TARGET/CONTROL ANALYSES FOR SANTA BARBARA COUNTY'S OPERATIONAL WINTER CLOUD SEEDING PROGRAM

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ABSTRACT: An operational winter cloud seeding program has been conducted most winter seasons in the Santa Barbara, California area since 1981. This program has been sponsored by the Santa Barbara County Water Agency (SBCWA). There have typically been two target areas: the Upper Santa Ynez drainage above Cachuma Dam located in the eastern part of Santa Barbara County, and the Twitchell Reservoir drainage (usually referred to as the Huasna-Alamo target area) located in the northern portion of Santa Barbara County and the southern portion of San Luis Obispo County. This operational program was implemented following the completion of the Santa Barbara II research program which provided indications of positive seeding effects from seeding convection bands some of which were statistically significant.

North American Weather Consultants (NAWC) performed an historical target/control analysis of this program for the Santa Barbara County Water Agency in 2013, which had not been attempted previously. This paper summarizes the work that was performed. A search for potential long-term target and control precipitation measurement sites was conducted which identified three acceptable control sites and four acceptable target sites (two in each of the intended target areas). Linear and multiple-linear regression equations were developed for each of the target areas using periods without any cloud seeding in either the control or target areas. Relatively high correlations were obtained between the control and target sites with r^2 values ranging from 0.84 to 0.91.

When these regression equations were used to predict the amount of precipitation for the December-March period for the two target areas during seeded seasons, and then compared to the actual amounts of precipitation, the average results for all the seeded seasons were:

- Upper Santa Ynez Target Area: Estimated increases of 19% to 21% from the linear and multiple-linear equations (24 seeded seasons).
- Huasna-Alamo Target Area: Estimated increases of 9% from both the linear and multiple-linear equations (27 seeded seasons).

1. INTRODUCTION AND BACKGROUND

An operational winter cloud seeding program has been conducted most winter seasons since 1981 sponsored by the Santa Barbara County Water Agency (SBCWA). There have typically been two target areas: the Upper Santa Ynez drainage above Cachuma Dam located in the eastern part of Santa Barbara County, and the Twitchell Reservoir drainage (usually referred to as the Huasna-Alamo target area) located in the northern portion of Santa Barbara County and the southern portion of San Luis Obispo County (Figure 1). For reference purposes, the distance between Lompoc and Santa Maria is 22 miles. The operational program has typically used both airborne and ground based seeding modes to target convection bands as they approach then pass over the two target areas. This operational program was implemented following the completion of the Santa Barbara II research program which provided indications of positive seeding effects from seeding convection bands some of which were statistically significant. Griffith, et al, 2005 provides an overview of the Santa Barbara II experiment and a discussion of the operational seeding program covering the 1981 – 2004 period. This operational program has continued to the present. Earlier references on the Santa Barbara II research program include: Elliott, et al, 1971 and Thompson, et al, 1975.

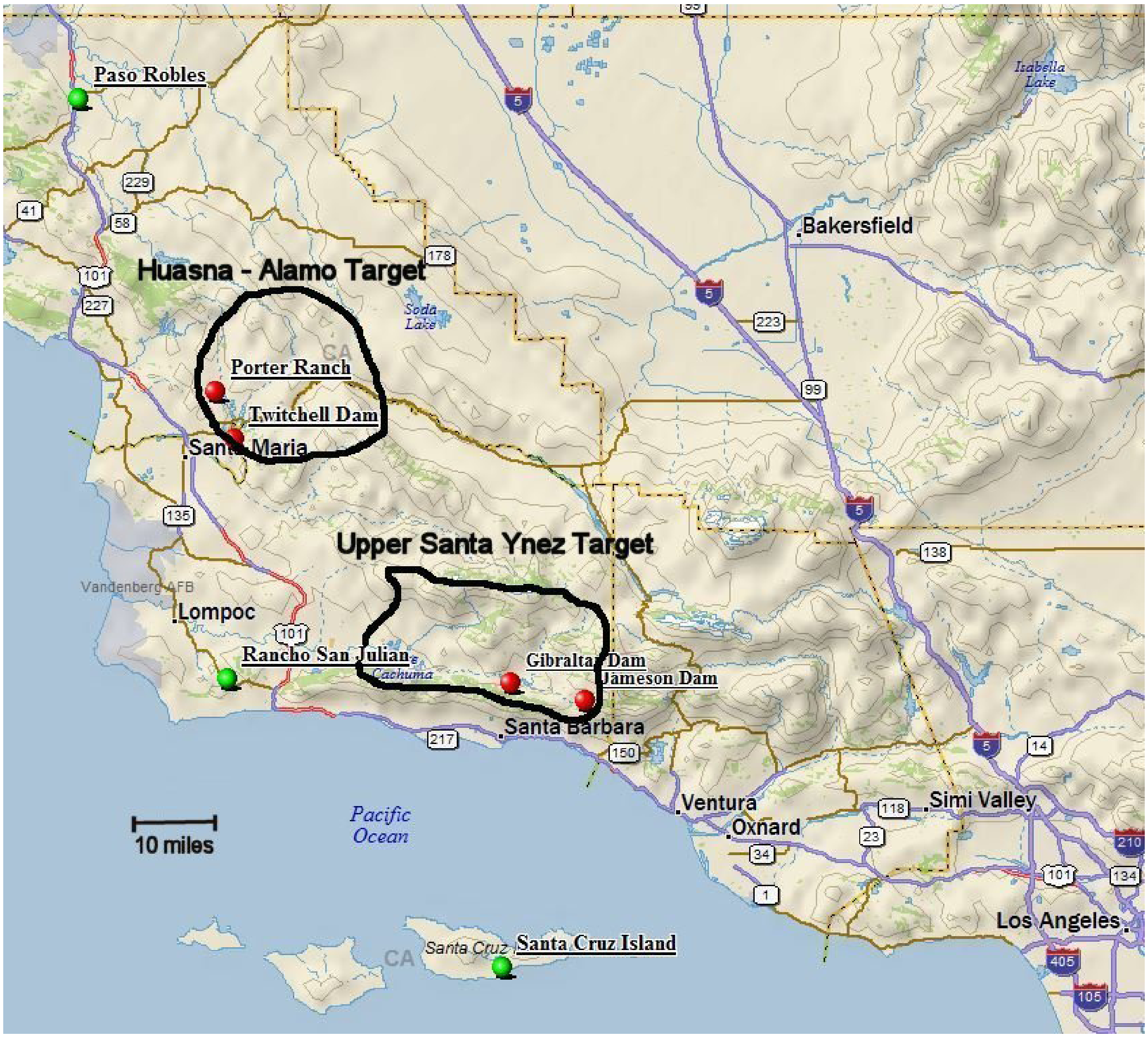

Figure 1: Map of the Two Cloud Seeing Target Areas and the Locations of Precipitation Control Sites (green) and Target Sites (red).

The task of determining the effects of cloud seeding has received considerable attention in recent years. Evaluating the results of a cloud seeding program for a single season is rather difficult, and such results should be viewed with appropriate caution. This difficulty stems from the large natural variability in the precipitation occurring in a given area from season to season, and between one area and another during a given season, and the relatively modest increases in precipitation that can be attributed to cloud seeding. Since cloud seeding is normally feasible only when existing clouds are near to (or already are) producing precipitation, it is not usually obvious if and how much the precipitation was actually increased by seeding due to this large natural variability. The ability to detect a seeding effect becomes a function of the magnitude of the seeding increase and the number of seeded events, compared with the natural variability in the precipitation pattern. Larger seeding effects can be detected more readily and with a smaller number of seeded cases than are required to detect smaller increases. Despite the difficulties involved, some techniques are available for evaluation of the effects of operational seeding programs. These techniques are not as rigorous or scientifically desirable as is the randomization technique used in research programs (e.g., the Santa Barbara II program), where typically about half the “seedable” storm events are randomly left unseeded. Most sponsors of operational cloud seeding programs do not wish to reduce the potential benefits of a cloud seeding program by half in order to better document the effects of the cloud seeding project. The less rigorous techniques do, however, offer helpful indications of the long-term effects of seeding on operational programs (Silverman, 2007, 2009 and 2010).

NAWC employs an historical target/control analysis to evaluate our operational cloud seeding programs (e.g., Griffith et al, 2009; Griffith et al, 2011). The target/control technique is one described by Dennis (1980). This technique is based on selection of a variable that would be affected by seeding (such as precipitation or snow water content). Records of the variable to be tested are acquired for an historical period of as many years duration as possible. Dennis (1980) suggests the need for a sufficient number of not seeded events (perhaps 30 or more) in order to assume the values are normally distributed. These records are partitioned into those located within the designated “target” area of the project and those in nearby “control” areas. Ideally, the control sites should be selected in areas meteorologically similar to the target area but unaffected by the seeding (or seeding from any other nearby projects). The historical data (e.g., precipitation and/or snow water content) in both the target and control areas are taken from past years that have not been subject to cloud seeding activities. These historical data are evaluated for the same seasonal period of time as when the seeding was later conducted. The target and control sets of data for the unseeded seasons are used to develop a linear or sometimes multiple-linear regression equation that can be used to predict the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then applied to the seeded period to estimate what the target area precipitation should have been without seeding, based on the control area precipitation. This allows a comparison to be made between the predicted seasonal target area precipitation and the actual observed precipitation that occurred during the seeded period to look for any differences potentially caused by the seeding activities. Typically the observed precipitation amounts are divided by the predicted amounts. If this ratio is greater than 1.0, there is an indication of more precipitation in the target area than that predicted from the control area precipitation. This technique had not been previously attempted by NAWC for the Santa Barbara operational program for the following reasons:

- Most storms that impact Santa Barbara County during the winter typically move from west to east so <u>upwind</u> control areas would preferably be over the Pacific Ocean.
- The seeding during the operational program might occasionally impact areas in Santa Barbara County outside the target areas, which could impact potential control sites.

These conditions would suggest that the best control areas (those not impacted by seeding) would be west or southwest of Santa Barbara County. Obviously this is not possible since these areas are over the Pacific Ocean (see Figure 1). If control sites were used that might be impacted by the cloud seeding and the seeding was effective, this would potentially raise the control area precipitation amounts during seeded periods. If these control amounts were entered into the regression equation or equations for the seeded periods, they would over-predict the amount of the estimated target precipitation. This would in turn lower the ratio of observed over predicted precipitation. In other words, this would cause an underestimate of any seeding effects.

2. SELECTION OF CONTROL AND UPPER SANTA YNEZ TARGET SITES

Given the above as background, NAWC in conjunction with SBCWA, conducted a search for possible long-term precipitation measurement sites which could be used to estimate potential seeding results from the SBCWA long-term cloud seeding program. Control sites were sought that would have minimal or no impact from the seeding program. Due to the long history of seeding operations in Santa Barbara County, with research and operational programs conducted during most years since 1950, sites with long and reliable records were identified for this analysis. This would provide a significant amount of historical data which would exclude the seeded periods from which historical regression equations could be developed. Dennis (1980) suggests the need for a sufficient number of not seeded events (perhaps 30 or more) in order to assume the values are normally distributed. NAWC's experience has been that longer historical records (preferably greater than 20 historical seasons without any seeding activity) lead to more representative regression equations for the evaluation of seasonal programs.

For the Santa Ynez target in eastern Santa Barbara County, monthly rainfall records (expressed in inches of precipitation) from Gibraltar Dam and Jameson Reservoir were available dating back to 1926 making these sites potentially suitable target sites. A search for potential control sites in Santa Barbara County identified the following possibilities: 1) Santa Barbara, 2) Rancho San Julian in southwestern Santa Barbara County, 3) Santa Cruz Island, 4) Betteravia, 5) Los Alamos, 6) Santa Maria and 7) Guadalupe. A site in San Luis Obispo County (Paso Robles) was also identified as a possible control site. All these sites had monthly precipitation data dating back to 1920 or before, although the Paso Robles site only had consistent data back to the 1926 water year. Of potential interest, the average annual water year rainfall for the 95 year period of record at Gibraltar Dam is 26.59″ with a maximum value of 73.12″. This site is in a favored location for orographic enhancement of rainfall due to the west-east oriented Santa Ynez Mountains ridgeline located a few miles south of this site and frequent strong low-level southerly winds being present in winter storms that impact the area.

After several quality control checks of the data available from these sites plus consideration of which possible control sites might be impacted by seeding, three control sites were selected: Rancho San Julian, Paso Robles, and Santa Cruz Island. In a similar fashion two target sites were selected: Gibraltar Dam and Jameson Reservoir. Figure 1 depicts the locations of these control and target sites. It can be seen from Figure 1 that the three control sites bracket the target area, a feature that has been found to provide better correlations between control and target areas.

These sites are maintained by public agencies (e.g., the SBCWA) with their own quality control procedures. For purposes of quality control of the precipitation data for this analysis, NAWC utilized an engineering tool known as a double-mass plot. These plots compare the historical trend between two given sets of data and help to identify any break points (i.e. change in slope of the line) that may indicate a long-term change in the relationship between the two data sets. NAWC has previously used this technique in selecting target and control sites for evaluations of a number of operational cloud seeding programs (e.g., Griffith, et al, 2009). In this application, if there is a break in the plots, it could be due to a site move, change in equipment used at the site, effects of cloud seeding programs, change in vegetation around the site over time, or other unknown reasons. Double mass plots are scatterplots of cumulative (in this case, precipitation) data for two sites over some time period. This technique was applied to sites tentatively identified as potential control or target sites. Figure 2 is an example of a double-mass plot showing a distinct change in the relationship between the control site average and a potential target site (West Big Pine) for the December-March period, but without any correspondence to the timing of a cloud seeding program. This break occurred in Water Year 1994 for unknown reasons. Figure 3 is an example of a plot where the relationship is not perfect, but there does not appear to be any significant change in the relationship between the two sites over time.

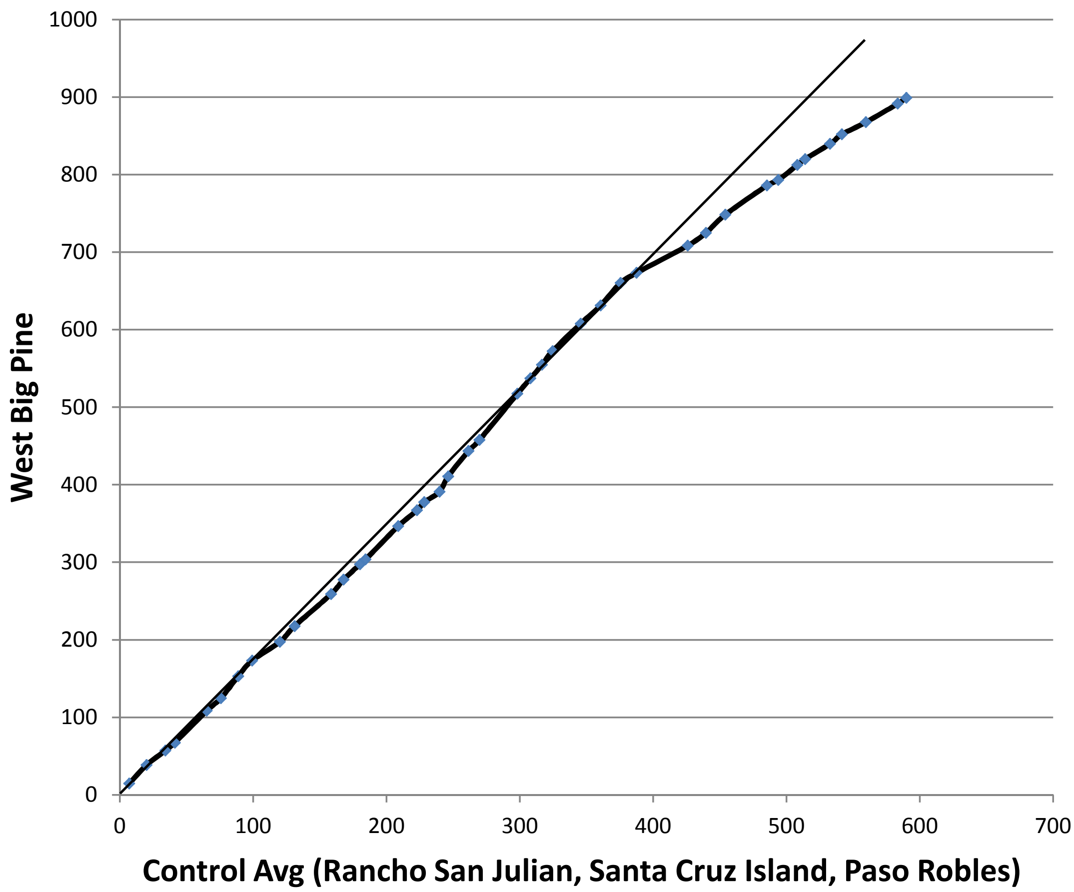

Figure 2: Double Mass Plot of West Big Pine December to March Precipitation versus the Average December to March Precipitation from Three Control Sites. A trend line has been added to illustrate the break in the plot.

Double-mass plots were used to eliminate some sites from consideration, due to long-term changes which did not correspond with the timing (beginning or end) of any cloud seeding programs. The remainder of the control sites (which would be largely unaffected by seeding) showed very similar patterns in terms of their long-term history, suggesting the data from those sites are of good quality for this analysis. Similar comparisons between target sites (which would have been affected by seeding after a certain point in time) also showed good agreement for the sites that were utilized. This gives confidence that the sites which exhibited different long-term trends in the double-mass plots (such as West Big Pine) were indeed outliers from the bulk of the data set and likely not reliable enough for use in the target/control analysis.

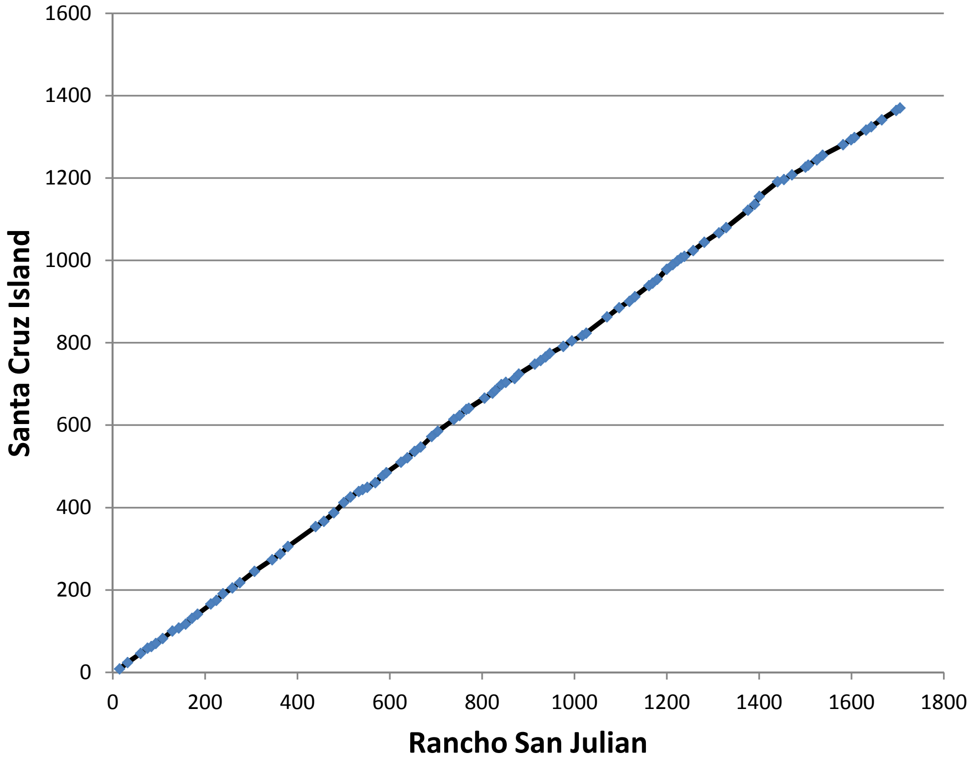

Figure 3: Double Mass plot of December to March Precipitation at Santa Cruz Island versus December to March Precipitation at Rancho San Julian.

3. SELECTION OF CONTROL AND HUASNA-ALAMO TARGET SITES

It was decided that the same three control sites identified for use in the Upper Santa Ynez target evaluation would be used in the Huasna-Alamo target evaluation e.g., Rancho San Julian, Paso Robles, and Santa Cruz Island based principally on the relatively high r^2 values obtained in the regression equations, plus a consideration of the sparcity of potential control gauges with long historical records. There were two sites in the target area that had publically available data: Shell Peak, which only had records dating back to the 1992 water year and was therefore rejected, and Twitchell Dam. Checks on the data quality from the Twitchell Dam site indicated that the data were of good quality for use in the analysis. Unfortunately, historical data from this site only dates back to water year 1963 which is a much shorter record than that of the two target sites used in the Upper Santa Ynez target area evaluation. Lacking suitable alternatives, the Twitchell Dam site was selected as a target site. Of potential interest, the average annual water year rainfall for the 52 year period of record at Twitchell Dam is 18.01″ with a maximum value of 47.11″. This site is further removed from the Santa Ynez ridgeline and consequently is subject to less orogaphic influence during storm periods.

SBCWA personnel suggested another possible target site. This site was located on the Porter Ranch in southern San Luis Obispo County within the intended target area (refer to Figure 1). It was found that there were some long-term precipitation observations available from this site that dated back to the 1952 water year. These observations had been made by members of the Porter family. It was discovered that there were only hand-written records available from this site. Due to the very desirable location of this site, it was arranged to borrow these hand written records. Monthly totals from this site were then digitized. It should be understood that data from this site were not collected and quality checked as would be the case of such public records as those from the Twitchell Dam site. Quality control checks (double mass plots) with other nearby sites indicated that these records appeared to be stable. It was decided to include data from this site in the evaluation which provided the evaluation with two target sites (the same number as the Upper Santa Ynez evaluation).

4. DEVELOPMENT OF THE REGRESSION EQUATIONS FOR THE UPPER SANTA YNEZ TARGET AREA

Development of target/control regression equations involves comparisons of the control site data to target site data (either a single target site or an average of target area data). In this case, all three control sites were used to develop regression equations for the historical (either pre-1951 or other not-seeded) seasons for the target area. For this evaluation, a sum of December-March precipitation was used for each not-seeded season. The December-March period was chosen because it was judged to be most representative of when seeding normally occurred during the operational seasons.

There were two basic types of regression equations that were developed: Linear regression, which averages the data from the three control sites to compare to that of the average of the two target sites; and multiple-linear regression, which considers each control site separately versus the average of the two target sites. The linear regression equation contains only a slope and offset term (of the form y= ax + b), while the multiple-linear regression contains a coefficient (or multiplier) term for each control site, plus an offset term. Both of these equations were based on the same set of historical seasons (water years 1926-1950; 1956-57; 1961-67; 1974-75; 1977; 1980-81; 1984; 1986; 2008-2009; 2012), a total of 44 seasons during which no seeding was conducted to impact the Upper Santa Ynez target area. Water years 1920-25, 1976, and 1979 had some missing data at one or more control sites and were not used. Other intervening seasons had either research or operational seeding programs conducted in the County.

The linear regression equation that was developed was:

(1) $y = 1.27x + 0.82$

where y is the predicted average Gibraltar/Jameson December – March precipitation and x is the average value of the three control site's December - March precipitation. The r^2 value was 0.84, which is a measure of the accuracy of the predictions (the variance). A perfect prediction would have an r^2 value of 1.0. The 0.84 value would be considered to represent a reasonably high correlation between the target and control sites. This equation had a standard error of 4.2″.

The multiple-linear regression equation was:

(2) y = + 0.71(Rancho San Julian) + 0.62 (Paso Robles) - 0.03 (Santa Cruz)+ 0.19

The r^2 value was 0.86, which is nearly the same as that obtained with the linear regression equation. This equation had a standard error of 4.1″.

5. DEVELOPMENT OF THE REGRESSION EQUATIONS FOR THE HUASNA-ALAMO TARGET AREA

As in the Upper Santa Ynez evaluation, linear and multiple-linear regression equations were developed. Both of these equations were based on the same set of 12 historical seasons (water years 1963-67, 74-75, 77, 80-81, 86, and 2008) during which no seeding was conducted to impact the Huasna-Alamo target area. The limited number of not-seeded seasons was determined by the shorter period of record that was available from the Twitchell Dam site. Water years 1976 and 1979 had some missing data at one or more control sites and were not used. Other intervening seasons either had research or operational seeding programs conducted in the County. A longer historical period than 12 seasons would have been highly desirable. The same December-March period was used in the development of these equations.

The linear regression equation that was developed was:

(3) $y = 0.87x + 0.36$

where y is the predicted average Twitchell Dam/ Porter Ranch average December - March precipitation and x is the average value of the three control site's December - March precipitation. The r^2 value of 0.87 indicates a reasonably high correlation exists between the target and control sites. This equation had a standard error of 2.0″.

The multiple-linear regression equation that was developed was:

(4) $y = 0.62$ (Rancho San Julian) + 0.15 (Paso Robles) + 0.15 (Santa Cruz) + .20

The r^2 value was 0.91, which is nearly the same as that obtained with the linear regression equation. This equation had a standard error of 1.8″.

Due to the uncertainty about the quality of the data from the Porter Ranch site, NAWC also developed linear and multiple-linear equations based solely on the Twitchell Dam data. The linear regression equation was:

(5) $y = 0.79x + 0.16$

with an r^2 value of 0.77 and a standard error of 2.4″.

The multiple-linear regression equation was:

(6) $y = 0.63$ (Rancho San Julian) + .18 (Paso Robles) – 0.10 (Santa Cruz) – 0.50

with an r^2 value of 0.87 and a standard error of 2.0″.

6. APPLICATION OF THE REGRESSION EQUATIONS TO EXAMINE POSSIBLE SEEDING EFFECTS IN THE UPPER SANTA YNEZ TARGET AREA

Once the regression equations were established, they were applied to seasons with operational seeding activities that targeted the Upper Santa Ynez target area (water years 1985; 1987-2007; 2010-11), a total of 24 seasons. No 2013 data had been obtained for Santa Cruz Island and therefore water year 2013 was not included.

The predicted value for each December – March season was compared to the observed value. This was done by dividing the observed values by the predicted values. If the resulting ratio was greater than 1.0, this would indicate more precipitation was observed than predicted at the target sites. Ratios less than 1.0 would indicate less precipitation than predicted.

In this evaluation, both the linear and multiple-linear regression evaluations yielded similar results. Table 1 provides the individual seeded season results from the linear regression equation. The resultant average observed/predicted ratios for the combination of the 24 seeded seasons was 1.21 for the linear equation and 1.19 for the multiple-linear equation. These ratios suggest an average 21% or 19% precipitation increase for the December – March period at Gibraltar Dam and Jameson Reservoir in the seeded seasons. These results are equivalent to an average of 4.3 or 4.0 inches of additional December – March rainfall based on the linear and multiple-linear equations, respectively. Possibly of interest is the observation that there were 13 ratios greater than 1.0 and 9 ratios that were less than 1.0.

Figure 4 was prepared to provide a graphic display of the indicated results from the linear regression equation. This figure indicates the variability of the results.

Table 1: Linear Regression Seeded Seasons Results, December-March Precipitation, Gibraltar Dam and Jameson Reservoir, Upper Santa Ynez Target Area.

Water Year	Control Average (inches)	Target Average (inches)	Target Predicted (inches)	Ratio Obs. / Pred.	Difference (inches)
1985	8.79	11.87	11.98	0.99	-0.11
1987	10.52	9.80	14.17	0.69	-4.37
1988	9.04	16.48	12.30	1.34	4.18
1989	6.90	12.45	9.57	1.30	2.88
1990	5.26	10.56	7.50	1.41	3.06
1991	15.54	30.46	20.55	1.48	9.91
1992	19.05	40.35	25.01	1.61	15.34
1993	26.42	54.59	34.36	1.59	20.23
1994	12.02	17.88	16.07	1.11	1.80
1995	38.37	60.37	49.52	1.22	10.85
1996	13.65	18.75	18.15	1.03	0.60
1997	14.48	15.77	19.20	0.82	-3.44
1998	31.26	58.63	40.50	1.45	18.13
1999	8.56	11.59	11.68	0.99	-0.10
2000	13.38	23.22	17.80	1.30	5.42
2001	20.41	30.81	26.73	1.15	4.07
2002	5.06	4.97	7.24	0.69	-2.27
2003	13.21	14.89	17.58	0.85	-2.69
2004	10.49	12.84	14.14	0.91	-1.30
2005	30.03	57.65	38.94	1.48	18.70
2006	14.31	20.83	18.98	1.10	1.84
2007	5.83	7.68	8.22	0.93	-0.54
2010	17.99	22.68	23.65	0.96	-0.98
2011	23.78	33.16	31.01	1.07	2.15
Seeded Mean	**15.60**	**24.93**	**20.62**	**1.21**	**4.31**

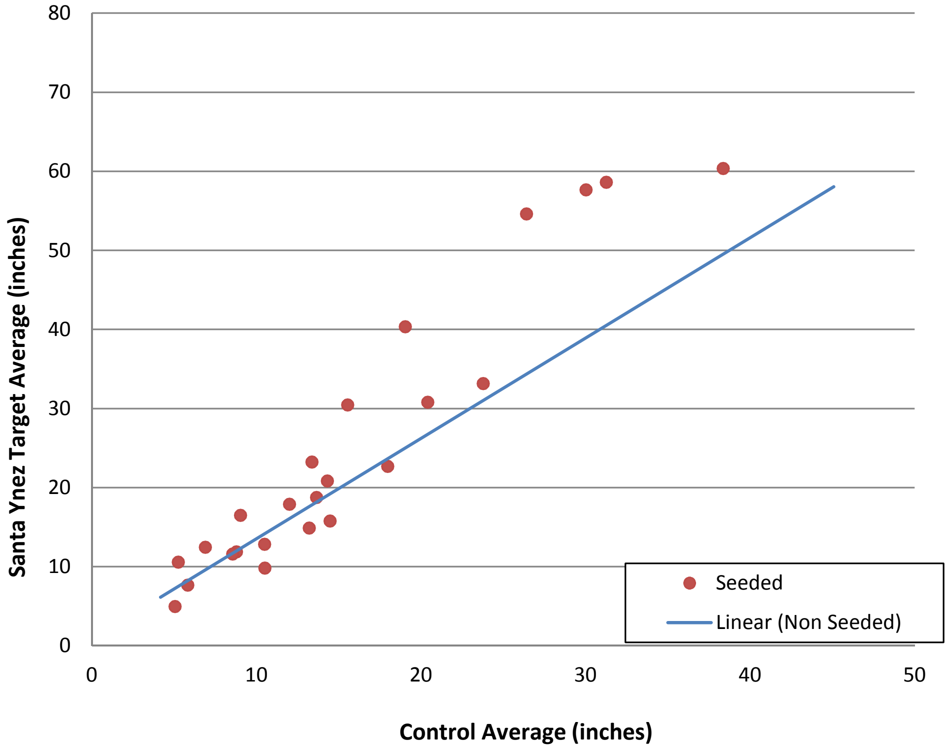

Figure 4: Plot of the Average Upper Santa Ynez Target Area Precipitation versus the Average Control Area Precipitation for the December-March Seeded Seasons. The diagonal blue line is the best fit linear regression line for the not-seeded seasons.

7. APPLICATION OF THE REGRESSION EQUATIONS TO EXAMINE POSSIBLE SEEDING EFFECTS IN THE HUASNA-ALAMO TARGET AREA

Once the regression equations were established, they were applied to seasons with operational seeding activities that targeted the Huasna-Alamo. A total of 27 years with operational seeding were evaluated for the Huasna-Alamo target (water years 1984-85, 1987-2007, and 2009-2012), similar to the Santa Ynez target except with the addition of water years 1984, 2009, and 2012 in which years only the Huasna-Alamo target was seeded. No 2013 data had been obtained for Santa Cruz Island and therefore water year 2013 was not included.

In this evaluation, both the linear and multiple-linear regression evaluations yielded the same average result for the combined Twitchell Dam and Porter Ranch average precipitation; a ratio of 1.09 for the 27 seeded seasons. Table 2 provides the individual seeded season results. These ratios suggest an average 9% precipitation increase for the December – March period when the Twitchell Reservoir and Porter Ranch data were averaged together. These results are equivalent to approximately an average of 1.1 inches of additional December – March rainfall based on the linear and multiple-linear equations. The individual season results are again rather variable even with relatively high r^2 values. Figure 5 was prepared to provide a graphic display of the indicated results from the linear regression equation. This figure indicates the variability of the results. Possibly of interest is the observation that there were 21 ratios greater than 1.0 and 6 ratios less than 1.0.

Due to uncertainties about the quality of the Porter Ranch precipitation data, calculations were made of the apparent impacts on just the Twitchell Dam precipitation gauge site. The indicated average results for that site are the same for both the linear and multiple-linear equations (a positive 17%). Table 3 provides the individual seeded season results. This 17% value is closer to the average ratios that were obtained in the Upper Santa Ynez evaluation (19 – 21%). The estimated average increase was 1.9 inches of water.

Table 2: Linear Regression Seeded Seasons Results, December-March Precipitation, Twitchell Dam and Porter Ranch Sites, Huasna-Alamo Target Area.

Water Year	Control Average (inches)	Target Average (inches)	Target Predicted (Inches)	Ratio Obs. / Pred.	Difference (inches)
1984	6.09	5.81	5.63	1.03	0.18
1985	8.79	10.12	7.97	1.27	2.15
1987	10.52	11.33	9.47	1.20	1.86
1988	9.04	9.09	8.19	1.11	0.90
1989	6.90	10.48	6.33	1.65	4.14
1990	5.26	6.37	4.91	1.30	1.45
1991	15.54	15.34	13.82	1.11	1.52
1992	19.05	14.97	16.86	0.89	-1.89
1993	26.42	23.16	23.24	1.00	-0.08
1994	12.02	10.46	10.76	0.97	-0.30
1995	38.37	26.83	33.59	0.80	-6.76
1996	13.65	19.19	12.18	1.58	7.01
1997	14.48	16.60	12.90	1.29	3.70
1998	31.26	30.72	27.43	1.12	3.29
1999	8.56	11.98	7.77	1.54	4.21
2000	13.38	17.18	11.94	1.44	5.24
2001	20.41	17.65	18.04	0.98	-0.39
2002	5.06	6.65	4.74	1.40	1.91
2003	13.21	10.56	11.79	0.89	-1.24
2004	10.49	10.30	9.45	1.09	0.85
2005	30.03	18.98	26.37	0.72	-7.39
2006	14.31	16.21	12.75	1.27	3.45
2007	5.83	6.95	5.40	1.29	1.55
2009	8.88	9.08	8.05	1.13	1.03
2010	17.99	16.15	15.93	1.01	0.22
2011	23.78	24.85	20.95	1.19	3.89
2012	6.54	6.43	6.02	1.07	0.40
Seeded Mean	**14.66**	**14.20**	**13.05**	**1.09**	**1.14**

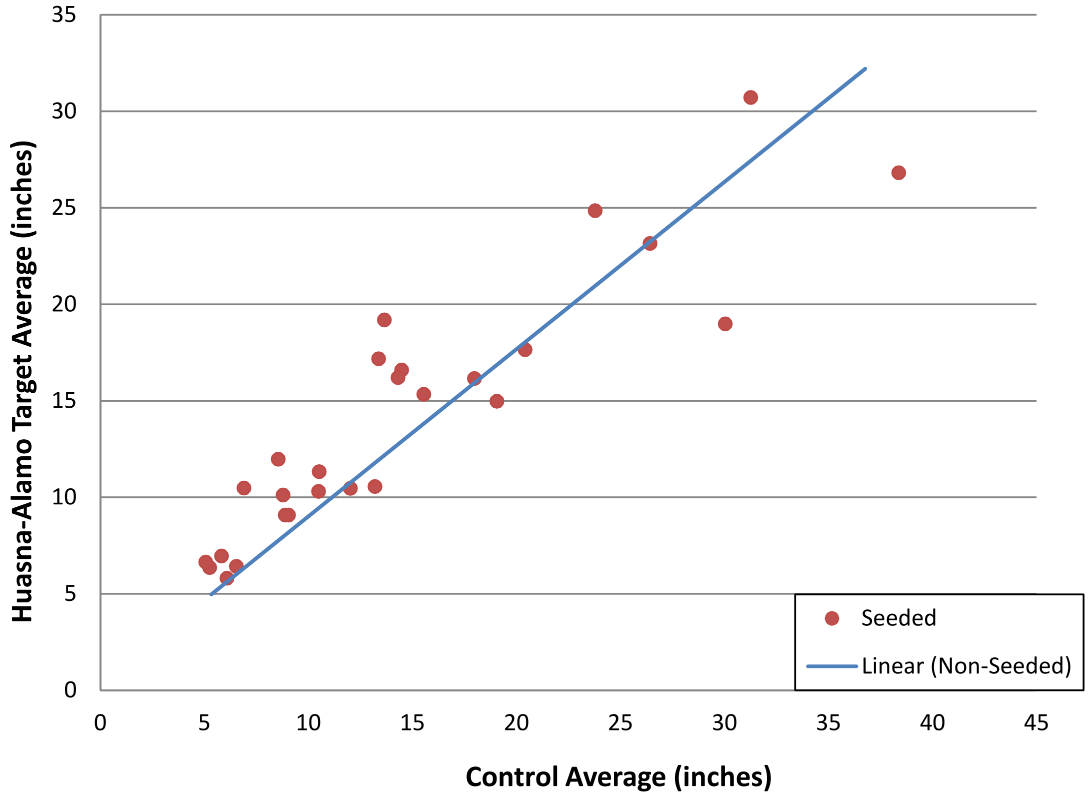

Figure 5: Plot of the Average Huasna-AlamoTarget Area Precipitation versus the Average Control Area Precipitation for the December-March Seeded Seasons. The diagonal blue line is the best fit linear regression line for the not-seeded seasons.

Table 3: Linear Regression Seeded Seasons Results, December-March Precipitation, Twitchell Dam, Huasna-Alamo Target Area.

Water Year	Control Average (inches)	Target Average (inches)	Target Predicted (inches)	Ratio Obs. / Pred.	Difference (inches)
1984	6.09	5.26	4.94	1.06	0.32
1985	8.79	10.16	7.07	1.44	3.09
1987	10.52	10.66	8.43	1.26	2.23
1988	9.04	8.03	7.27	1.11	0.76
1989	6.90	10.06	5.58	1.80	4.48
1990	5.26	6.98	4.29	1.63	2.69
1991	15.54	13.74	12.38	1.11	1.36
1992	19.05	14.61	15.14	0.96	-0.53
1993	26.42	22.85	20.94	1.09	1.91
1994	12.02	9.95	9.61	1.04	0.34
1995	38.37	26.42	30.33	0.87	-3.91
1996	13.65	18.48	10.89	1.70	7.59
1997	14.48	15.38	11.55	1.33	3.83
1998	31.26	30.44	24.74	1.23	5.70
1999	8.56	12.53	6.89	1.82	5.64
2000	13.38	18.23	10.68	1.71	7.55
2001	20.41	17.03	16.21	1.05	0.82
2002	5.06	6.36	4.14	1.54	2.22
2003	13.21	9.30	10.54	0.88	-1.24
2004	10.49	9.52	8.41	1.13	1.11
2005	30.03	17.75	23.78	0.75	-6.03
2006	14.31	13.79	11.41	1.21	2.38
2007	5.83	6.65	4.74	1.40	1.91
2009	8.88	8.81	7.14	1.23	1.67
2010	17.99	14.99	14.30	1.05	0.69
Seeded Mean	**14.66**	**13.62**	**11.69**	**1.17**	**1.94**

8. SUMMARY AND DISCUSSION OF INDICATED RESULTS

8.1 Indications for the Upper Santa Ynez Target Area

Three control sites (Rancho San Julian, Paso Robles and Santa Cruz Island) and two target sites (Gibraltar Dam and Jameson Reservoir) with long-term records dating back to 1926 were identified that were used to develop both regression equations. Control sites were selected from areas that were expected to have minimal seeding impacts during the seeding seasons. More control and target sites would have been desirable but choices were limited due to the need for long term records and for the control site locations to be in areas not expected to be affected by the cloud seeding activities. Long-term records were desired since there have been a number of seeding projects conducted in Santa Barbara County that date back to the 1950's. These years had to be excluded due to the unknown impacts of these programs on precipitation in the operational program's target areas. Linear and multiple-linear regression equations were developed from these data sets based upon average December through March seasonal precipitation values.

The resultant observed/predicted ratios for the combination of the 24 seeded seasons were 1.21 for the linear and 1.19 for the multiple-linear equations. These ratios suggest approximately an average 21% or 19% precipitation average increase for the December – March period at Gibraltar Dam and Jameson Reservoir in the seeded seasons. These results are equivalent to approximately an average of 4.3 and 4.0 inches of additional December – March rainfall based on the linear and multiple-linear equations, respectively. Application of the one-tailed Student's t test suggests that there is only a 16-18% probability that these differences are due to chance. The inference is that the indicated differences are likely due to the cloud seeding program. The individual season results were rather variable even with reasonably high r^2 values. Although there were several seasonal ratio values less than 1.0, it is considered unlikely that there is any potential of reducing precipitation through cloud seeding. Such ratios for individual seasons are to be expected occasionally because of the imperfections built into the regression equation prediction technique. Similar fluctuations have been observed in target/control analyses of other winter cloud seeding programs conducted by NAWC as documented in annual reports on these programs.

Often there is a significant amount of season-to-season variability in the indicated results of seeding using the historical target/control evaluation technique, even when the regression equation correlation coefficients are high. Different predominate storm tracks in different seasons can impact the indicated results. Some winter seasons may contain more "seedable" storm periods than others. For these and other reasons, the focus should be on the accumulated results derived from a number of seeded seasons rather than focusing on individual season results. In other words, the average estimated increases of 19% to 21% are more representative of the likely impacts of the seeding program than any individual seasons observed over predicted ratio. The 19-21% values are surprisingly similar to estimates of seeding potential in the Upper Santa Ynez target area contained in a NAWC report to the Santa Barbara County Flood Control and Water Conservation District and Water Agency that estimated approximately an 18% average seasonal increase at Juncal Dam (Jameson Reservoir) and Gibraltar Dam, the same precipitation gauges used in this analysis (Solak, et al, 1996).

The estimated 19% to 21% increases are on the high side when compared with a range of potential effects of 5% to 15% contained in the Weather Modification's Capability Statement on Weather Modification (WMA 2011) and the 0% to 15% range of indicated increases from eleven long-term programs conducted in the Sierra Nevada (Silverman, 2010).

8.2 Indications for the Huasna-Alamo Target Area

Twitchell Dam was determined to be in a location that would make it a representative target site. Another site, Porter Ranch, had unpublished daily records dating back to the 1952 water year. These records were digitized then used in combination with the Twitchell Dam site to represent the Huasna-Alamo target area. It should be understood that data from the Porter Ranch site were not collected and quality checked as would be the case of such public records as those from the Twitchell Dam site. For example, it is unknown if the same type of precipitation gauge was used throughout the long history of this site. It is unknown if the location of this gauge may have stayed the same or if it was moved from time to time. These factors could impact the data quality from this site.

As in the Upper Santa Ynez evaluation, linear and multiple-linear equations were developed based upon the same three control sites, with the Porter Ranch and Twitchell Dam sites as target sites. The linear and multiple-linear equations were then used to predict the expected average of the Porter Ranch and Twitchell Dam December-March precipitation for 27 previous seasons in which seeding was conducted to impact the Huasna-Alamo target area.

The resultant observed/predicted ratios for the combination of the 27 seeded seasons were both 1.09 for the linear and the multiple-linear equations. This ratio suggests an average 9% precipitation increase for the December – March period at the Porter Ranch and Twitchell Dam sites in the seeded seasons. These results are equivalent to approximately an average of 1.1 inches of additional December – March rainfall based on the linear and multiple-linear equations. Application of the one-tailed Student's t test suggests that there is a 28-29% probability that these differences are due to chance.

Due to some potential concerns with the Porter Ranch data, calculations were made of the apparent effects of cloud seeding by only using Twitchell Dam to represent the Huasna-Alamo target area. The resulting observed over predicted ratios were both 1.17 for the linear and multiple-linear regression equations, suggesting a 17% increase with an average of 2.0 inches of additional rainfall per season. Application of the one-tailed Student's t test suggests that there is only a 14% probability that this difference was due to chance. NAWC interprets this to mean that the difference is likely due to the cloud seeding program.

8.3 <u>Discussion of the Indicated Results</u>

The historical target/control regression technique offers one means to estimate the effects of cloud seeding from operational cloud seeding programs. As applied to the Santa Barbara program a few considerations should be kept in mind:

- More than two precipitation gauges in the two target areas and more than three control gauges would have been highly desirable. More gauges would provide better information on the distribution of rainfall in the target and control areas. For example, how representative are two sites considering the size and differences in topography of the two target areas? Due to the requirement for sites with long periods of record and the complications of earlier cloud seeding programs being conducted over Santa Barbara County before the operational seeding began, a number of potential precipitation gauges in the target and control areas were eliminated from consideration.
- The length of record for the selected target and control gauges is important. NAWC's experience has been that longer periods (preferably more than 20 seasons) of record from the historical not-seeded period lead to the development of more accurate regression equations. There were only 12 historical seasons available for analysis in the Huasna-Alamo analysis. Equations with high r^2 values and low standard errors provide more accurate estimates of any potential seeding effects. This would indicate that the evaluations of the Upper Santa Ynez program may be somewhat more accurate that those conducted for the Huasna-Alamo target area.
- It is encouraging that the results from the linear and multiple-linear regression equations were quite similar for both target areas. Such similarity using different mathematical techniques increases the level of confidence in the results.
- The potential average amounts of increases in seasonal rainfall are likely underestimated since these estimates were made for a four-month, December through March period but the programs in Santa Barbara County are frequently conducted for the five-month period of November 15th though April 15th each seeded season.

- Any positive seeding impacts on any of the control sites during the seeded seasons would raise the predicted "natural" precipitation thus lowering any estimated increases due to the seeding.

The individual season's results are rather variable even with relatively high r^2 values as demonstrated in Figures 4 and 5. These figures indicate high season-to-season variability in the indicated results of seeding using the historical target/control evaluation technique. Even when the regression equation correlation coefficients are relatively high, there can still be significant variability in the predictions. Whether some of this variability is due to different seeding effectiveness from season to season is unknown. Different predominate storm tracks in different seasons can impact the results. Some winter seasons may contain more "seedable" storm periods than others. For these and other reasons, NAWC focuses on the accumulated results (e.g. average or mean values) derived from a number of seeded seasons rather than focusing on individual season's results such as those provided in Table 1. It may take 15-20 or more seeded seasons to reach the point where the indicated results seem to stabilize (Silverman, 2007).

REFERENCES

Dennis, A.S., 1980: Weather Modification by Cloud Seeding. Academic Press, *International Geophysics Series*, Volume **24**, 267 p.

Elliott, R.D., P. St Amand, and J.R. Thompson, 1971: Santa Barbara Pyrotechnic Cloud Seeding Test Results 1967-70. *AMS Journal of Applied Meteorology*, **10**, 785-795.

Griffith, D.A., M.E. Solak, R.B. Almy and D. Gibbs, 2005: The Santa Barbara Cloud Seeding Project in Coastal Southern California, Summary of Results and Their Implications. *WMA Journal of Weather Modification*, **37**, 21-27.

Griffith, D.A., M.E. Solak and D.P. Yorty, 2009: 30+ Winter Seasons of Operational Cloud Seeding in Utah. *WMA Journal of Weather Modification*, **41**, 23-37.

Griffith, D.A., M.E. Solak and D.P. Yorty, 2011: A Winter Operational Cloud Seeding Program: Upper Gunnison River Basin, Colorado. *WMA Journal of Weather Modification*, **43**, 29-43.

Silverman, B.A., 2007: On the Use of Ratio Statistics for the Evaluation of Operational cloud Seeding programs. *WMA Journal of Weather Modification*, **39**, 50-59.

Silverman, B.A., 2009: An Independent Statistical Evaluation of the Vail Operational Cloud Seeding Program. *WMA Journal of Weather Modification*, **41**, 7-14.

Silverman, B.A., 2010: An Evaluation of Eleven Operational Cloud Seeding Programs in the Watersheds of the Sierra Nevada Mountains. *Atmospheric Research*, **97**,526-539.

Solak, M. E., J. Girdzus, D. A. Griffith, 1996: Precipitation Augmentation Potential from Convection Band Cloud Seeding in Santa Barbara County. Prepared for Santa Barbara County Flood Control & Water Conservation Dist. and Water Agency NAWC Report WM 96-3, 42p.

Thompson, J. R., K. J. Brown, and R. D. Elliott, 1975: Santa Barbara Convective Band Seeding Test Program. NAWC final report 6-135 to U. S. Naval Weapons Center, 79 p.

WMA, 2011: Capabilities Statement on Weather Modification. Adopted September 2011.