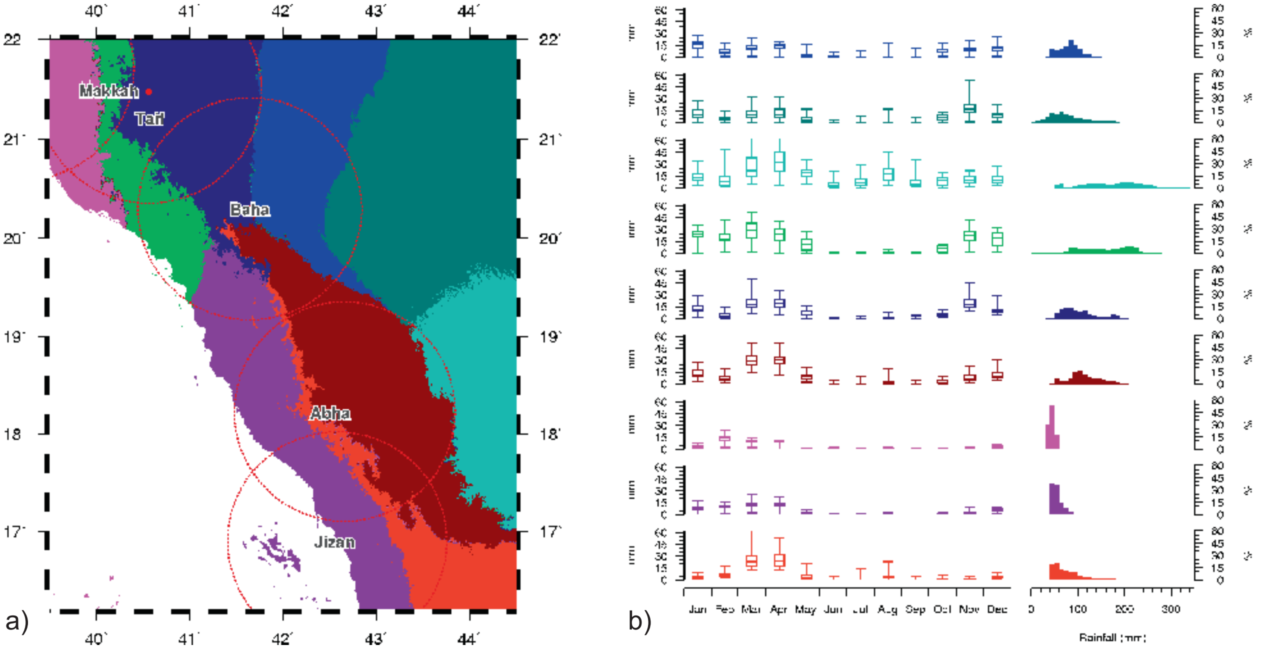


Figure 9: Results of SOM analysis in the southwest region of Saudi Arabia. Panel (a) shows the spatial distribution of the nine regions identified on the SOM analysis. Panel (b) shows the seasonal distribution of rainfall based on the SOM categorization.

of its precipitation during the winter months (November-January). Rainfall tends to be light during the peak in the rainy season. The desert highlands to the east has maximum peak in rainfall in the spring (March-April) without the secondary peak in the summer months. Rainfall accumulations in this region also tend to be less than precipitation observed over the escarpment.

This analysis indicates there are two periods in which we can focus our efforts to study the feasibility of seeding for clouds that are located near or on top of the escarpment (our region of interest). Based on this analysis, we have focused our intensive airborne field program on the summer peak in August. However, we are planning to conduct a study of spring clouds in future field programs.

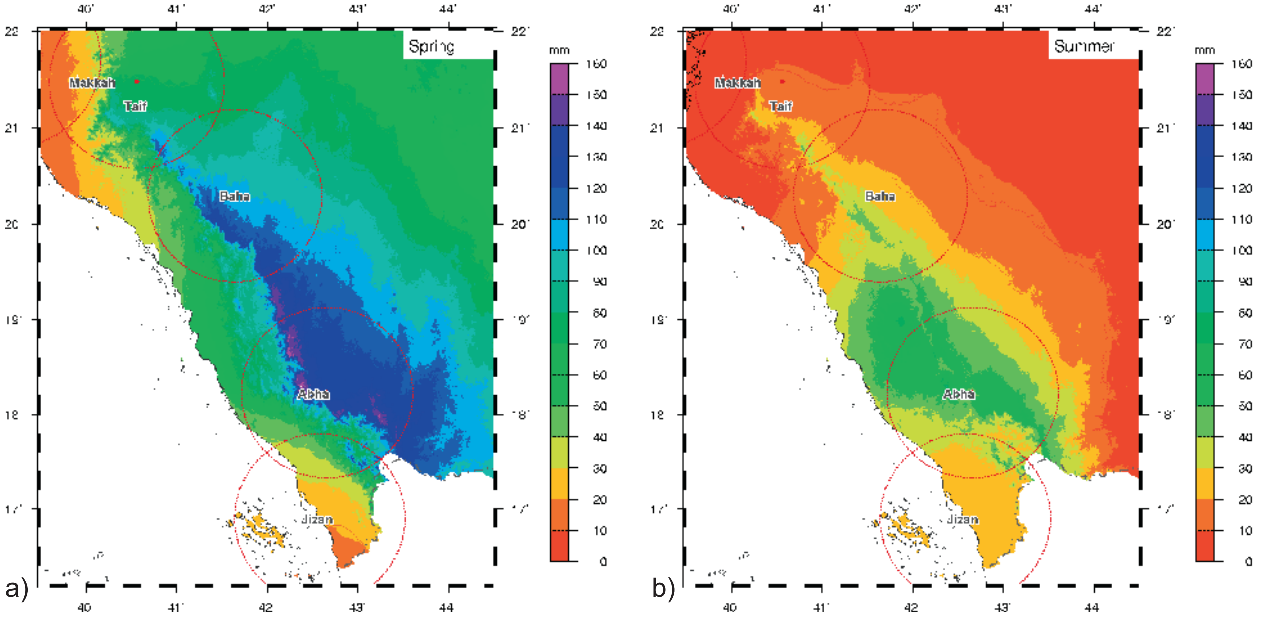


Figure 10: Spatial distribution of rainfall in the southwest region of Saudi Arabia for a) spring (March-May) and summer (June-August).

The spatial distribution of spring rainfall and summer rainfall is shown in Figs. 10a and 10b, respectively. As expected, the rainfall patterns during the spring and summer follow the terrain features along the escarpment. The peak in rainfall is located along the highest peaks to the north and southeast of Abha. Maximum rainfall observed is about 160 mm. The rainfall pattern extends eastward over the escarpment highlands with very little rainfall occurring below the escarpment. The summer rainfall has a different pattern. A peak is also observed on the top of the escarpment. However, it is about a factor of 2 less than the spring peak. It is interesting to note that there is a region of higher rainfall below the escarpment. This area is adjacent to the highest mountain peaks. There can be strong easterly upper level steering winds that propagate the storms westward after developing at the top of the escarpment. Overall, the spring and summer rainfall patterns are consistent with the SOM analysis.

4. OBSERVATIONS FROM THE 2009 FIELD PROGRAM

4.1 Meteorological Summary

During the summer 2009 field campaign, the meteorological conditions varied from the previous field study conducted in the southwest region during 2008. The start of the 2009 season saw a warm dry inversion imbedded in the mid atmosphere, which was not present in four of the previous five years. This inversion acted as a cap to the lower atmosphere and impeded vertical motion and intense convection over this area. Normally, this inversion inhibits convection during the late spring and early summer (May-June). However, these conditions existed for most of the summer 2009. A typical sounding (02 August 2009) for these conditions is shown in Fig. 11.

During the typical summer, the inter-tropical convergence zone (ITCZ) was far enough north by early August to supply moisture to the mid levels of the atmosphere and in turn erode the steep inversion shown in Fig. 11. An example sounding (12 August 2009) for a more unstable atmosphere is shown in Fig. 12. An evaluation of the thermodynamic conditions in the latter part of the month showed a influx of moisture from the ITCZ and the erosion of the inversion during the final week of the field study, which is more typical for atmospheric conditions for this time of year.

An analysis of the radiosonde observations for Abha (OEAB) during the month of August over the previous ten years was performed and the results (Table 3) showed that the strong inversion during August 2009 was not necessarily anomalous although it occurred at a different time than for the 2008 field campaign. During the preceding ten years seven of the ten years had no strong inversion present at the beginning of the period but one did exist at some point during all ten of those years.

Based on analysis of the dynamic and thermodynamic conditions, we have developed a simplified conceptual model for convection in the southwest

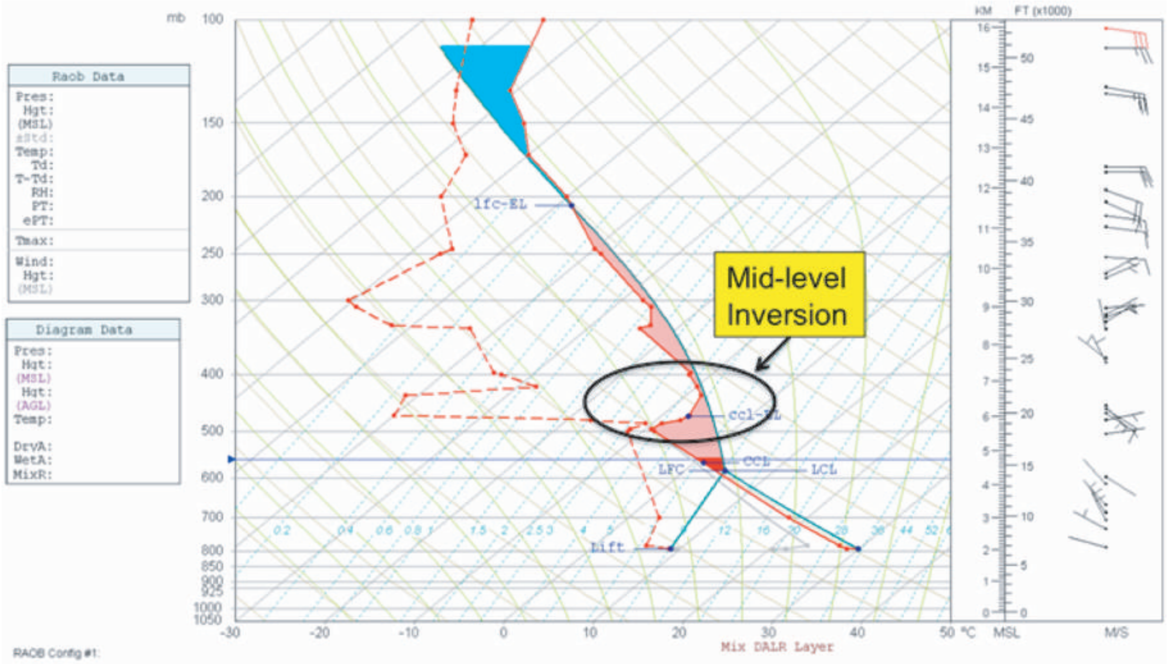


Figure 11: Abha (OEAB) sounding from 02 August 2009 at 0000 UTC.

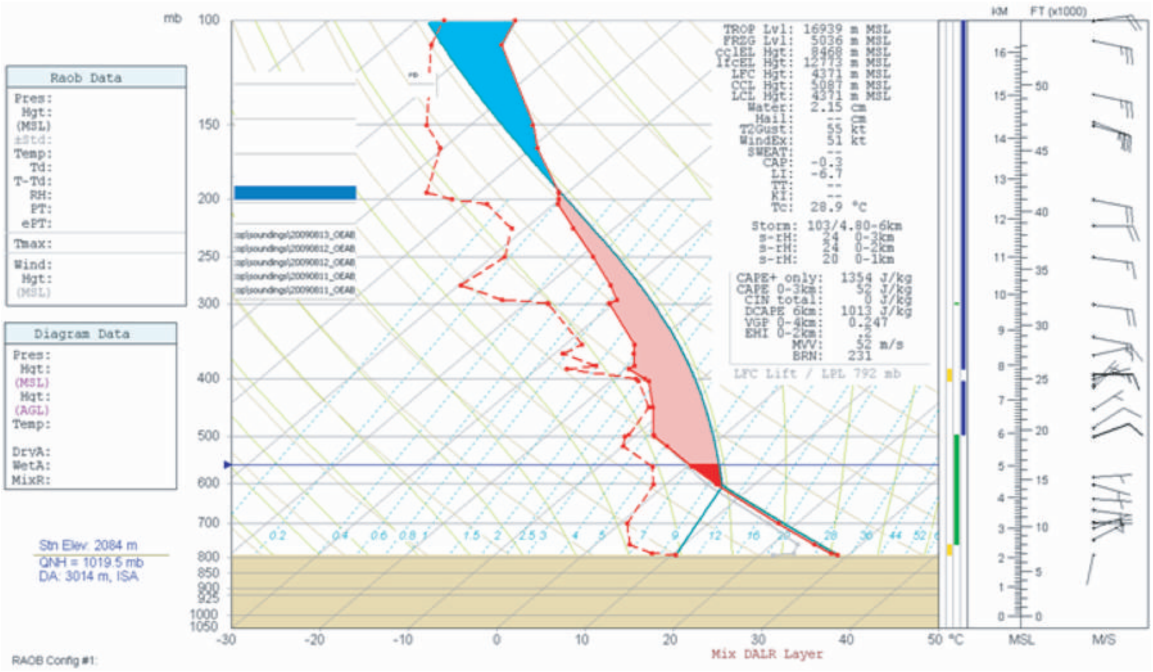
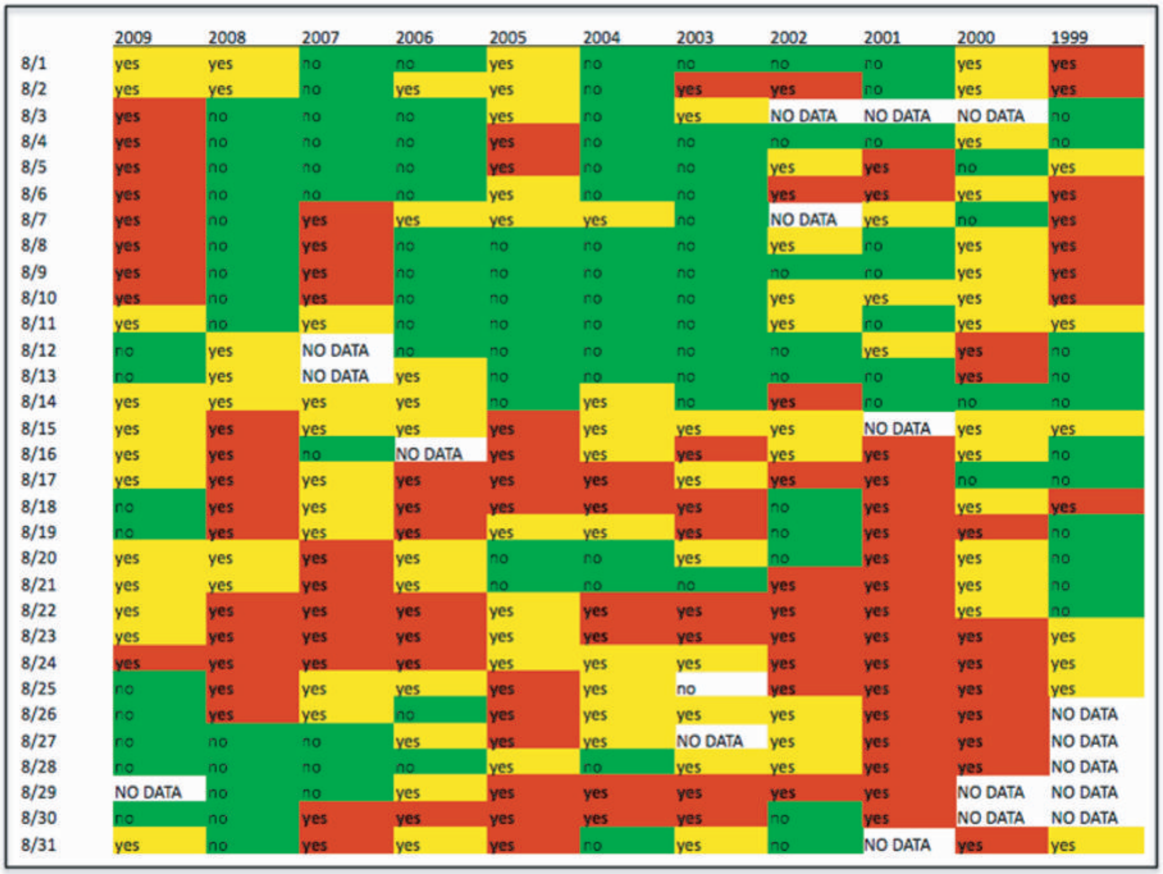


Figure 12: Abha (OEAB) sounding from 12 August 2009 at 0000 UTC.

Table 3: A characterization of each day during August between 1999 – 2009 by the presence of a strong inversion (RED), a weak inversion (YELLOW), no inversion (GREEN), or no data (WHITE) at the mid levels of the atmosphere from the Abha (OEAB) radiosonde database.



	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000	1999
8/1	🟨 yes	🟨 yes	🟩 no	🟩 no	🟨 yes	🟩 no	🟩 no	🟩 no	🟩 no	🟨 yes	🟥 yes
8/2	🟨 yes	🟨 yes	🟩 no	🟨 yes	🟨 yes	🟩 no	🟥 yes	🟥 yes	🟩 no	🟨 yes	🟥 yes
8/3	🟥 yes	🟩 no	🟩 no	🟩 no	🟨 yes	🟩 no	🟨 yes	NO DATA	NO DATA	NO DATA	🟩 no
8/4	🟥 yes	🟩 no	🟩 no	🟩 no	🟥 yes	🟩 no	🟩 no	🟩 no	🟩 no	🟨 yes	🟩 no
8/5	🟥 yes	🟩 no	🟩 no	🟩 no	🟥 yes	🟩 no	🟩 no	🟨 yes	🟥 yes	🟩 no	🟨 yes
8/6	🟥 yes	🟩 no	🟩 no	🟩 no	🟨 yes	🟩 no	🟩 no	🟥 yes	🟥 yes	🟨 yes	🟥 yes
8/7	🟥 yes	🟩 no	🟥 yes	🟨 yes	🟨 yes	🟨 yes	🟩 no	NO DATA	🟨 yes	🟩 no	🟥 yes
8/8	🟥 yes	🟩 no	🟥 yes	🟩 no	🟩 no	🟩 no	🟩 no	🟨 yes	🟩 no	🟨 yes	🟥 yes
8/9	🟥 yes	🟩 no	🟥 yes	🟩 no	🟩 no	🟩 no	🟩 no	🟩 no	🟩 no	🟨 yes	🟥 yes
8/10	🟥 yes	🟩 no	🟥 yes	🟩 no	🟩 no	🟩 no	🟩 no	🟨 yes	🟨 yes	🟨 yes	🟥 yes
8/11	🟨 yes	🟩 no	🟨 yes	🟩 no	🟩 no	🟩 no	🟩 no	🟨 yes	🟩 no	🟨 yes	🟨 yes
8/12	🟩 no	🟨 yes	NO DATA	🟩 no	🟩 no	🟩 no	🟩 no	🟩 no	🟨 yes	🟥 yes	🟩 no
8/13	🟩 no	🟨 yes	NO DATA	🟨 yes	🟩 no	🟩 no	🟩 no	🟩 no	🟩 no	🟥 yes	🟩 no
8/14	🟨 yes	🟨 yes	🟨 yes	🟨 yes	🟩 no	🟨 yes	🟩 no	🟥 yes	🟩 no	🟩 no	🟩 no
8/15	🟨 yes	🟥 yes	🟨 yes	🟨 yes	🟥 yes	🟨 yes	🟨 yes	🟨 yes	NO DATA	🟨 yes	🟨 yes
8/16	🟨 yes	🟥 yes	🟩 no	NO DATA	🟥 yes	🟨 yes	🟥 yes	🟨 yes	🟥 yes	🟨 yes	🟩 no
8/17	🟨 yes	🟥 yes	🟨 yes	🟥 yes	🟥 yes	🟥 yes	🟨 yes	🟥 yes	🟥 yes	🟩 no	🟩 no
8/18	🟩 no	🟥 yes	🟨 yes	🟥 yes	🟥 yes	🟥 yes	🟥 yes	🟩 no	🟥 yes	🟨 yes	🟥 yes
8/19	🟩 no	🟥 yes	🟨 yes	🟥 yes	🟨 yes	🟨 yes	🟥 yes	🟩 no	🟥 yes	🟥 yes	🟩 no
8/20	🟨 yes	🟨 yes	🟥 yes	🟨 yes	🟩 no	🟩 no	🟨 yes	🟩 no	🟥 yes	🟨 yes	🟩 no
8/21	🟨 yes	🟨 yes	🟥 yes	🟨 yes	🟩 no	🟩 no	🟩 no	🟥 yes	🟥 yes	🟨 yes	🟩 no
8/22	🟨 yes	🟥 yes	🟥 yes	🟥 yes	🟨 yes	🟥 yes	🟥 yes	🟥 yes	🟥 yes	🟨 yes	🟩 no
8/23	🟨 yes	🟥 yes	🟥 yes	🟥 yes	🟨 yes	🟥 yes	🟥 yes	🟥 yes	🟥 yes	🟥 yes	🟨 yes
8/24	🟥 yes	🟥 yes	🟥 yes	🟥 yes	🟨 yes	🟨 yes	🟨 yes	🟥 yes	🟥 yes	🟥 yes	🟨 yes
8/25	🟩 no	🟥 yes	🟨 yes	🟨 yes	🟥 yes	🟨 yes	no	🟥 yes	🟥 yes	🟥 yes	🟨 yes
8/26	🟩 no	🟥 yes	🟨 yes	🟩 no	🟥 yes	🟨 yes	🟨 yes	🟨 yes	🟥 yes	🟥 yes	NO DATA
8/27	🟩 no	🟩 no	🟩 no	🟨 yes	🟥 yes	🟨 yes	NO DATA	🟨 yes	🟥 yes	🟥 yes	NO DATA
8/28	🟩 no	🟩 no	🟩 no	🟩 no	🟨 yes	🟩 no	🟨 yes	🟨 yes	🟥 yes	🟥 yes	NO DATA
8/29	NO DATA	🟩 no	🟩 no	🟨 yes	🟥 yes	🟥 yes	🟥 yes	🟥 yes	🟥 yes	NO DATA	NO DATA
8/30	🟩 no	🟩 no	🟥 yes	🟥 yes	🟥 yes	🟥 yes	🟥 yes	🟩 no	🟥 yes	NO DATA	NO DATA
8/31	🟨 yes	🟩 no	🟥 yes	🟨 yes	🟥 yes	🟩 no	🟨 yes	🟩 no	NO DATA	🟥 yes	🟨 yes

region of Saudi Arabia, which is shown in Fig. 13. The conceptual model shows that the mid to upper levels are dominated by easterly flow. There is a daily diurnal sea breeze mechanism which creates southwesterly flow from the Red Sea that when orographically lifted along the escarpment induces convective cloud development. To the east of the escarpment, there is a weak to moderate easterly flow from the desert which forces dry air to the region on a daily basis. The interaction between the moist and buoyant airmass from the Red Sea and the dry (and relatively clean) airmass from the desert creates a moisture convergence boundary that becomes the focus for the initiation of convection. The difference in moisture between the two air masses is large with differences in dewpoint temperature of ~20°C. Depending on how strong (or weak) the dry flow from the east is on a particular day, the later (or earlier) convective initiation will occur. On rare days when the easterly flow at the surface is particularly strong and the mid-level inversion is present, convective initiation over the southwest region may not occur at all.

4.2 Radar Observations

In support of cloud seeding feasibility study in the southwest region of Saudi Arabia, we have been archiving data from the network of five C-Band radars (Abha, Baha, Jeddah, Jizan, and Taif) located in this region. Data have been quality controlled to remove ground clutter and spurious echo. Data from each radar have been merged into a common grid using TITAN. The TITAN storm track algorithm has been applied to the merged dataset. The algorithm was used to identify cells associated with precipitation features. For this analysis, a TITAN cell was defined as a continuous reflectivity area equal or greater than 30 dBZ. Many attributes of each cell is then computed by the TITAN algorithm. This section highlights some of the key characteristics of the cells, which include the spatial distribution of cells, the distribution of maximum reflectivity, distribution of cell height, and the diurnal cycle of cell frequency and precipitation flux. The analysis was done on cells observed in summer 2008, summer 2009, and spring 2009 to explore the seasonal differences in precipitation.

The spatial distribution of cells for both spring and summer is interesting to study. The pattern of cell location matches the climatological distribution of rainfall quite well. The cell patterns for spring and summer is shown in Fig. 14a and Fig. 14b, respectively. The observed cells are clearly associated with the location of the escarpment. In the spring, the cells are associated with the mountain peaks south of Abha, west of Abha, and south of Abha toward the Yemen border. The maximum number of cells is observed over Souda Mountain, west of Abha. The maximum number of cells observed in the spring is around 400. It is interesting to observe that no cells are observed west of the escarpment, but there is a broad region of cells observed over the highlands to the east toward the desert region. This analysis supports the long term climatology

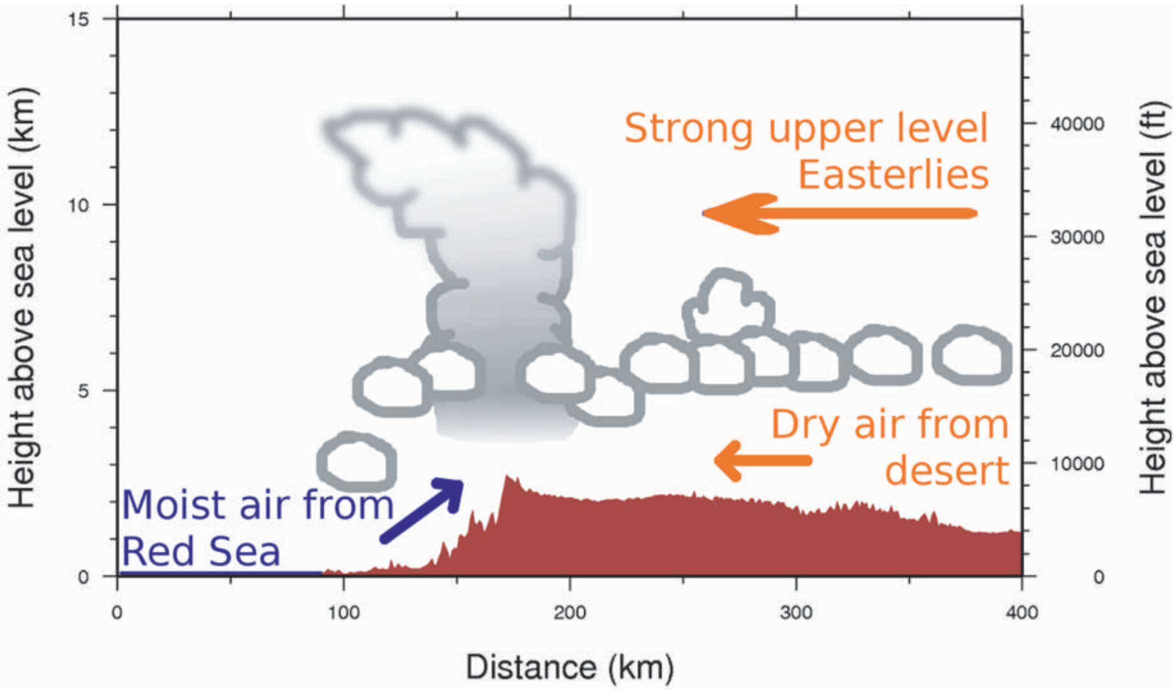


Figure 13: Conceptual model for conditions leading to convective development over the southwest region of Saudi Arabia during the summer.

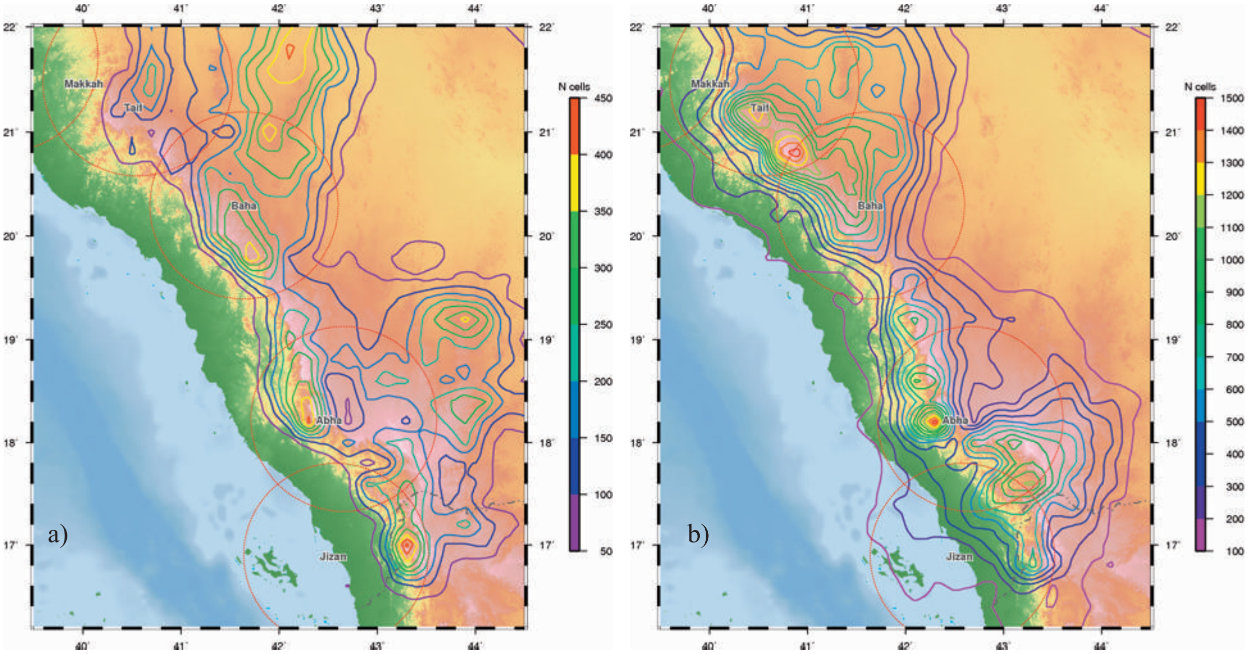


Figure 14: Spatial distribution of number of cells estimate by radar in the southwest region of Saudi Arabia for (a) spring 2009 and (b) summer 2009.

that this region receives a significant portion of the annual precipitation in the spring.

During summer, the peak over Souda Mountain reaches a maximum of over 1500 cells. A secondary maximum was once again located to the southeast of Abha near the Yemen boarder. The number of cells rapidly decreases moving away from the top of the escarpment. However, there is a non-zero number of cells observed west of the escarpment associated with the easterly steering winds moving the storms westward.

It is interesting to note that during the summer season, there is over three times the number of cells observed over certain locations. However, the rainfall observed during the summer is on the order of a factor of two less than spring. This would indicate that in the summer, much of the precipitation observed by radar (e.g., above the surface) does not reach the surface. For both seasons, it is clear that convection is driven by the orographic lift over the escarpment.

The boxplot showing the distribution of maximum reflectivity for summer 2008 (left), summer 2009 (middle), spring 2009 (right) is presented in Fig. 15a. The distributions range from about 26 dBZ to values greater than 65 dBZ. The maximum reflectivity values > 65 dBZ are likely due to ground clutter contamination. However, on occasion, hail was observed with these cells. For summer 2008, the 25% quartile, median, and 75% quartile are 43, 49, and 56 dBZ, respectively. In comparison, the summer 2009 25% quartile, median, and 75% quartile values are 34, 37, and 43 dBZ, respectively. The values for spring 2009 are even lower at 32, 35, and 39 dBZ. This is indicating a large variability in cell intensity between the three seasons. The cells observed in summer 2008 were significantly more intense than in summer 2009. This difference in intensity is likely associated with the strong capping inversion that was observed most of the period. The results indicate spring cells tend to be weaker than cells observed in the summer.

The boxplot of cell heights is shown in Fig. 15b. The distribution is surprisingly different from the trend in maximum reflectivity. With higher maximum reflectivity, it would seem there would be deeper convection. The opposite is observed. For summer 2008, the 25%, median, and 75% quartiles are 3.0, 4.1, and 7.5 km, respectively. The cell heights observed in summer 2009 have a narrow distribution in comparison with the median value of around 7.2 km and lower and upper quartiles ranging from 6.5 km to 8 km. The median cell heights differ on the order of 3 km, which is significant. This needs to be investigated further, but could also be linked to the strength of the capping inversion. The spring cell heights are distributed in between the summer observations. The median cell height for spring 2009 is around 6.5 km and the lower quartile is 5.2 km and upper quartile is 7.5 km.

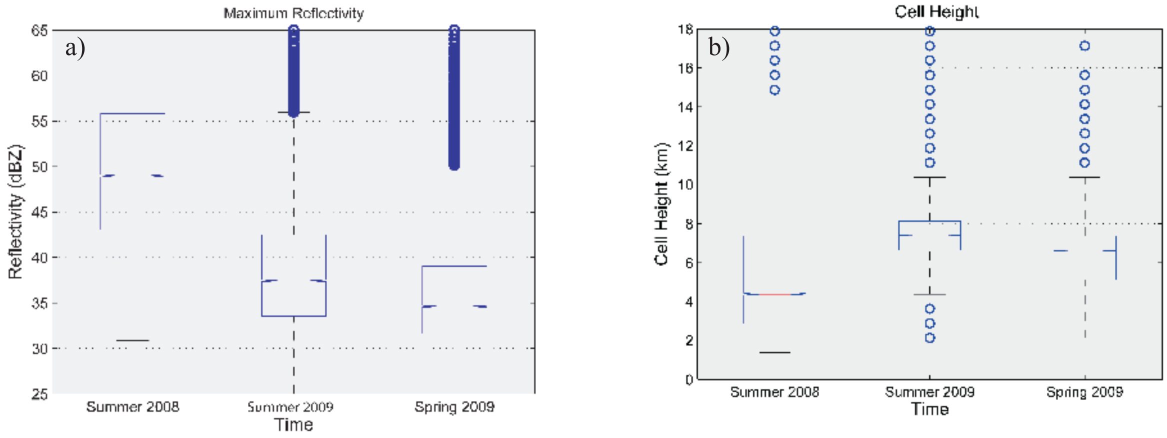


Figure 15: Boxplots showing the distribution of (a) maximum reflectivity and (b) cell height for cells observed in summer 2008, summer 2009, and spring 2009.

The diurnal cycle for cell initiation and cell precipitation flux is shown in Figs. 16a and 16b, respectively. There is a clear signal in the time of cell initiation that is associated with peak in diurnal heating and the timing of the sea breeze interacting with the topography along the escarpment. The summer cells have similar peak in cell occurrence, which occurs around 1400-1600 LT. There are about 200 cells observed each hour during the peak in 2009 compared to 2008. In 2008, the diurnal peak of cells tended to last longer into the evening. Based on the sounding analysis, conditions were more favorable in 2008 for longer periods of storm development. There are a relatively few storms observed during the night time hours. These results would indicate that a daytime seeding operation would be required, which is favorable for safe operations especially since complex terrain is a limiting factor. The spring cells have a distinct distribution. There is a broad late afternoon peak between about 1600 and 2100 LT. For these cells, many would occur after sunset, which could affect seeding operations.

Figure 16b also shows a peak in precipitation flux in the afternoon, which corresponds to the peak in afternoon heating. It is interesting to note that the average precipitation flux in summer 2008 is over a factor of two greater than in 2009. This supports the previous analysis showing the distribution of maximum reflectivity significantly higher in the summer in 2008 than in summer 2009. The precipitation flux analysis indicates that spring storms tend to generate less rainfall on average than summertime storms. These results clearly show there is a significant seasonal variability observed in the storm cells observed in the southwest region. This will make evaluating cloud seeding operations difficult.

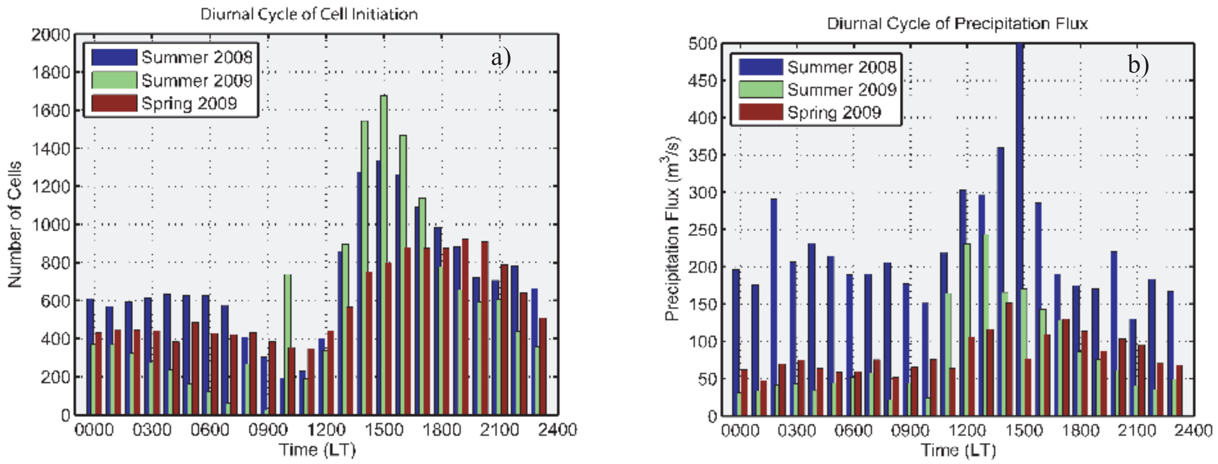


Figure 16: Diurnal cycle of (a) storm cell count and (b) precipitation flux in the southwest region of Saudi Arabia for the summer 2008 (blue), summer 2009 (green), and spring 2009 (red).

4.3 Surface Aerosol Observations

Averaged size distributions and hygroscopic growth distributions measured at the surface site are shown in Fig. 17 and 18. The regional aerosol possessed a persistent accumulation mode that dominated the number concentration even in this arid and dusty region, though supermicron particles accounted for roughly 83% of the particle volume (~mass) concentration. As shown in Fig. 18, the hygroscopic growth distributions of the particles in the accumulation mode size range possess two modes, with the more concentrated of the two comprised of particles having hygroscopicity similar to that of pure sulfate particles. As is evident in the study-average size distributions shown in Fig. 17, the accumulation mode concentration was about twice as high in the air mass behind the sea breeze front as in that ahead of it. Interestingly, the size distribution of the coarse mode and the hygroscopicity and size distribution shape of the accumulation mode differed little in the pre- and post-sea breeze air masses.

4.4 Aircraft Observations

Figure 19 shows the spatial location of flight tracks for the 35 research flights conducted during the 2009 field program. Two main types of flights were conducted during the field program: boundary layer flights and cloud physics flights. The boundary layer flights, shown as a box pattern in Fig. 19, were conducted in the morning hours to document the antecedent aerosol and thermodynamic conditions before convection developed in the afternoon. These flights were also conducted over the surface aerosol site to help determine the link between the surface and the sub-cloud boundary layer.

Cloud physics flights were conducted to document the cumuliform clouds that were observed along the escarpment. Cumuliform clouds were sampled under both warm and supercooled conditions. Deep cumulus clouds were characterized by flying several successively higher constant altitude cloud penetrations. Convective towers that developed on

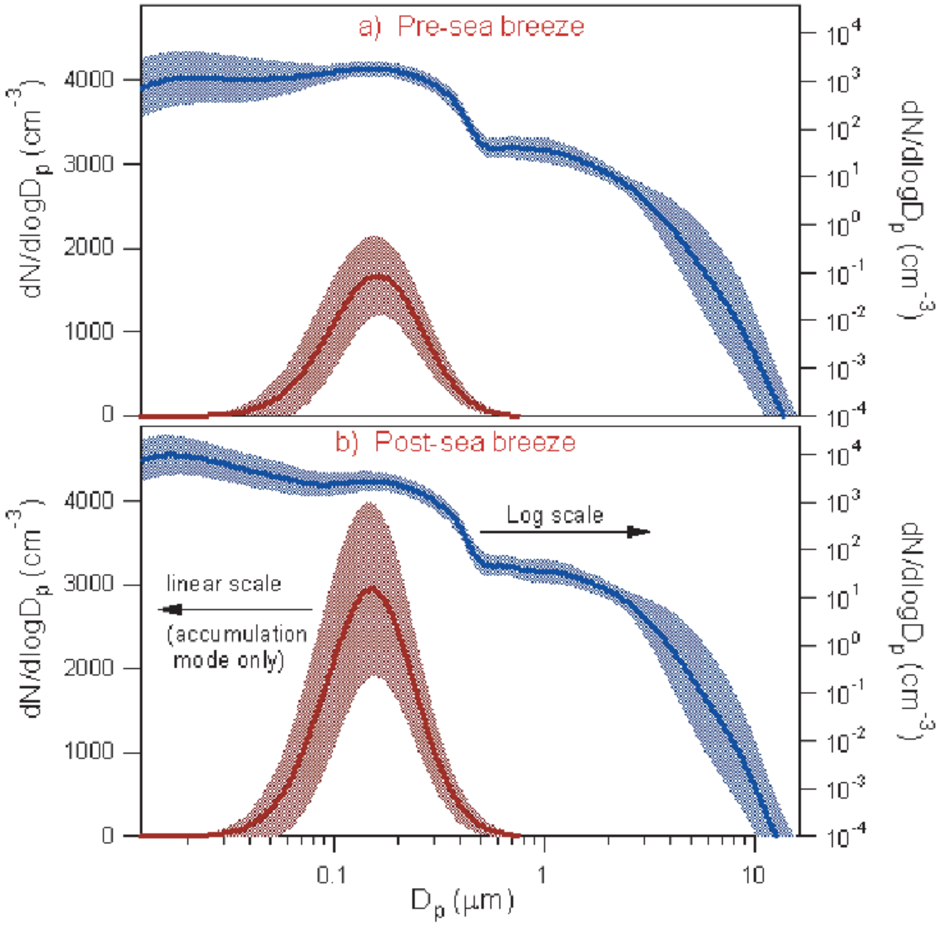


Figure 17: Study averaged aerosol size distributions measured from the surface site. The solid lines represent the mean values and the shaded areas represent ±1 arithmetic (linear scale) or geometric (log scale) standard deviation.

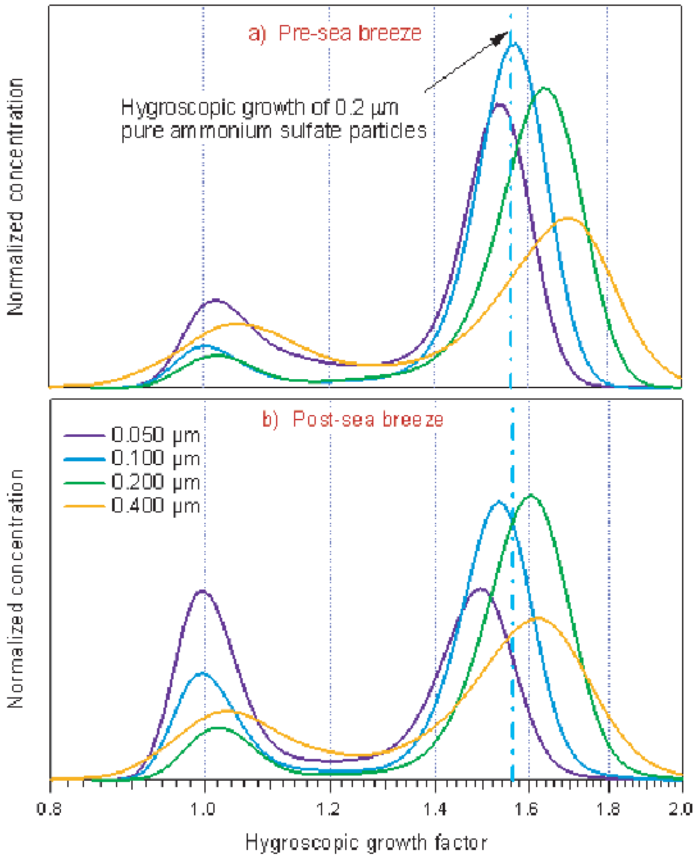


Figure 18: Study averaged aerosol hygroscopic growth distributions measured from the surface site.

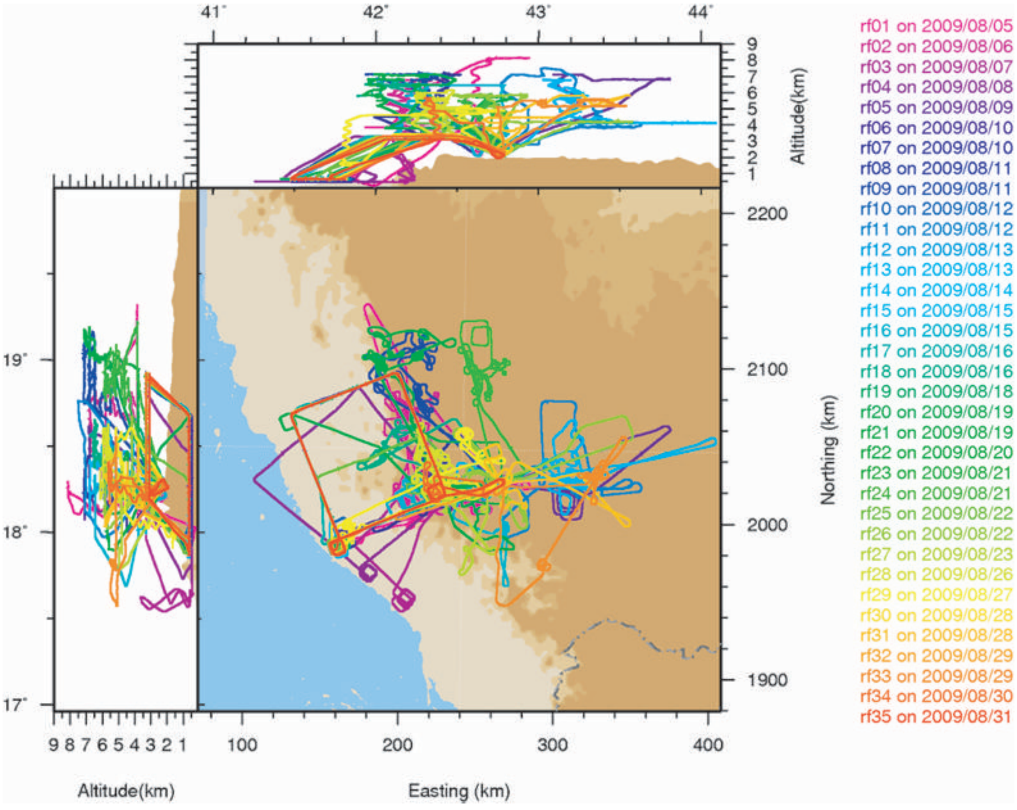


Figure 19: Flight tracks over the southwest region of Saudi Arabia during the 2009 field program.

top of the stable inversion were characterized by flying at the convective cloud top just above the inversion. Aerosol measurements were made above the instrumented surface site and during the climb to cloud base height. The aircraft pilots, who are knowledgeable in the interpretation of heavy precipitation echoes from on-board weather radar, avoid areas of precipitation, associated downdrafts and hail. Therefore most of the cloud penetrations were done in cumulus towers growing above the stable altocumulus inversion, which restricts the dataset to non-precipitating mixed-phase clouds less than 5 km in diameter at 300 m below cloud top. These flights were conducted over the escarpment over an area of complex terrain coinciding with a moisture gradient and an area of enhanced convection.

In general the FSSP and CDP PSDs were described by a similar size distribution; however, the CDP measured a higher concentration of droplets than the FSSP. At a size of 15 µm, the tail of the size distribution of the FSSP diverges from that of the CDP, with the FSSP measuring higher concentrations, greater than an order of magnitude higher at sizes larger than 20 µm. This divergence is thought to be due to shattering. This divergence is also observed if the FSSP PSD is extrapolated to the 2D-S. The CDP matches well with the 2D-S when the PSD is extrapolated along a straight line, implying that the CDP and 2D-S are reasonable in the overlapping range. The CIP particle number concentration is lower than the 2D-S in the 25 - 100 µm range and the FSSP and CDP in the 25 - 50 µm range. This is consistent with observations of under counting in optical array probes for particle sizes smaller than 200 µm (Korolev *et al.* 1990). Good agreement between $2DS_V$ and $2DS_H$ is observed consistently.

The 2D-S provides an improved measurement capability in a size range that is very important for observations of the evolution of droplet coalescence and cloud ice. The following analysis describes the PSD in clouds that are targeted for cloud top-seeding in the southwest region of Saudi Arabia. As mentioned earlier, these cumulus towers were growing above a stable altocumulus inversion. Figure 20 is a lifecycle schematic diagram of a convective unit that develops above the stable altocumulus inversion. Figure 21 shows the aircraft flight track for a typical measurement profile on 11 August 2009. This flight is representative of the type of measurements conducted during the observation period. Figure 22 shows a photograph of a convective tower that was sampled on this flight.

The following section describes the evolution of cloud ice by the analysis of PSDs on 11 August 2009. Cloud penetrations were conducted by flying a sequence of constant altitude cloud penetrations varying from the top of the altocumulus layer (stage s) to the convective cloud top in the developing (d) and young mature (m) stage. Pictures of the cloud before penetration are shown in Figure 23. A series of PSDs from 11 August are shown in Figure 24 and Figure 25. Figure 26 shows a time series of the LWC, temperature, FSSP concentrations and 2D-S concentrations. Table 4 shows the cloud penetration data.

The first penetration in this series was P1. The aircraft penetrated a small isolated towering cumulus that was developing in an area with scattered

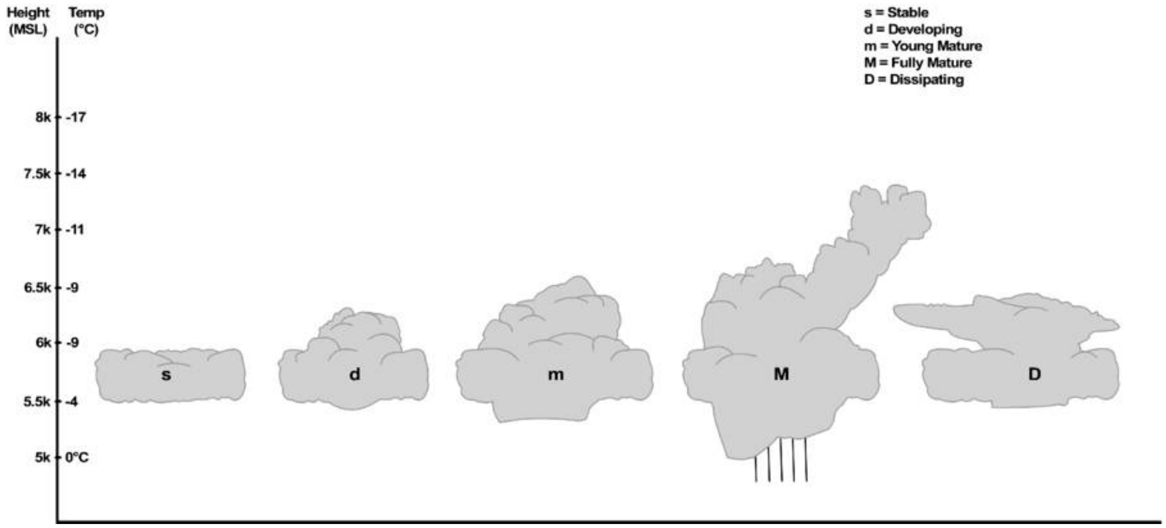


Figure 20: Schematic representation of the southwest region convective lifecycle in a marginally stable atmosphere. The stages represented are: (s) stable; (d) developing; (m) young mature; (M) fully mature; (D) dissipating.

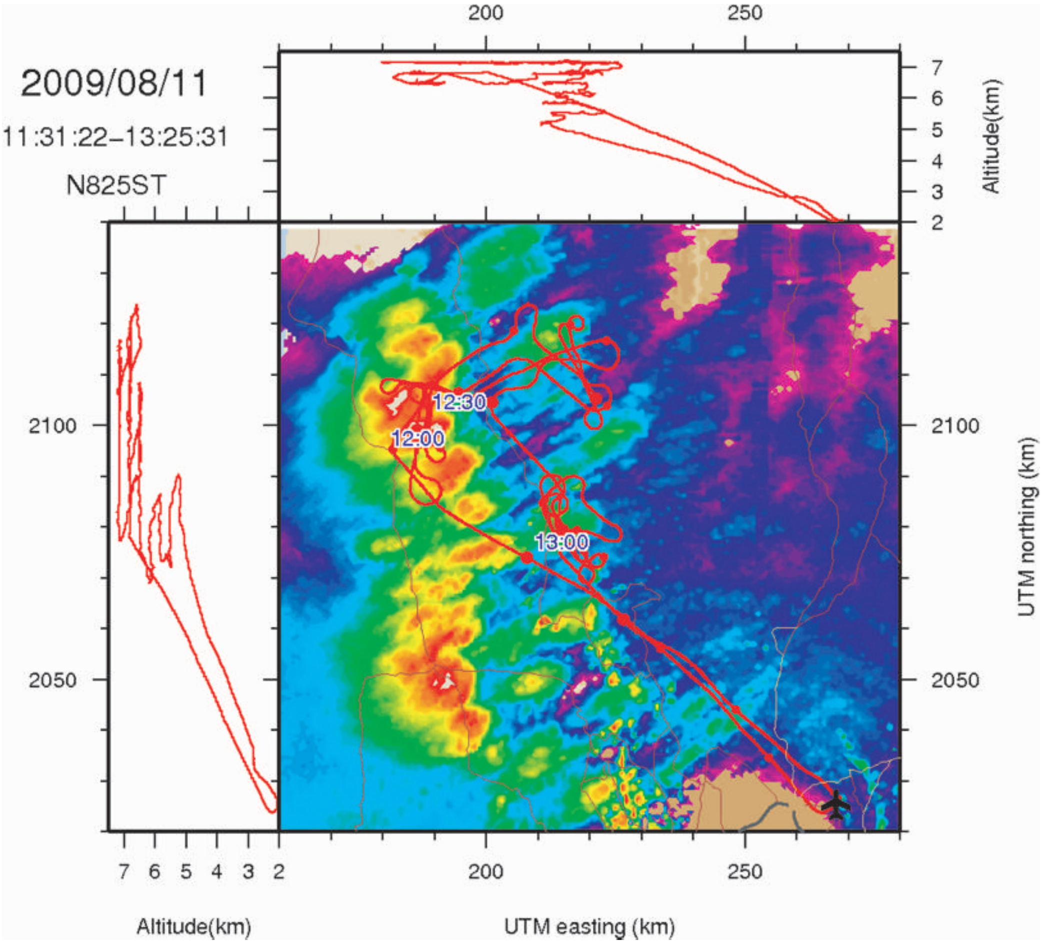
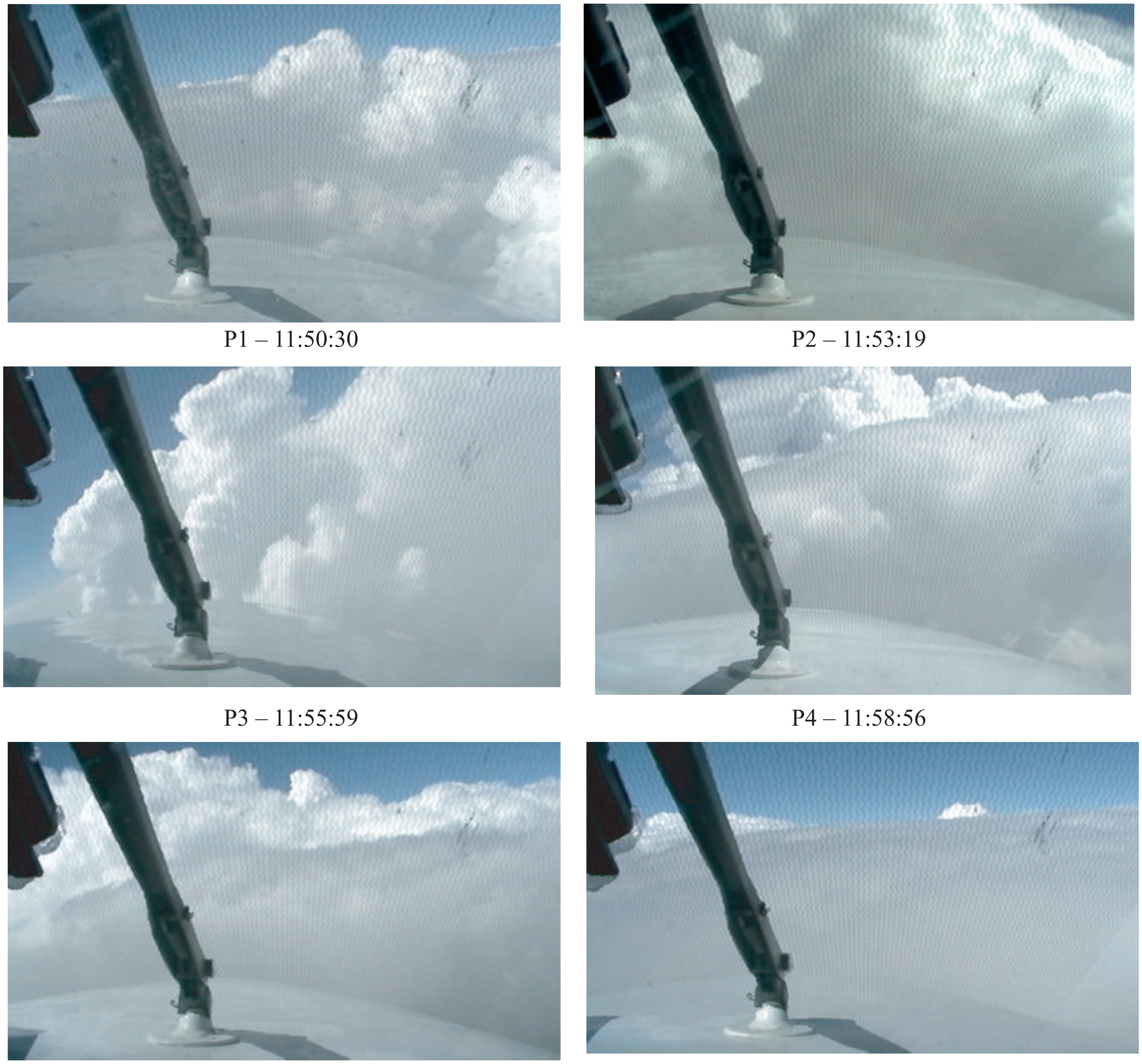


Figure 21: Radar reflectivity overlaid with flight tracks on 11 August 2009.

Figure 22: Photograph taken from the research aircraft on 11 August 2009 of a fully mature (stage M) cloud.



P1 – 11:50:30

P2 – 11:53:19

P3 – 11:55:59

P4 – 11:58:56

P5 – 12:04:00

P6 – 12:07:03

Figure 23: Pictures taken from the aircraft video of each cloud before penetration. The text indicates the penetration number and the time the picture was taken. Time is in UTC.

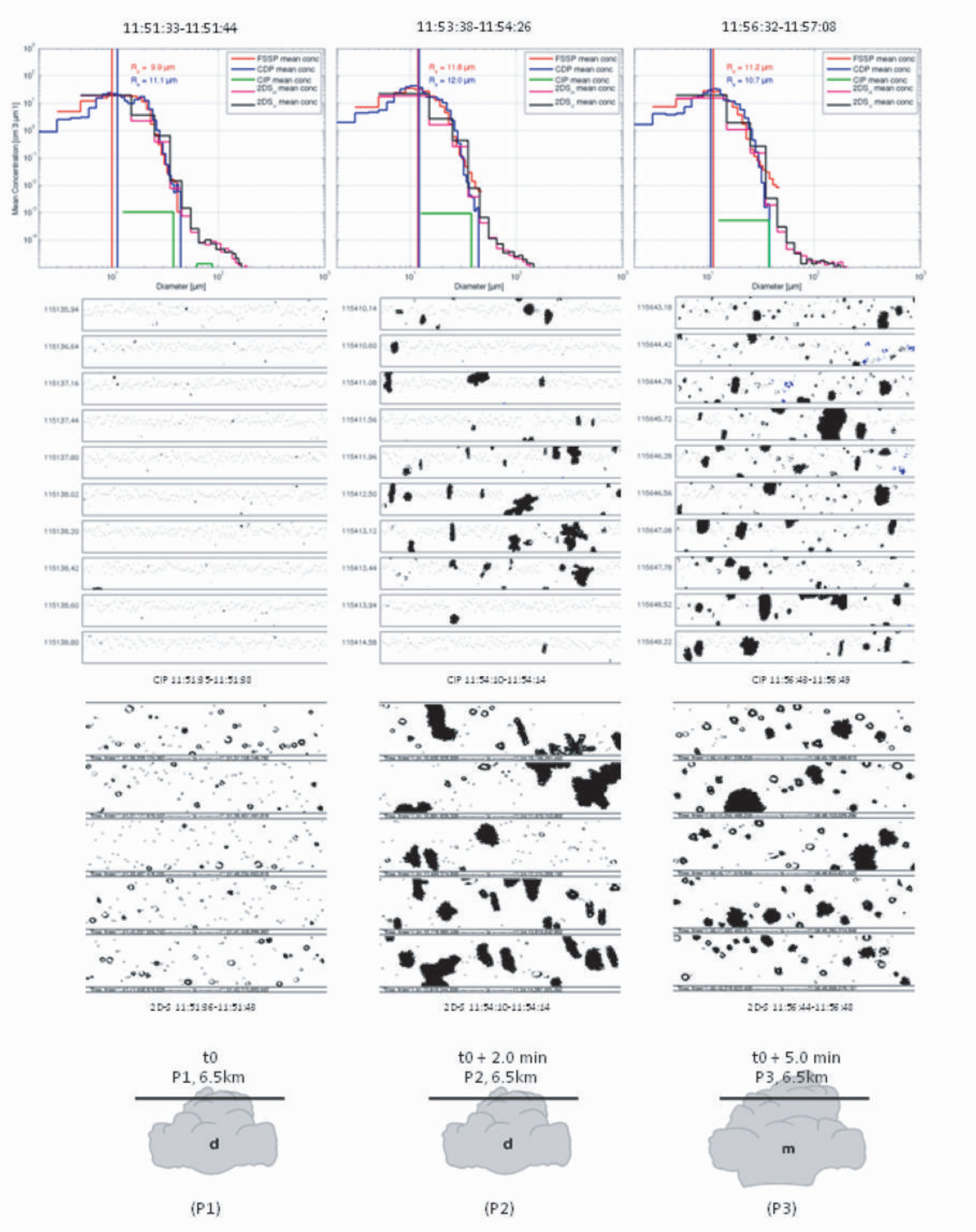


Figure 24: Summary of the microphysical data collected from the aircraft on 11 August 2009 for cloud penetrations P1, P2 and P3. The top figures show the PSDs from the CDP, FSSP, CIP and 2D-S averaged over the period identified in the top of the figure. The middle figures shows a subset of CIP images collected during the cloud penetration. he 2D-S images are shown below the CIP images. The first 50 particles from the $2DS_H$ (excluding end rejects) for the specified time period are shown. The bottom figures show a schematic of the cloud penetration. The height of a CIP image strip is 1550 µm. The height of a 2D-S image strip is 1280 µm.

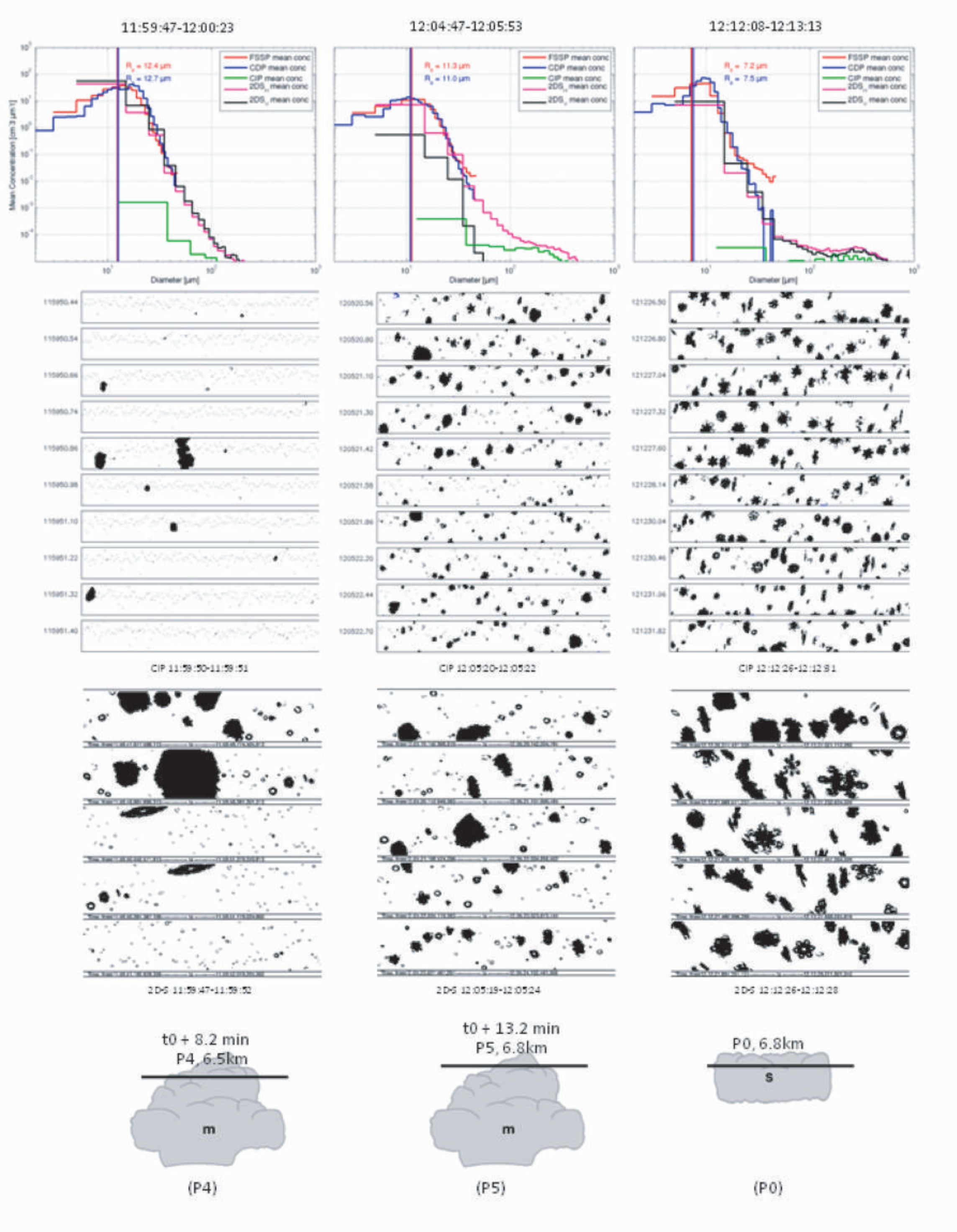


Figure 25: Same as in Figure 20 but for cloud penetrations P4, P5 and P0.

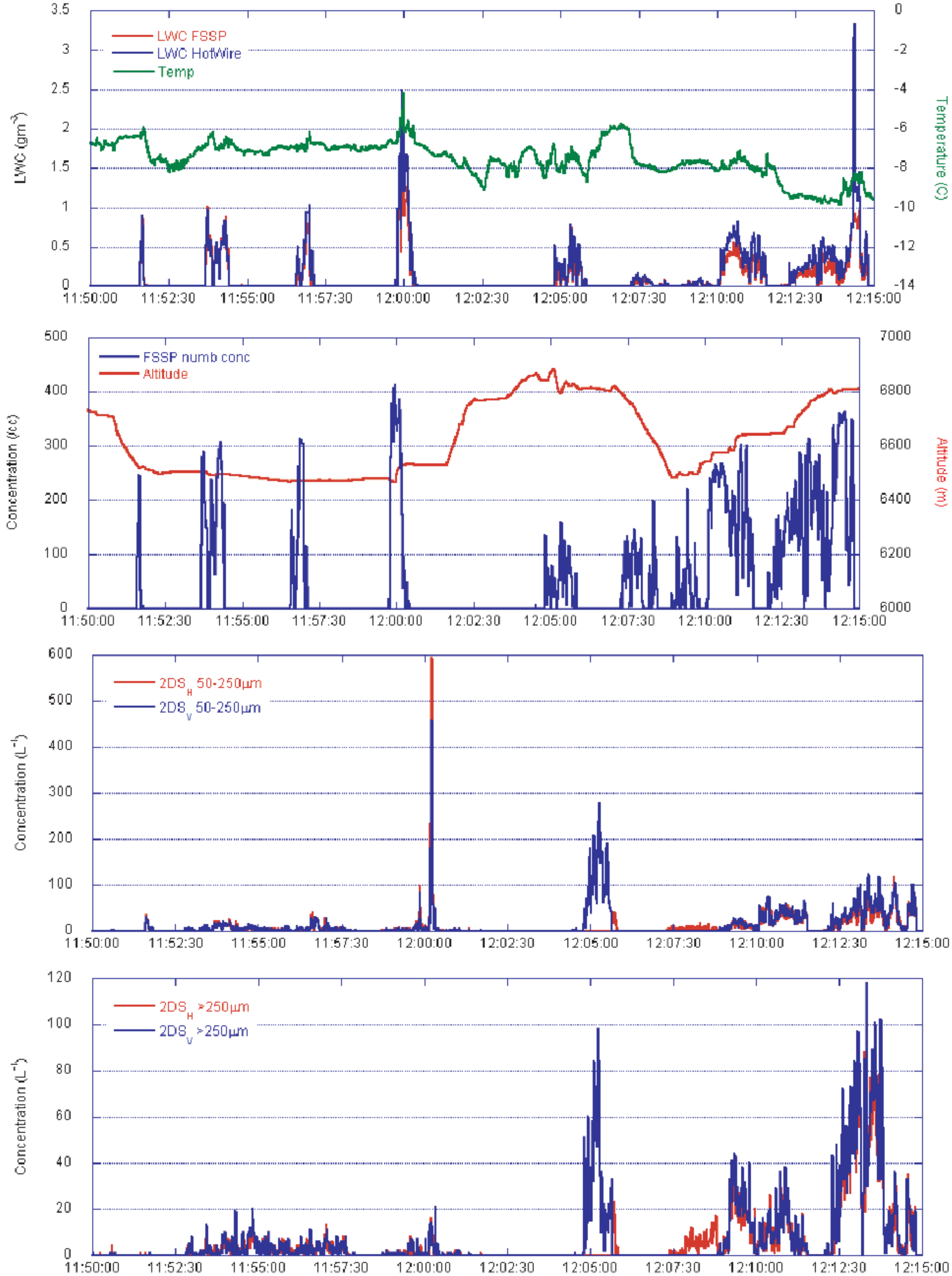


Figure 26: Time series of LWC, temperature, FSSP concentrations and 2D-S concentrations.

Table 4: Cloud physics measurements made by the WMI King Air on 11 August 2009.

Penetration number, stage of development	PSD averaging time	FSSP numb conc (cm^{-3})	LWC (gm^{-3})	Temperature (°C)	Penetration height (km)	Time from first penetration (t_0)
P1, d	11:51:33-11:51:44	470	0.9	-6.0	6.5	t_0
P2, d	11:53:38-11:54:26	520	1.0	-6.5	6.5	t_0 + 2.0 min
P3, m	11:56:32-11:57:08	530	1.0	-7.0	6.5	t_0 + 5.0 min
P4, m	11:59:47-12:00:23	700	2.5	-6.5	6.5	t_0 + 8.2 min
P5, m	12:04:47-12:05:53	500	0.8	-8.0	6.8	t_0 + 13.2 min
P0, s	12:12:08-12:13:13	430	0.4	-9.5	6.8	

altocumulus cover immediately below the cloud formation level. The penetration was done at 6.5 km (-6.0°C) just below cloud top and lasted 11 seconds which indicates that the cloud was about 1.1 km in diameter. The CIP image strips show a large number of the pixel particles, with fewer particles with 3 or 4 pixels. The 2D-S is at 10μm resolution so it adds more detail to the particle shape. The 2D-S images appear to be made up of droplets that vary in number from droplets with a few pixels to larger droplets that are spherical and hollow (out of focus). Detailed inspection of the CIP and 2D-S images suggests that the particles are mostly supercooled liquid water drops (although graupel with smooth edges may be misclassified as water drops in this size range). The PSD plot in Figure 24 shows that the FSSP and CDP effective radius (R_e) are 9.9 and 11.1 μm respectively. Agreement between the CDP and FSSP is good, although the CDP shows a bimodal distribution that is not apparent in the FSSP. This bimodality in the CDP produces a larger R_e. The $2DS_V$ and $2DS_H$ size distributions match the tail of the CDP and FSSP indicating that shattering is not a problem in this case. The excellent agreement between the probes (the CIP is ignored at diameter < 100μm) gives some significance to the bimodality of the CDP. It is important to note that drops as large as 200μm are measured in the tail of the 2D-S size distribution and can also be seen in the 2D-S image strips. Concentrations of particles in the 50-250μm range reach 35/L. These are assumed to be drops.

One can speculate that the bimodality and the broadness of the size distribution may indicate that droplet coalescence is active in the early phases of cloud development. Formation of large droplets in supercooled clouds remains a classical problem in cloud microphysics. The combined growth time of a droplet by condensation and coalescence to a size of, say, 200 μm in a typical cumulus cloud is greater than an hour. This is much greater than the lifetime of small precipitating cumulus clouds. It is not well understood which processes produce fast broadening of the size distribution as is observed here. Some may attribute the source of large droplets to giant cloud condensation nuclei (GCCN) (e.g., Beard and Ochs 1993). In this case 35/L of drops larger than 25 μm is measured. Measurements of the aerosol size distribution indicate that the supermicron aerosol concentration could be as high as 50 cm^{-3} up to heights of 4km in some cases. If a small percentage of this coarse mode aerosol is soluble, then GCCN could be the mechanism by which large droplets form. Others have suggested that stochastic effects during condensational growth of droplets may lead to production of large droplets (Cooper 1989). A uniform supersaturation leads to a narrow size distribution. Turbulent fluctuations in vertical velocities create a fluctuating supersaturation and a broad droplet size distribution. It is also possible that aerosol particles are injected above the altocumulus deck as a result of evaporation leaving a residual hygroscopic aerosol. Evaporated residuals could be larger and/or more hygroscopic than other particles. One possible source of these residual GCCN is the evaporation of coalesced droplets. Explaining how the large droplets form is beyond the scope of this paper; however coalescence due to GCCN, entrainment mixing, variable supersaturations and cloud processing of aerosol are all viable mechanisms for droplet growth in southwest region clouds.

The subsequent penetration was done 2 minutes later at the same altitude and a temperature of -6.5°C when the cloud was still in the development stage. Figure 23 shows that the cloud had continued to develop and spread over a larger area. It is estimated that the cloud grew to 4.8km in diameter. Excellent agreement is observed between the cloud probes with the CDP and FSSP R_e being almost equal. No large change is observed in the shape of the PSDs in P1 and P2 although differences in hydrometeor type and concentrations are noted. The CIP and 2D-S image strips show that a small concentration of needles, graupel and dendrites formed. The concentrations of these ice particles >250μm are 20/L. A large concentration of small droplets is also present. The presence of ice particles is uncommon at a temperature of -6.5°C and 2 minutes after the previous penetration when no ice was found. Formation of ice crystals by primary ice nucleation may be possible in the heavily dust loaded aerosol although nucleation freezing temperatures of dust particles from the central region of Saudi Arabia were much lower than -6.5°C. Nevertheless a more detailed analysis including calculations and modeling are needed to understand the occurrence of these ice particles.

P3 was done in the young mature stage of development at a temperature of -7.0°C. This is characterized by a lowering of the cloud base and a predominant ice hydrometeor type. The cloud droplet and ice concentrations are similar to the previous penetration except that no large droplets are found in the 2D-S images. The large droplets (>100μm) quickly freeze to graupel and the smaller droplets (<20μm) are depleted by riming processes.

The subsequent penetration (P4) was also done in a young mature cloud and a temperature of -6.5°C, however, a more vigorous updraft of 16 ms^{-1} was encountered. The FSSP measured a maximum concentration of $700cm^{-3}$ and a liquid water content of $2.5gm^{-3}$. Most of the hydrometeors are cloud droplets; however occasional graupel can be seen in the 2D-S images. The concentration of particles in the 50-250μm range reach 595/L and inspection of the 2D-S images cannot rule out the presence of large droplets. Once again it appears that GCCN could be the source of the large droplets. This time the cloud appears to be feeding from the boundary layer aerosol which would bring a larger concentration of aerosol and GCCN, and therefore a higher concentration of droplets.

P5 is the last penetration of the series at a temperature of -8.0°C. The cloud is still in the young mature stage. The FSSP concentration and liquid water content drop to 500 cm^{-3} and $0.8gm^{-3}$ respectively. Most of the hydrometeors are now graupel of various sizes below 1mm in size. The PSD shows a broad tail extending from the main body of the droplet mode to 600μm. The concentration of particles in the 50-250μm range drops to 280/L while the concentrations of ice particles >250μm increases to 98/L. This is an indication that riming is very active and the liquid water content is quickly depleted resulting in the growth of graupel.

In order to study the extent of mixing between the convective clouds and the adjacent layered cloud, the aircraft measured the altocumulus layer at 6.8km. This is penetration P0 at a temperature of -9.5°C. The CIP and 2D-S show a mixture of ice hydrometeors types including dendrites, graupel and needles. The altocumulus cloud that was penetrated appeared to be detached from other high level cloud so the presence of dendritic crystals is surprising. Dendritic growth occurs in a temperature region of -12°C to -17°C where large aggregates have a tendency to form (Hobbs et al. 1974). This growth is most marked at about -15°C when the arrival of water vapor over the crystal surface is a maximum (Mason 1953). The altocumulus deck must have interacted with a decaying convective tower reaching colder temperatures for the dendrite to be present. The PSD shows a flat distribution at sizes between 100 to 600μm. A droplet mode is still present in the PSD indicating that the layer consists of mixed-phase hydrometeors. Lack of agreement is observed between the FSSP and the CDP at sizes larger than 20μm. This is attributed to ice shattering on the sampling shroud of the FSSP.

This analysis has demonstrated that duplicate cloud physics probes are needed in order to fully understand the fine details of complex mixed-phase clouds like those that develop in the southwest region of Saudi Arabia region. The 2D-S and CDP combination give more detailed and accurate information in mixed-phase clouds and ice clouds as these probes are less prone to shattering effects. The FSSP showed better agreement with the CDP when ice hydrometeors were not present or found in low concentrations. It was also found that CIP concentrations are too low at sizes < 100 μm.

The southwest region's clouds seem to develop graupel quickly by the freezing of droplets in the 50-200μm range. These large droplets could be the result of GCCN that form by the activation of a small percentage of coarse mode aerosols. Once the large droplets form, these quickly freeze and become graupel. The small droplets (<20 μm) remain supercooled and are important in the growth of graupel by riming. High liquid water content (>2gm^{-3}) can be encountered once the cloud is in the young mature stage and a cloud base generation area has formed. More boundary layer GCCN are entrained through the cloud base in vigorous updrafts forming more large droplets that quickly freeze into graupel. Graupel up to 1mm in diameter quickly forms and is present in concentrations reaching 100/L. This process produces graupel showers that initiate at temperatures around -8.0°C. Once the showers form the cloud becomes fully mature and quickly dissipates into the altocumulus layer. The altocumulus contains mixed-phase hydrometeors including ice particles that are only observed in clouds with colder tops. The altocumulus may also have a role in releasing GCCN above the inversion layer by the evaporation of cloud hydrometeors at the top of the inversion. The extent of this aerosol regeneration at the altocumulus cloud top is unknown.

5. CONCLUDING REMARKS

This paper provides an overview of an ongoing project in the southwest region of Saudi Arabia. The focus of the study was to examine clouds and precipitation observed on top of the escarpment where most of the cloud seeding occurs. The escarpment provides a focus for orographic precipitation as a result of complex interactions with the Red Sea sea breeze and upper level thermodynamics. We utilized a radar network to evaluate the precipitation features, a surface station to examine surface aerosols, and research aircraft to study aerosol and cloud properties. We presented an evaluation of a long-term, 50-yr rainfall climatology, which shows a distinct peak in rainfall occurring in March-April and in August. A SOM analysis was conducted and it was shown there were nine distinct precipitation regions over the southwest Saudi Arabia. We focused our study on the two sub-regions located on the top of the escarpment. The region along the escarpment is associated with the largest amounts of rainfall in the southwest (and all of Saudi Arabia). The region just east of the escarpment also experiences extreme rainfall events. The region below the escarpment and near the Red Sea receives most of its precipitation in winter months while the desert highlands to the east have maximum peak rainfall in the spring. The peak in rainfall occurs along the highest peaks to the north and southeast of Abha, with the summer rainfall being twice that observed in the spring.

There is a distinct diurnal cycle that was observed in the three seasons that were examined: summer 2008, summer 2009, and spring 2009. A clear signal was found in the time of cell initiation associated with maximum diurnal heating and entrainment of moisture by the sea breeze interacting with the topography along the escarpment. During the summer periods, the maximum peak in storm initiation occurred around 1400 and 1600 LT. The peak in storm initiation during spring was much broader between 1600 and 2100 LT. Analysis of cell characteristics indicated there was large seasonal variability. Cells observed in summer 2008 were the most intense followed by summer 2009 and lastly spring of 2009. Because cells tended to form during the day time, at least for summertime convection, potential seeding operations could be conducted during daylight hours. However, because of the large seasonal variability, evaluating cloud seeding operations could be difficult.

The regional aerosol can be characterized by a persistent accumulation mode having hygroscopic properties consistent with a sulfate-rich aged aerosol. The concentration of particles in the accumulation mode, and consequently the CCN concentration, was considerably higher in the air mass behind the sea breeze as in that ahead of it.

Aircraft measurements have shown that clouds develop graupel quickly by the freezing of droplets in the 50-200μm range. Once the large droplets form, these quickly freeze and become graupel.

A large amount of data has been collected that have provided some understanding on the characteristics of clouds and precipitation in the southwest region of Saudi Arabia. Some of the key insights are (1) Observations have helped confirm and describe large annual variability in precipitation in Saudi Arabia; (2) A new conceptual model is described for summer precipitation formation in the southwest region; (3) Convective cells tend to be short-lived with complicated microphysics; (4) The presence and concentration of large cloud droplets suggest that GCCN broaden the cloud droplet spectrum; (5) Ice-phase microphysics is important and seems to be efficient. This has important ramifications for cloud seeding.

The synoptic scale and micro scale complexities of convective clouds that develop in the southwest region of Saudi Arabia present a challenge in producing a final assessment of cloud seeding for precipitation enhancement. The area of interest, surrounded by a prevailing dry climate, present a unique opportunity of studying cloud seeding technologies in a region where freshwater is scarce. A large investment has been made in obtaining measurements in the Central and Southwest regions of Saudi Arabia. Advancements have been made in measurement capabilities and level of understanding of aerosol-cloud interactions and precipitation properties of the region. Future work includes: (1) more detailed measurements of aerosol and cloud microphysics with a special focus on GCCN and cloud droplet and ice crystal residuals, (2) hygroscopic seeding experiments focusing on identifying the exact seeded cloud volume with sulfur hexafluoride gas tracer, and (3) glaciogenic seeding following a randomization scheme with strict cloud selection criteria.

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WMA Annual Meeting

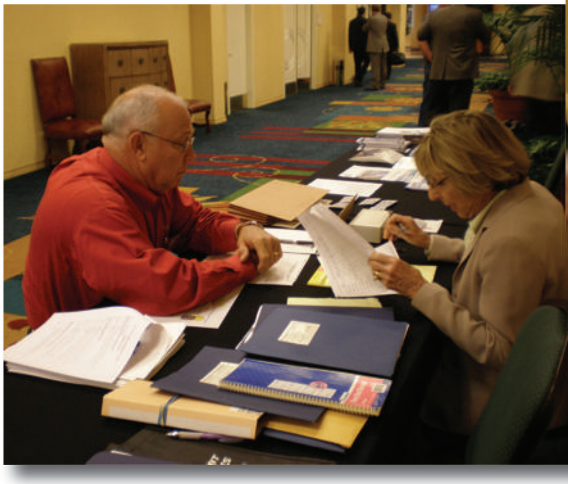
Upper left: Duncan Axisa, Farren Hiscutt, Terry Krauss, and Daryl O'Dowd.

Upper right: Don Griffith, Gary Walker, and Duncan Axisa.

Center, left: WMA Dinner; below: Hilda and Don Duckering and Nati Glick at check-in

Bottom left: Gary Walker and Hilda Duckering; right: Masataka Murakami, O. Sen and Darryl O'Dowd

2009



Anaheim, California

THE IMPACT OF GLACIOGENIC SEEDING ON OROGRAPHIC CLOUD PROCESSES: PRELIMINARY RESULTS FROM THE WYOMING WEATHER MODIFICATION PILOT PROJECT

Bart Geerts*[1], Qun Miao[1], Yang Yang[1], Roy Rasmussen[2], Daniel Breed[2], and Barry Lawrence[3]

[1]Department of Atmospheric Science, University of Wyoming
[2]Research Applications Laboratory, National Center for Atmospheric Research
[3]Wyoming Water Development Office

Cloud seeding has long been and remains the most widely practiced method of advertent weather modification (Qiu and Cressey, 2008). It is remarkable that notwithstanding all the data collected and the high level of experimental control compared to typical research on cloud and precipitation processes, the effectiveness of cloud seeding in enhancing precipitation remains uncertain (Bruintjes, 1999; National Research Council, 2003). Numerous statistical studies have been conducted to assess changes in surface precipitation, often with mixed or questionable results. The level of noise in natural systems compared to the magnitude of the signal makes verification of precipitation enhancement extremely difficult (Garstang *et al.*, 2005). Numerous studies and reports have pointed to the need for field measurements that document the cloud microphysical "chain of events" that lead to an alteration of surface precipitation.

Ground-based glaciogenic cloud seeding has been conducted over the mountains of southeast Wyoming as part of the Wyoming Weather Modification Pilot Project since the winter of 2007-08 (National Center for Atmospheric Research, 2009). A cross-over design involving two serial mountain ranges, both with control and target snow gauges, is being used in an ongoing randomized seeding experiment. Here we report on a piggy-back study that uses data from an airborne vertically-pointing mm-wave Doppler radar to study the cloud microphysical effect of glaciogenic seeding of cold-season orographic clouds. Fixed flight tracks were flown downstream of AgI generators in the Medicine Bow Mountains. The airborne radar data from seven flights, each with a no-seeding period followed by a seeding period, indicate that AgI seeding significantly increased radar reflectivity and thus snowfall rate near the ground.

The fixed flight legs and the terrain are shown in Fig. 1. The University of Wyoming King Air aircraft carried *in situ* cloud probes and the 94 GHz Wyoming Cloud Radar (WCR), with fixed antennas pointing to the nadir and the zenith. To our knowledge, this is the first time a nadir-pointing airborne radar has been used to assess the cloud microphysical impact of glaciogenic seeding. The nadir view provides radar data within ~30 m of the ground, whereas the commonly used ground-based scanning radars can only "look" above complex terrain.

A total of 70 seed and 44 no-seed passes were flown over the four downwind legs on seven days. (A "seed" pass is one with at least two of the three generators in operation.) All WCR reflectivity profiles have been synthesized in the form of a *frequency-by-altitude display* or FAD (Yuter and Houze, 1995), both for the no-seed passes (Fig. 2a) and the seed passes (Fig. 2b). In essence the WCR profiles, at ~30 m vertical and along-track resolutions, were remapped as a function of height above ground level (AGL), and the reflectivity values were then binned in the FADs. Most storms were rather shallow; in many cases the clouds were confined to the mountain proximity. WCR reflectivity generally increased towards the ground, indicating low-level ice crystal growth in both seeded and unseeded conditions. Snowfall occurred at all times, and it was generally light. The temperature at the level of the three generators was close to or just below -8°C.

High reflectivity values (>10 dBZ) were more commonly encountered during seeding. The average reflectivity (Z) near the ground was 1.0 dB higher (Fig. 2c). This converts to an average increase in snowfall rate (S) of about 25% during seeding, according to a theoretical Z-S relationship specific to 94 GHz radars (Matrosov, 2007). Flight-level microphysical probe data compared with near-flight-level WCR reflectivity data confirm that this theoretical Z-S relationship is representative. The shift in reflectivity in the boundary layer during

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*Corresponding author : Bart Geerts, University of Wyoming, Laramie, WY 82071, USA. email: geerts@uwyo.edu

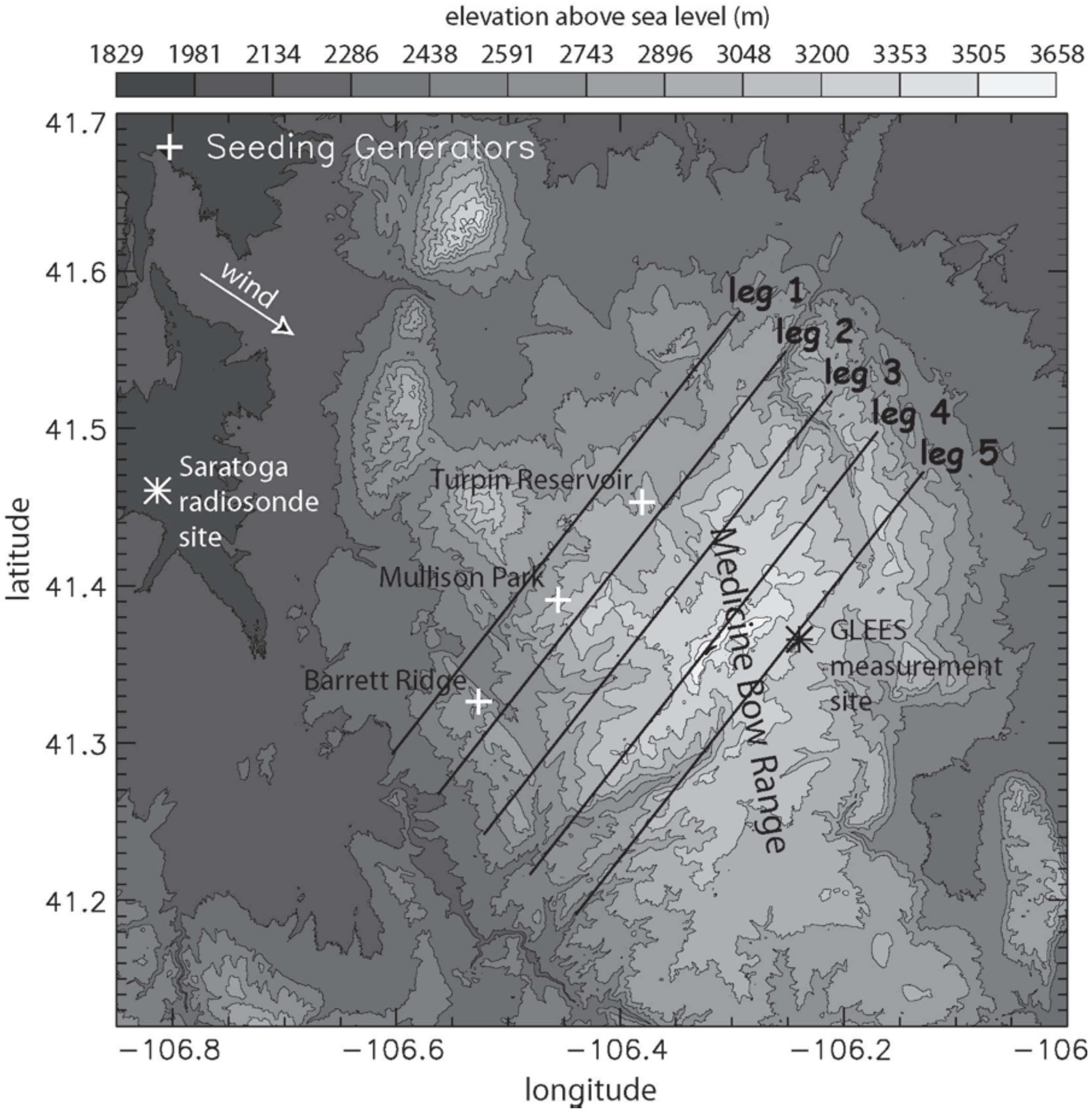

Figure 1: Terrain map of the Medicine Bow Range in Wyoming, showing the AgI generators and the fixed flight legs. The flight level was constant at 4267 m.

seeding, with an enhanced (reduced) probability in the >10 dBZ (-2 to +10 dBZ) range (Fig. 2c), is statistically significant at the 95% level, but not at the 99% level, according to a comparison of the seed – no-seed difference with 1000 random samples of all 114 flight passes. A partitioning of the data, into days with more stratified flow and less stable flow, yields physically meaningful results that corroborate our interpretation that the enhancement of near-surface reflectivity and snowfall is due to AgI seeding.

Caution is warranted in view of the large natural variability of weather conditions and the small size of the dataset. This work is preliminary and needs to be followed up with a longer field campaign under similar as well as more diverse weather conditions. Such a campaign should include ground-based instruments, such as vertically pointing or scanning radars and particle sizing and imaging probes.

More information can be found in a paper currently under review (Geerts *et al.* 2010).

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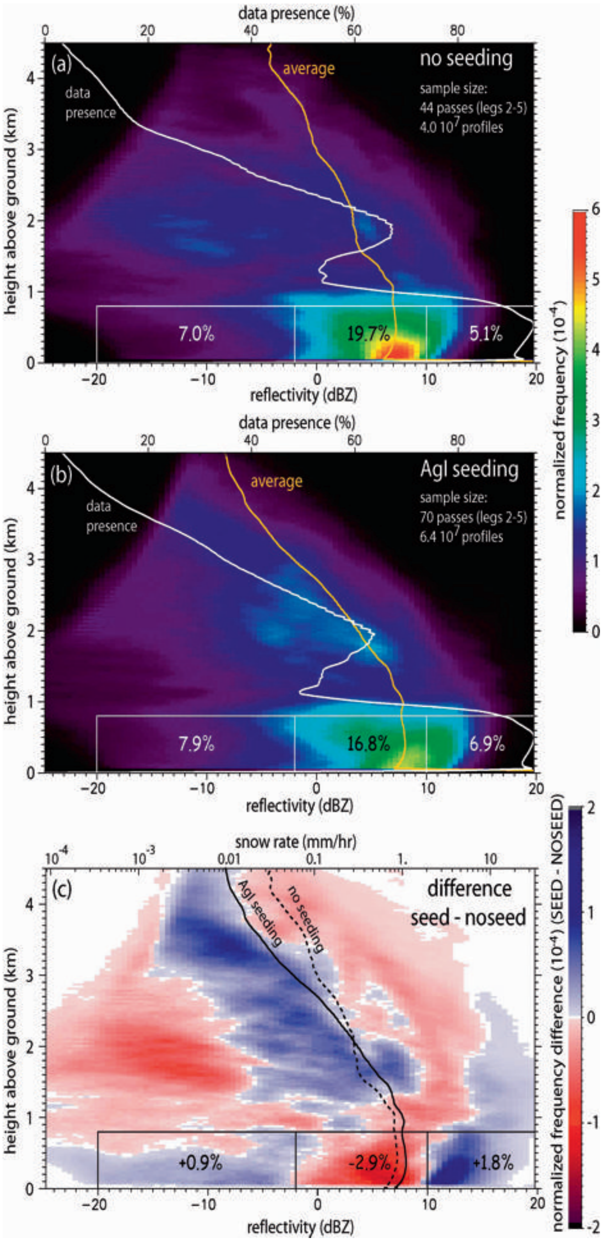

Figure 2: Normalized FAD of WCR reflectivity (Z) for all flight legs downwind of the AgI generators on seven flights, during (a) no-seed and (b) seed conditions. Also shown are cumulative normalized frequencies in three boxes near the ground, expressed as a percentage, the mean reflectivity profile (yellow line) and the "data presence" (white line), i.e. the percentage of WCR range gates with radar echo as a function of height. The difference between the data in (b) and in (a) is shown in (c), together with the mean profiles from (a) and (b), and the difference within the three boxes. The snow rate (S), shown in the upper abscissa of (c), is inferred from $S=0.11\ Z^{1.25}$ *(Matrosov, 2007).*

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TEXAS WEATHER MODIFICATION OPERATIONS IN 2009

Robert E. Rhodes[1*], Stephanie D. Beall[2], Todd R. Flanagan[3],
Jennifer Wright[4] and Arquimedes Ruiz-Columbié[5]

[1]WTWMA, 8696 Hangar Rd., San Angelo, TX 76904
[2]SWTREA, P.O. Box 1433, Carrizo Springs, TX 78334
[3]STWMA, 110 Wyoming Blvd. Pleasanton, TX 78064
[4]PGCD, P.O. Box 637, White Deer, TX 79097
[5]Active Influence & Scientific Management, 6506 86th St, Lubbock, TX 79424

ABSTRACT. Weather modification operations continued in 2009 over the state of Texas. During the 2009 season, a total of seven projects were operational in Texas conducting rain enhancement and, in one project, hail suppression operations. Operations for 2009 were very good over the western projects but rainfall and seedable conditions over the south was below average due to a prolonged drought. Most of the state was dry, with the exception of West Texas and parts of the Panhandle. This paper will serve as an update for the Texas projects in 2009, offering a comprehensive summary of each of the operational projects in the state. Additionally, this paper will provide an analysis of the Texas projects conducted by Active Influence and Scientific Management.

1. INTRODUCTION

Weather modification operations continued over Texas during 2009. While weather modification has occurred over the state for decades, recent operational programs have been consistently enhancing rainfall since the turn of the twenty-first century.

During the 2009 season, seven projects were operational: Panhandle Groundwater Conservation District's (PGCD) precipitation enhancement project in White Deer, Seeding Operations and Atmospheric Research (SOAR) in Plains, Trans-Pecos Weather Modification Association (TPWMA) in Pecos, West Texas Weather Modification Association (WTWMA) in San Angelo, Southwest Texas Rain Enhancement Association (SWTREA) in both Carrizo Springs and Pleasanton, South Texas Weather Modification Association (STWMA) in Pleasanton, and the Edwards Aquifer Authority's (EAA) precipitation enhancement project. The EAA project is operated by the STWMA and the SWTREA. A map showing the location of all the projects is presented in Figure 1.

2. TEXAS WEATHER IN 2009

Weather over Texas during the year was different from the last two years. Drought persisted over South Texas throughout the majority of the year while parts of West Texas and the Panhandle were wet with several instances of record or nearly record rainfall totals. An area of high pressure laid over the Gulf and southern Texas through most of the convective season, inhibiting thunderstorms over South Texas. The Texas Panhandle and West Texas were subject to an increased number of well-structured frontal boundaries through mid-season. Frontal boundaries are typically not responsible for weather over west-central Texas after June.

The Texas coast often receives relief from tropical systems but the 2009 tropical season did not offer significant rainfall to Texas. However, the ridge, which prolonged significant drought over South Texas through August, lifted during the later half of September, bringing the region much desired relief. Figure 2 illustrates the radar-derived yearly rainfall for Texas.

3. PROJECT SUMMARIES

3.1 Panhandle Groundwater Conservation District (PGCD)

The conclusion of the Panhandle Groundwater Conservation District's (PGCD) 2009 Precipitation Enhancement Program marked the tenth year of cloud seeding in the Texas Panhandle. This season began with the first mission on April 26th and concluded on September 25th with the last mission. The mission on September 25th was the latest season flight since the inception of the program in 2000. Typically, the season runs from April 15th until September 30th; however, if suitable opportunities are present before the 15th the season will commence.

The 2009 seeding season contained 25 days with seeding events, which consisted of 32 seeding missions and 23 reconnaissance missions. Several days during the summer were marginal days for thunderstorm development, which resulted in more reconnaissance missions than any other year in the past. According to Active Influence and Scientific Management (AISM), during the seeding events we seeded 32 clouds which consisted of nine small clouds, 10 large clouds and 13 type B clouds.

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*Corresponding author: R.E. Rhodes, WTWMA, 8696 Hangar Rd., San Angelo, TX 76904 USA; E-mail: meteorologist@wtwma.com

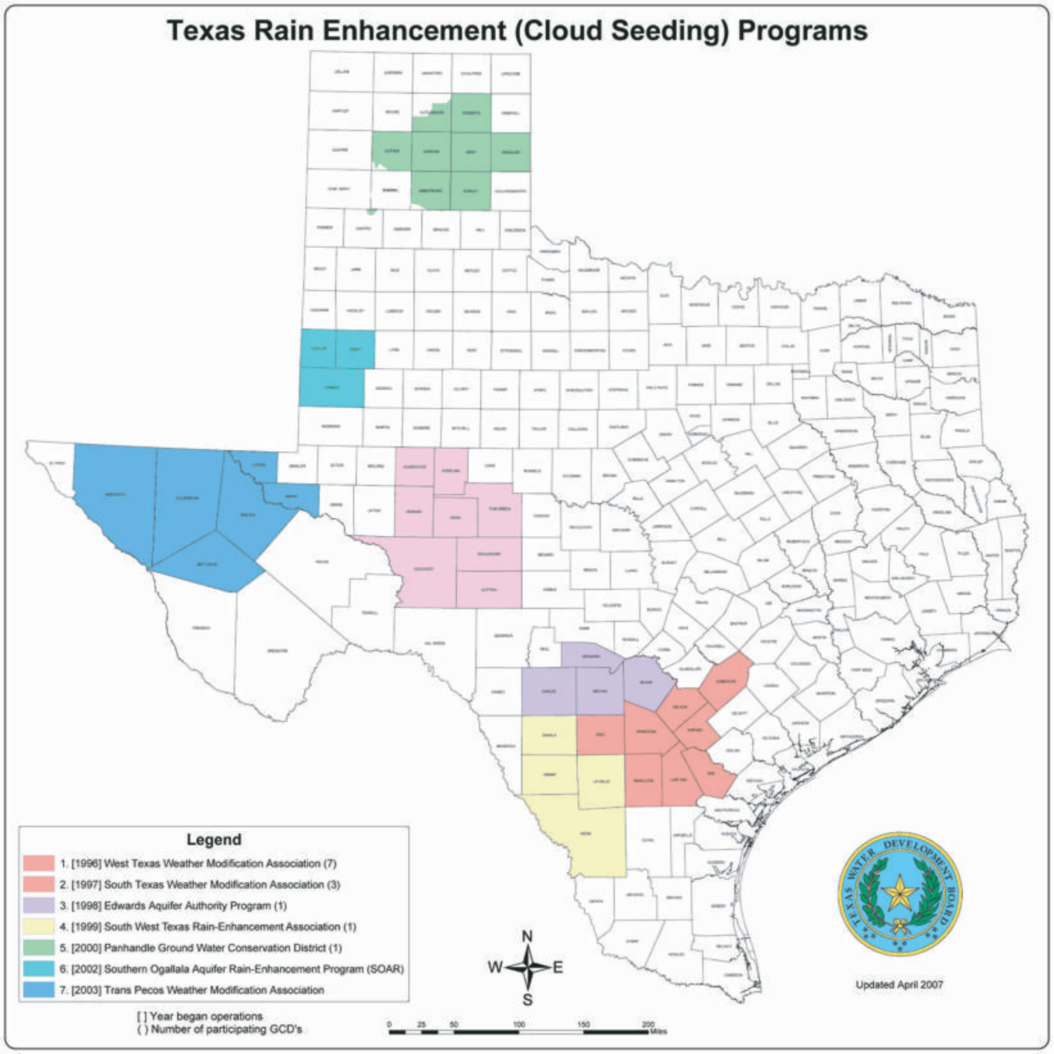

Figure 1. Locations of Weather Modification Programs in Texas in 2008

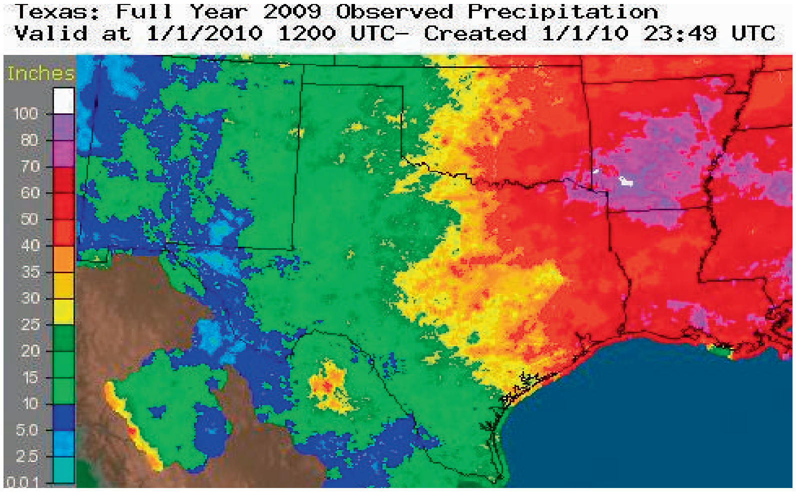

Figure 2. Radar-derived yearly precipitation for Texas in 2009. Image courtesy of NWS Precipitation Analysis website, http://www.srh.noaa.gov/rfcshare/precip_analysis_new.php .

The seeding of these clouds helped to produce an additional 717,900 acre-feet of water which translates to on average about 1.65 inches across the water District. Taking into account the raw rain gauge data, the 1.65 inches can be translated to a 10 percent increase per county in rainfall received.

The economic value of this additional 10 percent of rainfall remained about the same as the 2008 season. The total cost of the seeding program in 2009 was $200,693. Considering this figure plus what an additional 1.65 inch per acre is worth, the District cost per acre is about five cents.

While most of the south Texas cloud seeding projects report about a strong drought, the Texas Panhandle experienced exactly the opposite. April, the start of the season, began a little dry with the majority of the Panhandle considered moderately dry by the U.S. Drought Monitor. During May and June, the Texas Panhandle was mostly drought free, and this is also when the majority of the seeding missions took place. There were six seeding days in May and seven days in June. July's weather pattern was dominated by high pressure; therefore, only one seeding day occurred and the Panhandle began to see some dry areas set in. August through September saw the return of the seasonal cold fronts and trough passages which brought many opportunities for rainfall. Any dry areas that were present in July were all clear as of November.

All of the counties within PGCD received more rainfall in 2009 than in 2008 from April to October (Table 1). Rick Husband International Airport in Amarillo recorded 8.07 inches of rainfall in August, which beat the record of 7.55 inches in 1974, according to the National Weather Service in Amarillo, Texas.

Table 1. April-October rainfall averages comparing 2008-2009

	2008	2009	Departure
Armstrong	14.5	17.8	3.2
Carson	16.3	23.2	6.9
Donley	17.1	17	0.1
Gray	17.6	19.4	1.8
Potter	16.6	14.1	2.5
Roberts	18.1	17	1.1
Wheeler	22.3	19.1	3.3
District Normal 16.43			

Normally, during the seeding season the weather events are concentrated either in the west or in the east in the Panhandle; however, that did not occur this year. See Table 2. Most of the weather events included all or most of the Texas Panhandle; therefore, the seeding was spread out through all of the District Counties. Donley County saw the most seeding days with 10 followed by Carson and Gray counties with nine days. The least amount of seeding days occurred in Potter and Wheeler counties with only five days.

This year's season brought a few changes to the project. A new pilot, Harrison Hoffman, joined the staff in June. Also, a new upgraded TITAN computer (Thunderstorm Identification, Tracking Analysis and Nowcasting) supplied by Weather Decision Technologies, Inc., was put into operation. The upgraded systems were put in place in all of the Texas projects. These new computers were necessary to handle the National Weather Service radar upgrades to super resolution in 2008.

The 2009 seeding season was overall average, but successful with an average increase of rainfall of 10 percent throughout the PGCD counties. The Texas Panhandle was very lucky to not participate in the drought that dominated South and Southwest Texas.

Table 2. PGCD Seasonal Summary

2009	Days	Seed Flights	Recon Flights	Flight Hours
April	2	3	3	7
May	6	9	0	18
June	7	9	6	30
July	1	1	6	10
August	4	5	6	19
September	5	5	2	11
Totals	25	32	23	95

3.2 West Texas Weather Modification Association (WTWMA)

Seeding operations started on March 25th and ended on October 8th with 56 operational days. Table 3 contains a summary. The number of operational days is the most on record for West Texas; previously, operations were conducted over 53 days in 2006 (see Table 4). Overall 190 clouds were seeded with 2,382 flares during 103 flights. The number of seeded clouds is the most since changing radar sources from 74-C to WSR-88D feed. In sum 9 reconnaissance flights were flown while making an attempt to find seedable clouds on marginal days. Pilots flew 267 flight hours. Full time pilot, Levi Sleeper, flew for the duration of the season; part time pilot availability and erratic storm development throughout the season made for a few late flight initiations. Some moderate repairs on aircraft, mainly the Piper Aztec 6730Y, had minor effects on operations.

Table 3. WTWMA Seasonal Summary

2009	Days	Flights	Recon	Hrs	Flares	Rainfall
25-Mar.	1	2	0	4	60	1.73
April	3	5	1	11.8	50	4.61
May	10	18	2	55.8	582	0.12
June	12	22	2	63.9	487	1.74
July	9	18	2	39.7	267	4.64
August	13	23	1	54.6	543	1.89
Sept	7	12	0	32.8	359	5.66
8-Oct.	1	3	1	4.5	54	2.92
Totals	56	103	9	267.1	2402	23.31

Throughout the rainy season of 2009, West Texas received a larger sum of rain than most of Texas. As of November 16, a value (23.85in) at San Angelo was above normal by 4.27 inches. Top 10 rainfalls at the San Angelo Regional airport during April and July in addition to periodic large rainfall events throughout the summer led to a well above normal season. Midland International was well below normal until July, receiving 6.55 inches during the month. August was the most active this season with 13 operational days. Precipitation and percent of normal maps show that much of Texas was well below normal except for West Texas and parts of central Texas during March and April. Most of Texas was dry through May. Western parts of the target area were well above normal in June and West-central Texas above normal in July. West Texas is shown to be dry August through September but drought stricken East-central and South Texas began to see some relief. The 2009 tropical season was very limited in the Atlantic Ocean and Caribbean without hurricanes moving onto the Texas Gulf Coast. The Pacific tropical season was more active with several instances of tropical moisture moving over Mexico and into West Texas.

The statistical reports conducted by AISM shows the majority of seeding operation results were excellent or very good; with average seasonal increases to precipitation at 17%. Arrival time to small clouds (91%) was excellent. Small clouds showed increases for precipitation mass at 102%, cloud mass increases of 55%, lifetime increases at 27%, increases to cloud area at 39%, cloud volume increases of 41%, and volume above 6km of 48%. Increases in precipitation mass by county were shown between 6% and 35.5%. Crockett County was below 10% but the low value is a consequence of large area. Reagan County was most favored in number of seeded clouds. In addition to glaciogenic seeding, West Texas also started a case study using one supplementary hygroscopic flare. Unfortunately, only 3 cases could be matched with a proper control sample. Further information can be read in the AISM evaluation (Ruiz-Columbié 2009. Total increases in precipitation for the target area were calculated at 1,851,542 acre-feet.

Table 4. WTWMA Multi-year comparison

WTWMA (2002-2009)					
	Seeded-Clouds	Operational Days	Flares Used	Increase Million ac-f	Annual Rainfall
2002	285	47	3024	0.78	14.41
2003	265	50	3184	0.76	19.76
2004	109	46	1140	1.35	30.48
2005	133	39	1524	1.26	20.4
2006	157	53	1810	1.7	17.65
2007	95	46	1166	1.19	32.05
2008	78	38	1420	1.18	19.00
2009	190	56	2382	1.85	25.54

3.3 Southwest Texas Rain Enhancement Association (SWTREA)

This year, 2009, was an unusual year over the southwestern most portion of Texas. Weatherwise, it was a hot and dry summer for most locations. As for weather modification, it was actually above average. This typically occurs during dry years. Usually in a drought, there is a lack of suitable clouds to go after. This makes the weather modification project operators even more diligent in their efforts to increase rainfall over the area. As a result, there were more reconnaissance flights this year than normal, with a total of 16 occurring during 2009. The early spring months offered a slow start to weather modification activities while the rest of the season was quite busy. The busiest month of the season was May, with a number of hail suppression flights taking place and in turn, a large amount of seeding material used. Flight activity increased dramatically during the latter half of the season as a strong area of high pressure that dominated the weather pattern for much of the summer months weakened. This information can be seen in Table 5. Another strange occurrence this year was that for the first time in six years, no flights occurred in the month of October. This was due to a number of the systems being embedded, which means that the thunderstorms were embedded in light rain, or low ceilings that hampered seeding at base.

Table 5. SWTREA Seasonal Summary

Month	Seeding Flights	Recon Flight	Flight Hours	Flares	AgI (g)
March	2	1	3.3	31	1240
April	1	1	3	53	2120
May	11	4	30.9	364	14560
June	7	2	11.6	155	6200
July	11	4	27.5	231	9240
August	9	1	18.9	130	5200
September	10	3	17.9	119	4720

Table 6 shows results from the past two seeding seasons. One thing to remember when looking at this table is that 2008 was a drought year and 2007 was a very wet year. In drought years, weather modification activities are more frequent and in wet years they are less frequent due to possible flooding and suspensions of operations due to very wet conditions. Project staff and the project target area remained the same as last year. For the most part, the year of 2009 was a tough one due to drought but nevertheless there were enough opportunities for a successful seeding season.

Table 6. SWTREA Bi-Annual Comparison

Month	Total number Flights		Flight Time Hours		Number of Flares		AgI Used	
	‘07	‘08	‘07	‘08	‘07	‘08	‘07	‘08
March	1	0	1.2	0	26	0	1,040	0
April	4	5	2.9	7.1	15	137	600	5,360
May	6	6	10.6	6	120	144	4,800	5,760
June	5	8	6.9	14.3	50	115	2,000	4,600
July	1	9	1.2	10.9	11	119	440	4,760
Aug.	13	18	23.4	30.7	160	229	6,400	9,160
Sept.	4	5	3.7	8.4	13	127	520	5,080
Oct.	4	1	4.6	1.1	30	14	1,100	560

3.4 South Texas Weather Modification Association (STWMA)

The 2009 season marked the 13th year of operations for the South Texas Weather Modification Association. In terms of operations, it was a near-normal year with 76 seeding flights over 44 days (see Table 7) along with an additional 13 reconnaissance flights. This compares to the 12-year average of 39 seeding days, 69 seeding flights and 7 reconnaissance flights. The long-term drought that began near the end of 2007 continued for much of the year before a dramatic shift in the weather patterns – likely attributed to the onset of El Niño – occurred in September. Despite the drought, there were many small convective clouds that presented themselves for seeding opportunities, and these accounted for the majority of seeding events during the year. Also, with the purchase of the Aztec twin engine plane late last year, nighttime seeding became possible.

Table 7. STWMA Seasonal Summary

MONTH	SEED DAYS	FLIGHTS	HOURS	AMOUNTS
March	0	1r	0.5	0
April	0	0	0	0
May	10	19+6r	48.9	11,680g
June	5	8	16.6	4,560g
July	11	20+3r	44.7	14,320g+6,000g
Aug.	10	17	28.2	6,600g+3,000g
Sept.	8	12+3r	21.8	4,920g+2,000g
TOTALS	44	76+13r	160.7	42,080g+11,000g

Table summary of operations in 2009. Under Flights, r refers to reconnaissance flight only, while the values to the right of the plus sign under *Amounts* refer to the amount of hygroscopic material (CaCl) used for seeding.

The first opportunity for seeding came on March 26th when a powerful storm system affected the state. A flight was launched but eventually low ceilings and the onset of severe weather resulted in the flight being a reconnaissance only. April would come and go with no seeding opportunities and below normal rainfall for the majority of the area; one exception was northern Wilson County where excessive rains from thunderstorms resulted in over six inches of rainfall in that area. During a two-day period in the second week of the month, record lows in the mid 30s were followed by record highs near 100°F.

The month of May would turn out to the busiest May since the inception of the program with 25 flights taking place over ten days, primarily during the latter half of the month. As is normally the case with convective rains, monthly totals varied considerably; while a good portion of the target area saw below normal rainfall, there were spots where rainfall totals were 150-200% of normal. May also signaled the return of the counties within the jurisdiction of the Edwards Aquifer Authority.

June, normally one of the wetter months of the year, turned out to be extremely dry with most locations in the target area receiving less than a quarter inch of rainfall. Five days during the month presented seedable clouds, including the first night mission on June 2nd. Around mid-month, a strong area of high pressure aloft parked over the area with a string of 100°F+ highs occurring – a foreshadowing of the intense heat that would follow later in the summer.

July was an average month in terms of the amount of seeding activity that occurred, with eleven days seeing seeding operations take place; these were spread out throughout the month. Many areas, particularly over the southern counties of the target area, saw below normal rainfall once again. Normally by July, convection is primarily generated by the seabreeze boundary and/or strong heating within a high precipitable water (PWAT) airmass (>1.75"); both were largely absent this month. In many cases, convection moved into the area from the north or developed along the Balcones Escarpment. The intense heat continued, with over 20 days of highs at or above 100°F. The experimental use of hygroscopic flares for seeding began in July, but these were used sparingly.

The intense heat continued into and peaked in August, with over 25 days recording highs at or above 100°F. The June to August period would end up being the hottest three-month period ever for many locations in south Texas. By month's end, Pleasanton had recorded 67 days with highs at or above 100°F! Rainfall was scarce as it was in June, with all but two small areas in the target area seeing well below normal rainfall. Still, small convective clouds were present on several days, with ten days seeing seeding operations take place. The majority of these missions occurred during the last week, when a major change in the weather pattern began. September saw the welcome rains that were sought after for many months, with the vast majority of the target area seeing above normal rainfall spread out evenly through the month. Some locations saw in excess of ten inches of rain. Tropical airmass intrusions with exceptionally high PWATs (>2.30") were common; unfortunately this also resulted in many unsuitable clouds for seeding. Still, there were eight days during the month where seeding occurred. The final day of seeding for the year occurred on September 28th. Wet weather continued through October, November and into December with the El Niño signal strengthening in the Pacific.

The annual radar analysis provided by AISM showed that seeding effects were positive in south-central Texas. The analysis indicated an average increase in rainfall of 11%, translating to over 540,000 acre-feet of water from 131 seeded clouds.

4. 2008 STATE EVALUATION BY ACTIVE INFLUENCE AND SCIENTIFIC MANAGEMENT

Cloud seeding missions began in March and ended in October. The PGCD, WTWMA, STWMA, SWTREA, and TPWMA were included within the 2009 Evaluation.

A total of 466 clouds were seeded and identified by TITAN software over 171 target area operational days. Overall 91 operational days were qualified as excellent, 40-very good, 27-good performance, 5-fair performance, and three were categorized as experimental. For the 466 clouds, 218 were designated small clouds, 126 large clouds, and 117 Type-B seeded clouds.

Small clouds (see Table 8) were seeded with 914 flares and received an excellent timing of 86% for an effective dose of 55 ice-nuclei per liter. Individual cells likely received closer to the desired dosage of 100 ice-nuclei per liter. An excellent increase of 95% in precipitation mass together with an increase of 43% in cloud mass illustrates that the seeded clouds grew at expenses of the environmental moisture (they are open systems) and used only a fraction of this moisture for their own maintenance. The increases in lifetime (27%), area (35%), volume (34%), volume above 6 km (39%), and precipitation flux (42%) are notable. There are slight increases in maximum reflectivity (1%), and in top height (3%). The seeded sub-sample seemed 40% more efficient than the control sub-sample. Results are evaluated as excellent for this sub-sample. The Estimated increases received from small clouds are 170,545 acre-feet.

Large clouds received 1,879 flares with an effective dose near 75 ice-nuclei per liter. On average, large clouds were 29 minutes old when the operations took place; the operation lasted about 32 minutes, and the large seeded clouds lived 215 minutes (3 hours and 35 minutes). The estimated increases received from large clouds are 2,264,139 acre-feet. Similarly, Type-B clouds received 2,223 flares with an effective dose near 60 ice-nuclei per liter. On average, Type B clouds were 124 minutes old when the operations took place; the operation lasted about 39 minutes, and the Type B seeded clouds lived 295 minutes (4 hours and 55 minutes). The estimated increases received from Type-B clouds are 1,331,414 acre-feet.

The total increases over the State of Texas throughout the 2009 season are estimated at 3,766,098 acre-feet. Percent of increases are broken down per county of the seeded region; PGCD micro-regionalization shows 15.6% increases over

Donley and 4.2% over Roberts. TPWMA shows Ward County allowed for 22.6% increases and 3.7% over Culberson. The best increases for WTWMA were 36% over Glasscock County and least of 6% over Crockett County (mainly due to county size); SWTREA held an 11.9% increase over Uvalde and 6.6% increase over La Salle; STWMA best results were seen over McMullen County at 16.1% and 5.8% over Bandera. South and Southwest Texas saw a significant drought throughout the seeding season holding average rainfall over the State of Texas to nearly 12 inches.

Results for the 2009 season were evaluated as excellent and a typical average seasonal increase in precipitation of 11.5% was recorded. Anti-hail seeding operations appeared to partially mitigate hail formation in corresponding storms. The Texas Weather Modification Association also began to use salt flares in addition to silver iodide flares in 2009. Too few cases were evaluated to gain a respective statistical evaluation; however, use of both flares appears to have a positive affect (Ruiz-Columbié 2008).

For many people, the increases in precipitation mass of over one million acre-feet are rather incomprehensible. Annually, a single person consumes 265 gallons (.008 acre-feet) of water. Household water uses on average is 50-100 tons which is equivalent to .445 and .885 acre-feet respectively. Additionally, water used to irrigate crops for making clothing and the food we eat is estimated at 1500-2000 tons or 13.27-17.70 acre-feet (Pearce 2007). Collectively, a single person uses on average 18.6 acre-feet each year. In the State of Texas, the cost of water ranges greatly from $300-$1,200 but for the purposes of this explanation we will use an average value of $750 per acre-foot. Using these values, the cost of water per person is $13,950 per year. The average statewide budget for weather modification operations is $1.6 million. AISM estimated the total increases in precipitation at 3,766,098 ac-ft in 2009 yields a cost of one acre-foot of water at $.42.

5. SUMMARY

During the 2009 season, a very large number of clouds were seeded in the state of Texas. A prolonged drought hindered seedable clouds over South Texas while West Texas and the Panhandle conditions performed above average. AISM's annual analysis concluded that the majority of seeded clouds were in the small category, all seeded cloud categories yielded increases in precipitation mass, with an inspiring 3.7 million acre-feet of water produced in the state's target and surrounding operational areas.

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Ruiz-Columbié, A., 2009: Annual evaluation report 2009, State of Texas. pp 9.

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Table 8. Seeded Sample versus Control Sample (218 couples, averages)

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	65 min	45 min	1.44	44 **(27)**
Area	73.9.0 km^2	49.7 km^2	1.49	49 **(35)**
Volume	251.6 km^3	158.0 km^3	1.58	58 **(34)**
Top Height	8.4 km	7.9 km	1.07	7 **(3)**
Max dBZ	53.5	51.3	1.04	4 **(1)**
Top Ht of max dBZ	3.8 km	3.8 km	1.00	0 **(-2)**
Volume above 6 km	66.9 km^3	40.3 km^3	1.62	62 **(39)**
Precip Flux	530.2 m^3/s	311.0 m^3/s	1.73	73 **(42)**
Precip Mass	2285.0 kton	1015.4 kton	2.30	130 **(95)**
Cloud Mass	191.4 kton	112.5 kton	1.71	71 **(43)**
η	12.0	8.9	1.36	36 **(40)**

SUMMARY OF A WEATHER MODIFICATION FEASIBILITY STUDY FOR WINTER SNOWPACK AUGMENTATION IN THE EASTERN SNAKE RIVER BASIN, IDAHO

Don A. Griffith*, Mark E. Solak and David P. Yorty

North American Weather Consultants, Inc.
Sandy, Utah 84093

Abstract. North American Weather Consultants performed a feasibility/preliminary design study for a potential operational winter cloud seeding program in the Eastern Snake River Basin Program (ESRBP) in Idaho. Two potential target areas were identified. One area was located along the south slopes of the Centennial Mountains and the Lion Head and Henrys Lake Mountains in northeastern Idaho. This area is denoted as the North Target Area. The other area encompasses all or portions of the Big Hole Range, the Snake Range, the Grays Lake Mountains, and the Aspen Range in eastern Idaho. This area is denoted as the East Target area. The primary program goal would be to increase winter snowpack in the target areas through operational cloud seeding.

Average increases of 5.5% in April 1st snow water contents for the North Target area and 7.6% for the East Target Area via cloud seeding were estimated through transference of the indicated results from the Climax I and II research programs. Simulations using empirically derived snowpack-streamflow relations yielded estimated average increases in March-July streamflow from two seeding modes totaling approximately 149,350 acre-feet (1.84×10^8 m^3) for the combination of the two areas. The costs per acre-foot for the estimated increases in March-July combined area streamflow range from $2.95 to $4.51 per acre-foot of additional water in an average water year. A preliminary design for an operational winter cloud seeding program is described. One preliminary winter season of supercooled liquid water and lower-level temperature and wind observations is recommended to determine the presence of supercooled liquid water and low-level temperature inversions.

1. INTRODUCTION

The Idaho Water Resource Board (IWRB) contracted with North American Weather Consultants (NAWC) of Sandy, Utah for the performance of a comprehensive study of the feasibility/design of applying modern cloud seeding methodology for winter snowpack augmentation in that portion of the Eastern Snake River Basin located in Idaho (Griffith *et al.* 2008). This paper presents the key elements, findings, conclusions and recommendations of the feasibility/design study. The study included a survey of relevant prior research and operational seeding programs, considerable analysis of program area-specific historical weather data, assessment of potential cloud seeding methods, plus evaluation techniques. Procedures and recommendations of the American Society of Civil Engineers (ASCE) publication entitled "Standard Practice for the Design and Operation of Precipitation Enhancement Projects" were utilized where appropriate (ASCE 2004). A preliminary operational program design was prepared, including identification of permit and reporting requirements. The study also included hydrologic estimates of the potential program yield in terms of additional runoff and the estimated costs associated with conduct of the program, based on different seeding modes. Preliminary benefit/cost estimates for the proposed program design were also provided.

The specific task areas comprising the full feasibility/design study included:

- Review and Summary of Prior Studies and Research
- Review and Analysis of Climatology of the Target Area
- Development of Preliminary Program Design
- Establishment of Operational Criteria
- Development of Monitoring and Evaluation

**Corresponding author address:* Don Griffith, North American Weather Consultants, Inc., 8180 South Highland Dr., Suite B-2, Sandy, UT; e-mail: dgriffith@nawcinc.com.

Methodology
- Review of Environmental and Legal Aspects
- Development of Cost Estimates
- Report Preparation
- Coordination Meetings and Presentations

2. PROGRAM GOALS AND SCOPE

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

3. TARGET AREAS

The proposed target areas consist of the terrain above 1982 m (6,500 feet MSL) elevation in two separate mountain complexes located in Eastern Idaho. The North Target Area is comprised of the south slopes of the Centennial Mountains and the Lion Head and Henrys Lake Mountains in northeastern Idaho. The second area, denoted the East area, encompasses all or portions of the Big Hole Range, the Snake Range, the Grays Lake Mountains, and the Aspen Range located in Eastern Idaho. Streams that originate in both of these areas provide streamflow to the Snake River. The proposed target area locations are depicted in Figure 1.

Runoff from these target areas benefit hydropower production, agriculture (both surface runoff and ground water recharge), municipalities (drinking water), as well as recreational interests. Approximately 70% of the annual precipitation in the target area accumulates during the October-April period, with area average snowpack water equivalent on April 1 of 44.7 cm (17.6 in) in the North Target Area and 38.9 cm (15.3 in) in the East area.

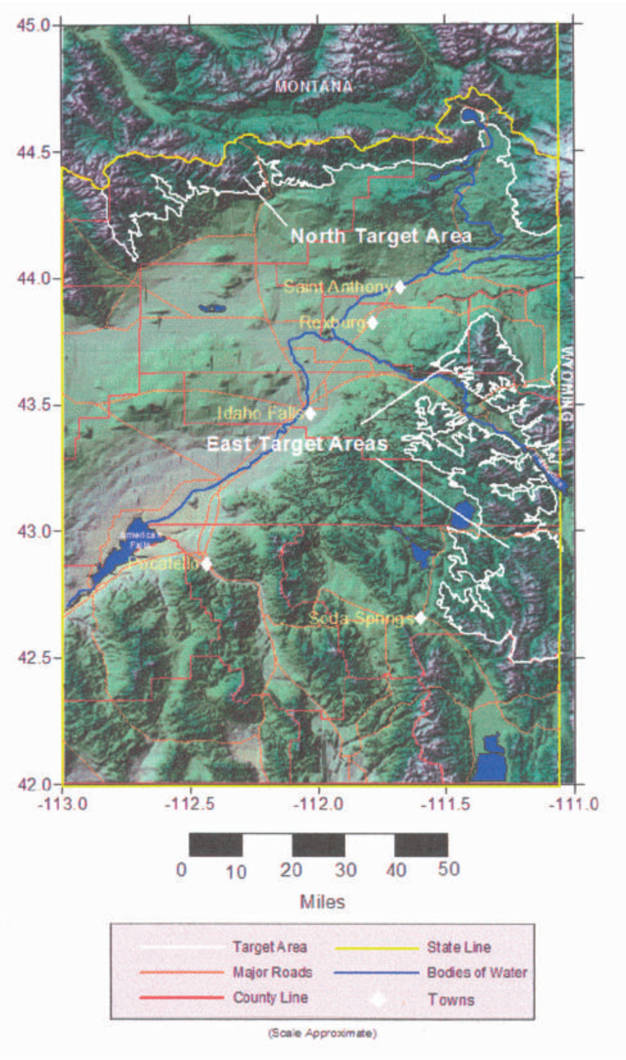

Figure 1. Proposed North and East Target Areas

4. SEEDING PROGRAM PRELIMINARY DESIGN

4.1 Seeding Methods and Materials

Storm periods affecting the potential target areas were identified for five winter seasons (water years 2003-2007) for the October-April period. Precipitation data from several Natural Resource Conservation Service's SNOwpack TELemetry (SNOTEL) sites were considered, and six-hour time blocks were selected when precipitation was clearly occurring in the target areas (in general, at least 0.254cm, 0.10 in) of precipitation during the six-hour period reported at one or more of the target SNOTEL sites). In all, 170 six-hour periods were identified and analyzed for the northern portion of the target, and 239 periods for the eastern portion. There was only approximately a 40% overlap in time periods identified for the two different portions, suggesting significant meteorological differences in precipitation patterns between the two areas. Detailed analyses of these storm periods were performed that included information on:

- Precipitation amounts and timing of occurrence
- 700 mb temperatures and winds
- Low-level atmospheric stability

Analyses were performed using this data set to estimate the percentage of the time the six-hour events would be considered "seedable" in each target area. These analyses, which are described in Section 5, indicated 37% of the events in the North Target Area and 38% of the events in the East area were considered seedable based upon cloud top temperature criteria.

Information obtained from the analysis of those six-hour precipitation periods was utilized to develop a number of the recommendations contained in the preliminary design. Some of these recommendations are summarized in the following.

Prevailing temperature regimes favor use of silver iodide, the most commonly used glaciogenic seeding agent, as the most effective seeding material. Evaluation of representative atmospheric (weather balloon) soundings, which document the vertical structure of the winter storm environment, suggests that effective seeding can frequently be accomplished using ground-based silver iodide nuclei generators. The data also show that in 57–58% of the seedable storm periods manually operated generators at lower elevations (the lowest cost release method) can be effective. Recall that the seedable events were estimated to only be 37 to 38% of the total number of storm periods that were analyzed. The manual generator seeding method has been used for decades to good effect on a seeding program for the Thomas and Smiths Forks located in southeastern Idaho and southwestern Wyoming from the 1950's through the mid-1980's (Griffith et al. 1983) as well as in various mountainous target areas in Utah from the 1970's to the present (Griffith et al. 2009). Recommended ground based generator locations are in the foothills and near the mouths of canyons. The recommended "core" operational program design, therefore, incorporates this method as its foundation. A network of about seventeen sites for the north area and twenty-three sites for the east area is recommended. Given the relatively narrow mountain barriers in the target area, use of a fast-acting silver iodide solution formulation is recommended.

Atmospheric temperature inversions could inhibit the vertical transport of seeding materials from lower elevations to the in-cloud supercooled liquid water regions over the upwind barrier slopes in some of the storm periods. Inversions were identified and documented in analysis of atmospheric soundings (NWS Boise and Salt Lake) taken during storm periods. During seedable situations these conditions were indicated to occur relatively infrequently. This factor plus the narrow width of the target area mountain barriers resulted in the recommendation that remotely controlled ground based generators not be considered for this program. Remote locations could potentially result in the release of seeding material above the inversions but the narrow barriers would not allow much time for the growth of ice crystals into snowflakes that could fall in the intended target areas. In addition to these factors, analyses described in Section 5.1 indicate that remote generators would only add less than a 1% increase in precipitation. An initial winter season of project area-specific rawinsonde measurements has been recommended, to allow closer consideration of the atmospheric stability and seeding material transport issues as they relate to the project design.

Airborne seeding with silver iodide may be conducted when the temperatures near the mountain crest height are too warm for silver iodide released from ground-based sites to be effective. Airborne seeding could also be effective in conditions where there are low-level atmospheric inversions. Assuming the ability to fly safely in the areas upwind of the intended target area, a seeding aircraft could be flown at a temperature level appropriate for near instantaneous activation of the silver iodide nuclei. Data analysis indicates that the use of aircraft seeding would enable seeding of the remainder of the seedable storm periods not considered seedable by the manual generator method. This represents an additional 42-43% beyond the 57-58% that are considered to be effectively seeded using manually operated ground generators. If airborne seeding is to be conducted, it is recommended that turbine engine aircraft be used. This recommendation is based primarily on aircraft performance as it relates to safety considerations, given the airframe icing that occurs during seeding operations. From some analyses of the timing of the seedable events, it appears that one aircraft could seed a large majority of these events (i.e., two aircraft would not be required). Potential bases of operations for the aircraft include airports at Pocatello and Idaho Falls. A decision regarding inclusion of aircraft seeding in the program design can be made at the sponsor's discretion. This decision could be based upon a benefit/cost analysis of this option.

4.2 Supplemental Meteorological Measurements

One winter season of supplemental data collection specific to the program area is proposed prior to a decision being made as to whether the fully operational ESRBP seeding program should be implemented. Measurements would include program specific rawinsonde (balloon) soundings to better characterize the structure of the storm environment, especially levels below mountain crest height and associated low level stability from the surface to crest height. A strategically located ridge-top icing rate detector site would document the occurrence of supercooled liquid water. Microwave radiometer observations (typically vertically pointing) could be added to document the vapor and liquid water integrated through the entire atmosphere during the winter storms. Analysis of data from these systems would help fine-tune the preliminary operational design. Comparison of the ice detector records with the radiometer data will indicate the extent to which a permanent ice detector site would be helpful in real time operational cloud seeding decision-making.

4.3 Seeding Effectiveness Evaluation

Seasonal evaluations of the effectiveness of the cloud seeding program will be based on historical target and control techniques (target and control sites with the corresponding regression equations are provided in the final report). As an option, some snow chemistry analyses could be added to verify that silver above background levels is observed at various sampling points in the target areas. Control sites selected for use in the development of the historical target/control evaluation methodology were selected in an attempt to avoid any potential contamination from cloud seeding programs being conducted in the Payette and Boise River Basins located northeast and east of Boise.

4.4 Summarized Key Elements of the Recommended Preliminary Seeding Program Design

- The target area will be those areas in Bonneville, Clark, Fremont and Madison Counties that lie above 2.0 km (6,500 feet), which are tributary to the Snake River.

- The primary operational period will be November through March. Seeding operations could be effectively extended into April, especially if a seeding aircraft were used on the program, although ground based seeding would still be effective as well.

- Silver iodide would be the seeding agent.

- A "core program" of lower elevation ground based generators is recommended. This core program could be supplemented by a seeding aircraft equipped with acetone/silver iodide generators if the estimated benefits constitute an acceptable multiple of the estimated costs to utilize this additional seeding mode. The use of remotely controlled ground based generators does not appear to offer any significant advantages.

- One winter season of data collection is proposed prior to the beginning of a full operational ESRBP. Data would be collected via rawinsonde observations, icing rate meter observations and possibly radiometer observations of liquid and vapor and atmospheric inversions to verify some of the conclusions and assumptions contained in the preliminary design.

- The ESRBP would be operationally oriented, with the following goals: The stated goal of the program is to increase winter snowpack in the target areas to provide additional spring and summer streamflow and recharge underground aquifers at a favorable benefit/cost ratio, without the creation of any significant negative environmental impacts.

- Due to the operational nature of the proposed program, i.e., the interest in producing as much additional water as possible, the seeding decisions would not be randomized. In other words, all suitable seeding opportunities would be seeded appropriately. In addition, there would not be an ongoing research component built into the program (beyond the first season of specialized measurements which could be used to fine-tune the design if necessary), although "piggyback" research components could be added to the core operational program if interest and additional funding from other sources is present, for example, the type of research that resulted from write-in funding to the Bureau of Reclamation for the recent Weather Damage Mitigation Program.

- Evaluations of the effectiveness of the cloud seeding program would be based upon historical target and control techniques (target and control sites with corresponding regression equations are provided in the final report), and possibly some snow chemistry analyses verifying that silver above background levels is being observed at various sampling points in the target areas.

- Qualified/experienced meteorologists should direct the seeding operations.

5. POTENTIAL YIELD/BENEFITS

5.1 Estimated Increases in Precipitation

Analysis of the variability in storm temperature structure over the program areas for a five winter season period was performed and then applied in conjunction with cloud top temperature partitioned seeding results from a research program in Colorado, Climax I and II (Mielke *et al.* 1981, Hess 1974) to estimate the anticipated effects for the ESRBP. These increases were +25% for cloud top temperatures of –20 to -5^{0}C and +10% for cloud top temperatures of –25 to –21^0 C. In this analysis these estimated seeding effects were applied to the six-hour precipitation events that fell within these ranges during a multi-season period. An event was considered "seedable" if the estimated cloud top temperature during the six-hour event was $\geq$ -26^{0}C. The resulting percentage of "seedable" six-hour periods was 37% in the North Target Area and 38% in the East Target Area. Using these results, the multi-season average estimated increases for the North and East Target Areas were calculated for the ground and airborne seeding modes (remote generators were not included based upon the discussion in Section 4.1 and in the following paragraph). The determination of whether a six-hour event was deemed "seedable" by the three different seeding modes was based upon the following stratifications:

For lower elevation manually-operated silver iodide generators

1. The low-level atmospheric stability (surface to the 700 mb level) was neutral or slightly stable.
2. The 700 mb temperature was ≤ -5^0 C.

For higher elevation remotely-operated silver iodide generators

1. The low-level atmospheric stability was moderately or very stable
2. The 700 mb temperature was ≤ -5^0 C.

For aircraft silver iodide seeding

1. The 700 mb temperature was > -5^0 C.

These increases were then applied to the April 1st snow water contents to estimate the potential average increases in snow water contents. Tables 1 and 2 summarize this information.

For the North Target Area there was an estimated 3.0% increase using ground-based generators, a 0.7% increase using remote generators and an additional 1.8% increase using aircraft seeding yielding a combined total of 5.5%. For the East Target Area there was an estimated 3.9% increase using ground-based generators, a 0.5% increase using remote generators and an additional 3.2% increase using aircraft seeding yielding a combined total of 7.6%. Due to the small indicated increases (less than 1%) through the use of remote generators in both areas, the decision was made to recommend that aircraft seeding could be used to supplement a manually-operated ground-based generator program. As a consequence, those cases which were indicated to be seedable from remote generators were assumed to be covered by aircraft seeding, so the aircraft seeding percentages were increased taking this factor into account. Such results compare favorably with a review of the estimated results of several similar winter orographic seeding programs conducted in the western states, some for decades, supporting the potential for precipitation augmentation. These estimates are also supported by the published Capability Statement of the Weather Modification Association (2005), which states "research results tend to be consistent with evaluations of randomized experiments and a substantial and growing number of operational programs where 5% - 15% increases in seasonal precipitation have been consistently reported." A Capability Statement of the American Meteorological Society (AMS 1998) states in part regarding precipitation increases "There is considerable evidence that, under certain conditions, precipitation from supercooled orographic clouds can be increased with existing techniques. Statistical analyses of precipitation records from long-term projects indicate that seasonal increases on the order of 10% have been realized." The American Society of Civil Engineers supports and encourages development of atmospheric water (also known as weather modification or cloud seeding) for beneficial uses, and has published a standard and manual of professional practice for cloud seeding for the purpose of precipitation enhancement (ASCE 2004, 2006).

Table 1. Estimated Increases in April 1st Snow Water Content for the North Target Area Based on Estimated November – March Precipitation Increases for Storm Periods using Cloud Top Temperature Estimates. Values in cm and (in)

Site	Apr. 1 SWE	Total Incr (5.5%)	Ground (3.0%)	Remote (0.7%)	Air (1.8%)
Big Springs SC	49.0 (19.3)	2.69 (1.06)	1.47 (0.58)	0.35 (0.14)	0.89 (0.35)
Camp Creek SC	24.9 (9.8)	1.37 (0.54)	0.74 (0.29)	0.18 (0.07)	0.46 (0.18)
Crab Creek*	41.7 (16.4)	2.29 (0.90)	1.24 (0.49)	0.28 (0.11)	0.76 (0.30)
Irving Creek SC	14.5 (5.7)	0.79 (0.31)	0.43 (0.17)	0.10 (0.04)	0.25 (0.10)
Island Park*	39.9 (15.7)	2.18 (0.86)	1.19 (0.47)	0.28 (0.11)	0.71 (0.28)
Latham Springs SC	83.8 (33.0)	4.62 (1.82)	2.81 (0.99)	0.58 (0.23)	1.50 (0.59)
Lucky Dog SC	64.0 (25.2)	3.53 (1.39)	1.93 (0.76)	0.46 (0.18)	1.14 (0.45)
Valley View SC	39.1 (15.4)	2.16 (0.85)	1.17 (0.46)	0.28 (0.11)	0.71 (0.28)
Webber Creek SC	5.0 (5.9)	0.81 (0.32)	0.46 (0.18)	0.10 (0.04)	0.28 (0.11)
White Elephant*	4.2 (29.2)	4.09 (1.61)	2.24 (0.88)	0.51 (0.20)	1.35 (0.53)
Mean	**44.7 (17.6)**	**2.46 (0.97)**	**1.35 (0.53)**	**0.30 (0.12)**	**0.81 (0.32)**

* SNOTEL site

Table 2. Estimated Increases in April 1st Snow Water Content for the East Target Area Based on Estimated November – March Precipitation Increases for Storm Periods using Cloud Top Temperature Estimates. Values in cm and (in)

Site	Apr 1 SWE	Total Incr (7.6%)	Ground (3.9%)	Remote (0.5%)	Air (3.2%)
Allen Ranch	26.7 (10.5)	2.03 (0.80)	1.04 (0.41)	0.13 (0.05)	0.86 (0.34)
Fall Creek	18.5 (7.3)	1.40 (0.55)	0.71 (0.28)	0.10 (0.04)	0.58 (0.23)
Lava Creek	39.9 (15.7)	3.02 (1.19)	1.55 (0.61)	0.20 (0.08)	1.27 (0.50)
Packsaddle Spring	74.4 (29.3)	5.66 (2.23)	2.90 (1.14)	0.38 (0.15)	2.39 (0.94)
Pine Creek Pass*	40.6 (16.0)	3.10 (1.22)	1.57 (0.62)	0.20 (0.08)	1.30 (0.51)
Somsen Ranch	34.0 (13.4)	2.59 (1.02)	1.32 (0.52)	0.20 (0.07)	1.09 (0.43)
State Line	38.1 (15.0)	2.90 (1.14)	1.50 (0.59)	0.20 (0.08)	1.24 (0.48)
Mean	**38.9 (15.3)**	**2.95 (1.16)**	**1.52 (0.60)**	**0.20 (0.08)**	**1.24 (0.49)**

* SNOTEL site

5.2 Estimated Increases in Streamflow

The estimated increases in precipitation were used to estimate the potential average increases in March through July surface runoff from the two target areas. These analyses were conducted for the eight sub-basins shown in Figure 2. Estimates were made of conservative and liberal levels (minimum and maximum increases in average March through July surface runoff from six of the eight sub-basins. The first two sub-basins (numbers 1 and 2 in Figure 2) have no surface water connection to the Snake River. There is, however, some local use of streamflow from these two sub-basins as well as some ground water recharge derived from these sub-basins. Some of the streamflow from sub-basins 1 and 2 is absorbed by the underlying porous volcanic rock common throughout eastern Idaho. Water from these porous underground aquifers emerges in the form of large springs along the banks of the Snake River in the area known as the "Thousand Springs" located northwest of Twin Falls.

Estimates for all the sub-basins (excluding #1-2) were summed, yielding a minimum - maximum range of estimated streamflow increases for the entire drainage area for each seeding mode for an average March through July period. The only sub-basin with estimates of this type in the North Target Area is #3, with all the other sub-basins included in this summation being in the East Target Area. Total estimated average March through July runoff increases due to seeding are estimated to be between 58,800 – 97,500 acre-feet for ground-based seeding only, and between about 110,500 – 188,200 acre-feet for ground plus aircraft seeding. Basin #3 estimates range from 17,800 - 24,400 acre-feet for ground-based seeding only and from

32,700 – 45,100 acre-feet for ground plus aircraft seeding, with the remainder of the total increases being derived from the East Target Area.

Table 3 summarizes the results for each sub-basin, as well as the total increases estimates. Table 4 summarizes the totals for the North Target Area, East Target Area, and the North and East Areas combined.

The midpoint of the minimum - maximum range of total (combined North and East Target Areas) estimated average March through July streamflow increases for the North Target Area is 21,100 acre-feet for ground-based seeding only, and 38,900 acre-feet for ground plus aircraft seeding.

The midpoint of the minimum - maximum range of total estimated average March through July streamflow increases for the East Target Area is 57,050 acre-feet for ground-based seeding only, and 110,450 acre-feet for ground plus aircraft seeding.

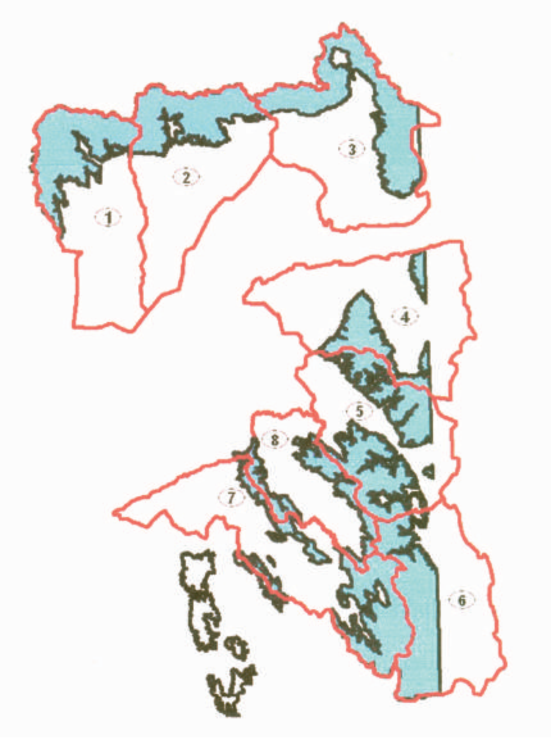

Figure 2. North and East Target Area Stream Sub-basins

Table 3. Summary of Sub-Basin and Estimated Total Streamflow Increases

Sub-basin	Base Streamflow (AF)	Ground-Based Increase (AF)		Aircraft Increase AF		Ground + Aircraft Increase (AF)	
		Min	Max	Min	Max	Min	Max
1 (Medicine Lodge)	61,115*	1,800*	NA	1600*	NA	3,400*	NA
2 (Beaver – Camas)	120,529*	3,600*	NA	3000*	NA	6,600*	NA
3 (Upper Henrys)	594,046	17,800	24,400	14,900	20,700	32,700	45,100
4 (Teton)	145,627	5,700	8,600	5,400	8,100	11,100	16,700
5 (Palisades)	485,903	19,000	34,000	17,900	32,600	36,900	66,600
6 (Salt River)	147,085	5,700	12,100	5,500	11,700	11,200	23,800
7 (Blackfoot)	209,757	8,200	13,400	7,700	13,000	15,900	26,400
8 (Willow Creek)	61,212	2,400	5,000	300	4,600	2,700	9,600
Total (excl. #1 and 2)	1,643,630	58,800	97,500	51,700	90,700	110,500	188,200

* Considered only local not regional streamflow and ground water re-charge; not included in totals

Table 4. Summary of North and East Target Areas Estimated Average Streamflow Increases

Target Area	Ground-Based only		Ground + Aircraft	
	Min	Max	Min	Max
Northern (Basin #3)	17,800	24,400	32,700	45,100
Eastern	41,000	73,100	77,800	143,100
Total	58,800	97,500	110,500	188,200

The midpoint of the minimum - maximum range of total (North and East Target Areas) estimated March through July streamflow increases is 78,150 acre-feet (4.8%) for ground-based seeding only, and 149,350 (9.1%) for ground plus aircraft seeding. Given all of the assumptions that have gone into the development of estimates of increases in streamflow due to cloud seeding, these values are perhaps most representative of the average increases in March through July streamflow that might be expected from the conduct of an operational cloud seeding program in the two proposed target areas. For comparison purposes, these estimated average streamflow values would correspond to average increases in April 1st snow water content of approximately 3.5% for ground based seeding and 6.6% increases in April 1st snow water content for ground plus aircraft seeding.

Table 4 indicates that higher amounts of streamflow may be produced from the East Target Area when compared with the North Target Area although there are some benefits in terms of enhanced local streamflow and ground water recharge from seeding in the North Target Area that are not accounted for in this comparison.

6. BENEFIT AND COST CONSIDERATIONS

Estimated increases in runoff for a "core program" using only manually operated silver iodide generators were calculated along with the attendant estimated costs. The estimated additional runoff and attendant costs were then calculated for the addition of one cloud seeding aircraft to the "core program." Preliminary estimates of the potential increase in runoff from the North and East Target Areas separately and the combination of the two target areas and associated costs are summarized in Tables 5 through 7. The combined costs in Table 7 contain some cost savings for the core program if operations are conducted for both areas. In a similar manner for the ground seeding plus aircraft-seeding mode it is assumed that the costs of one seeding aircraft are divided between the two program areas.

The estimated cost per acre-foot of additional runoff ranges from $2.77 to $14.99 depending upon the target area and method(s) of seeding used. It is beyond the scope of this report to estimate the potential value of the increased runoff. Should such an analysis be attempted, estimates of benefit/cost ratios could be calculated. The additional water would benefit regional water supplies for agricultural and municipal use as well as hydroelectric power generation. If the value of the additional water volume to recreation, fisheries, tourism, threatened and endangered species, and downstream uses could be quantified and included, the projected value would be even greater.

<u>The values provided in Tables 5 through 7 are for an average water year</u>**.** Costs per acre-foot would decline in above normal water years and increase in below normal water years. These values are also for the mid-point values between calculated minimum and maximum increases in streamflow; similar costs could be calculated for the minimum and maximum estimated streamflow increases using the data provided in this section.

7. CONCLUDING REMARKS

This feasibility/design study has determined that an effective winter cloud seeding program can be established and operated for a portion of the Eastern Snake River Basin located in eastern Idaho. The program has the potential to enhance the snowpack by 5.5 - 7.6% during an average winter season, with the resultant additional average March through July runoff estimated to range from 78,150 to 149,350 acre-feet depending upon whether ground seeding only or ground seeding plus airborne seeding is utilized.

The estimated costs to achieve these increases in March through July combined area streamflow are $2.95 to $4.51 per acre-foot. Conduct of the proposed single winter season of area-specific meteorological monitoring prior to the start of operational seeding would serve to refine the preliminary program design. The estimated cost of this one season of observations is $243,750.

A review was conducted of the potential environmental impacts of the proposed program that included consideration of downwind effects, toxicity of seeding agents, avalanches, snow removal, and previous environmental impact studies. This review concluded that no significant environmental impacts would occur through implementation of this program.

The operation of a joint program between the East Target Area identified in this study and adjacent mountain ranges in western Wyoming should be considered. North American Weather Consultants conducted a similar design/feasibility study for the Salt and Wyoming Ranges in western Wyoming (Griffith *et al.* 2007). It was concluded that an operational winter cloud seeding program was feasible for those Wyoming Mountain Ranges. There could be some economy of scale and other mutual benefits in developing an inter-state program covering the East Target Area in Idaho and the Salt and Wyoming Ranges in Wyoming.

Table 5. Estimated Average Costs to Produce Additional March – July Streamflow, North Target Area

	Core Program (CP)	CP Plus Aircraft
Ave. Cost to Produce Extra Water	$139,775	$583,175
Ave. Water Year Streamflow Increase	21,100	38,900
Cost Per Acre-foot	$6.62	$14.99

Table 6. Estimated Average Costs to Produce Additional March – July Streamflow, East Target Area

	Core Program (CP)	CP Plus Aircraft
Ave. Cost to Produce Extra Water	$158,275	$601,675
Ave. Water Year Streamflow Increase	57,050	110,450
Cost Per Acre-foot	$2.77	$5.45

Table 7. Estimated Average Costs to Produce Additional March – July Streamflow, Combined North and East Target Areas

	Core Program (CP)	CP Plus Aircraft
Ave. Cost to Produce Extra Water	$230,280	$673,680
Ave. Water Year Streamflow Increase	78,150	149,350
Cost Per Acre-foot	$2.95	$4.51

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CLOUD SEEDING AND THE RAPID CITY FLOOD OF 1972

Arnett Dennis*

Rapid City, South Dakota

Summary

Rapid City, South Dakota is built along the banks of Rapid Creek, where it emerges from the eastern side of the Black Hills. In 1972 its population was approximately 60,000. On the night of June 9-10 of that year, torrential rain upstream of Rapid City caused the creek to overflow its banks and devastate adjacent areas of the city.

That summer the Institute of Atmospheric Sciences (IAS) of the South Dakota School of Mines and Technology (Mines) was conducting research into cloud seeding under a contract with the U.S. Bureau of Reclamation (Reclamation), as a part of Reclamation's Project Skywater. The research project, called Cloud Catcher, was directed from a radar site located near the Rapid City Regional Airport. The project was randomized, and used a floating-target design. Each test case consisted of a cluster of convective clouds tracked by radar.

As word got around that the IAS had conducted two experimental cloud seeding flights on June 9, many persons raised the possibility that the seeding might have contributed to the severity of the flood. Others disagreed, arguing that the seeding agent used on that day, which was ordinary table salt, could never have produced such a devastating storm. The controversy was fanned by inflammatory columns in the popular press. An extreme example of such writing was an article in the *National Tattler* of December 24, 1972, titled "Govt. weather tampering is causing world floods." Because of the threat of law suits, IAS personnel were not free to rebut such misleading statements until all legal issues were resolved, which took until 1982.

The present author has written a detailed account of the controversy, which involved the appointment of a Board of Inquiry by the State of South Dakota, newspaper columns, letters to editors, administrative claims against Reclamation, and legal actions that extended to 1982. The detailed account is available on the web sites of the IAS and of the Weather Modification Association (WMA). http://www.ias.sdsmt.edu and http://www.weathermodification.org/publication_repository.htm.

The account provides a brief description of the convective clouds which bring rain to the Black Hills in early summer, and continues with a discussion of the possible effects of seeding clouds with finely powdered sodium chloride (salt). Next comes a description of the weather situation as it developed on that day, which is reproduced here in abbreviated form.

The general weather pattern on June 9 featured a ridge of high pressure aloft over the Great Plains, and an upper low off the West Coast. The Rapid City radiosonde showed a dry layer above a moist layer next to the ground. Winds were light southeasterly near the ground, veering to light southwesterly aloft. Use of a numerical cloud model showed that formation of showers was unlikely as long as the dry layer persisted. However, the 500-mb prognostic charts indicated that a small disturbance approaching from the southwest would likely moisten the air mass enough to allow the formation of showers and thunderstorms by late afternoon.

As showers did develop during the afternoon, two cloud seeding flights were conducted. The first was directed at clouds to the northwest of Rapid City. The cloud-seeding aircraft, which was loaded with about 350 lb of salt, took off at 2:54 pm, and a test case was declared as soon as it reached the shower area. The crew released powdered salt on several seeding passes in updrafts below non-precipitating clouds close to the existing showers until 3:43 pm. The aircraft landed at 3:49 pm (all times MDT).

The second seeding mission was directed at clouds south of Rapid City. The crew seeded non-precipitating clouds close to existing showers between 4:58 and 5:37 pm; the seeding runs began while the test case was centered about 25 miles southeast of Fairburn, and ended close to Fairburn itself. The aircraft landed at 5:53 pm.

**Corresponding author*: Dr. Arnett Dennis, 3931 Ridgemoor Drive, Rapid City, SD 57702; e-mail asdennis@rushmore.com

The radar returns showed the largest cloud in the second test case developing into a tall thunderstorm as it approached the eastern foothills to affect the Battle Creek basin, which is south of the Rapid Creek basin. At 5:45 pm a computerized radar display showed that the strongest cell within the test case was in the vicinity of Fairburn, had an echo top just above 50,000 ft, and showed a maximum reflectivity factor of 68 dbZ, which suggested a rainfall rate of several inches per hour. It was not possible to be precise, because hail shafts can also produce very high reflectivity factors. This group of clouds moved very rapidly northwestward.

Meanwhile, heavy rain had developed over parts of the northern Black Hills, leading to several telephone conversations between Cloud Catcher's operations director at the IAS radar site and National Weather Service (NWS) staff on duty at the Rapid City Regional Airport. At 6:30 pm the operations director described to them a band of heavy rain extending well over 50 miles from north to south along the east side of the Black Hills. The NWS forecasters decided that a flood warning was required for the northern Black Hills. After clearing their decision with a hydrologic center in Sioux City, Iowa, they released the flood warning to the media at 7:15 pm. They soon extended the warning to include the central Black Hills as well, with specific mention of possible flooding on Rapid Creek.

By that time rain had been falling for an hour or so around Pactola Dam, which is on Rapid Creek some 15 miles upstream of Rapid City, but the city, and much of the drainage area between the dam and the city, received only a few sprinkles during the early evening. Shortly after 7 pm a thunderstorm moving northwestward brushed the southwest side of the city, dropping a moderate amount of rain there, and torrential rain in the Rapid Creek basin a few miles upstream. Other large, rapidly moving convective clouds followed it into the hills, and merged into an almost stationary mesoscale convective system (MCS) a few miles to the west. Because most of the clouds joining the MCS dropped little or no rainfall until they had moved beyond the city, most people in town were unaware that places only a few miles to the west were being flooded.

The flood crest reached the west side of Rapid City before 11 pm, and the peak flow in the city occurred about midnight. The U.S. Geological Survey later estimated that it exceeded 50,000 cubic feet per second (cfs), about 100 times the normal flow of the creek, and roughly four times the estimated peak flow of the second biggest flood on Rapid Creek, which occurred in 1907.

On June 13 the director of the IAS, Dr. Richard Schleusener, made a formal report to the office of the governor of South Dakota through Dr. Harvey Fraser, the president of Mines, denying allegations that cloud seeding had caused or augmented the flood. Schleusener emphasized that the storms around and below Pactola Dam had not been seeded. He also stated that, ".. it is ridiculous to think that with a few hundred pounds of finely ground table salt disbursed from a single airplane we could cause twelve inches of rain in a few hours." The governor, Richard Kneip, released a statement in which he quoted some of Schleusener's language, and asked people to avoid spreading rumors. Long-time critics of cloud seeders immediately denounced Schleusener's statement as self-serving.

Interior and Reclamation officials in Washington were concerned with the possibility of legal complications arising from Reclamation's sponsorship of the June 9 cloud seeding flights. Two Reclamation scientists came to Rapid City to interview IAS staff about the events of June 9. IAS personnel involved in the experiments met with them to go over the available data. They looked at time-lapse radar data, logs from the seeding aircraft, and the general weather situation of June 9. They were particularly interested in the estimates of the total rainfall from the test cases, which were already available from the radar data recorded and analyzed by the online minicomputer. The first case of June 9 dropped about 1500 acre-feet of rain, and the second case dropped about 4500 acre-feet.

Preliminary estimates of the total rainfall in the Black Hills on June 9 were coming in between 400,000 and 500,000 acre-feet. Therefore the Reclamation scientists concluded that the 6000 acre-feet measured in the two test cases combined did not contribute significantly to the rainfall totals for that day. They also concluded that the seeding did not cause the flooding rains that followed a short time later. Their findings were reported through channels.

State officials in the Division of Weather Modification (DWM) and elsewhere decided soon after Gov. Kneip's press release of June 13 that an outside review was needed. The governor therefore appointed a three-person Board of Inquiry (Board) to review the events of June 9, and submit a report. The Board was chaired by Dr. Pierre St. Amand, a geophysicist of the Naval Ordnance Test Station in California; the other two members were Robert Elliott, the long-time president of North American Weather Consultants, and Ray Jay Davis, a lawyer who was active in the Weather Modification Association (WMA).

The committee members decided that they should have a report ready to present at the American Meteorological Society's (AMS) Third Conference on Weather Modification, which was set for the last week of June in Rapid City. Following the conclusion of the conference on June 29, many people stayed to hear St. Amand present the preliminary Board report on the impact of cloud seeding on the flood. The report was critical of the decision to launch a second seeding flight on June 9, but concluded that, "In the absence of seeding, the result would have been the same."

The paper covers the events mentioned above in detail, and also reviews the major contributions to the debate by critics. These include letters to the editor of the *Bulletin of the AMS* by Jack Reed; columns in the Denver Post and other newspapers by Dr. Peter Metzger, a biochemist from Boulder, Colorado; and an article by David Howell, which was published in *Environmental Action* and introduced into the Congressional Record in 1973.

Two flood survivors, and the heirs of several persons who had died in the flood, filed a total of six administrative claims with the U.S. Dept. of the Interior in 1974 seeking almost $4,000,000 in damages. The claims erroneously identified the June 9 cloud seeders as Reclamation employees. After the claims were denied, the heirs of five of the victims named in the claims filed a lawsuit (Lunsford vs. United States) in Federal court in June 1975 seeking $1,725,000 in damages. The suit alleged that cloud seeding by a Government contractor on June 9, 1972 had been conducted in a careless and reckless manner, and had contributed to the flooding of Rapid Creek.

Mines had an insurance policy covering damages due to seeding effects up to $2,000,000, and the U.S. Government was an additional named insured. A law firm in New York City was hired by the insurance company to direct the defense against the suit. The Federal Tort Claims Act allows suits against the Government for negligence on the part of its employees, but not for negligence on the part of contractor personnel. Recognizing that fact, the plaintiffs alleged that Reclamation's employees had been negligent, in that they failed to supervise the experiments properly. The plaintiffs also sought to have their suit classified as a class action. This move was a great threat to the Government, as it could have opened the door to claims for hundreds of millions of dollars in damages to persons not named in the suit. However, the request for classification as a class action was denied in 1976, and the denial was upheld on appeal. The lawyers defending the government moved for dismissal of the case. Following several court hearings and discovery proceedings regarding the terms of the contract between Reclamation and Mines, the suit was finally dismissed in 1982.

The issue of causation was never argued in court. The detailed account examines several suggested ways that cloud seeding might have influenced the storms of June 9, and finds them wanting. Essentially, the critics hypothesized that seeding intensified the storms, and pointed out that no one can prove otherwise. Their explanations of how salt particles could intensify the storms lack detail, and, in some cases, involve errors about basic cloud physics.

The account concludes with a brief discussion of the problems involved in the forecasting of flash floods in general, and of the Rapid City flood in particular. One source of information that might have proved useful on June 9, if available in real time, was the pibal data collected as a part of Cloud Catcher. These data showed a mid-level jet blowing from the southeast into the southern Black Hills during the afternoon, with peak winds near 75 mph at 15,000 ft above sea level. Such unusual winds are a partial explanation for the record-breaking rainfall rates observed along the east side of the Black Hills. A regional scale atmospheric model has been used to simulate the June 9 storm; the results suggest that such models may eventually prove useful in predicting the onset of flooding rains over mountainous terrain.

In Memoriam

Joanne Simpson

1923-2010

PERSONAL REMEMBRANCES OF JOANNE SIMPSON AND HER CONTRIBUTIONS TO WEATHER MODIFICATION

William Woodley

After a long, incredibly-productive career as a scientist, Dr. Joanne Simpson has died. This is not a time to be sad. It is a time to celebrate who Joanne was and what she did for us personally and for our science. I do that here with respect to her interests and contributions to weather modification. This is not intended as a formal review of her accomplishments in weather modification.

I first met Joanne in 1962 when Joe Golden and I were undergraduate students at the University of California at Los Angeles (UCLA) majoring in meteorology. Joanne was on the faculty and was known as Dr. Joanne Malkus by virtue of her marriage to Dr. Wilhelm Malkus, who also was on the UCLA faculty. Being engaged in the continuing battle for the rightful place of women in science and meteorology, I found Joanne a tough, no-nonsense, intimidating professor. She was the first woman Ph.D. in meteorology, and I was somewhat awed by her. Later I learned that if I worked hard in her courses and showed genuine interest in meteorology, Joanne was very supportive and protective. In some respects then, and later, I realized that Joanne was much like a lioness protecting her cubs. It was important to have her on your side.

During the latter part of her tenure at UCLA, Joanne Malkus, having shown great expertise in tropical meteorology, cumulus clouds, and hurricanes, was heavily involved in studies addressing the possibility of hurricane mitigation through glaciogenic cloud seeding, an idea that had been tested initially in Project Cirrus in 1947. The seeding of hurricane Esther in 1961 led to the formation of Project Stormfury with Robert H. Simpson as its initial Director. By 1963 Joanne Malkus and Robert Simpson had married and with the seeding of hurricane Beulah Dr. Joanne Simpson became Director of Project Stormfury in the Experimental Meteorology Branch (EMB) in the Environmental Science Services Administration (ESSA). Joanne and Bob had worked together on the Stormfury seeding hypothesis that underwent at least two iterations. These involved the glaciogenic seeding of strong convective (”Hot Towers”) towers near the storm core, either within or just outside the eyewall, to perturb the pressure and wind fields and force the hurricane eyewall to reorganize at a larger radius, leading to decreases of the maximum winds. These hypotheses were predicated on the existence of supercooled cloud water in the strong convective cloud towers to fuel the needed seeding-induced releases of latent heat that would stimulate cloud growth. Bob Simpson was the strongest proponent of its existence.

During Joanne Simpson’s tenure as Director of Project Stormfury she focused on the effects of on-top glaciogenic seeding of vigorous tropical cumulus clouds, reasoning that it would be easier to interpret the effects of seeding within the hurricane by experimenting first on its convective building-blocks. Non-randomized and randomized seedings were conducted over the Caribbean Sea in 1963 and 1965, respectively. The analyses indicated that the seeding with silver iodide rockets had been effective in glaciating the clouds and increasing their top heights and that Joanne’s simple one-dimensional cloud model showed skill in predicting the growth behaviors of the seeded and non-seeded clouds. The paper by Simpson, Brier and Simpson in the *Journal of Atmospheric Sciences* (Simpson et al., 1967) describing these results is a classic, winning the three authors the Department of Commerce Distinguished Authorship Award. I think it was Joanne’s best weather mod paper because it had a huge impact on weather modification for years to come. [Simpson, J., G.W. Brier and R.H. Simpson, 1967: Stormfury Cumulus seeding experiment 1965: Statistical analyses and main results. *J. Atmos. Sci.*, **24,** 508-521]**.** This is the only reference that will be given in this testimonial.

The Stormfury cumulus experiments were a turning point in Joanne’s career. Although the core Stormfury seeding experiment presented an exciting scientific challenge, the program itself was mired in red tape and government regulations that drove Joanne up the wall. Natural hurricane variability and the uncertainty regarding the existence of supercooled liquid water in hurricane clouds only served to make things more difficult. Listening to Joanne interact with top Department of Commerce (DOC) officials would have been worth the price of admission. Joanne did not tolerate incompetence and fools, well and there was a lot of that at ESSA/DOC. If it were not for Bob Simpson who perpetually ran interference for her and calmed the waters, Joanne would not have lasted more than six months as Director of Stormfury. As it was, she resigned her Stormfury Directorship in 1967 after about four years at the helm, planning to move her group (Experimental Meteorology Branch) and research interests in what she later called “dynamic cloud seeding” to Miami, Florida under what was ultimately called the Experimental Meteorology Laboratory (EML). She too was excited about the matters addressed in her seminal, award-winning paper. Bob Simpson, who was a major meteorological force in his own right, moved with Joanne to Miami and became the Director of the National Hurricane Center. The center of gravity for hurricane interests, activity, and leadership had shifted to the south from Washington, D.C.

I played a significant role in that move and in the subsequent activity. At the time of the move, EMB in Washington, D.C. consisted of Joanne Simpson, four support personnel, Victor Wiggert (deceased), Ron Holle and myself, with Robert (Rob) Sax in the wings as a student employee. Joanne had been quietly putting together a cumulus research group for some time and we were its initial members. Ron Holle, Joe Golden, and I had received our M.S. Degrees in Meteorology from Florida State University in 1966 and Joe and I had decided to go on for the Ph.D. To my good fortune, Joanne recruited me with a full-time government position to work with her on dynamic seeding concepts, especially to determine for my Ph.D. dissertation what effect on-top glaciogenic seeding had on precipitation as estimated by land-based radar. I continued as a graduate student at Florida State University (FSU) with Dr. Noel LaSeur as my major professor, but Joanne Simpson was my de facto major professor. Such a life! I considered myself to be very fortunate.

Despite my great position, Joanne almost had to fire me because of another woman. I had been dating a young woman at FSU named Marlene Kingirski for some time, but things had gotten out of hand by the fall of 1967. My family inherited a twin-engine Piper Apache aircraft when my father died in 1962 and I was the only person in the family who knew how to fly it. I was using the aircraft to fly back and forth from California to Florida. I was probably the only graduate student at FSU who had his own aircraft. After I moved to Miami, Marlene remained in Tallahassee to continue her undergraduate studies in education. I was using the aircraft every two weeks, weather permitting, to fly to Tallahassee on Friday evening to be with Marlene, returning to Miami on Sunday evening. This worked fine for a while until I began to invent reasons why I could not make it back to Miami on Sunday night. I missed a number of key Monday morning meetings and my good friend and EML colleague Ron Holle was beside himself because of my irresponsible actions. As a woman of the world who understood the totality of life, Joanne Simpson was no dummy with respect to my interactions with Marlene and she tried to be understanding. However, after yet another instance of my being absent on Monday morning, Joanne called me into her office and really chewed me out for my behavior. I thought I was a goner for sure. I felt really bad because I was so personally indebted to her.

As it turned out, I changed my ways and acted more responsibly. It helped that Marlene and I were married on March 23, 1968 (and have been married for 42 years), and my flights to Tallahassee ended. Marlene joined me in Miami where she began intern teaching and I made plans for a randomized study of individually seeded clouds over South Florida. Joanne showed me a lot of respect and gave me the room that I needed to design, execute and evaluate these experiments in 1968 and in 1970. My focus was to be on the effect of glaciogenic seeding, as practiced over the Caribbean, on cloud heights and rainfall. At my age of 26 I thought I knew everything and I thought subliminally that seeding had already been shown to make bigger clouds and bigger clouds produce more rainfall. Therefore, seeding over South Florida was going to make more rain. It took me a few years to realize that it was more complicated than this.

Meanwhile, Joanne continued to recruit talented people for our Experimental Meteorology Laboratory, bringing in Al Miller, Bill Cotton, Roger Pielke, and Rob Sax and later John Cunning and Cecilia Girz Griffith. There were, of course, many students from high school and from colleges. Each individual made significant scientific contributions to the group effort.

Working for Joanne was a great experience at a time when weather modification was in vogue nationally. It may sound corny, but we were more of a family than a working group with a minimum of internal squabbling, although we did have occasional squabbles with a few individuals in the sister National Hurricane Research Laboratory concerning the allocation of resources. It was pretty much us against the world as we strove to make gains in what we viewed as a new area of weather mod investigation, led by a person who was fiercely dedicated to her research and to her people. I liked working for Joanne. It was challenging and exciting --- the way I think research should be conducted in a government laboratory. Each day was potentially an adventure with Joanne Simpson around.

Joanne Simpson was a workaholic, yet she and Bob managed to do more than just work. They had a real zest for life, frequently engaging in sailing and in extensive travel. Joanne also engaged in ballet and in reading mystery novels. Unfortunately, she had a habit of coming to work regardless of her physical state. She shared her germs with us with impunity and we all ran for cover when she arrived sick for work lest we get contaminated. After exposure to her work, however, Joanne was a new person and her sick symptoms seemed to disappear. Her work had healed her! Her physical maladies receded into the background as she became engrossed in her work.

Joanne and Bob Simpson had a good sense of humor and Joe Golden and I could not resist lampooning them for their foibles, as we did for many other individuals with whom we had contact. Certainly we were fair game as well. Joe and I had made a habit of writing satirical skits put to music and sound effects and then teaming up with the young meteorologists of the day who were willing to throw caution to the wind in presenting the skit to a large audience, consisting of the very individuals who were being lampooned in the skit. We did it once as undergraduates at UCLA and twice in the Department of Meteorology at Florida State University as graduate students and twice in Miami as young professionals with members of EML, NHRL, NHC and the University of Miami in attendance. We have the audio for most of the skits and some video of the later skits. All of what we did was in fun and we got away with it because what we presented was so gloriously absurd that it was difficult to separate fact from fiction.

Joanne and Bob Simpson were the objects of our teasing in both Miami skits and they laughed along with everyone else. In one of the skits we introduced “Alphie” the magic forecasting roach, who was the main hurricane track-forecasting tool at the National Hurricane Center. In another we had a woman wearing a tutu representing Joanne Simpson brought to her office on a stretcher and on an IV drip, looking as though she should be in the hospital. After brief exposure to her work environment and her work notes, however, Joanne showed a remarkable recovery as she went to work. Bob Simpson roared in laughter at this, but Joanne could only muster a grin. We had come pretty close to the edge. By the way, the person playing Joanne Simpson was Susie Anthes. Such skit participation was typical because of the good interpersonal chemistry that existed among the up-and-coming employees and their spouses at the time.

The Florida single cloud experiments in 1968 and 1970 went as I had expected in showing statistically significant increases in cloud height and rain volume, although the results were not as clean as I had led myself to believe. They were adequate for my Ph.D. and acceptable for publication. As it turns out, others were understandably more skeptical.

It was at this point that I made the biggest mistake of my professional career to date by promoting the conduct of a randomized area seeding experiment that came to be known as the Florida Area Cumulus Experiment (FACE). In retrospect, with the benefit of additional knowledge, this was a very naive action on my part. Again, I thought that if seeding increased the rainfall from individual clouds, it ought to increase the rainfall over an area by seeding groups of convective clouds. I wrote the design and Joanne went along with it, but she was not as enthused as I thought she might be. My biggest mistakes were defining a huge area for operations and evaluation covering 13,000 km^2 and then failing to estimate how many case days would be needed to establish seeding efficacy. Thus, if blame is to be assigned for the FACE effort, the blame is mine and not Joanne’s. Regardless of credit or blame, FACE ultimately had repercussions in weather modification throughout the world.

FACE was an ambitious effort and we did a good job in conducting the experiments during what came to be known as FACE-1 in the years 1970 through 1976, with 1973 through 1976 being the most intensive seasons. Randomized seeding was done in all seasons, but detailed cloud microphysical measurements with multiple aircraft and observations from the FACE mesonetwork, radar, and satellite observations, and model simulations were made in FACE 1973 in recognition that better understanding of Florida convective systems would be necessary if FACE was to be successful. It could not be a “black box” experiment.

All of this did not happen by magic. It took a substantial investment by the Environmental Research Laboratories to make it happen and Joanne Simpson was put into the position once again to have to battle for the funds, in an increasingly austere fiscal environment. Joanne did not like battling for funds. By 1974 she was looking elsewhere for career satisfaction, and she announced that she was leaving government service. She had tired of the usual government red tape and our continuing battle for research funds. Further, Joanne was becoming nostalgic about returning to university life at the same time she was being recruited for a prestigious position at the University of Virginia. We sent her off to that position in the spring of 1974 following a spectacular nighttime tropical luau on Key Biscayne with coconut palms and wafting tropical breezes under a full moon. Once she and Bob were in Charlottesville, VA, Joanne took up her faculty position and they joined with Dr. Michael Garstang to form Simpson Weather Associates (SWA), which is a going concern today.

Although Joanne had left Miami, she did not go "cold turkey" with respect to FACE, offering advice to me and continuing to work on FACE analyses, especially the application of Bayesian statistics to the analyses of the FACE experiments. With the passage of time, however, Joanne became less involved as she focused on her new interests at the University of Virginia. By 1979 she had left the University to begin a long illustrious productive career with NASA at the Goddard Space Flight Laboratory where she developed new mentoring relationships with young scientists, most notably Dr. Daniel Rosenfeld, who would prove to be her bridge back to the FACE experiments. Joanne had a knack for identifying and supporting talented people. Meanwhile Bob Simpson put his energies into Simpson Weather Associates.

The FACE effort had arrived at a crossroads by 1976. Although the program had gone well and suggested positive effects of rain-enhancement seeding, none of the FACE crew felt that we had run the definitive experiment. The question was what to do next. One group, led by Dr. John Flueck (deceased), one of the statistical advisors to FACE, recommended that we run the definitive confirmatory experiment to be known as FACE-2. The other group felt that we should get back to basics with observations and numerical model simulations to increase our understanding of convective processes under the banner of a new effort called the Cumulus Dynamics and Microphysics Program (CDMP). When all was said and done, those promoting the confirmatory experiment had won the day because the supplemental money necessary to fund CDMP did not exist. This decision did not sit well with prominent outside advisors to FACE, most notably Dr. Bernie Silverman, and with Sax, Cotton and Pielke within the FACE group, who eventually left for greener professional pastures. Joanne Simpson had seen this coming several years earlier and it is one of the reasons that she left government service for the University of Virginia.

Although FACE-2 provided a "textbook" example of how to design, conduct, and evaluate a confirmatory cloud seeding experiment for which I am very proud, it did not confirm FACE-1 as many had warned would be the case. Some viewed this as a failure of the FACE effort, but FACE was much more than a "black-box" seeding experiment. It ultimately produced 111 formal publications plus an additional 162 non-refereed reports and conference papers. FACE provided the stimulus for my redesign of the seeding effort to include a much smaller (2,000 km^2) floating test area for seeding and evaluation. FACE led to further testing of dynamic seeding concepts in Texas and Thailand in programs in which I played a leadership role in conjunction with Dr. Daniel Rosenfeld, with whom I have had a long productive scientific collaboration. None of this would have happened had Joanne Simpson not planted the initial seeds with Project Stormfury.

In concluding my remembrances of Joanne Simpson, I want to thank Bob Simpson for helping Joanne navigate the mine fields of life, helping her be all she wanted to be. When I first learned that Joanne and Bob were to be married, I thought privately that there was no way that these two talented but volatile people would be married for very long. I could not have been more wrong, considering that they were still together and in love nearly 45 years later when Joanne died. My testimony is for Joanne, but beneath it all, it is for Bob Simpson as well.

The world is a much better place for Joanne Simpson having lived. She was a great scientist and a visionary who pioneered the rightful role and place for women in science. She was a leader in many areas of scientific investigation, especially tropical meteorology and severe storms, and much of it had its start with her weather modification investigations. Joanne was an incredible mentor and defender of young scientists. Through all of this she still took the time to help me and many others with their career aspirations. I will be grateful for that the rest of my life. Joanne knew of my gratitude, but I never took the opportunity to put it all down on paper. Although I regret that I have done so for her posthumously, at least my testimony is there for her posterity and for Bob Simpson who was at the center of Joanne's life.

COMMENTS ON MURALIKRISHNA *ET AL.* "DESIGN AND EVALUATION OF HYGROSCOPIC SEEDING OPERATIONS IN ANDHRA PRADESH, INDIA"

Dr. Andrey Sinkevich*

Chief of Department of Cloud Physics
A.I.Voeikov Main Geophysical Observatory
St. Petersburg, Russia

I am skeptical about results presented in this article. I participated in seeding operations in Andhra Pradesh with the Weather Modification, Incorporated (WMI), team during operations in 2004 (September-October). I worked with radar data and carried out operational seeding duties. Very deep convection was observed during that period. Cloud tops reached 15-18 km. The cold rain process predominated. Hygroscopic seeding was not practically used during that period by the WMI team; rather, AgI seeding was used. There were some attempts of AGNI Aviation, Inc, (India) to use hygroscopic flares to seed altocumulus clouds, but cloud characteristics and possible rain increase associated with these types of clouds seemed miserable in comparison with rain produced by the deep cumulus. Moreover, these hygroscopic seeding operations were carried out for nearly a week and caused a lot of doubts that time. Most of seeding operations during 2003 were also carried out with AgI as far as I know.

It is not clear how the authors separate AgI seeding results from Hygro seeding. Is it possible to do this for 2003-2004?

Another remark deals with the reagent used. Weather Modification, Inc., used hygroscopic flares producing particle sizes typically less than 1 μm. Muralikrishna et al. state that the seeding flares produced particles of optimal size 5-10 μm. Do we have different types of reagent? If it is so, it will be very interesting to get more information about these new flares.

To evaluate the scientific level of the presented article it will be really important to get answers on the above questions.

I am going also to state that the AgI seeding conducted in 2004 produced really encouraging results in India. For results of our investigations which deal with seeding efficiency were already presented, see:

Krauss, T.W., W. Shaw, A.A. Sinkevich, and V. Makitov, 2005: Exploratory physical and statistical assessment of the results of cloud seeding in India 2004. Proceedings, International Workshop on Weather Modification and Cloud Seeding Technologies for Rain Water Enhancement. Jan 27-28, 2005. Jawaharial Nehru Technological Univ., Hyderabad, India.

Krauss T.W., W. Shaw, A.A. Sinkevich, V.S. Makitov, 2006: Cloud seeding in India and physical and statistical assessment of the results. *Russian Meteorology and Hydrology*, **N7**, 24-33.

Krauss, T. W., A.A. Sinkevich, N.E. Veremey, Yu. A. Dovgaluk, V.D.Stepanenko, 2007: Investigation of the large vertical depth Cb (Andhra Pradesh province, India, 2004, September 28) . *Russian Meteorology and Hydrology*, **N1,** 30-42.

Krauss, T.W., A.A. Sinkevich, N.E. Veremey, Yu. A. Dovgaluk, V.D.Stepanenko, 2007: Investigation of Large Vertical Depth Cb in India. 4th European Conference on Severe Storms, Trieste, ITALY

**Corresponding author*: Dr. Andrey Sinkevich, Chief of Department of Cloud Physics, A.I.Voeikov Main Geophysical Observatory, St. Petersburg, Russia; e-mail: sinkev@email.com

REPLY TO COMMENT ON:

DESIGN AND EVALUATION OF HYGROSCOPIC SEEDING OPERATIONS IN ANDHRA PRADESH, INDIA

Iyyanki V. Muralikrishna

Centre for Atmospheric Sciences, Jawaharlal Nehru Technological University
Hyderabad India

On the question of separating the results obtained using AgI from those obtained using hygroscopic seeding materials:

As stated the paper deals with the results obtained from the seeding operations in Andhra Pradesh. A case by case study was carried out and in the final analysis only those clouds that were seeded with hygroscopic agents of flares were considered. It should also be noted that in the years from 2005-2008 predominantly warm cloud seeding with hygroscopic flares was undertaken with considerable success.

The authors are also aware of the fact that the 2004 operations used large quantities of silver iodide ejectable flares. A case by case study was carried out using TITAN software and based on the results a set of protocols were designed to be followed during the operations from 2005 onward. The protocols identified different set of conditions for warm and cold clouds which were followed in the subsequent years.

On the question concerning particle sizes produced by the hygroscopic flares:

After considerable debate and experimentation across the state it was felt that for precipitation it would be desirable to have particle sizes in the range of 5 – 10 μ. Indigenous flares were prepared and tested with particles in the above mentioned ranges. For all the later years indigenously prepared calcium chloride flares are being used.

**Corresponding author*: Iyyanki V. Muralikrishna, Centre for Atmospheric Sciences, Jawaharlal Nehru Technological University, Hyderabad India; e-mail:iyyanki@icorg.org

COMMENTS ON THE GRIFFITH *ET AL.* REPORT ON OPERATIONAL CLOUD SEEDING PROGRAMS IN UTAH

Bernard A. Silverman, PhD

Consulting Meteorologist
Centennial, CO, USA

The report by Griffith *et al.* (2009) on operational cloud seeding programs in Utah states the following conclusion: "*The NAWC* (the Utah programs seeding contractor) *utilized an historical target/control regression analysis technique to estimate the effects of cloud seeding in the various target areas in Utah. These analyses suggest average seasonal effects ranging from 3-21%.*" The quoted increases attributed to seeding are the range of point estimates from the evaluation of the various Utah target areas (their Table 2), point estimates that Griffith *et al.* have taken literally. Except for giving the correlation coefficients for the various target/control relationships, Griffith *et al.* do not provide any details about the specific evaluations that produced these results or their interpretation of them. Of particular importance, Griffith *et al.* do not provide a measure of the statistical certainty of each of the point estimates, i.e., a confidence interval and/or a P-value for each of the estimated seeding effects. **They did not provide it despite the fact that the description by Dennis (1980) of the <u>historical target/control regression analysis methodology for evaluating operational (non-randomized) cloud seeding programs</u> includes a statistical method of determining the statistical significance and/or the confidence interval of the point estimate of the seeding effect as well as a statistical method for determining the point estimate of the seeding effect.** The statistical significance of a point estimate of a seeding effect is determined by its P-value and/or its confidence interval. The World Meteorological Organization (WMO 2007) recommends that "*Confidence intervals should be included in the statistical analyses to provide an estimate of the strength of the seeding effect so informed judgments can be made about its cost effectiveness and societal significance*". Thus, Griffith *et al.* present no statistical basis for rejecting the null hypothesis that seeding had <u>no</u> effect on the average seasonal precipitation at any of the Utah operational program target areas. What then is the basis for the unsubstantiated conclusion by Griffith *et al.* that their historical target/control regression analyses suggest average seasonal effects from 3-21% for the various target areas of Utah?

Complicating the interpretation of the evaluation of the Utah operational cloud seeding programs by the historical target/control regression analysis are the results of several studies that indicate this evaluation method is not robust for such applications and that this lack of robustness affects the reliability and accuracy of the estimates of the seeding effect that it produces. Nevertheless, Griffith *et al.* present the results and conclusions of their evaluation without any caveats. Consider the results of the following relevant studies:

1. Dennis (1980) stated "*Although the basic idea involved in the historical regression analysis is intuitively appealing, there are a number of difficulties with it.*" He identified some of these difficulties, including:

   a) reliability of the results unless the underlying data sets conform to the normal distribution which, for precipitation data, requires an appropriate data transformation. Since Griffith *et al.* use seasonal precipitation values averaged over multiple sites, the distributions of their target and control response variables are not highly skewed; however, they do not conform to the normal distribution,

   b) unconscious bias in the selection of data in post-hoc evaluations;

   c) difficulty in eliminating residual uncertainties; and

   d) representativeness of the target/control relationship and its stability in time. Dennis stated that *"The most serious difficulty with the historical regression method has to do with the stability in time of the target-control relationship. This difficulty arose very early in the evaluation of operational cloud seeding projects. MacCready (1952) performed an evaluation of a winter cloud seeding project in central Arizona using the historical regression technique and reported*

**Corresponding author*: Dr. Bernard A. Silverman, 7038 E. Peakview Place, Englewood, CO 80111; e-mail: silvermanb@aol.com

> *indications of a significant increase in rainfall. Brier and Enger (1952) performed several tests of the same project using different controls and different historical periods for establishing the target-control regression line. Their results showed considerable variation in the apparent rainfall increase due to seeding”*.

2. Brier and Enger (1952) showed that the variation between sequences of years is different from (less than) the variation between random samples of years.

3. Gabriel and Petrondas (1983) examined whether evaluation methods based on operational/historical comparisons, like the historical target/control regression analysis method, is valid for precipitation data, i.e., whether it is robust to departures from the assumptions under which it was derived and does it allow valid inferences, at least approximately, when they are not. The study used annual precipitation data, the distribution of which was not skewed like hourly or daily precipitation tends to be but was still not Gaussian (normal). They concluded that operational/historical comparison methods tend to produce appreciably more significant results than they properly should. This prompted them to state, *“One cannot but wonder how many of the past findings of ‘encouraging’ results by cloud seeders may have been a consequence of the radical character of statistical tests when applied to precipitation data”*. Gabriel and Petrondas suggested that statements of significance made on the basis of operational/historical comparisons should be discounted; rather they should be augmented by a factor that is proportional to the number of years involved in the operational/historical comparison.

4. Silverman (2007) evaluated the Kings River operational cloud seeding program for seeding effects on annual streamflow using both the historical target/control regression analysis method and the more robust bias-adjusted regression ratio. It is important to note that Silverman made an adjustment to the regression ratio results to compensate for the bias introduced by using data from a non-randomized program in order to enable the ratio statistics method (Gabriel 1999) to yield valid inferences for operational/historical comparisons. As suggested by Gabriel and Petrondas (1983), the computed P-values from the regression ratio results were multiplied by a bias-adjustment factor, the magnitude of which was chosen to achieve confidence interval results with the bias-adjusted regression ratio evaluations that were statistically comparable to those obtained from re-randomization analysis. Silverman found that the historical target/control regression analysis method overestimated the effects of seeding. The estimate by the historical target/control regression analysis was greater than that estimated by the bias-adjusted regression ratio by almost a factor of two after 5 years of seeding; however, the difference in the estimates by the two statistical methods narrowed as the number of operational seeding years increased until they became comparable after about 25 operational seeding years. A similar comparison of the two evaluation methods was done for several other seeding targets in the Sierra watersheds and the results for those targets were consistent with those for the Kings River, i.e., the historical target/control regression analysis method overestimates the seeding effect, especially during the first 25 years of operational seeding. The result for the Mono Creek (MNO) sub-basin of the San Joaquin watershed (Fig. 1) is another example of what was found. It should be noted that the horizontal axis starts after 10 seeded years, the same as that shown for the Kings River, the reason being that it takes about that long before the statistical estimate of a possible seeding effect becomes unequivocally apparent.

Prompted by my doubts about the accuracy and statistical meaning of these evaluation results, I requested copies of the response variable data so I could independently check the results by repeating the evaluations using re-randomization (permutation) analysis. I had honored Griffith’s request and provided him with the response variable data that I used in my Vail evaluation study (Silverman 2009) and I asked him to reciprocate by providing me with the response variable data that he used in his Utah report (Griffith *et al.* 2009). Griffith turned down my request. Originally, I intended to check the results by repeating the evaluations using the bias-adjusted regression ratio method. However, Griffith’s e-mail response to my data request stated that *“If you were to do your ratio analysis and the results were different than ours, it appears you will believe your results are right and ours are wrong”*. I responded by saying *“I am now using Monte Carlo permutation (re-randomization) statistics in my evaluations as I did in my 2009 JWM paper on the San Joaquin evaluation. That is what I am planning to use in my re-analysis of the Utah programs in order to put the Utah evaluation results on a more robust statistical footing and not to imply that your results are not correct”.* Tukey *et al.* (1978) stated that *“Re-randomization analyses can be applied to any (numerical) summary comparison of seeded results with unseeded ones”* and that it (re-randomization analyses) offers the most secure basis for drawing statistical conclusions about the effectiveness of weather modification programs. Re-randomization analysis is a non-parametric method of analysis that is based solely on the response variable data itself. It does not depend on any assumptions about the distribution shape and its associated properties or about independence of the data from one time to another so robustness is not an issue. Nevertheless, Griffith refused to provide the Utah programs response variable data.

One cannot help but wonder why Griffith refused to provide the Utah data. If Griffith *et al.* believe that the historical target/control regression method yields reliable and accurate estimates of the seeding effect, then one would think that they would welcome an independent evaluation using re-randomization, a statistical method of unquestioned validity, since it would corroborate their results. My request for the data is consistent with the WMA's recommendation (Boe *et al.* 2004) that states *"We (WMA) recommend that evaluation techniques presently being applied to operational programs be independently reviewed and as necessary revised to reduce biases and increase statistical robustness to the extent possible. Recognizing that randomization is not considered to be a viable option for most operational seeding programs, we acknowledge there is much room for improvement in most present evaluations, many of which are presently done in-house".*

The results of the Utah programs will remain in doubt until an evaluation of the Utah target areas is done using a more robust statistical method than historical target/control regression analysis. To assure that the new evaluation is independent and unbiased, it should be carried out in accordance with the recommendation of the WMO Statement on Weather Modification (WMO 2007) which states *"Weather modification managers are encouraged to add scientifically accepted evaluation methodologies to be undertaken by experts independent of the operators".* I thought that Griffith agreed when he stated in his response to my data request that *"I believe an independent statistician should review the application of the standard historical regression techniques versus your and Ruben's double ratio* (regression ratio) *method to determine the reasons for potential differences".* I suggest that re-randomization (permutation) analysis should be included in this study.

In requesting the data, I assumed that authors of published papers in the *Journal of Weather Modification* (*JWM*), as is the case with most scientific journals, were required as a condition of publication to provide the data they used to obtain their results and conclusions to interested/concerned readers who request it. However, it turns out that I was mistaken about the *JWM*'s publication policy with regard to this matter. I was disappointed to learn that the Weather Modification Association (WMA) encourages but does not require authors of *JWM* papers to provide their data to readers who request it. Since requiring readers to accept results and conclusions on faith is not consistent with the pursuit of scientific understanding, I strongly recommend that the WMA change the JWM publication policy with regard to this matter. The WMA should

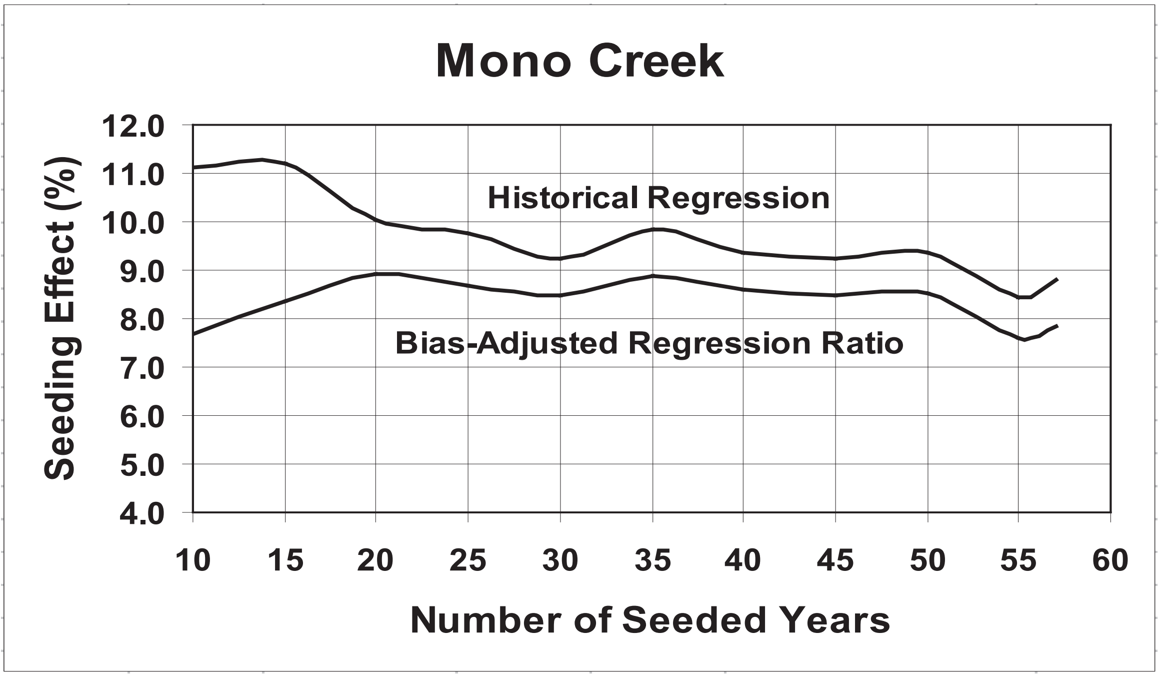

Figure 1. Cumulative year effect of seeding for Mono Creek (MNO) estimated by the historical regression method and the bias-adjusted regression ratio method.

establish well-defined (not optional) guidelines for authors and reviewers that cover all aspects of the processing and publication of manuscripts in the JWM, the aim being to publish in a timely manner high quality contributions to the advancement of the science and practice of weather modification.

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REPLY TO SILVERMAN COMMENTS ON WMA JOURNAL PAPER ENTITLED "30+ WINTER SEASONS OF OPERATIONAL CLOUD SEEDING IN UTAH", GRIFFITH *ET AL.* 2009

Don A. Griffith, David P. Yorty, and Mark E. Solak

North American Weather Consultants
Sandy, Utah

1. INTRODUCTION

North American Weather Consultants (NAWC) published a peer-reviewed paper in the WMA 2009 *Journal of Weather Modification* entitled "30+ Winter Seasons of Operational Cloud Seeding in Utah", Griffith *et al.* 2009." That overview paper describes several operational winter cloud seeding programs being conducted in Utah (Griffith *et al.* 2009), hereafter referred to as Griffith. The paper included estimations of seeding effects using an historical target/control method to assess the ongoing non-randomized seeding projects. Silverman (2010) has submitted comments to the Editor of the WMA *Journal of Weather Modification* questioning the basis and accuracy of estimates of seeding effectiveness summarized in the Griffith paper.

Silverman has in recent years published four peer-reviewed papers in the WMA *Journal of Weather Modification* focused on evaluations of long-term winter operational cloud seeding programs utilizing a "ratio statistics" methodology (Gabriel 1999). The Silverman paper on the San Joaquin project also employs Monte Carlo permutation (re-randomization) statistics, a method he considers to be of "unquestioned validity." The four Silverman papers and the target areas that were analyzed are:

- Silverman, 2007, Kings River Drainage, Sierra Nevada, California
- Silverman, 2008, Kern River Drainage, Sierra Nevada, California
- Silverman, 2009a, San Joaquin Drainage, Sierra Nevada, California
- Silverman, 2009b, Vail Ski Area and Surrounding Areas, Colorado.

In his comments, Silverman is portraying himself as an unbiased, independent expert, wanting to apply his adaptation of the bias-adjusted regression ratio and re-randomization methods, as used in the four analyses listed above, to the Utah projects.

It needs to be emphasized at the outset that there are basically two types of weather modification programs: research programs and operational programs. One of the primary goals of a research program is to document the efficacy of the treatment with the associated confidence intervals and statistical significance of the indicated results. This is not the primary concern in the conduct of operational programs where the primary goal is to produce more water, reduce hail damage, etc. Operational program designs typically by necessity have less sophisticated (less robust) techniques applied to them to provide estimates of the potential results of the treatment. The Utah programs that Griffith reported on were all operational programs.

2. NAWC RESPONSE

Silverman, in his comment, states: "The report by Griffith *et al.* (2009) on operational cloud seeding programs in Utah states the following conclusion: "The NAWC (the Utah programs seeding contractor) utilized an historical target/control regression analysis technique to estimate the effects of cloud seeding in the various target areas in Utah. These analyses suggest average seasonal effects ranging from 3-21%." The quoted increases attributed to seeding are the range of point estimates from the evaluation of the various Utah target areas (their Table 2), point estimates that Griffith *et al.* have taken literally. Except for giving the correlation coefficients for the various target/control relationships, Griffith *et al.* do not provide any details about the specific evaluations that produced these results or their interpretation of them. Of particular importance, Griffith *et al.* do not provide a measure of the statistical certainty of each of the point estimates, i.e., a confidence interval and/or a P-value for each of the estimated seeding effects."…. "The statistical significance of a point estimate of a seeding effect is determined by its P-value and/or its confidence interval. The World Meteorological Organization (WMO 2007) recommends that "Confidence intervals should be included in the statistical analyses to provide an estimate of the strength of the seeding effect so informed judgments can be made about its cost effectiveness and societal significance". Thus,

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**Corresponding author*: Mr. Don Griffith, North American Weather Consultants, Inc., 8180 South Highland Dr., Suite B-2, Sandy, UT 84093 ; e-mail: dgriffith@nawcinc.com

Griffith et al present no statistical basis for rejecting the null hypothesis that seeding had no effect on the average seasonal precipitation at any of the Utah operational program target areas. What then is the basis for the unsubstantiated conclusion by Griffith *et al.* that their historical target/control regression analyses suggest average seasonal effects from 3-21% for the various target areas of Utah?"

Silverman basically contends that a more robust statistical technique needs to be applied to the Utah data to provide statistically more significant results. As an aside, Silverman raises an objection to the use of point estimates, yet Smith (Smith 2009) criticized Silverman for doing the same thing in his Kern River paper (Silverman 2008).

As indicated in the Introduction, it needs to be stated that the Utah seeding programs are not randomized experiments. Quoting from Hess (1974), "The weather scientist recognizes the large natural variability of rainfall and cloud characteristics in space and time, and sees the need for appropriate statistical methods to cope with the problems of uncertainties, for, as expressed by F. Mosteller and J.W. Tukey in 1968, "One hallmark of the statistically conscious investigator is his firm belief that however the survey, experiment or observational program actually turned out, it could have turned out somewhat differently." Statistical methods designed to handle these problems were developed by R.A. Fisher (1960) in connection with the design and analysis of comparative experiments in biological and agricultural research, where large and only partly controllable variability is present. The basic ideas involve (1) *replication*, from which a quantitative estimate can be made of the variability of the response to treatment, and (2) *randomization,* a process of allocating treatments to the experimental material by tossing a coin (or equivalent procedure), which may make it possible for the experimenter to attribute whatever effects he observes to the treatment and the treatment only."

A reference that explains the ratio statistics methodology as adapted by Silverman in his various WMA *Journal of Weather Modification* evaluation papers has as its title "Ratio Statistics for **Randomized** (emphasis added) Experiments in Precipitation Stimulation (Gabriel, 1999)! NAWC does not have the Tukey (1978) reference (cited by Silverman) in-house but we suspect that it is directed at the evaluation of randomized programs since in Silverman's comment he applies the term response variable data when discussing this reference. Restating the obvious, the Utah seeding programs are not experimental in nature or design.

Based upon the above, the thought that more robust statistical analyses can be applied to the Utah data sets to derive ranges of effects and their statistical significance is open to some question. Silverman himself has alluded to this problem in the four recent referenced publications regarding his application of the "ratio statistics" to several non-randomized data sets. For example, quoting from Silverman 2007, "From a rigorous statistical standpoint, the suggested effects that are indicated must be confirmed through new, *a priori*, randomized experiments specifically designed to establish their validity." Similar statements are found in Silverman's other three WMA papers. In other words, Silverman goes back to the basic premises for application of statistical tests as summarized by Hess: 1) replication and 2) randomization. From Silverman's San Joaquin paper (Silverman 2009), "It is emphasized that this study is an a posteriori evaluation of a non-randomized seeding operation. In addition, this evaluation is an exploratory study that involves consideration of a multiplicity of hypotheses/analyses, some of which are suggested by the results of previous analyses. In view of these considerations, the results should be interpreted as measures of the strength of the suggested seeding effect and not as measures of **statistical significance** (emphasis added)." In light of this second statement, how can Silverman make the statement about NAWC's paper, "What then is the basis for the unsubstantiated conclusion by Griffith *et al.* that their historical target/control regression analyses suggest average seasonal effects from 3-21% for the various target areas of Utah? When Silverman uses the term basis in this context we infer he is saying what is the **statistical basis**. We interpret statistical basis as valid statistical significance tests applied to randomized data sets.

Based upon Silverman's own statements found in his four publications, he likewise has failed to provide credible statistical evidence that seeding increased the average streamflow in the Kings, Kern and San Joaquin River programs in California and the Vail program in Colorado. The tone of Silverman's papers implies that he has provided "proof" of the efficacy of cloud seeding in several non-randomized program areas that he has analyzed. NAWC disagrees that this is the case; rather, he has provided indications that these programs have been successful. The perception that ratio statistics provides the ultimate statistical analysis tool (even as applied to randomized data sets) is dispelled in Ruben Gabriel's 1999 paper which contains the following statement, "This paper does not argue that ratio statistics are best but presents tools for making correct inferences about them, given that they have been much used and are likely to continue being used." Further, application of Silverman's adaptation of the ratio statistics method has not been reanalyzed and verified by an independent statistics expert, so his call for its use widely, and his attendant request for the Utah data, are premature.

Silverman mentions concerns attributed to Dennis (1980) regarding the historical regression approach. NAWC offers the following comments regarding these concerns.

"Reliability of the results unless the underlying data sets conform to the normal distribution which, for precipitation data, requires an appropriate data transformation." Quoting from Dennis (1980) "Rainfall observations say for one hour or day at a point, tend to be highly skewed, with most observations near zero and a long tail extending to large amounts". NAWC utilizes longer-term data, either three or four-month cumulative values or April 1st snow water contents that are also cumulative values. Further, NAWC deals with averages of multiple sites (not point measurements) for the control and target average values. These data are not highly skewed, as demonstrated in Figure 1, which is a frequency plot of the average control area values for the Central/Southern Utah program for both the not seeded and seeded periods. We have chosen to not apply transformations in our basic estimations. Dennis states that rainfall distributions can be normalized by data transformations, but that caution is necessary in interpreting the results of experiments analyzed with the aid of transformations. Silverman notes that the distribution of the Utah target and control response variables are not highly skewed, but that they do not conform to the normal distribution.

"Unconscious bias in the selection of data in *post-hoc* evaluations." As described in Griffith, NAWC typically establishes target and control stations to be used in its evaluations at project outset or early in the lifetime of its operational programs. These target and control sites and the resultant regression equations are typically maintained without changes throughout the lifetime of the seeding program. Changes are typically made only if observations are discontinued at one or more target or control sites. As a consequence, NAWC evaluations should not be considered strictly *post hoc* evaluations as suggested by Silverman, rather they could be considered essentially *a priori*. Incidentally, most of Silverman's analyses as reported in the WMA *Journal of Weather Modification* would be considered *post hoc* evaluations, the possible exception being the San Joaquin which uses target and control stream gaging stations previously established by Henderson (2003).

"Difficulty in eliminating residual uncertainties." Dennis (1980), in discussing this concern, states, "A number of possible biases are dealt with rather simply. Agreements before a program begins as to which rain gages are to be included in calculating target and control rainfall, for example, go far toward eliminating both unconscious bias and any temptation to select data to demonstrate a desired result (Court 1960). As discussed in the previous bulleted item, NAWC typically follows this recommendation in evaluating its operational programs.

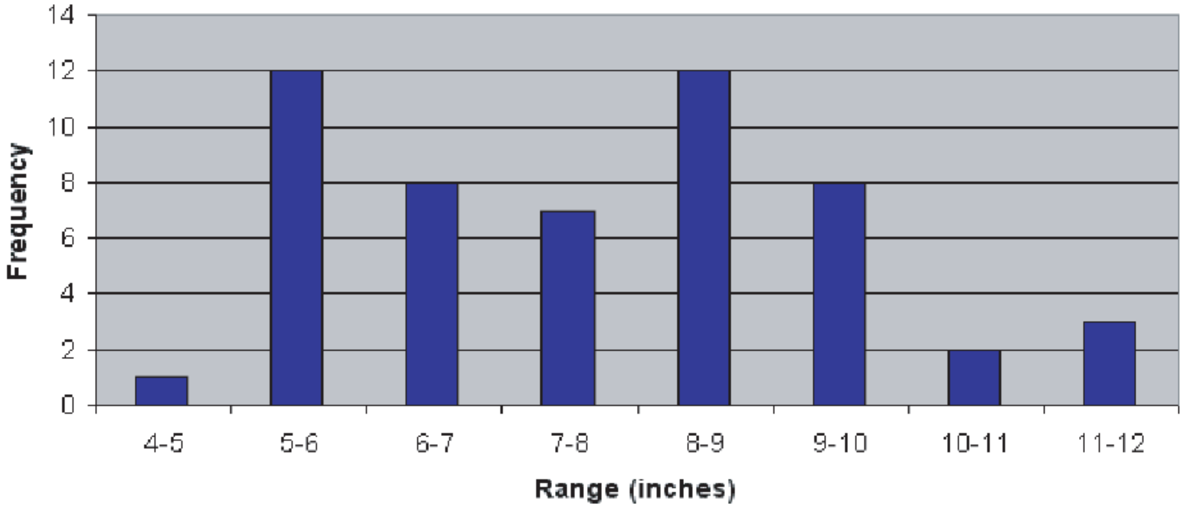

Figure 1. Distribution of Average Seasonal Control Site Precipitation for the Central/Southern Utah Program, Precipitation Evaluation, 1957-2009

"Representativeness of the target-control relationship and its stability in time." Quoting from Dennis (1980) "The most serious difficulty with the historical regression method has to do with the stability in time of the target-control relationship." "Neyman and Scott (1961) have hypothesized that the lack of stability in the target-control relationship is related to the occurrence of specific storm types, some of which favor the target area and some of which favor the control area." ... "The best that can be done appears to follow the criteria noted above for the selection of control areas and to be alert to any obvious changes in weather patterns that could distort the target-control relationship. One must not go to extremes in this regard; obviously, if one looked long enough, one could always find *something* that was different between the historical period and the operational period (Gabriel 1979)." NAWC has generally attempted to address this concern by careful selection of target and control sites (as described in Griffith) as recommended by Dennis (e.g., as close to target areas as possible, in areas typically upwind to avoid contamination, and selecting target and control sites at similar elevations). In fact, we often attempt to bracket the target area geographically (in a crosswind sense) with control sites in order to address the concern of storms favoring one area over another during specific storms or perhaps extending through an entire season. NAWC interprets the discussion contained in Dennis (1980) to be directed at short time intervals, e.g., individual storm periods. NAWC's evaluations utilize seasonal data that would be less subject to this concern since storm tracks change from storm to storm and any large differences between two areas are frequently dampened over longer time periods.

Silverman makes the statement "Silverman (2007) evaluated the Kings River operational cloud seeding program for seeding effects using both the historical target-control regression analysis method and the more robust bias-adjusted regression ratio." Silverman implies that these are different methods. NAWC contends that both methods are based upon the historical target-control analysis method. The bias-adjusted regression ratio method only contains some adjustments to the basic method that are primarily oriented at attempting to establish statistical significance of the results. That brings us back to our original argument, with which Silverman essentially agreed, that, in essence, one couldn't establish rigorous statistical significance from non-randomized programs.

Lacking randomization, any analyses of data can be subject to intentional or unintentional bias. Silverman states that Griffith refused to provide the Utah data sets to him. One of the reasons cited to Silverman for this decision was Silverman's statement in an e-mail that said "Based on the comparative results between my evaluations using the historical regression method in my Kings River evaluation paper (JWM 2007), I fear that the historical regression method may have yielded overly optimistic results for the Utah data." He further states in his comments, "Prompted by my doubts about the accuracy and statistical meaning of these evaluation results, I requested copies of the response variable data…" These comments indicate potential bias. Bias will always be a question when dealing with non-randomized data. Griffith questioned Silverman in this regard in his response to Silverman's e-mail "I have several concerns related to your request. If you were to do your ratio analysis and the results were different than ours, it appears you will believe your results are right and our results are wrong. This may or may not be the case. I believe an independent statistician should review the application of the standard historical regression techniques versus your and Ruben's double ratio method to determine the reasons for potential differences. I found it interesting that you apparently did not compare the results of the two methods in your Vail, San Joaquin and Kern analyses as reported in the WMA *Journal of Weather Modification*." Griffith asked Silverman several other questions in this e-mail none of which were answered. Silverman continued to demand that NAWC provide him with the Utah data. Since Silverman failed to respond to Griffith's questions, NAWC chose not to provide these data to Silverman.

Since the Utah seeding programs are not randomized, NAWC has typically chosen to not state statistical significance levels in our analyses. An exception to that can be found in Griffith *et al.* (1997). A re-randomization statistics method was applied to the longest-standing Utah seeding program. The results of 1,000 random draws indicated that the regression-indicated average seasonal precipitation excess of 14.6% in the target area is significant at better than the 5% level. NAWC more commonly uses the term "estimate(s)" when discussing the results of its seeding effectiveness efforts. Silverman's analyses likewise provide "estimates of effects" which should not be considered as conclusive "proof" of the confidence intervals or the statistical significance of these ranges of the non-randomized programs that he has analyzed. The question then of which "estimate" is best is then seen as a discussion of relative rather than absolute accuracy that an expert in statistics can best ascertain.

3. DISCUSSION OF RELEVANT ISSUES

With the background provided in the above, some of the ramifications of Silverman's comments may be examined. It is concluded from Silverman's reference to his Kings River paper that he apparently believes that the results using the historical regression technique may overstate the results for short periods of say 5-10 years but then seem to converge, giving very similar results to the ratio method once approximately 25 years of evaluation are achieved. This conclusion is based upon Figure 4 from Silverman (2007) reproduced here as Figure 2. Silverman states that, "The estimate by the historical target control regression analysis was greater than that estimated by the bias adjusted regression ratio by almost a factor of two after 5 years of seeding." Oddly, Figure 2 from Silverman (2007) only provides information after ten years of seeding, not for five years. **Of significance is the fact that the difference between the two types of evaluations as presented in Figure 2 only varies by an approximate 2% difference at most after ten years and declines to approximately a 1% difference in about fourteen years.** In Silverman's comments on Griffith, he provided a plot similar to Figure 2 but from Silverman's analysis of the San Joaquin cloud seeding program (this figure was not included in Silverman's 2009 paper that discusses this program). Silverman's figure, for the Mono Creek drainage, is reproduced as Figure 3. A couple of observations regarding this figure are as follows. It would appear both the historical regression and the bias-adjusted regression ratio methods "overestimated" the seeding effects in the early years of the San Joaquin program and then merged towards lower values over longer durations. This trend is the opposite of that in Figure 2 on an adjacent program in the Sierra (Kings) in which the apparent "seeding effect" started at lower values but increased over time. The maximum estimated seeding effect difference between the two methods in the early years of the San Joaquin program is approximately 4% declining to approximately 1% after 20 years. Due to the non-randomized nature of the data, NAWC does not endorse the apparent conclusion reached by Silverman that the bias-adjusted **estimate** is correct and the historical regression **estimate** is incorrect in the early years of these programs.

In order to examine this time evolution of seeding effects on some of the Utah data sets, NAWC selected two of the longest term programs referred to as the Northern and Central/Southern Utah programs in Griffith. NAWC used the same technique as Silverman in his Vail paper (Silverman 2009) in plotting the time evolution of the apparent cumulative seeding effect (expressed as a percentage

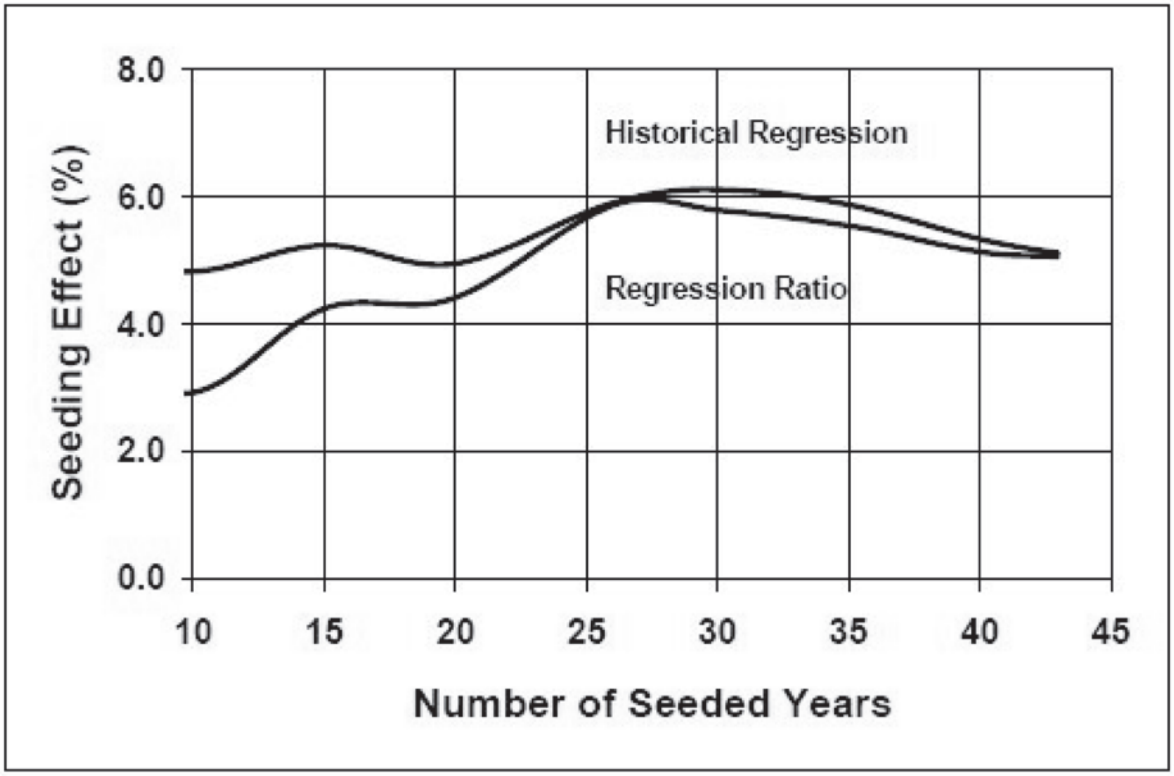

Figure 2. Kings River Program, Cumulative Year Effect of Seeding Estimated by the Historical Regression Method and the Regression Ratio Method (Silverman 2007)

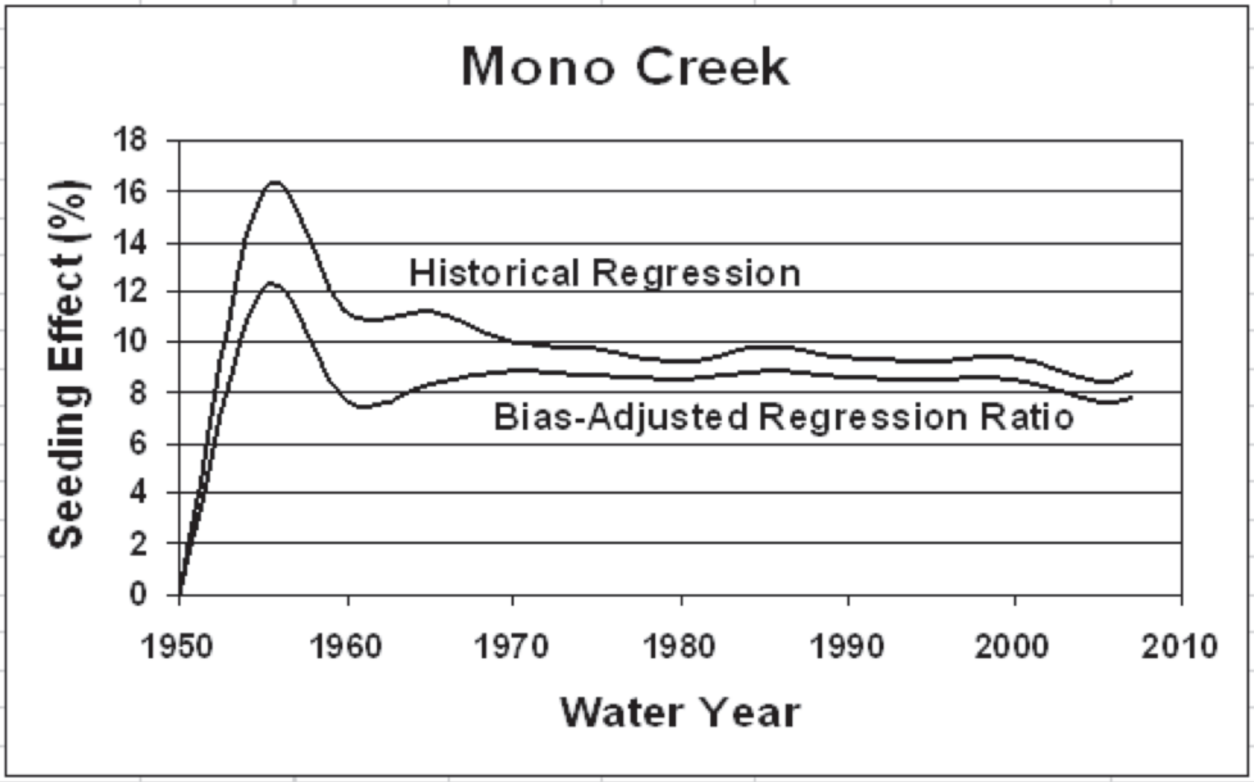

Figure 3. Mono Creek, Cumulative Year Effect of Seeding Estimated by the Historical Regression Method and the Bias-adjusted Regression Ratio Method (Silverman Comment).

increase) for these programs. The results are provided in Figures 4 and 5. Contrary to the supposition that the estimated seeding effects were high in the early years of seeding, these figures indicate that the apparent effects were lower in the early years of the programs but then stabilized at higher levels after 10-15 seasons of seeding. For comparison of the indications provided in Figures 4 and 5 with the Vail program, NAWC prepared a plot for one of the sub-basins in the Vail analysis as reported by Silverman (2009). Several of the target streamflow records used by Silverman in his analyses were rather short records (e.g. 11-14 years). One station did have a longer period of record, the Upper Gore Creek (GUP) station with records from 1948-2005. Silverman indicated the highest correlated control gage was one named the Frying Pan River below Ruedi (FRR), which had available data from 1909-2005. NAWC calculated the linear regression relationship between the two stations for the historical, not seeded period of 1948-1976. NAWC then used the resulting regression equation to calculate the annual indications of possible seeding effects during the seeded years of 1977-2005. NAWC prepared Figure 6 for Upper Gore Creek, which shows the evolution of apparent seeding effects on this sub-basin. This figure actually shows an opposite effect to those found on the two Utah programs (Figures 4 and 5) and on the Kings River program (Figure 2) but the same as that found for Mono Creek on the San Joaquin program (Figure 3). Figure 6 indicates the estimated seeding effects were higher in the early seasons of seeding then stabilized at lower levels after approximately 10 seasons. **Obviously, there is not much consistency in the trends of the indicated seeding effects in the early seasons of these long-term operational programs. The important factor in the comparison (Figures 2 and 3) of the two methods (historical regression and bias-adjusted regression ratio) is that the "indicated results" from the two methods merge with time to the extent that the differences are only about 1% after approximately a 20-year period. Silverman (2007), in discussing the Kings River program, contains the following statement: "Assuming that the relationship derived from the historical period is representative of the operational period, as is the case here, the historical regression method may, indeed, yield reasonably precise estimates of a multi-year effect of seeding provided that the natural variability is averaged over a sufficiently long period of years."**

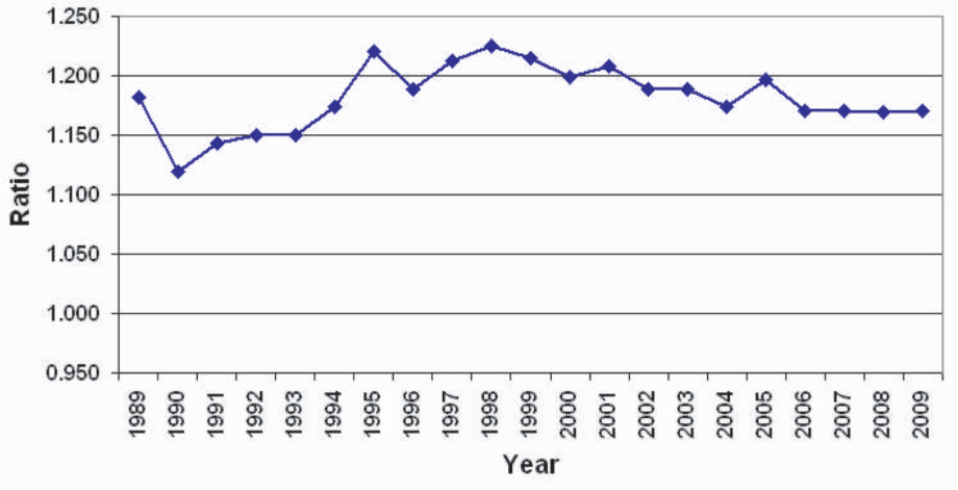

Figure 4. Northern Utah Program, Cumulative Mean Ratio (actual over predicted precipitation) for Seeded Years 1989-2009

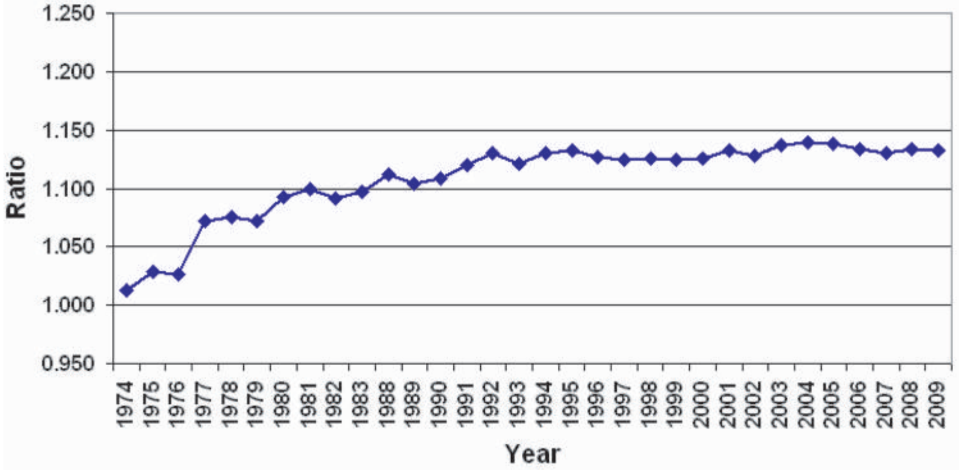

Figure 5. Central/Southern Utah Program, Cumulative Mean Ratio (actual over predicted precipitation) for Seeded Years, 1974-2009

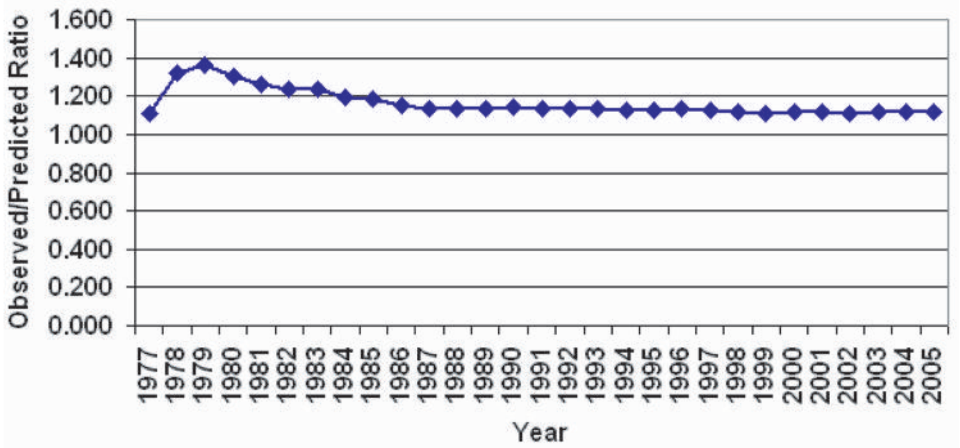

Figure 6. Vail Program, Cumulative Mean Ratio (actual over predicted streamflow) for Seeded Years 1977-2005, for Gore Creek

Three of the six Utah programs as evaluated by Griffith are of durations from 19-29 years (Table 2 in Griffith). Two of the remaining programs are of 13- and 15-year durations, respectively. As a consequence it is concluded that the historical regression results from 4 of the 6 evaluated Utah programs would differ no more than 1-2% if the bias-adjusted ratio method were applied to these programs. It needs to be stated that NAWC normally indicates to its clients that it will take several seasons (on the order of 10 seasons) before the **estimates** of possible seeding effects begin to stabilize.

Of potential interest in this discussion is another type of NAWC analysis that has been applied to the longer term Northern and Central/Southern Utah seeding programs, an engineering technique commonly called a "double mass" plot. In this technique, two variables can be plotted in a cumulative fashion that will demonstrate how the two variables may be correlated. For the Northern and Central/Southern Utah programs, the average seasonal December through February or December through March values from the historical not seeded and the seeded periods are plotted for the control area averages versus the target area averages. Each successive season's data are added to the accumulated values for the combined prior seasons of data. If the two variables are well correlated, then a straight line can be drawn through the individual points. If there is a change in the relationship between the two variables with time, a "break" in the straight line will appear. Figures 7 and 8 provide that type of plot for the Northern and Central/Southern Utah seeding programs. There are obvious "breaks" upward in both of these plots, which coincide approximately with the beginning of cloud seeding programs in these target areas. Trend lines drawn through the data following these breaks appear as nearly straight lines, which imply that the apparent effects of seeding are rather constant over time. NAWC prepared a similar plot for the Upper Gore Creek site versus the Frying Pan site in the Vail program area (Figure 9). This figure contains a break upward in the plot (more streamflow at the target site compared to the control site) that is also approximately coincident with the beginning of the cloud seeding program in 1977. Interestingly, the plot in this figure suggests variability in the apparent seeding effects. For example, the upward break in the line seems to flatten out during the period of approximately 1983 to 1990. This implies a reduction in the seeding effect during this period for some unknown reason or reasons. No such prominent breaks are evident in the two Utah plots (Figures 7 and 8), which implies more consistent effects of seeding.

Silverman asks for an independent and unbiased analysis of the Utah seeding programs, citing a WMO statement. Since we are discussing WMA publications, we provide the following quotes from the WMA Statement on Standards and Ethics adopted in 2005 under the heading of Relationships with the Meteorological Profession:

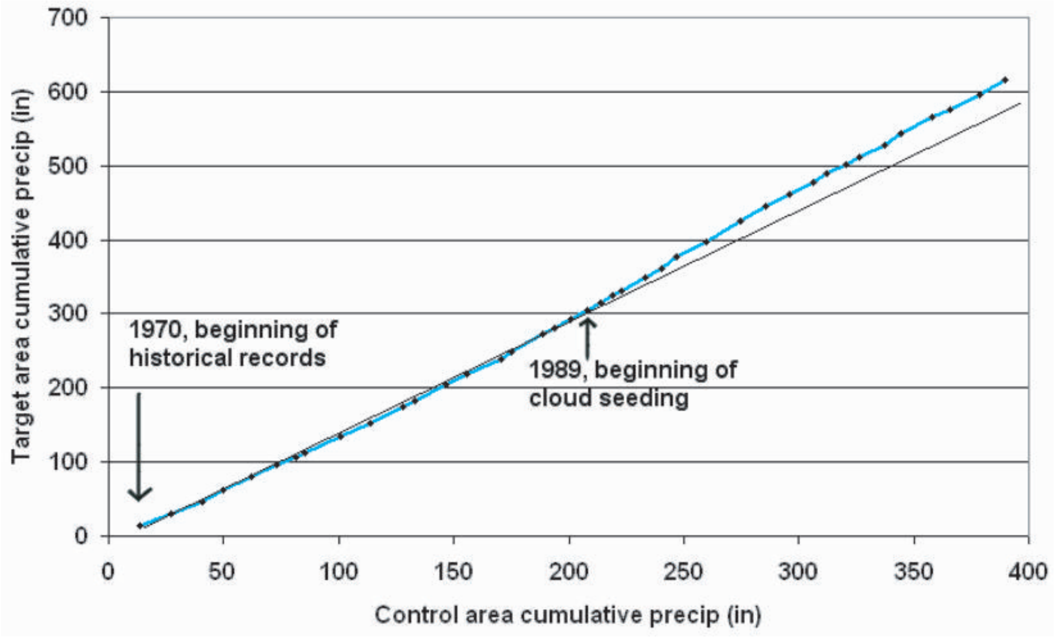

Figure 7. Northern Utah Program, December - February Precipitation, Double-Mass Plot, 1970-2008

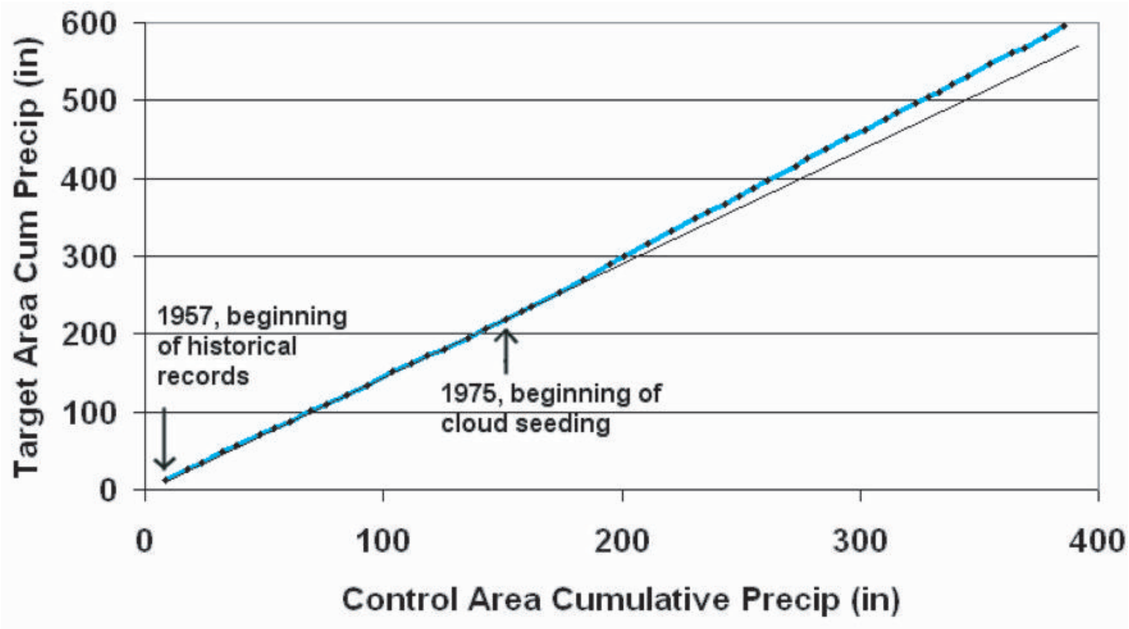

Figure 8. Central/Southern Utah Program, December – March Precipitation, Double Mass Plot, 1957-2008 (excludes water years 1985-1987)

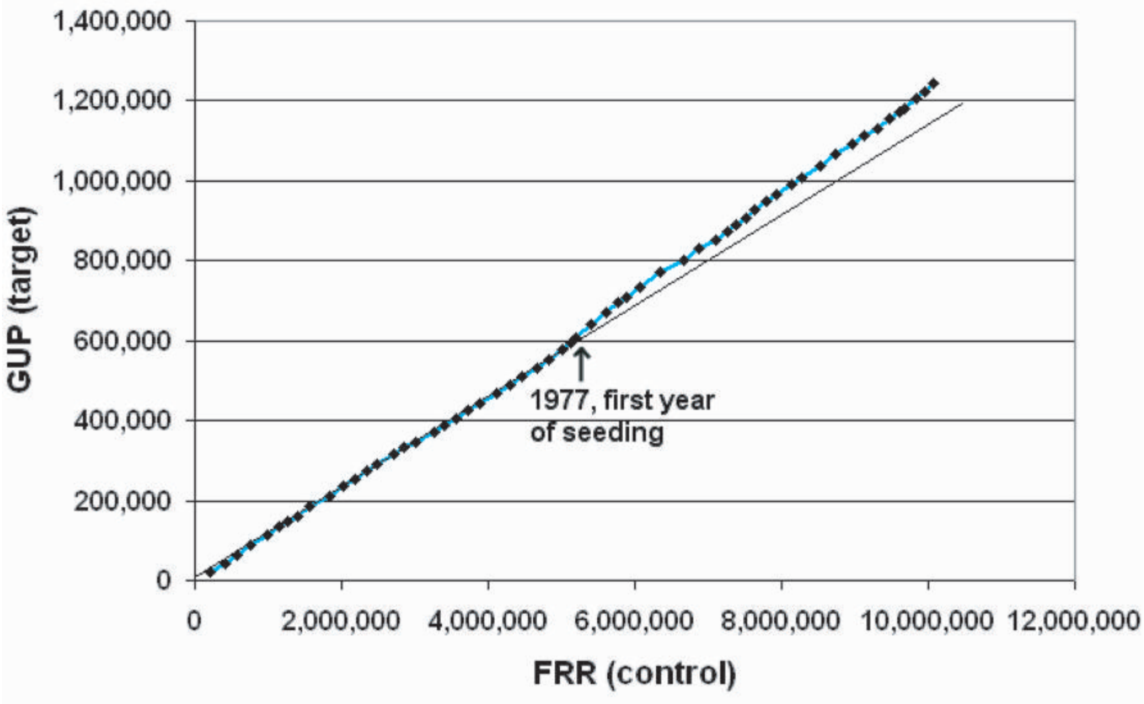

Figure 9. Vail Program, Double Mass Plot of Annual Streamflow, Upper Gore Creek versus Fryingpan River

"The **operator or manager** (emphasis added) will endeavor to contribute new knowledge to the profession by making known significant results from operational and research programs." ... "Evaluations of projects are strongly encouraged. Any limitations to evaluation will be reported to the client. Procedures to be used in evaluations should be specified in advance." Note that the evaluations are to be done by the weather modification operator, not a third party. NAWC routinely follows these requirements in the conduct of its programs. The Griffith overview paper is an example of NAWC following the first requirement and appropriately reporting the results of its evaluation efforts as estimates and indications, not as statistically significant proof of effectiveness. Recognizing the limitations of the evaluation technique applied to non-randomized data, NAWC does not state any measures suggesting statistical significance.

For the record, it perhaps should be stated that "independent" verification of some of the evaluations NAWC's Utah cloud seeding programs have been conducted by the Utah Division of Water Resources. A 2000 report (Stauffer and Williams 2010) when discussing NAWC evaluations states, "The data and analyses in NAWC evaluations have been reviewed and confirmed by the Division of Water Resources. In addition, target and control analyses have also been made for April 1 snow water content. The April 1 snow water content analyses are important because relationships can be developed to estimate runoff based on April 1 snow water content."

4. FINAL COMMENTS

Silverman's analyses of four long-term operational cloud seeding projects have provided some interesting insights into prospective techniques for estimating the effectiveness of winter orographic cloud seeding efforts. However, the four analyses are *a posteriori* and are applied to non-randomized projects, so the analyses and their indicated results carry the same caveats as similar analyses conducted by others over the years. They have not undergone unbiased, independent verification by a qualified (expert) statistician. Accordingly, the results must be viewed with caution and presented appropriately as indications, and certainly not proof, of seeding effects. "Proof" is not possible from operational programs, only indications. To illustrate this point, if Silverman's four papers had been published prior to the publication of the National Research Council 2003 report would there have been changes in any of the conclusions of this report regarding the efficacy of winter cloud seeding based upon Silverman's papers? NAWC's clients and clients of other firms do not expect the type of "proof" or robust testing that Silverman seeks from these operational programs. The question becomes, whom are we trying to convince in the evaluation of operational programs? Certainly not the scientific community that will reject any evaluations not conducted on a research program with the main tent pole being a randomized design. We are then talking about providing "estimates" of effectiveness to program sponsors that include municipal water managers, irrigation district water managers, hydroelectric facility managers, farming organizations, and state regulators. These managers do not demand the 5% significance level "proof" of effectiveness as is demanded from research programs. These groups are also typically not interested in confidence intervals. Would such managers be concerned if the indicated point estimate from two different evaluation techniques indicated a maximum difference of 2% in the early years of a program but then became nearly the same after 25 years (as was the case in Silverman's analysis of the Kings River program)? Probably not!

One only needs to look at the large number of operational programs being conducted around the world without "robust" evaluations being applied to them as evidence of the above conclusion. This fact seemed to confound those that authored the 2003 NRC report. It almost seemed that the authors were asking: If there is not scientific proof of the efficacy of cloud seeding, why are all these operational programs being conducted?

NAWC believes at least some of the answers to this question regarding winter orographic cloud seeding programs are:

1. The potential for "new" water from precipitation augmentation programs, which may be used to offset the ever-increasing demands being placed on fresh water supplies due to expanding populations.

2. A perceived substantial return on investment. Various studies of U.S. programs indicate additional streamflow derived from winter snow augmentation costs on the order of a few dollars per acre foot to produce, often resulting in estimated benefit to cost ratios of ~5-10/1 or higher.

3. A lower expectation of "proof" that cloud seeding "works". The managers of water districts, municipalities, hydroelectric companies, irrigated agricultural districts, farm groups, etc. often do not have the luxury of demanding a 95% confidence level in making decisions in their day to day world so why should they demand this level of

confidence to fund a cloud seeding program?

Estimations of the effectiveness of non-randomized operational seeding projects are important but challenging. Such efforts must continue and will, no doubt, generate lively debate as they do.

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COMMENTS ON SILVERMAN'S PAPER PUBLISHED IN THE WMA 2009 *JOURNAL OF WEATHER MODIFICATION* ENTITLED " AN INDEPENDENT STATISTICAL EVALUATION OF THE VAIL OPERATIONAL CLOUD SEEDING PROGRAM"

Don A. Griffith*, David P. Yorty, and Mark E. Solak

North American Weather Consultants, Sandy, Utah

1. INTRODUCTION

This is an interesting paper that was published by Silverman. The length of the Vail seeding program lends itself to detailed analysis. North American Weather Consultants (NAWC) does have a few comments as well as concerns regarding this paper. These comments and concerns are addressed in the following.

A quote from Silverman states "Silverman (2007) showed that it is imperative to use as a control or controls, to the extent that available data permits, the streamflow station or stations that yield the most precise results." He showed the control or combination of controls that had the highest correlation with the target and, especially, the lowest standard deviation of the residuals (differences between the observed and predicted values) will yield the most precise evaluation results. NAWC readily agrees with that statement, however, examination of the correlations obtained in this study as provided in Table 4 in The Vail paper (Silverman 2009a) suggests this ideal was not obtained. The r^2 values obtained were significantly lower than those previously obtained by Silverman in the analyses he has performed on long-term Sierra Nevada programs (Silverman, 2007, 2008, 2009b). Values from Table 2 from Silverman (2009) indicate the correlation coefficients in his Vail analysis ranged from 0.775 to 0.918 or r^2 values of 0.60 to 0.84; values considerably lower than he established for the three California programs where the r^2 values ranged from 0.96 to 0.98.

2. DISCUSSION

A general concern regarding Silverman's Vail analysis is the high estimates of seeding effects in some of the sub-basin target areas. For example, the GBH and GPT estimated average increases are +28.8 and +18.5%, respectively. These are high numbers especially considering that these are estimates of increases in annual streamflow values and that the cloud seeding program is only conducted during some of the winter months. The 28.8% value is considerably higher than the Weather Modification Association Statement of Capabilities (WMA 2005) for winter seeding programs that contains an expected range of 5-15% increases. There are several potential explanations for these high estimates. The two target stations (GBH and GPT) happen to have the two lowest correlations with the selected control station (FRR). The r^2 values are only 0.60 for the GBH site and 0.66 for the GPT site. The historical not seeded periods for these two stations are also short (13 not seeded seasons for the GBH site and only 9 not seeded seasons for the GPT site). As Silverman mentions in his Vail paper, "A potential control is a streamflow station that has not been seeded, is highly correlated with the target, and has a long enough record of full natural flow data during the historical and operational period to support a meaningful evaluation." NAWC questions whether these criteria have been satisfied in Silverman's analysis, especially for the two target stations that have the highest indicated seeding increases. The other factor of concern is the very small size of these sub-target basins. The sizes of these basins were not reported by Silverman but are 4.5 square miles for the GBH site and 5.3 square miles for the GPT site according to USGS records. These are very small drainages especially when placed in the context of the typical sizes of winter operational cloud seeding target areas that might range from several hundred to several thousand square miles. The data from Silverman's Tables 1 and 3 may be combined to provide an estimate of the average increases in streamflow for all of the sub-basin target areas for an average water year. The results are provided in Table 1.

The total calculated average increase (column 5) from Table 1 when divided by the average annual runoff (column 3) provides an estimated average increase for all the individual target basins combined in an average water year. The result is an estimated 8.4% for the combined watersheds. The total size of the combined watersheds is 149.2 square miles; still a small area in terms of an intended winter cloud seeding program target percentage increases

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*Corresponding author: Mr. Don Griffith, North American Weather Consultants, Inc., 8180 South Highland Dr., Suite B-2, Sandy, UT 84093 ; e-mail: dgriffith@nawcinc.com

in annual streamflow. A couple of explanations for these results could be the short historical periods and low correlations for these two sub-basins (as discussed in the above) and/or possible channeling of seeding material during seeded storms favoring these areas. When the results are merged over the entire area (albeit still a rather small area), the indicated average increase of 8.4% becomes much more reasonable. NAWC concludes that very small sub-areas in a large winter time cloud seeding area may show indications of rather high seeding increases but when results are averaged over larger target areas, the results are likely to fall within the 5-15% increase range as contained in the WMA Statement of Capabilities. Stated another way, it is highly unlikely that cloud seeding over a more typical sized winter cloud seeding target area could produce an average seasonal increase of 28%.

Of potential interest to this discussion is another type of NAWC analysis that has been applied to longer-term winter cloud seeding programs. This is an engineering analysis technique commonly called "double mass" plots. Using this technique, two variables can be plotted in a cumulative fashion that will demonstrate how the two variables may be correlated over time. Each successive season's data are added to the accumulated values for the combined prior seasons of data. If the two variables are well correlated, a straight line can be drawn through the individual points. If there is a change in the relationship between the two variables with time, a "break" in the straight line will appear.

NAWC applied the double mass technique to one of the target basins found in Silverman's analysis (Upper Gore Creek, GUP) and one of the control stations (Fryingpan River near Ruedi, FRR). The Upper Gore Creek and Fryingpan sites were selected since they had long historical not seeded data (1948-1976) and since Silverman had concentrated his analyses on those using the Fryingpan site as his primary control site. Annual data were plotted using the double-mass technique for the period of 1948-2005. This plot is provided as Figure 1.

There are a couple of interesting features in Figure 1. First, there is a break upward in the plot indicating more streamflow at the target station than at the control station, which appears to be coincident with the start of the seeding program in 1977. This provides strong, independent support that the indicated increases in Silverman's analysis are real and are related to the cloud seeding activities. There are a couple of more subtle differences that may be important. The slope of the line decreases during the years from approximately 1981 through 1989. The slope of the line increases beginning approximately with 2001 continuing through 2005. If it is assumed that the breaks we are seeing on this plot are due to seeding effects, then why did the effectiveness of seeding appear to decrease during the 1981-1989 period and why did the apparent effectiveness increase beginning in 2001?

The double mass approach seems to be more sensitive in suggesting differences in seeding effectiveness than Silverman's technique of plotting the "time evolution of seeding effect." Compare Silverman's Figure number 3 from his paper, reproduced here as Figure 2, with the above Figure 1. A couple of clarifications are necessary regarding Figure 2.

Table 1. Target Basin Characteristics and Calculated Increases in Annual Streamflow

Gaging Station Name	Gaging Station Symbol	Drainage Area (mi^2)	Ave. Annual Runoff (ac. ft.)	Ave. % Increase	Calculated Ave. Increase (ac.ft.)
Piney R.	PNY	86.2	54,234	+6.3	3,416
Booth Cr.	GBO	6.0	8,091	+9.3	752
Middle Cr.	MID	5.9	3,944	+7.9	312
Pitkin Cr.	GPT	5.3	7,395	+18.5	1368
Bighorn Cr.	GBH	4.5	5,482	+28.8	1579
Upper Gore Cr.	GUP	14.4	20,523	+11.1	2278
Black Gore Cr.	GBL	12.6	12,052	+4.6	554
Turkey Cr.	TMW	14.3	10,312	-2.0	(21)
Totals		**149.2**	**122,033**	**+8.4**	**10,238**

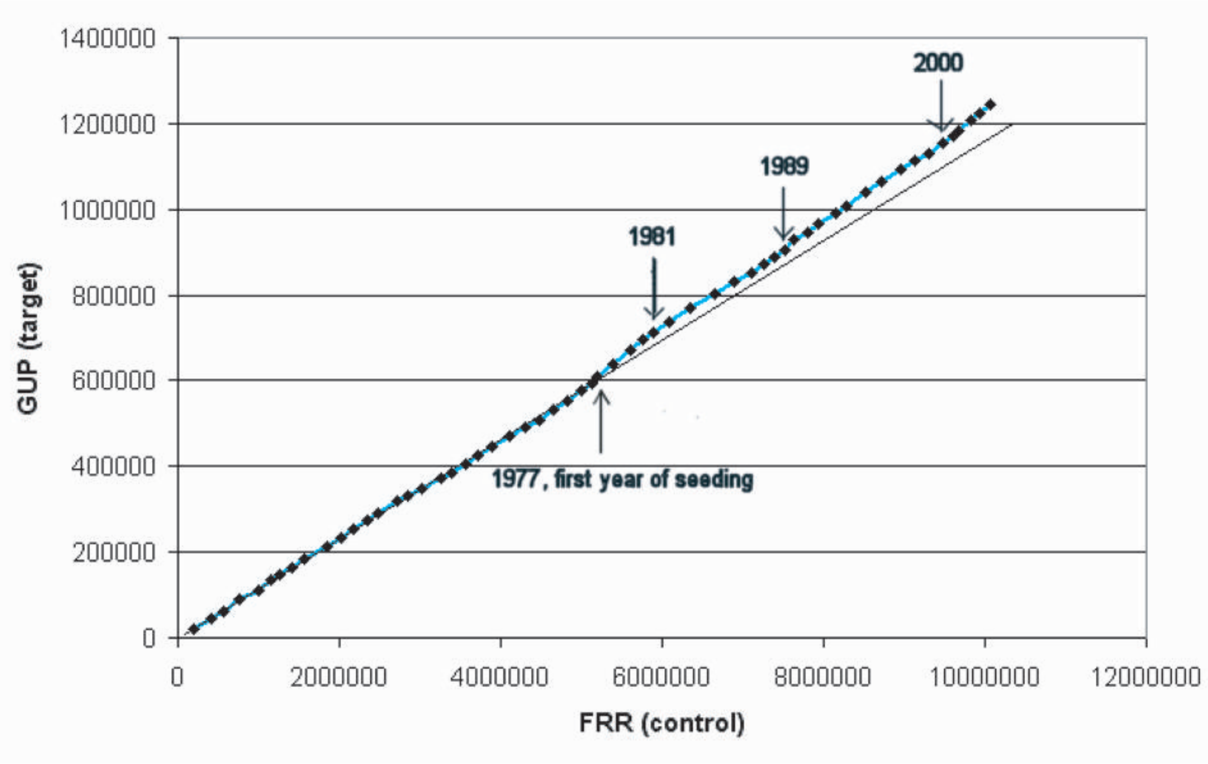

Figure 1. Double Mass Plot of Annual Streamflow, Upper Gore Creek versus Fryingpan River

This display begins in 1985 but the seeding program began in 1977. For this reason it is easier to look for the increase in seeding effectiveness during the 2001-2005 period rather than the decrease in the 1981-1989 period. Additionally, the reader needs to look at trace number 5 in Figure 2, which is the one for Upper Gore Creek. This trace does not appear to indicate the increase in effectiveness depicted in Figure 1.

In passing it is worth noting the utility of the double mass plot in selecting target and control sites when using the historical target/control evaluation technique. The stability of the site's relationships can be readily assessed using this technique. Silverman considered several stream gaging stations as potential control sites. One station that he considered was West Divide Creek (WDC). Two other control sites considered by Silverman were the South Fork of the White River (WSF) at Buford and the North Fork of the White River (WNF) at Buford. NAWC prepared double mass plots for WSF versus WNF, Figure 3 and WDC versus WSF, Figure 4. Figure 3 indicates a stable relationship between the South Fork and the North Fork of the White River sites. Figure 4, however indicates a break in the record for West Divide Creek versus the South Fork of the White River beginning in about 1966. The plot in Figure 4 becomes quite variable after 1966. Since Figure 3 indicates stability in the relationship between the South and North Forks of the White River, it is concluded that there is considerable variability in the West Divide Creek streamflow records after 1966 for unknown reasons. As a consequence, West Divide Creek would be a poor choice for a control station. Fortunately, although Silverman initially considered West Divide Creek as a control site, he based most of his analyses on using the Fryingpan site near Ruedi (FRR) as his primary control gage. This appears to be a good choice based upon a similar double mass plot that NAWC prepared for FRR versus WSF (South Fork of the White River at Buford) provided in Figure 5. Figure 5 indicates a stable relationship between these sites. Another interesting insight can be gathered from Figure 5. One of the assumptions in selecting control sites is that they are not affected by the seeding program to be evaluated or by other cloud seeding programs in the area for that matter. Figure 5 substantiates this assumption.

3. GENERAL COMMENTS

Finally, some general comments on Silverman's Vail paper are as follows. The Vail seeding program is not a randomized experiment and Silverman's analyses are *a posteriori*. Quoting from Hess (1974), "The weather scientist recognizes the large

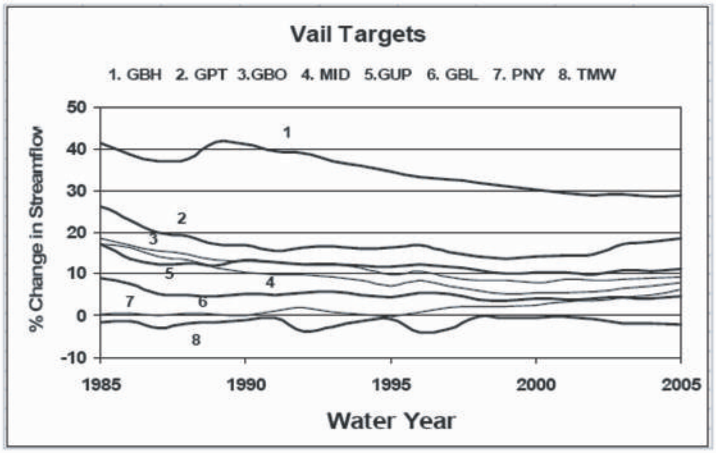

Figure 2. Time Evolution of the Seeding Effect (% change in streamflow)

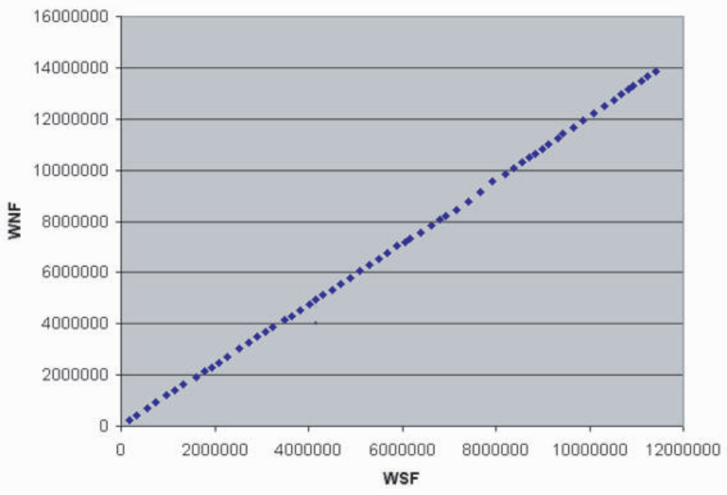

Figure 3. Double Mass Plot of Annual Streamflow, South Fork of White River versus North Fork of White River

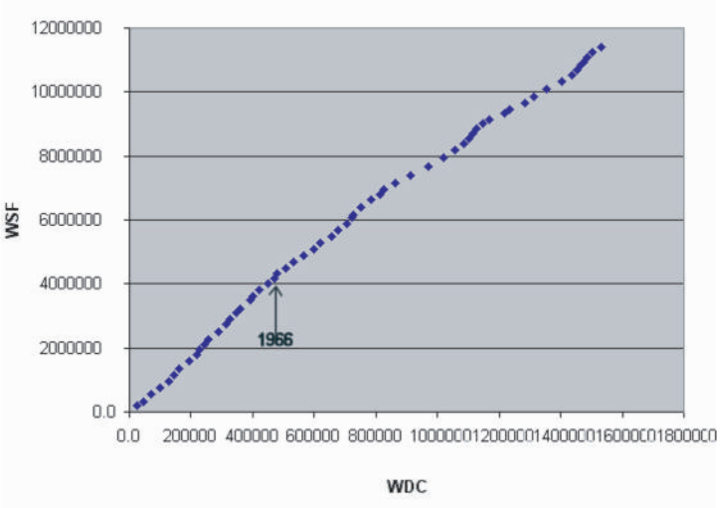

Figure 4. Double Mass Plot of Annual Streamflow, West Divide Creek versus South Fork of White River

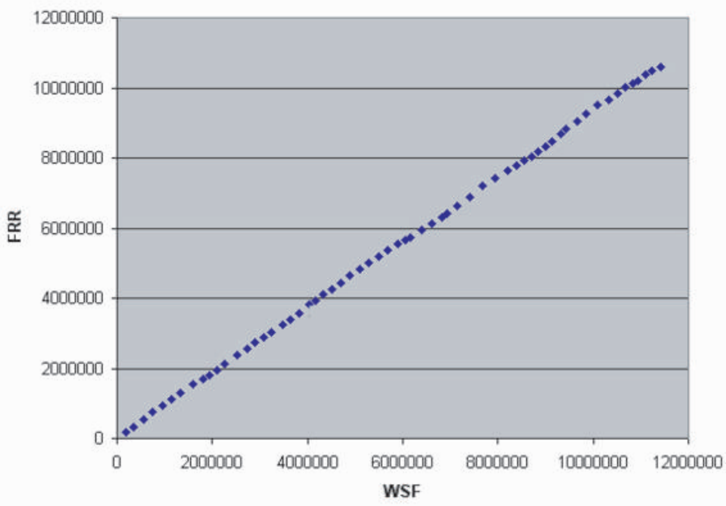

Figure 5. Double Mass Plot of Annual Streamflow, South Fork of White River versus Fryingpan River

natural variability of rainfall and cloud characteristics in space and time, and sees the need for appropriate statistical methods to cope with the problems of uncertainties, for, as expressed by F. Mosteller and J.W. Tukey in 1968, 'One hallmark of the statistically conscious investigator is his firm belief that however the survey, experiment or observational program actually turned out, it could have turned out somewhat differently.' Statistical methods were designed by R.A. Fisher (1960) to handle these problems in connection with the design and analysis of comparative experiments in biological and agricultural research, where large and only partly controllable variability is present. The basic ideas involve (1) *replication*, from which a quantative estimate can be made of the variability of the response to treatment, and (2) *randomization,* a process of allocating treatments to the experimental material by tossing a coin (or equivalent procedure), which may make it possible for the experimenter to attribute whatever effects he observes to the treatment and the treatment only. **Together, these two principles enable one to make a valid assessment of the uncertainty of the result in terms of a probability statement or by setting confidence limits** (emphasis added)."

A reference that explains the ratio statistics methodology as applied by Silverman in his Vail paper is "Ratio Statistics for **Randomized** (emphasis added) Experiments in Precipitation Stimulation (Gabriel, 1999).

Based upon the above, the statement in the Abstract of Silverman's Vail paper, "Evidence for statistically significant (underline added) seeding effects ranging from +6.3 to +28.8% was found for 5 of the 8 seeding targets" is highly questionable. Silverman makes a contradictory statement later in this same paper as follows stating, "It is emphasized that this study is an *a posteriori* evaluation of a non-randomized seeding operation. In addition, this evaluation is an exploratory study that involves consideration of a multiplicity of analyses, some of which are suggested by the results of previous analyses. With such a large number of tests, a few are likely to yield significance strictly by chance. In view of these considerations, the results of the evaluations in this study must be viewed with caution. **It is emphasized that the results should be interpreted as measures of the strength of the suggested seeding effect. From a rigorous statistical viewpoint, the suggested effects that are indicated must be confirmed through new, *a priori*, randomized experiments specifically designed to establish their validity.**" (emphasis added). This self-stated contradiction imposes limitations on the interpretation and statements regarding statistical significance and confidence intervals in Silverman's Vail analysis. Silverman's analysis provides **"estimates"** of the results of cloud seeding but does not provide **"statistical proof"** of the significance of these estimates as strongly implied in this paper. Similar contradictions are found in Silverman's other three recently published papers in the WMA regarding analyses of long-term non-randomized winter cloud seeding programs (Silverman, 2007, 2008, 2009b). Furthermore, the titles of two of the four papers by Silverman use the term "Statistical Evaluation", a term, which NAWC considers misleading, based upon the above discussion.

NAWC believes that the standard historical target/control analysis technique, when applied correctly, is entirely adequate in providing estimates of potential increases due to cloud seeding from long-term, non-randomized programs. More sophisticated techniques, such as those proposed by Silverman (which is actually an adaptation of the historical target/control technique) add little to this standard approach since the data are non-randomized and statements on statistical significance and confidence intervals are therefore not valid. There are several considerations that go into the development of good historical target/control evaluations. Dennis (1980) listed several questions regarding the use of the historical target/control regression technique. These concerns and the approach or approaches that NAWC uses to address each are summarized in the following:

1. "Reliability of the results unless the underlying data sets conform to the normal distribution which, for precipitation data, requires an appropriate data transformation." Quoting from Dennis (1980) "Rainfall observations say for one hour or day at a point, tend to be highly skewed, with most observations near zero and a long tail extending to large amounts." NAWC utilizes longer-term data, either three or four-month cumulative precipitation values or April 1st snow water contents that are also cumulative values. Further, NAWC deals with averages of multiple sites (not a point measurement) for the control and target average values. These data are not highly skewed.

2. "Unconscious bias in the selection of data in post-hoc evaluations." As described in Griffith, et al, 2009, NAWC normally establishes target and control stations for use in its evaluations early in the lifetime of its operational programs. These target and control sites and the resultant regression equations are typically maintained throughout the lifetime of the seeding program. Changes are typically made only if observations are discontinued at one or more target or control sites. As a consequence, NAWC evaluations would be considered *a priori* evaluations.

3. "Difficulty in eliminating residual uncertainties." Dennis (1980) in discussing this concern states, " A number of possible biases are dealt with rather simply. Agreements before a program begins as to which rain gages are to be included in calculating target and control rainfall, for example, go far toward eliminating both unconscious bias and any temptation to select data to demonstrate a desired result (Court, 1960). As discussed in the above, NAWC typically follows this recommendation in evaluating its operational programs usually following the first season of operation.

4. "Representativeness of the target-control relationship and its stability in time." Quoting from Dennis (1980) "The most serious difficulty with the historical regression method has to do with the stability in time of the target-control relationship." ... "Neyman and Scott (1961) have hypothesized that the lack of stability in the target-control relationship is related to the occurrence of specific storm types, some of which favor the target area and some of which favor the control area." ... "The best that can be done appears to follow the criteria noted above for the selection of control areas and to be alert to any obvious changes in weather patterns that could distort the target-control relationship. One must not go to extremes in this regard; obviously, if one looked long enough, one could always find *something* that was different between the historical period and the operational period (Gabriel, 1979)." NAWC has generally attempted to address this concern by careful selection of target and control sites (as described in Griffith, et al, 2009) as recommended by Dennis (e.g. as close to target areas as possible, in areas typically upwind to avoid contamination, and selecting target and control sites at similar elevations). In fact, we often attempt to geographically bracket the target area with control sites in order to address the concern of storms favoring one area over another during specific storms or perhaps extending through an entire season. NAWC interprets the discussion contained in Dennis (1980) to be directed at short time intervals, e.g., individual storm periods. NAWC's evaluations utilize seasonal data over periods of as many seasons as possible for which quality records are available that would be less subject to this concern since storm tracks change from storm to storm and any large departures between two areas are frequently dampened over longer time periods.

In addition to these concerns, the development of good target/control relationships needs to be concerned with the following:

1. Selecting target and control sites with quality data (no breaks in records, no station moves, continuity of data between stations which can be checked utilizing the double mass plotting technique) with adequate periods of not seeded historical data upon which the regression equations may be based.

2. Insuring that neither the cloud seeding program being evaluated nor other cloud seeding programs in the area do not impact the selected control stations either during the historical or seeded periods.

3. Determining which types of data to use. For example, each type of high elevation precipitation measurement technique has various disadvantages (e.g., precipitation gage catch reductions in high winds, drifting snow over snow pillows, snow melt at south facing sites as compared to north facing sites at similar elevations).

4. Achieving good relationships between the target and control sites as evidenced by high correlation coefficients.

NAWC carefully considers the above concerns in the development of evaluations of the operational programs conducted by NAWC.

4. SUMMARY

Silverman's analyses of the Vail Project and seeding projects in California have provided some interesting insights into prospective techniques for estimating the effectiveness of winter orographic cloud seeding efforts. In the case of the Vail analyses, areal averaging of the results for the small project target area provides an estimated 8.4 % increase in annual streamflow, falling within the generally-accepted 5% to 15% range of expected possible effects for that type of project. However, because the Vail and similar California analyses are *a posteriori* and are applied to non-randomized projects, the analyses and their indicated results carry the same caveats as similar analyses conducted by others over the years. Accordingly, the results must be viewed with caution and presented appropriately as indications, and certainly not proof, of seeding effects. Estimations of the effectiveness of non-randomized operational seeding projects are important but challenging. Such efforts must continue and will, no doubt, generate lively debate as they do.

Acknowledgement. Dr. Bernard Silverman provided copies of the streamflow data used in his analyses to North American Weather Consultants.

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REPLY TO THE COMMENTS BY GRIFFITH *ET AL.* ON SILVERMAN'S PAPER ENTITLED "AN INDEPENDENT STATISTICAL EVALUATION OF THE VAIL OPERATIONAL CLOUD SEEDING PROGRAM"

Bernard A. Silverman*, PhD

Consulting Meteorologist, Centennial, CO, USA

Griffith *et al.* (2010) express a number of comments and concerns about Silverman's evaluation of the Vail operational cloud seeding program (Silverman, 2009a). This Reply addresses those comments and concerns in the order in which they were presented in the Comments by Griffith et al.

Griffith *et al.* state that NAWC readily agrees with Silverman's statement, "*Silverman (2007) showed that it is imperative to use as a control or controls,* ***to the extent that available data permits*** ***(emphasis added)****, the streamflow station or stations that yield the most precise results.*", but they go on to say, *"......however, examination of the correlations obtained in this study as provided in Table 4 in The Vail paper (Silverman 2009a) suggests this ideal was not obtained*". They point out that *"The* r^2 *values obtained were significantly lower than those previously obtained by Silverman in the analyses he has performed on long-term Sierra Nevada programs"*

I hasten to point out that, **to the extent that available data permitted**, I used the control with the highest correlation with each target. Of course I would have preferred to use a control or controls with a higher correlation but none were available. Nevertheless, the controls that I did use improved the precision (reduced the standard error of the estimate) of the evaluations considerably. I also hasten to point out that I did draw the reader's attention (on Page 12) to the fact that "*the target-control correlation coefficients for the Vail targets are substantially smaller than those found for the evaluation of the operational seeding programs in the watersheds of the Sierra Nevada Mountains"* The physical reasons why this is the case is a matter worthy of further investigation.

Griffith *et al.* are concerned that the point estimates of the seeding effect at some of the Vail sub-basins (particularly GBH and GPT) are higher than one would expect according to the Weather Modificaiton Association Capability Statement on Weather Modification (WMA, 2005). They speculate as to the cause by saying "*A couple of explanations for these results could be the short historical periods and low correlations for these two sub-basins (as discussed in the above) and/or possible channeling of seeding material during seeded storms favoring these areas".* They also point out that the Vail sub-basins are considerably smaller in area than the areas of the watersheds in most winter cloud seeding programs and suggest that "...... *it is highly unlikely that cloud seeding over a more typical sized winter cloud seeding target area could produce an average increase of 28%* (as estimated for GBH)".

I too was concerned that the point estimates of the seeding effect for some of the Vail sub-basins were much larger than that achieved in similar cloud seeding programs. Therefore, I checked and double-checked the data processing and evaluation calculations to make sure they were accurate. In addition, I followed a suggestion by one of reviewers of the paper and repeated the evaluation of GBH using seven different controls in addition to the primary one that was used (FRR) in order to make sure the result using FRR was not an anomaly. I presented these results in Table 4 of Silverman (2009a). Since the results of the evaluation using the other 7 controls were statistically comparable to the results obtained using FRR as the control, I concluded "*Therefore, it is reasonable to conclude that the estimates of the seeding effect using FRR as the control for all of the targets, as given in Table 3, are statistically credible*".

It is unlikely that the low correlations of GBH and GPT with FRR was the cause of the higher point estimates of the seeding effect than was found in similar cloud seeding programs. The primary effect of lower correlations is to decrease the precision of the estimate (increase its standard error of estimate). Lower correlations can result in an increase as well as decrease in the magnitude of a point estimate (see Table 4 of Silverman, 2009a). In any event, the decrease or increase is very much smaller than the difference between the calculated point estimates and what would expect according to the WMA Capability Statement on Weather Modification (WMA, 2005).

It is also unlikely that the relatively short historical periods for GBH and GPT had an appreciable effect on the point estimates of the seeding effect. The result produced by the bias-adjusted regression ratio method is much less sensitive to the length of the historical period than is the result produced by the

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**Corresponding author*: Dr. Bernard A. Silverman, 7038 E. Peakview Place, Englewood, CO 80111; e-mail: silvermanb@aol.com

historical target/control regression analysis method. The target/control regression relationship in the historical target/control regression method is used to predict what would have occurred in the absence of seeding and is solely dependent on the data for the historical period. On the other hand, the target/control relationship in the bias-adjusted regression ratio method is used to reduce the standard error of the estimate and is based on the data for both the historical period and the usually much longer operational period.

Having established the statistical credibility of the result for GBH I speculated that "*The fact that the seeding effect changes rapidly over the very short distances between seeding targets suggests, as one possible explanation, that the silver iodide nuclei from the ground generators are channeled by the terrain into a focused plume, and not widely dispersed as intended"*. Finally, I agree with the speculation by Griffith et al that it is highly unlikely that cloud seeding over a more typical sized winter cloud seeding target area could produce an average increase as large as that for GBH (28%). I agree, not because it is not scientifically possible, but because it is logistically difficult to seed a more typical sized winter cloud seeding target area as efficiently as the small area of GBH was apparently seeded.

Griffith *et al.* promote the use of double mass plots in the evaluation of cloud seeding programs and illustrate its usefulness in the Vail evaluation. They apply it to the Vail sub-basin area of Upper Gore Creek (GUP) and show how the "breaks" in the plot suggest major changes in seeding effectiveness. They speculate that the double mass approach is more sensitive in suggesting differences in seeding effectiveness than Silverman's technique of plotting the "time evolution of seeding effect". They also illustrate the utility of the double mass plot in selecting target and control sites when using a historical target/control evaluation technique.

I agree that the double mass plot is a useful tool in a target/control evaluation of cloud seeding programs. It can provide useful qualitative information of the type illustrated in the Comment by Griffith *et al.*; however, it cannot provide accurate quantitative estimates of the seeding effect and its statistical characteristics. It should be applied within the limits of its capabilities. I do, however, question whether the double mass plot is more sensitive in suggesting meaningful differences in seeding effectiveness than Silverman's technique of plotting the "time evolution of seeding effect". In comparing the two types of plots, it should be recognized that the double mass plot reflects the year-to-year changes in seeding effectiveness while the time evolution plot reflects how the cumulative evaluation is affected by those year-to-year changes in seeding effectiveness. A potential change in seeding effectiveness or its physical cause cannot be very important if a "break" on the double mass plot signals a possible change in seeding effectiveness and that possible change in seeding effectiveness is not apparent on the time evolution plot. Consider the following example - A double mass plot and time evolution plot for the Pitman Creek (PIT) sub-basin of the San Joaquin operational cloud seeding program is given in Fig. 1 and Fig. 2, respectively. The result for PIT was chosen because ground seeding started in 1951 and was supplemented by aircraft seeding in 1975. Both of these events should show up on the double mass plot and the effect of adding the aircraft seeding should show up on the time evolution plot. Other major changes in seeding effectiveness should show up on both plots. I leave it to the reader to decide which of the two plots best reveals the meaningful differences in seeding effectiveness. In any event, I suggest that both plots should be used. All the tools in our arsenal of analysis techniques should be used to maximize the amount of information that can be obtained.

Griffith *et al.* allege that I make contradictory statements about the estimates of the seeding effect and their statistical meaning in Silverman, (2009a) and in Silverman's other statistical evaluations of long-term, non-randomized winter cloud seeding programs (Silverman, 2007, 2008, 2009b). They also allege that *"Silverman's analysis provides* ***"estimates"*** *of the results of cloud seeding but does not provide* ***"statistical proof"*** *of the significance of these estimates as strongly implied in this paper"*. Furthermore, they claim that my use of the term "Statistical Evaluation" in the titles of 2 of my 4 papers is misleading.

There are no contradictory statements in my presentation of the results. Simply stated, in each of my evaluation papers that they cite, I did the following: 1) I evaluated the operational cloud seeding program(s) using a statistical methodology (ratio statistics) that was empirically tailored (bias-adjusted regression ratio) to provide valid inferences for operational/historical comparisons (non-randomized data) [Note: for Silverman (2009b) I used the Monte Carlo permutation (re-randomization) method which is inherently valid], 2) I presented the resulting estimates of the seeding effect indicating which of the estimates of the seeding effect were statistically significant based on the statistical methodology that was used, and 3) I discussed the caveats associated with each set of results. I did not imply that the results provided **"statistical proof"** of the significance of the estimates of the seeding effect; rather, I concluded each paper with the statement “*From a rigorous statistical viewpoint, the suggested effects that are indicated must be confirmed through new, a priori, randomized experiments specifically designed to establish their validity”* Finally, given the fact that I conducted statistical analyses in my 4 evaluation papers, I fail to understand why anyone would think that the use of the term “Statistical Evaluation” in the titles of 2 of my 4 papers is misleading. A review of the literature will show that it is common practice to use the term “Statistical Evaluation” in the title of papers that describe cloud seeding programs that have been subjected to statistical analyses and evaluations.

Griffith *et al.* state “*NAWC believes that the standard historical target/control analysis technique, when applied correctly, is entirely adequate in providing estimates of potential increases due to cloud seeding from long-term, non-randomized programs. More sophisticated techniques, such as those proposed by Silverman (which is actually an adaptation of the historical target/control technique) add little to this standard approach since the data are non-randomized and statements on statistical significance and confidence intervals are therefore not valid.*’

The reluctance by Griffith*et al.* to accept a more reliable and more robust statistical methodology is inconsistent with the WMA’s recommendation (Boe et al, 2004) that states *“We (WMA) recommend that evaluation techniques presently being applied to operational programs be independently reviewed and as necessary revised to reduce biases and increase statistical robustness to the extent possible. Recognizing that randomization is not considered to be a viable option for most operational seeding programs, we acknowledge there is much room for improvement in most present evaluations, many of which are presently done in-house”.* The historical target/control regression analysis technique does not provide reliable estimates of potential increases due to cloud seeding from long-term, non-randomized programs. I refer the reader to Silverman (2007, 2010) for a thorough analysis of the deficiencies of the historical target/control regression analysis method. A summary of these deficiencies are as follows: 1) it is not robust to departures from the assumptions under which it was derived, 2) lack of robustness affects the reliability and accuracy of the estimates of the seeding effect that it produces, 3) it overestimates the effects of seeding, and 4) it tends to produce appreciably more significant results than it properly should. On the other hand, the ratio statistics analysis technique, that Gabriel (1999) derived for randomized data, is considerably more robust and produces estimates of seeding that are statistically comparable to those from re-randomization analysis through the application of an adjustment factor suggested by Gabriel and Petrondas (1983) to compensate for the bias introduced by using data from a non-randomized program (Silverman, 2007, 2010).

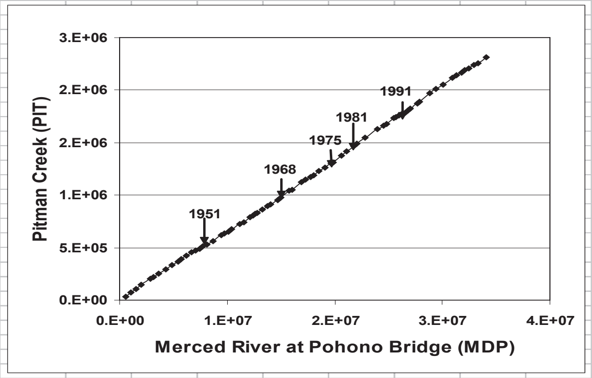

Figure 1. Double mass plot of the target Pitman Creek (PIT) against the control Merced River at Pohono Bridge (MDP) The arrows point to the water year when ground (1951) and aircraft (1975) seeding started, and water years when major changes in seeding effectiveness are evident on the time evolution plot (Figure 2).

The World Meteorological Organization (WMO, 2007) recommends “*Confidence intervals should be included in the statistical analyses to provide an estimate of the strength of the seeding effect so informed judgments can be made about its cost effectiveness and societal significance*”. The point estimates of the seeding effect along with their statements of statistical significance and confidence

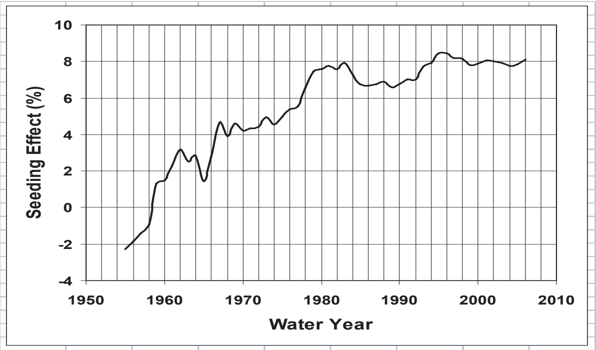

Figure 2. Cumulative year effect of seeding (time evolution of seeding effectiveness) plot for the Pitman Creek (PIT) sub-basin. The seeding is evaluated as a function of the cumulative number of years of seeding, i.e., initially the first 5 seeded years (1951-1955), then the first 6 seeded years (1951-1956), then the first 7 seeded years (1951-1957), ... , and finally all seeded years (1951-2006). The seeding effect calculated for each seeded water year is the value that would have been obtained if the evaluation were done for all seeded years up to and including that water year.

intervals should be provided; however, the limitations of the historical target/control regression technique should be recognized and its associated caveats should be acknowledged. It would be misleading to present a point estimate of the seeding effect without presenting a basis for establishing its statistical significance, i.e., its confidence interval and/or its P-value. This is especially true for the historical target/control regression method which produces point estimates whose reliability and accuracy are questionable. And, of course, statements of statistical significance and confidence intervals are entirely valid if they are determined through re-randomization and those from the bias-adjusted regression ratio are statistically comparable to those from re-randomization.

I disagree with the characterization of ratio statistics as "*an adaptation of the historical target/control technique*". Since ratios are widely used in the evaluation of weather modification experiments, Gabriel (1993) derived the randomization distributions of ratio statistics and the means and the standard errors of the asymptotic distributions of these ratios and their logarithms, distributions that are important to the correct application and interpretation of this type of statistics. In view of the above points, the bias-adjusted regression ratio is considerably more reliable and accurate than the historical target/control regression technique and, therefore, adds a lot more to the analysis. Even better yet would be to use re-randomization analysis, a statistical method of unquestioned validity.

Griffith *et al.* state *"......... because the Vail and similar California analyses are a posteriori and are applied to non-randomized projects, the analyses and their indicated results carry the same caveats as similar analyses conducted by others over the years*."

I most certainly agree with their statement; therefore, I discussed the caveats associated with the results in each of my evaluation papers (Silverman, 2007, 2008, 2009a, 2009b). Given their statement, I find it very interesting that Griffith *et al.* (2009) did not feel that they needed to mention the caveats associated with the results of their statistical evaluation of the Utah operational cloud seeding programs using the historical target/control regression analysis technique. Griffith *et al.* have a problem accepting the results produced by the ratio statistics method, a method that is based on sound statistical principles, but they have no problem with the results produced by the historical target/control regression analysis method, results that they accept without any caveats (Griffith *et al.* 2009). They implicitly accept without any qualifications the unsubstantiated assumption of the historical regression method that the target/control regression relationship derived for the historical period predicts with statistical certainty what would have occurred during the operational period in the absence of seeding.

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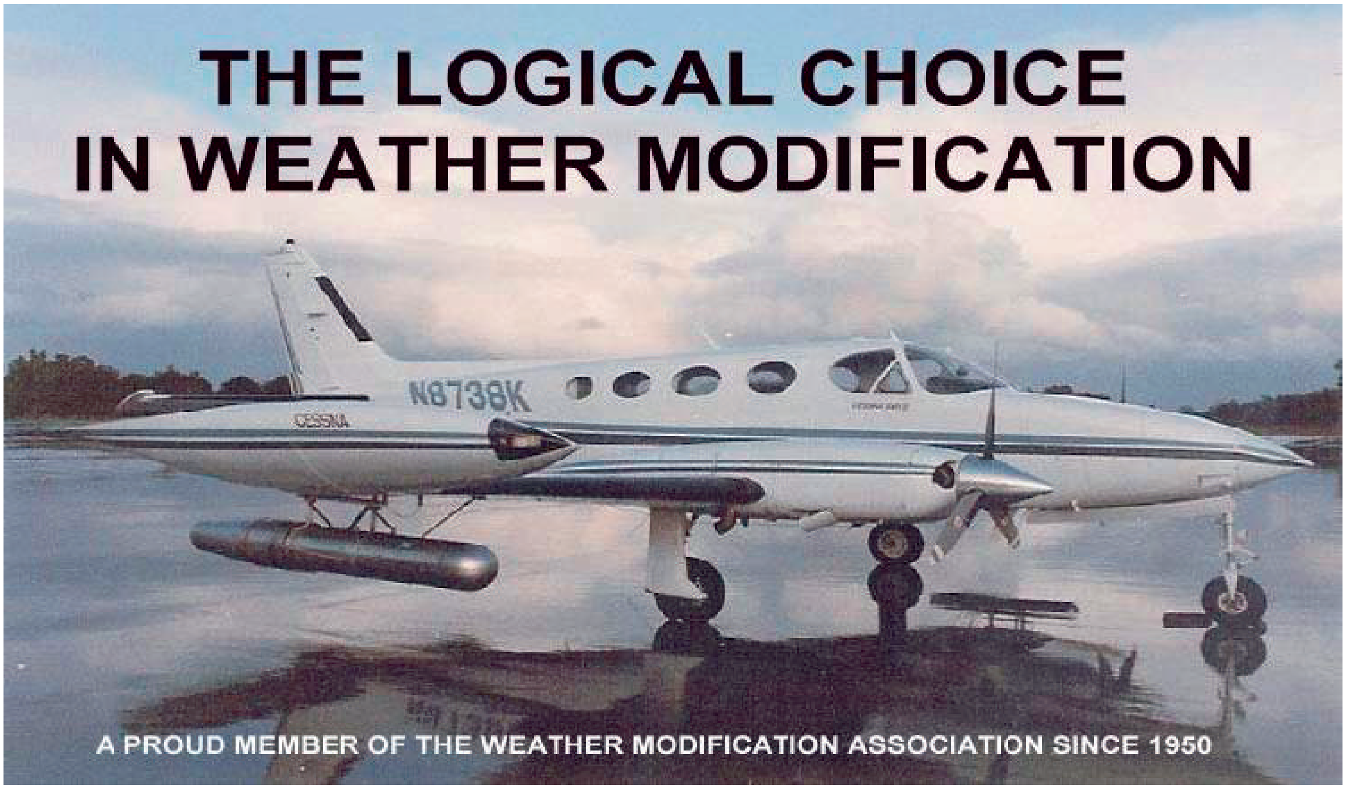

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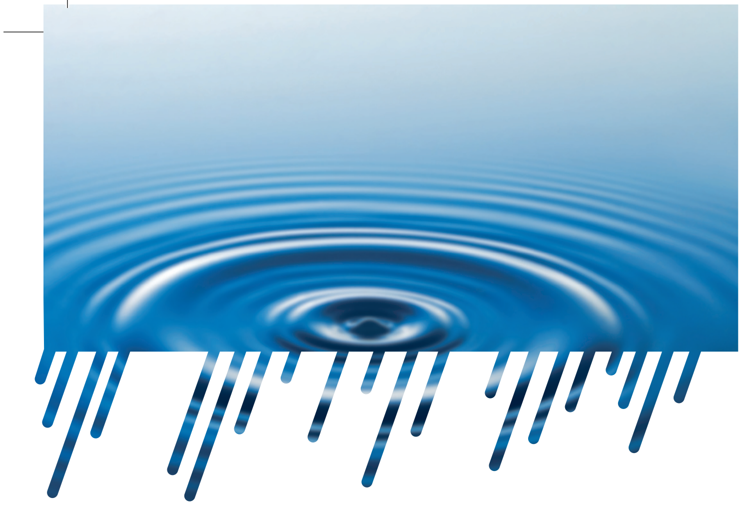

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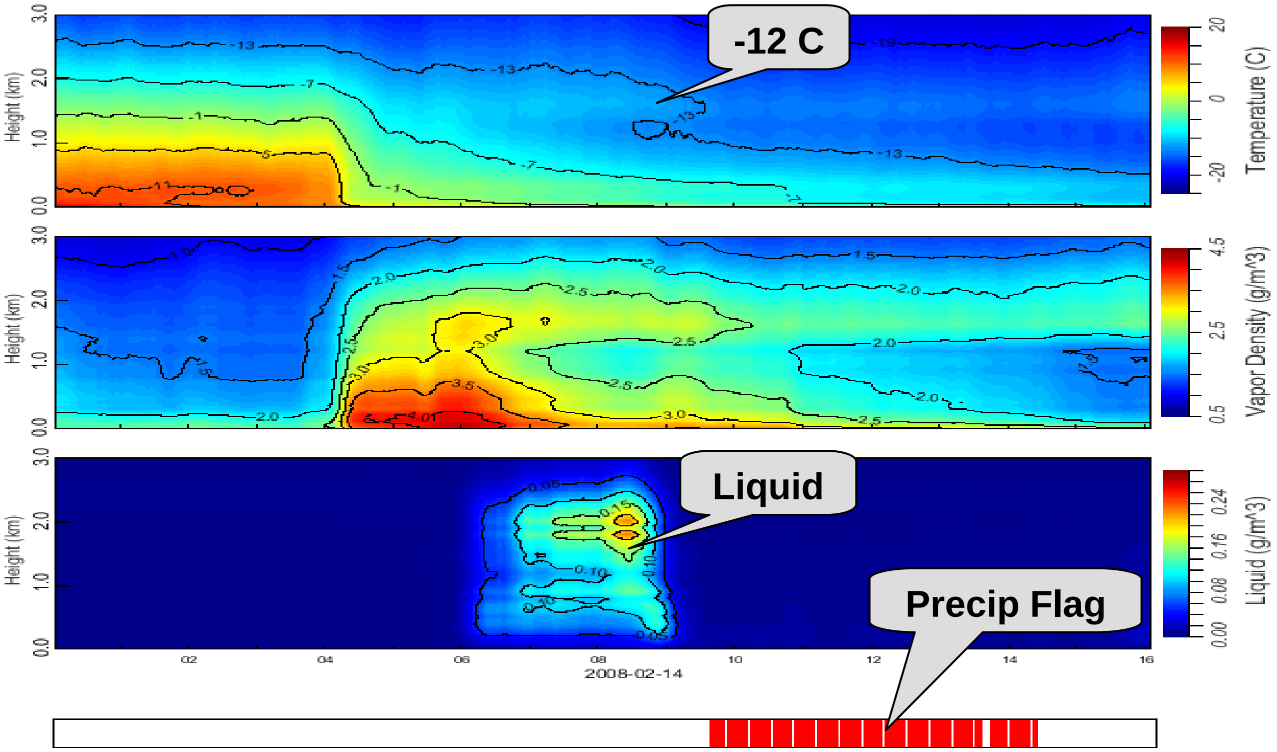
- ***Local or Remote Control and Display via Internet***
- ***Ideal for Cloud Seeding***



Cloud liquid near -12 C is an ideal cloud seeding target. Snowfall is indicated by precipitation flag.

- **Supercooled Liquid Detection**
- **Vapor-Liquid-Ice Transition Sensing**
- **High Productivity Weather Modification**

Dr. Randolph 'Stick' Ware
Chief Scientist, VP Sales
Radiometrics Corporation

303 532-2313 office
303 817-2063 cell
www.radiometrics.com