Cloud Seeding Annual Report

Lake Lopez Drainage
2020 Winter Season

Prepared For:

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Department of Public Works

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WEATHER MODIFICATION

The Science Behind Cloud Seeding

The Science

The cloud-seeding process aids precipitation formation by enhancing ice crystal production in clouds. When the ice crystals grow sufficiently, they become snowflakes and fall to the ground.

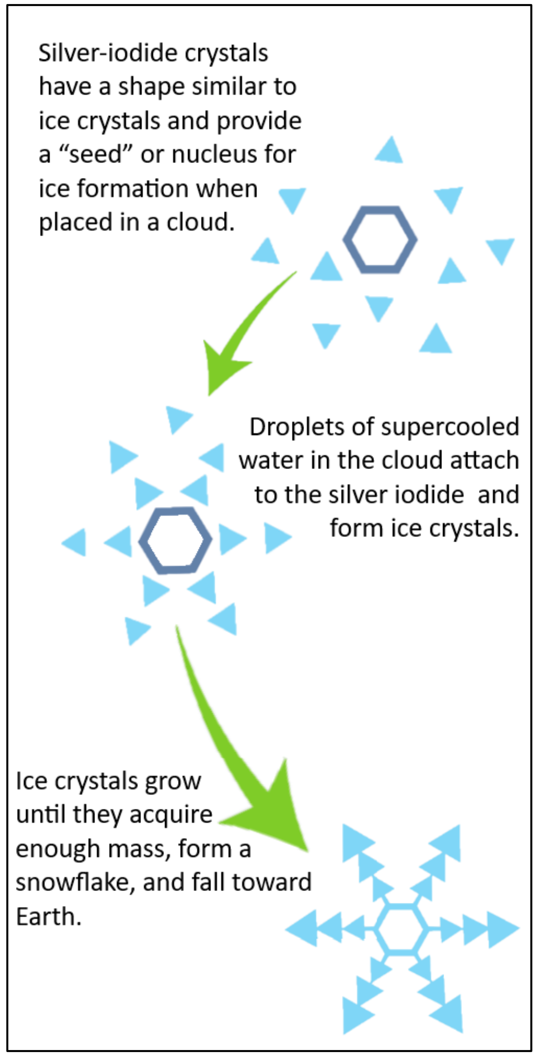
Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

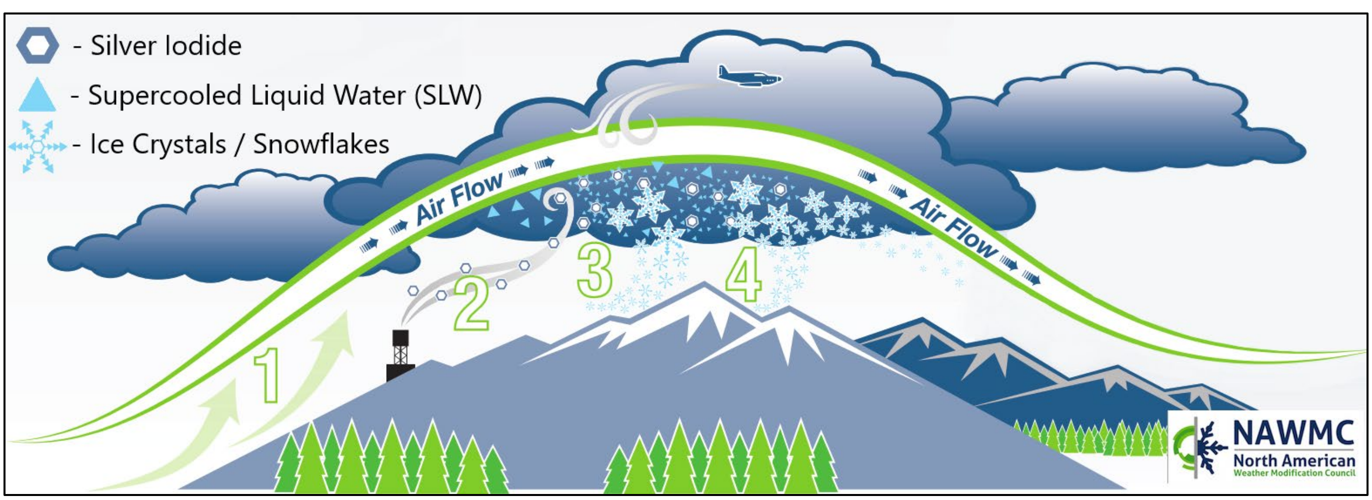
Safety

Research has clearly documented that cloud seeding with silver-iodide aerosols shows no environmentally harmful effect. Iodine is a component of many necessary amino acids. Silver is both quite inert and naturally occurring, the amounts released are far less than background silver already present in unseeded areas.

Effectiveness

Numerous studies performed by universities, professional research organizations, private utility companies and weather modification providers have conclusively demonstrated the ability for Silver Iodide to augment precipitation under the proper atmospheric conditions.





EXCUTIVE SUMMARY

For the 2020 winter season, cloud seeding operations were conducted to enhance precipitation in the Lake Lopez Drainage located in southern San Luis Obispo County. A project-dedicated aircraft and pilot were located at the Santa Maria Public Airport during the season. Two previously established ground-based seeding locations were utilized. These sites were located at Mt. Lospe and Berros Peak. The operational period ran from January 9, 2020 to April 15, 2020.

The aircraft contained specialized flare racks that were able to deliver high-output seeding material into the cloud base when convective bands moved across the County. The cloud seeding equipment at the ground-based sites provided the ability to fire the same high-output silver iodide seeding flares from remote locations. Operations for the ground seeding and aerial project were directed by North American Weather Consultant's (NAWC) project meteorologists who operated from NAWC's headquarters in Sandy, Utah. Close coordination of all seeding activities was maintained with Jill Ogren of the Department of Public Works.

The ENSO (El Niño-Southern Oscillation) phase was classified as a neutral event during the 2019-2020 winter season. Precipitation was mostly below normal for the northern half of the state while slightly better conditions developed for the southern half of California. From the beginning of the water year (July 1, 2019 through April 15, 2020) for southern San Luis Obispo County, rainfall percentages ranged from 70% to 95% of normal at County gauge sites.

Table 7-1 shows precipitation amounts from six Automatic Local Evaluation in Realtime (ALERT) stations in San Luis Obispo County. The table shows monthly data for those stations, as well as January through April precipitation. This table illustrates a roller coaster rainy season between very dry conditions in January and February, followed by very wet conditions in March and April, which are highlighted in blue.

Table 1
2020 Monthly Precipitation Data for San Luis Obispo County

Location	January	February	March	April	January - April Precipitation
Arroyo Grande Creek	0.57	0	6.21	2.04	8.82
Davis Peak	0.55	0.08	4.7	2.43	7.76

Lopez Dam	0.63	0.18	5.24	2.72	8.77
Salinas Dam	0.63	0	5.10	2.60	8.33
Santa Margarita	0.66	0.08	4.57	2.56	7.87
San Luis Obispo Reservoir	0.39	0	5.97	2.56	8.92
Percent of Normal Precipitation Range	10-20%	0%	115-190%	119-266%	

Seeding opportunities occurred on six days during the 2020 operational season. A total of 30 flares were successfully burned at the two ground sites, releasing an estimated 486 grams of seeding material. In addition, one seeding flight occurred totaling 1.25 hours, dispensing a total of 151.2g of AgI. Unfortunately, no seeding opportunities occurred during the months of January and February, as very dry conditions developed and continued for a prolonged period. March and April offered a more conducive pattern for seeding operations, with very wet conditions developing. March and April precipitation, along with a wet December prior to the start of the project, resulted in only somewhat below to near normal 2020 Water Year precipitation totals through the end of April, with most locations in southern San Luis Obispo County ranging from 70 to 95% of normal precipitation. No seeding suspensions were enacted during the three-month operational period.

An analysis was planned to evaluate the benefit of the program for the 2020 operational season. Regression equations were developed in order to perform a target/control analysis for the Lake Lopez. Streamflow data was used as the target sites and precipitation was used for the control. At the time that this report was finalize, the streamflow data was unavailable from the USGS, as well as some precipitation data. As soon as this data becomes available, the analysis will be performed and submitted to project administrator for consideration.

Mid-Season Program Modifications

At the beginning of March, we lost our beloved pilot John Renoir, who had served the weather modification community for over 20 years before his passing. Finding a replacement pilot, with adequate weather modification experience for the insurance provider and recent training in the make and model of aircraft, proved to be an impossible endeavor. Fortunately, NAWC was able to draw on our operational programs based in Fresno and Santa Barbara to continue services unhindered by the circumstances.

We received approval from the Kings River Conservation District to use their dedicated pilot and aircraft to fly one cloud seeding mission in March, and Santa Barbara County allowed us to make use of their Automated High Output Ground Seeding (AHOGS) network to target the remaining storms in March and April.

Recommendations

As identified in the original feasibility study (Griffith et al.), the Lopez Lake Watershed is an ideal location for cloud seeding operations. The convective bands which are common meteorological occurrences in the winter months, contain high concentrations of SLW and favorable wind regimes creating ideal circumstances for nucleation by silver iodide. It is thus our recommendation that we continue the operational cloud seeding project for the 2020-2021 season. There are, however, adjustments to the program that NAWC feels would result in a more effective and efficient program.

Monthly precipitation is often highly variable in Southern California and along California's Central Coast. It is not uncommon for some months to be above normal in terms of rainfall and others drastically below. The shorter a programs operational season, the more likely critical seeding opportunities will be missed. Experience has shown that a four to five-month program allows the weather modification provider to more effectively mitigate for drier months protecting the vested interests of water districts. NAWC, therefore, recommends a program running from December 1 to April 1st or 15th.

NAWC has identified three possible pilots and secured an aircraft, if an aerial program is desired. We would, however, encourage the technical review committee to reconsider the original findings of the feasibility study and move towards a ground-based network, similar to the one used in Santa Barbara. Ground-based seeding programs have been found to be more reliable and efficient when seeding coastal storms, particularly convective bands. Our most recent research, as published in the official Weather Modification Journal, indicates that increases in precipitation of up to 20% are achievable utilizing this seeding method. More importantly, as ground based programs are more economical and efficient to operate, a full five-month program is more feasible.

Santa Barbara County Water Agency is willing to adopt a partnership for one of their AHOGS systems. In addition to this shared location, NAWC would recommend selecting one or two additional sites near or around the Lopez Lake target area for AHOGS system installations. In response to the loss of the program dedicated pilot last season, NAWC has agreed to provide any new AHOGS systems installed this year, free of charge.

Summary of Operations for a Winter Cloud Seeding Program for the
Lake Lopez Drainage in
Southern San Luis Obispo Counties
Water Year 2020

NAWC Report WM 20-2

1.0 INTRODUCTION

North American Weather Consultants (NAWC) conducted its first season of cloud seeding operations during the 2019-2020 winter season with the County of San Luis Obispo Department of Public Works. The Agency issued a Request for Proposals (RFP) on September 16, 2019 for a cloud seeding program of up to a three-season duration. Proposals were due on September 30, 2019. NAWC bid on the RFP and was subsequently awarded this contract on December 17, 2019.

NAWC, with headquarters in Sandy, Utah, conducted a three-month cloud seeding program for the Agency from January 9, 2020 through April 15, 2020. Aerial and ground seeding were conducted during the 2020 winter season for the Lake Lopez Drainage in southern San Luis Obispo County. The aircraft arrived at the Santa Maria Public Airport in early January and was equipped with two flares racks that contained burn in place silver iodide flares. A pilot arrived at the Santa Maria Public Airport on January 5, 2020 and was stationed there through the majority of the operational season.

Two previously established ground-based seeding sites were also operated during the last month of the program. These sites were Mt. Lospe, located in northwestern Santa Barbara County and Berros Peak, just east of Nipomo in southern San Luis Obispo County. The cloud seeding equipment located at these sites provided the ability to fire high-output seeding flares from these remote locations in real time on a 24/7 basis. All seeding decisions were made by Weather Modification Association (WMA) certified project meteorologists. All seeding decisions included consultation with Agency project personnel prior to and during the seeding periods.

The 2020 winter season brought a mix of conditions to the project area during the three month operational season. The December-February period was one of the driest ever, not just for San Luis Obispo County but for most of California. Figure 1.1 shows just how dry the December through February period was for the Lake Lopez drainage and surrounding areas. During March, however, the weather pattern changed dramatically when a number of systems affected San Luis Obispo County. Total precipitation amounts for March were much above the average. April offered a few more storm systems to the area as well as opportunities for seeding operations. A complete summary of weather and cloud seeding operations can be found in Section 4.

Table 1-1 provides rainfall totals for stations with established normals in the county for the season through April 15, 2020. This year was categorized as near normal which was only possible with the very wet month of March experienced in the county.

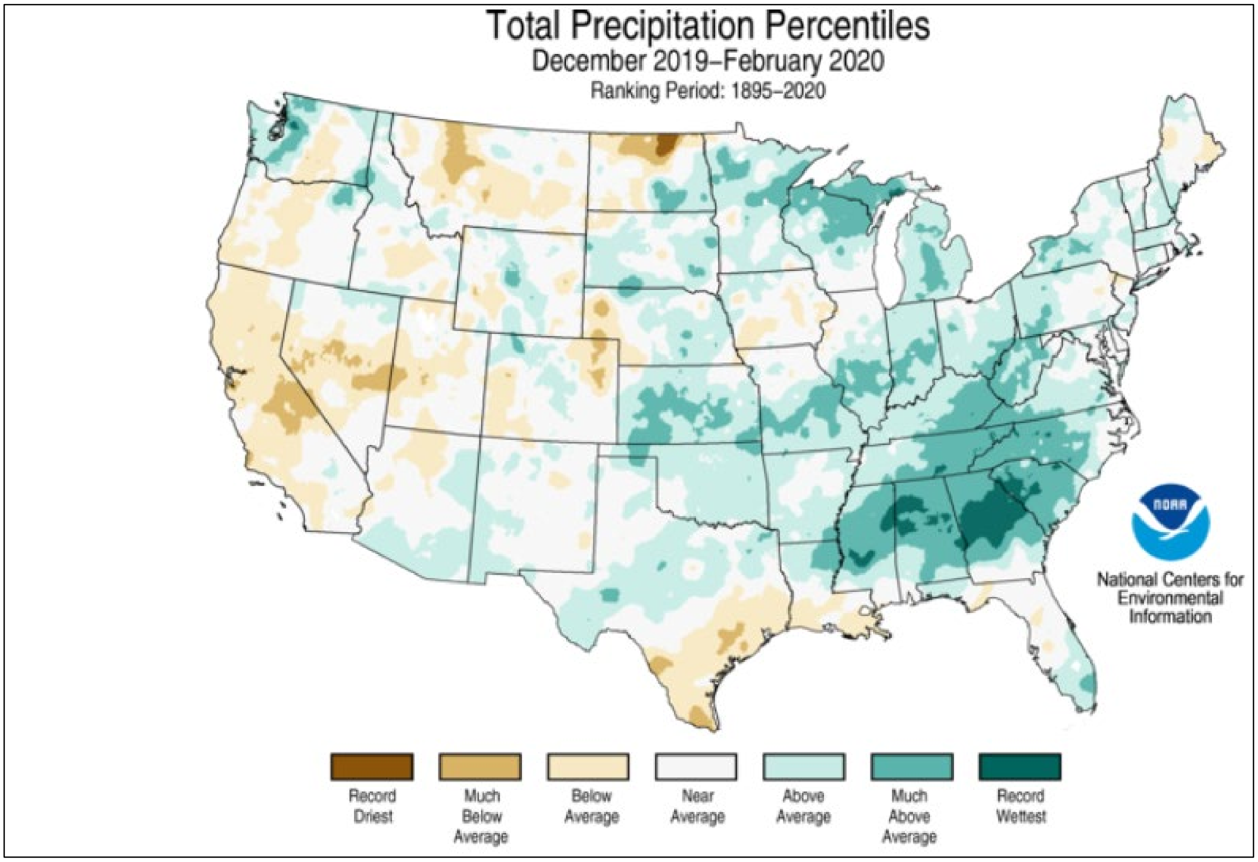


Figure 1.1 December 2019 – February 2020 Precipitation Percentiles

Table 1-1

Seasonal Rainfall for San Luis Obispo County ALERT sites through April 15, 2020

Gauge Location	Water Year Precipitation (inches) through April 15
Arroyo Grande Creek	14.94
Davis Peak	14.97
Lopez Dam	16.07
Salina Dam	15.97
Santa Margarita	14.06
San Luis Obispo Res.	15.36

Figure 1.2 shows storage at Lopez Reservoir from the start of 2020 to the end of the seeding program on April 15. This graphic shows how the dam was losing storage from the beginning of the year until around March 1, 2020. This correlates well with the dry conditions experienced during January and February. Levels began to rebound throughout the month of March and the first half of April with the return of precipitation to the County. If this graph only reflects precipitation dependent rises and falls, it is very representative of not only storage but the precipitation trends while the program was operational.

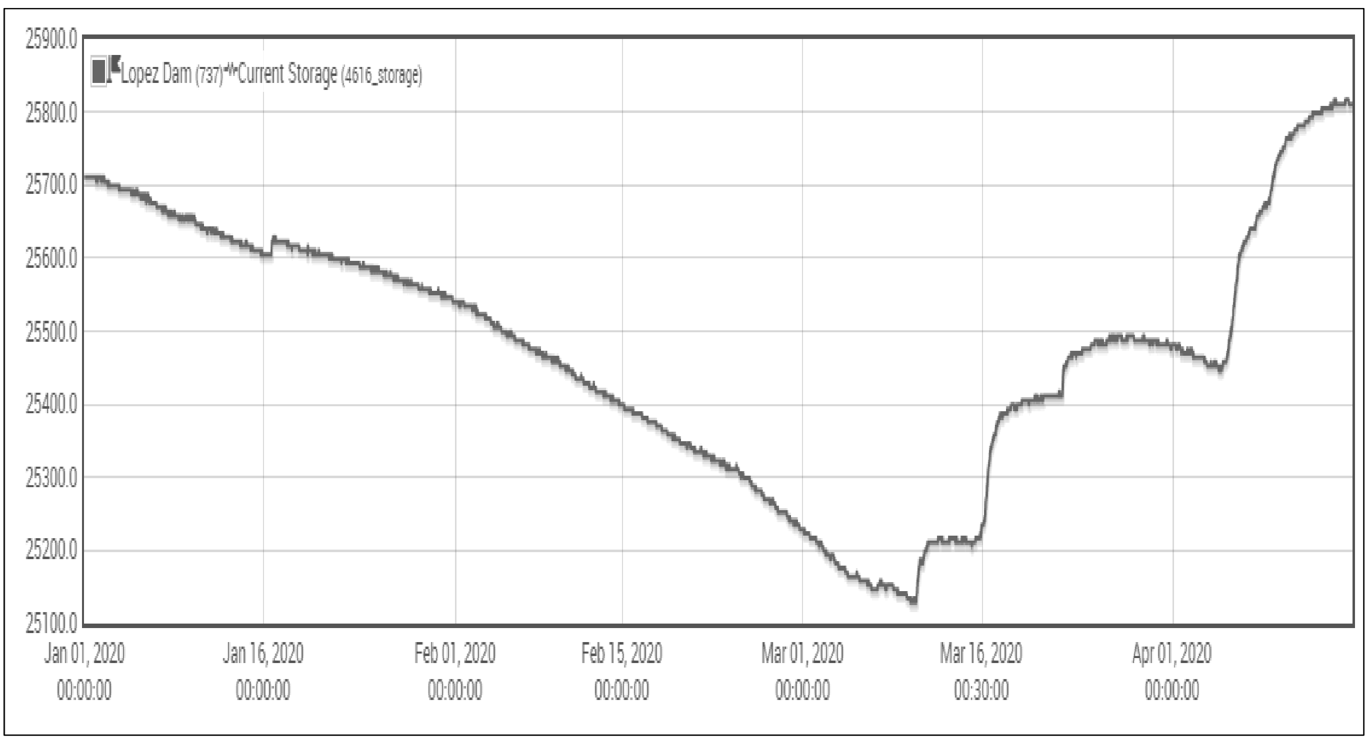


Figure 1.2 January 1 – April 15, 2020 Storage at Lopez Dam

Figure 1.3 shows a drought monitor comparison for December 31, 2019 and April 14, 2020. It shows a shift from no drought conditions for the state of California to severe drought conditions by mid April. As of April 14, 2020, the drought monitor images indicated that nearly half of the state was in some stage of drought. The primary driver in the development of drought conditions into mid April was a specific pattern that developed across the state for the month of March. Figure 1.4 shows a precipitation departure from normal for the month of March. It can be seen when looking at California that the southern half of the state was very much above normal while the northern half of the state was below normal. The wetter than normal amounts are also seen over the southwestern U.S. This pattern is representative of closed lows that more frequently impacted the southern half of the state and the southwestern U.S., a pattern sometimes observed during the springtime months.

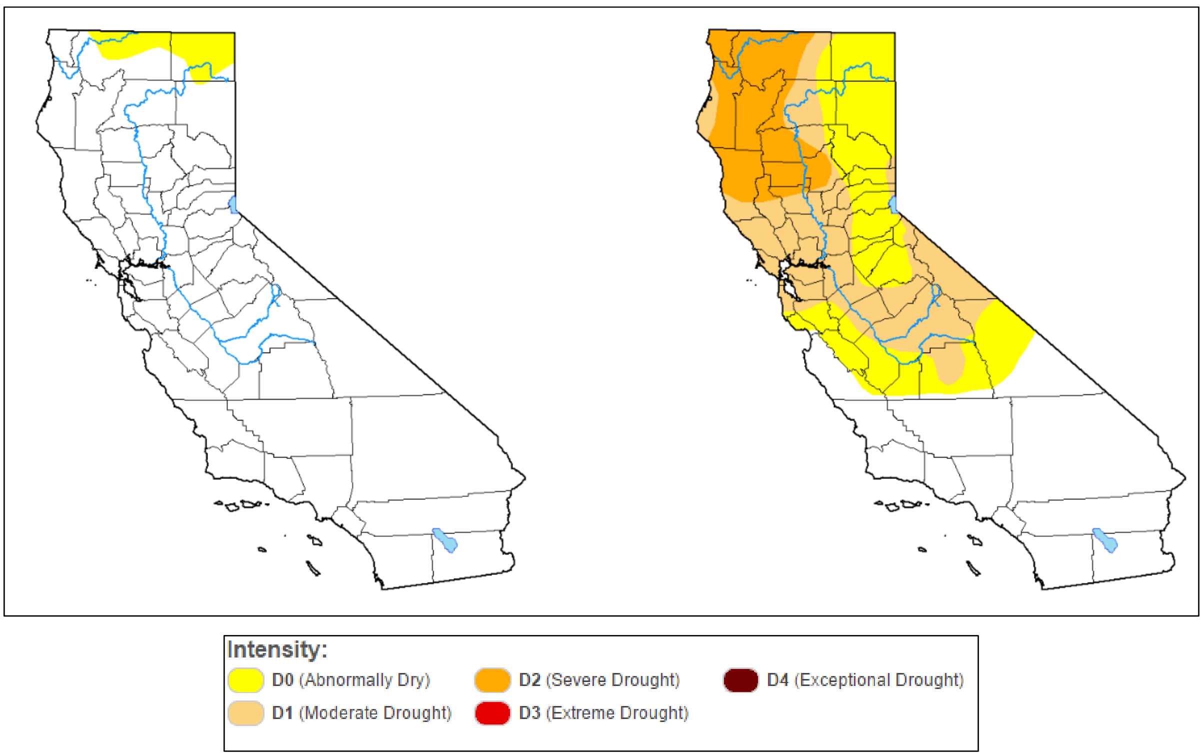


Figure 1.3 U.S. Drought Monitor Conditions for California for December 31, 2019 (left) and April 14, 2020 (right).

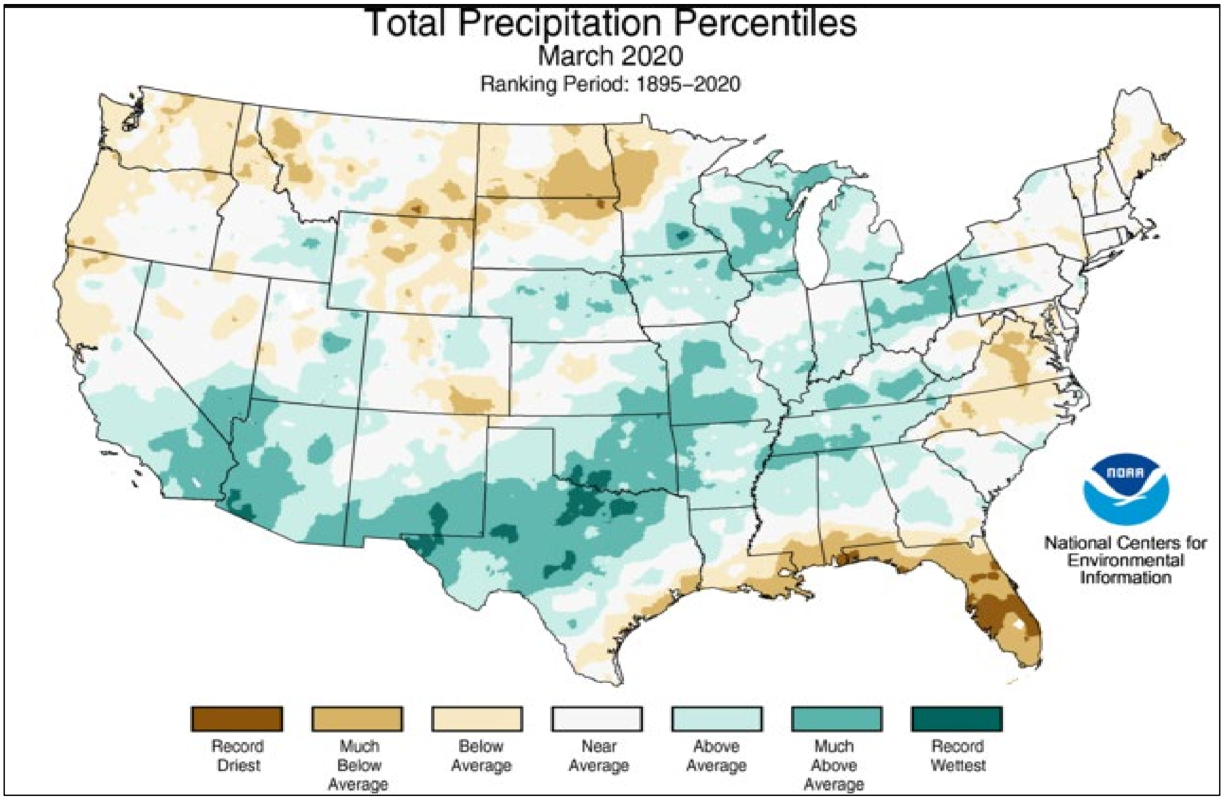


Figure 1.4 Total precipitation Percentiles – March 2020

This report contains discussions on project operations, a short theory of cloud seeding, project design, equipment and personnel and summaries and recommendations. Table 1-2 is a list of all the acronyms that will follow in this report.

Table 1-2
Project Acronyms Definitions

Acronym	Description
AFB	Air Force Base
AFWA	Air Force Weather Agency
AHOGS	Automated High Output Ground Seeding
ALERT Network	Automated Local Evaluation in Real Time
APCO	Advanced Process Control and Optimization
ARL	Air Resources Laboratory
CSU	Colorado State University
ENSO	El Nino Southern Oscillation
FAA	Federal Aviation Administration
FACE	Florida Area Cumulus Experiment
FSL	Forecast System Laboratory
HRRR	High Resolution Rapid Refresh

HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory (Model)
GMT	Greenwich mean time
ICE	Ice Crystal Engineering
NAWC	North American Weather Consultants
NCAR	National Center for Atmospheric Research
NEXRAD	Next Generation Radar
NOAA	National Oceanic and Atmospheric Association
NWS	National Weather Service
PDT	Pacific Daylight Time
PST	Pacific Standard Time
READY	Real-Time Environmental Applications and Display System
SBCWA	Santa Barbara County Water Agency
SLW	Supercooled Liquid Water
WMA	Weather Modification Association
WRF	Weather Research and Forecasting

2.0 THEORY OF CLOUD SEEDING FOR PRECIPITATION AUGMENTATION AND RESULTS OF PREVIOUS RESEARCH AND OPERATIONAL PROGRAMS CONDUCTED ON CALIFORNIA'S CENTRAL COAST

Two theories have evolved concerning the potential to augment precipitation. One theory postulates that a natural cloud's efficiency in producing precipitation can be increased, while the other theory postulates that seeding can enhance cloud development, leading to additional precipitation. The first theory has often been referred to as the *static* seeding hypothesis while the second relies upon *dynamic* effects of cloud growth. In many situations, both processes could be operative, whereby a cloud's precipitation efficiency is increased and the cloud is made to grow larger due to the seeding.

Clouds contain water vapor, water droplets and frequently ice crystals if cloud temperatures drop below freezing. Discoveries in the late 1940's established that minute particles of silver iodide, when injected into a cloud that contained supercooled (colder than freezing) cloud droplets, would cause those droplets to freeze (Vonnegut, 1947). Supercooled cloud droplets frequently exist in clouds, as evidenced by icing on aircraft. These supercooled water droplets are the normal targets of most modern day cloud seeding programs.

2.1 <u>Precipitation Processes</u>

There are two basic mechanisms that produce precipitation: collision coalescence and ice formation. Coalescence is defined as "The growth of raindrops by the collision and coalescence of cloud drops and or small precipitation particles." This process is especially important in tropical locations in the production of rainfall but it can also be a factor in the production of rainfall in more temperate climates like those found in Santa Barbara County. Ice nucleation (as described in the Bergeron-Findeisen theory) consists of a process in which precipitation particles may form within a mixed cloud, i.e. one composed of both ice crystals and liquid water drops. In such clouds the ice crystals will gain mass by sublimation (formation of a solid phase directly from a vapor phase) at the expense of the liquid drops surrounding the ice crystals. Upon attaining sufficient weight, the ice crystals begin to fall and may become regular snowflakes under favorable conditions. Precipitation will subsequently reach the ground as either snow or rain, depending on the location of the freezing level relative to the surface. Of interest to this discussion is the fact that cloud droplets often exist in portions of clouds that are colder than freezing. In fact, pure water droplets in a very clean laboratory environment can be cooled to -39°C before they will freeze through a process known as homogeneous nucleation. This Bergeron-Findeisen process is important in the production of snow and rain in the more temperate climates like those found in Santa Barbara County. The presence of supercooled water droplets in clouds is often the focus of attempts to artificially modify clouds.

2.2 Ice Nucleation

For supercooled cloud droplets to freeze at temperatures warmer than -39°C they need to encounter an impurity. There are particles present in the atmosphere that possess the ability to cause these supercooled droplets to freeze, which are known as freezing nuclei or ice nuclei. Research has demonstrated that certain natural particles (e.g., soil particles, and a certain type of bacteria) in the atmosphere serve as freezing nuclei. The conversion of a supercooled water droplet into an ice crystal is referred to as nucleation. It is known that the nucleating efficiency of these naturally occurring freezing nuclei increases with decreasing temperatures. It has also been established that naturally occurring freezing nuclei active in the temperature range of approximately -5° to -15°C are relatively rare. Research has also shown that minute particles of silver iodide begin to act effectively as freezing nuclei at temperatures colder than -5°C (Dennis, 1980). Some more recently developed seeding formulations show nucleation at temperatures as warm as -4°C. Silver iodide (sometimes a silver iodide complex) is the agent most commonly used to "seed" clouds, a process often referred to as "cloud seeding."

There are two types of ice nucleation: condensation-freezing and contact. In condensation freezing, a nucleus first serves as a condensation nucleus in forming a cloud droplet. At temperatures of approximately -5°C or colder this same nucleus can serve as freezing nuclei. In other words, under the right conditions, a nucleus can a) cause condensation, forming a cloud droplet and b) then promote freezing on the same nucleus, forming an ice crystal. Contact nucleation, as the name implies, means that a freezing nucleus must come in physical contact with a supercooled cloud droplet, thus causing it to freeze (as long as the temperature of the cloud droplet is cold enough for the freezing nuclei to be active). Contact nucleation can be a relatively slow process (from a few to tens of minutes) compared to condensation-freezing nucleation, which can be quite rapid (on the order of one to a few minutes).

2.3 Impacts of Silver Iodide Seeding

Since a scarcity of natural ice nuclei commonly exists in the atmosphere at temperatures in the range of -5° to -15°C, many clouds may be inefficient at converting water droplets into ice crystals. The addition of silver iodide nuclei to these cloud regions can produce additional ice crystals which, under the right conditions, grow into snowflakes and fall out of the cloud as either snow or rain. This increase in efficiency is usually referred to as a *static* seeding effect.

In the process of converting supercooled cloud droplets into ice crystals, additional heat is added to the cloud due to the release of the latent heat of fusion. This additional heat may invigorate the circulation of air within the clouds, resulting in a *dynamic* effect. This postulated *dynamic* effect was the basis for a National Oceanic and Atmospheric Association (NOAA) research program conducted in Florida known as the Florida Area Cumulus Experiment (FACE). Two different phases of FACE 1, 1970-76 and FACE 2, 1978-80 (Woodley et al., 1983) indicated increases in area wide rainfall, but results fell short of strict statistical acceptance criteria. Rainfall increases from seeded convection bands in the Santa Barbara II research program (Brown et al., 1974) were attributed to both *static* and *dynamic* effects. NAWC conducted this research program in Santa Barbara County with funding from the Naval Weapons Center at China Lake.

2.4 Santa Barbara II Research Program

There was an early research program conducted in Santa Barbara County, termed Santa Barbara I, which was conducted from 1957-1960 and was sponsored by various organizations including the State of California, The University of California, Santa Barbara and Ventura counties, the National Science Foundation, the U.S. Weather Bureau and the U.S. Forest Service. This program employed randomized seeding of storm periods using ground-based silver iodide solution generators. Results from this research program indicated increases of 45% but were not statistically significant. Further information about this program can be found in Appendix A of this report. A second research program conducted in the county was known as the Santa Barbara II program, which was conducted during the winter seasons of 1967 to 1973. Santa Barbara II was conducted in two primary phases. Phase I consisted of the release of silver iodide from a ground site located near 2,600 feet MSL in the Santa Ynez Mountains northwest of Santa Barbara. These silver iodide releases were made as "convection bands" passed overhead. The releases were conducted on a random seed or no-seed decision basis in order to obtain baseline non-seeded (natural) rainfall information for comparison. A large network of recording precipitation gauges was installed for the research program (Figure 2.1). The amount of precipitation that fell from each seeded or non-seeded convection band was determined at each precipitation gauge location. Average convection band precipitation for seeded and non-seeded events was calculated for each rain gauge location. Figure 2.2 shows the results of seeding from the ground as contours of the ratios of average seeded band precipitation to the non-seeded band precipitation.

Ratios greater than 1.0 are common in Figure 2.2. A ratio of 1.50 would indicate a 50 percent increase in precipitation from seeded convection bands. The high ratios in southwestern Kern County are not significant in terms of amounts of additional rainfall since the convection bands (both seeded and non-seeded) rapidly lose intensity as they enter the San Joaquin Valley. In other words, a high percentage applied to a low base amount does not yield much additional precipitation. These apparent effects may be due to delayed ice nucleation which would be expected with the type of seeding flares used in this experiment that operated by contact nucleation which is a relatively slow process.

The low amounts of natural precipitation in southwest Kern County results from evaporation in “downslope” flow in the winter storms that affect this area. Such predominant “downslope flow” areas are frequently known as rain-shadow areas in the lee of mountain ranges. Figure 2.3 dramatically exhibits this feature from the coastal mountains in Central and Southern California, which are wet, to the San Joaquin and Imperial Valleys, which are dry. The 1.5 ratios along the backbone of the Santa Ynez Mountains are, however, significant in terms of rainfall amounts since this area receives higher natural precipitation during winter storms due to “upslope” flow. This upslope flow is also known as an orographic effect and accounts for many mountainous areas in the west receiving more precipitation than adjoining valleys (especially downwind valleys). It was concluded that convection band precipitation was increased over a large area using this ground-based seeding approach.

In a similar experiment, phase II employed an aircraft to release silver iodide (generated by silver iodide - acetone wing tip generators) into the convection bands as they approached the Santa Barbara County coastline west of Vandenberg Air Force Base. The convection bands to be seeded were also randomly selected. Figure 2.4 provides the results. Again, a large area of higher precipitation amounts is indicated in seeded convection bands compared to non-seeded convection bands. Notice the westward shift of the effect in this experiment versus the ground-based experiment. This feature is physically plausible since the aircraft seeding was normally conducted off the coastline in the vicinity of Vandenberg AFB (i.e., west of the ground-based release point).

A study of the contribution of "convection band" precipitation to the total winter precipitation in Santa Barbara County and surrounding areas was conducted in the analysis of the Santa Barbara II research program. This study indicated that convection bands contributed approximately one-half of the total winter precipitation in this area (Figure 2.5).

If it is assumed that all convection bands could be seeded in a given rainy season and that a 50 percent increase was produced, the result would be a 25 percent increase in total rainy season precipitation if we assume the convection bands would have contributed one half of the rainy season's rainfall. Two NAWC reports (Thompson et al., 1988 and Solak et al., 1996) provided a more precise quantification of the optimal seasonal seeding increases that might be expected at Juncal and Gibraltar Dams (i.e., 18-22%) from seeding convection bands.

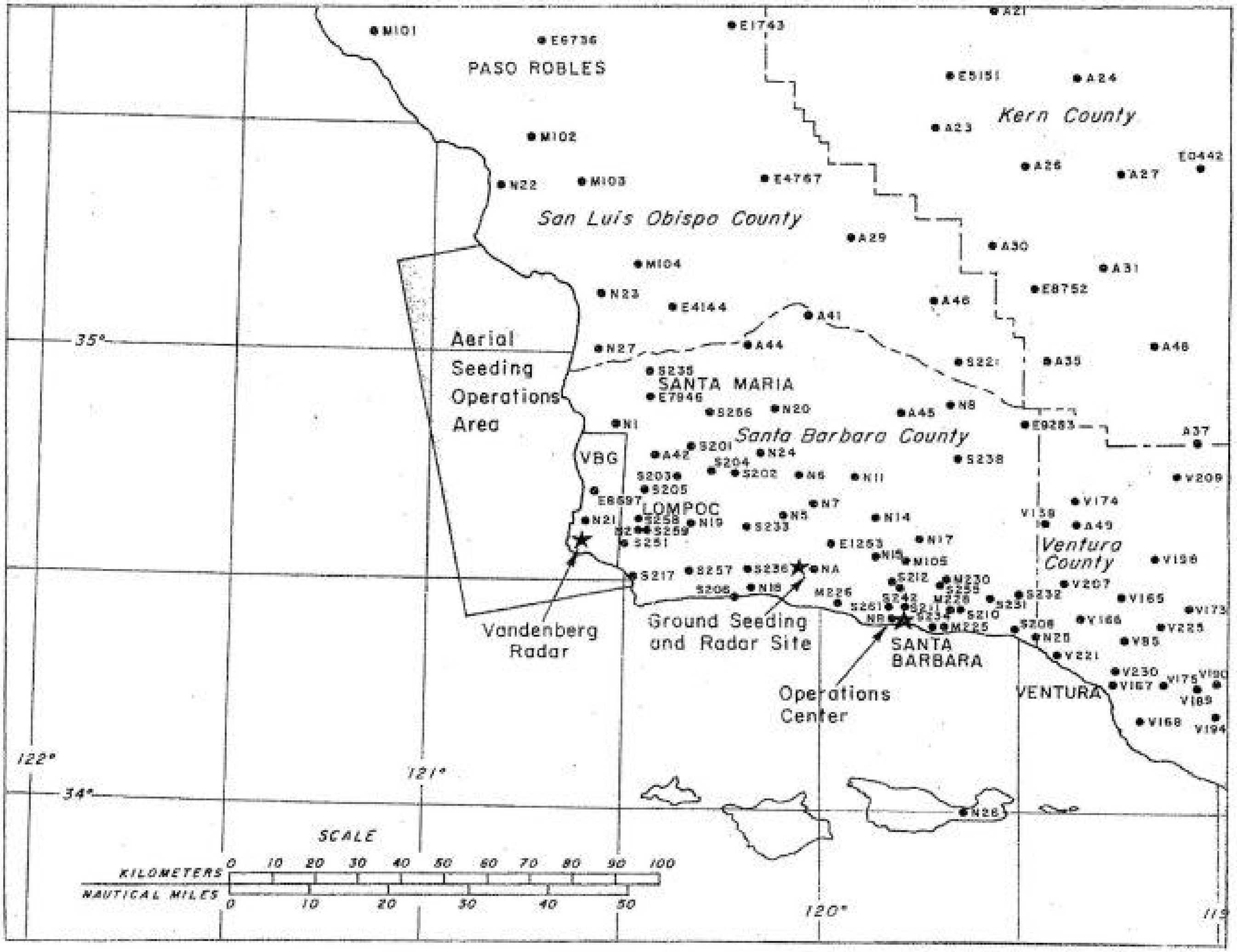


Figure 2.1 Santa Barbara II Project Map showing Rain Gauges, radar and seeding sites

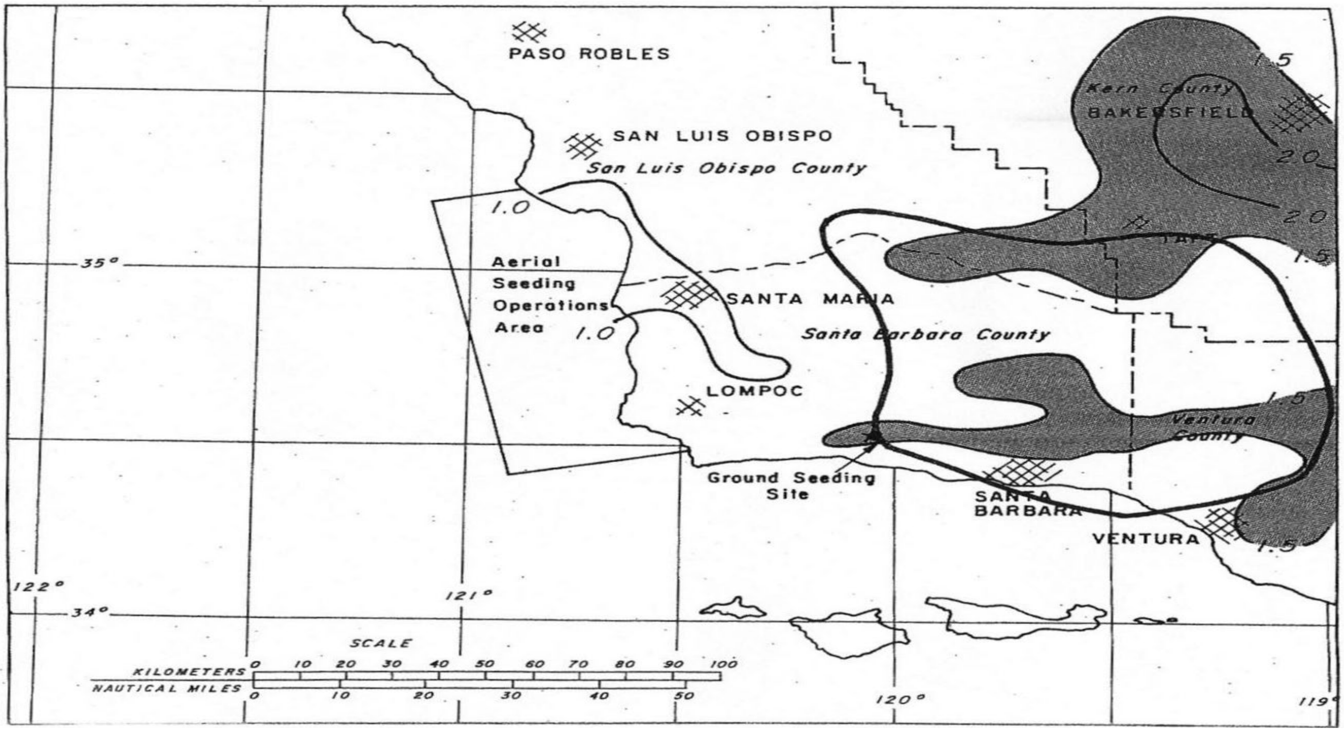


Figure 2.2 Seeded/Not-Seeded Ratios of Band Precipitation for Phase I Ground Operations

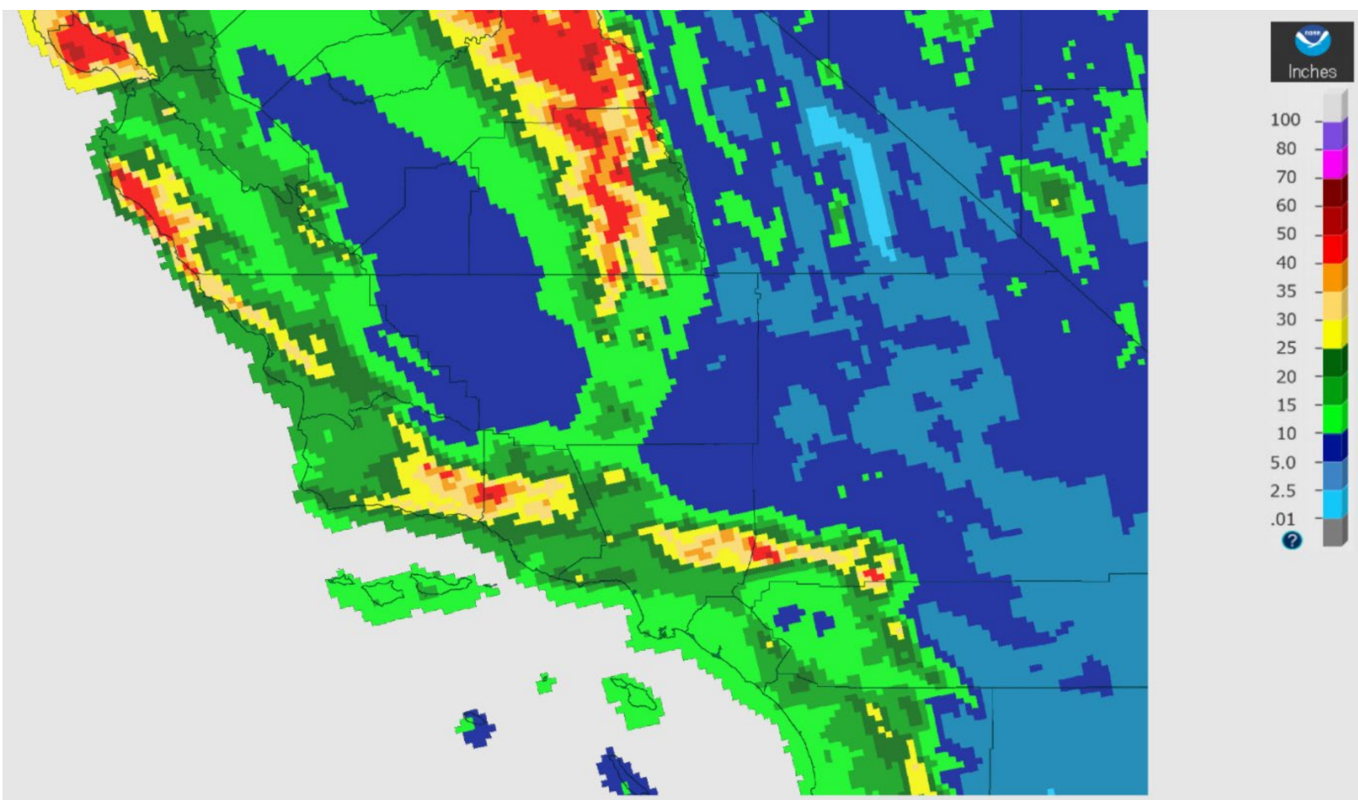


Figure 2.3 Annual Average Precipitation (inches), Southern California 1980-2010

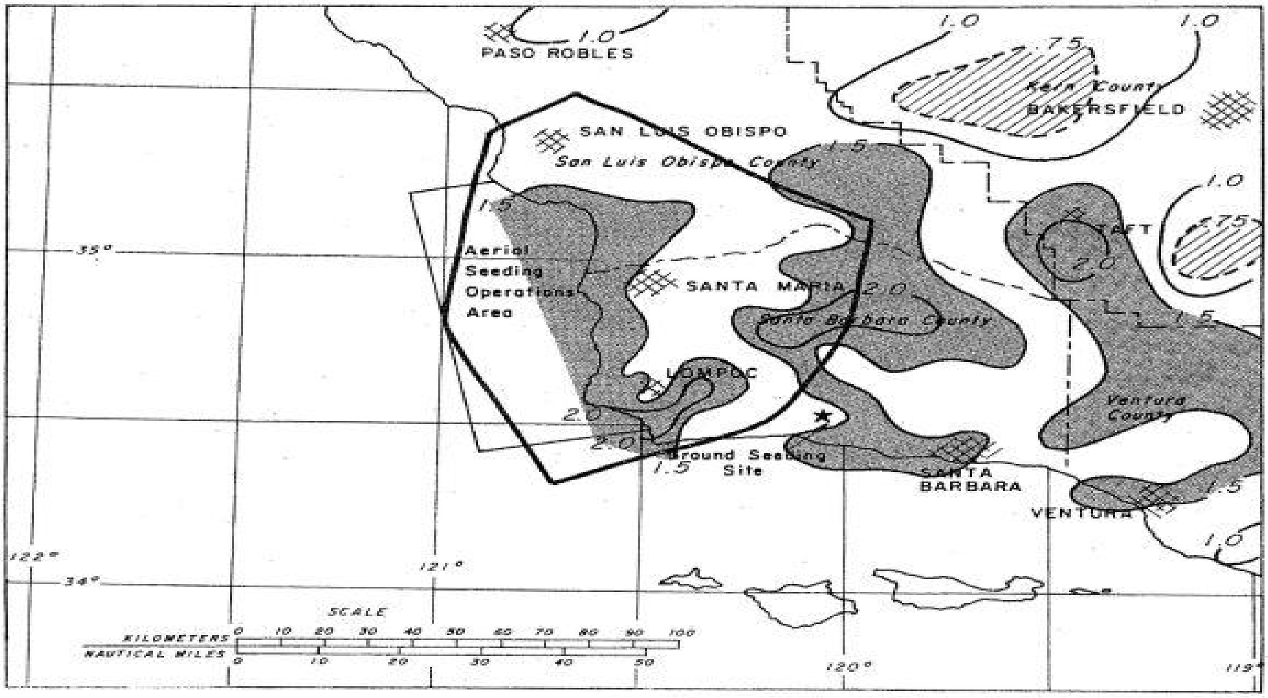


Figure 2.4 Seeded/Not-Seeded Ratios of Band Precipitation for Phase II Aerial Operations

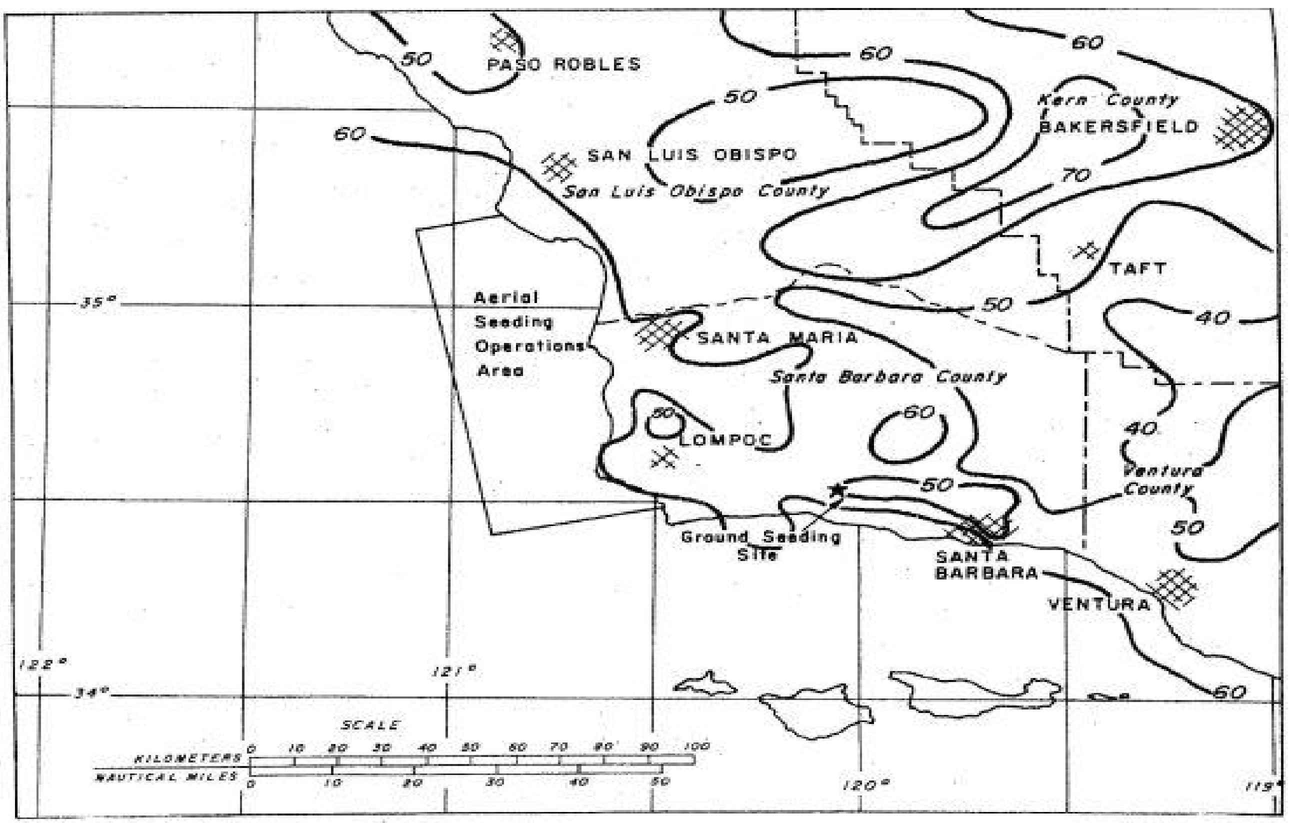


Figure 2.5 Percentage of Winter Precipitation Occurring in Convection Bands during the 1970-1974 seasons

For illustration purposes, Figure 2.6 provides a sequence of six radar images of a convection band as it moved into Santa Barbara County on April 11, 2010. The radar images are from the Vandenberg AFB NEXRAD radar site. Table 2-1 provides 30 minute interval rainfall values observed at Orcutt during the passage of this convection band. The highest 15-minute rainfall total (not shown in the table) was 0.35 inches between 1725 and 1740 PDT during the passage of the heaviest portion of the band, corresponding to the time period between the 2nd and 3rd images in the sequence. Short- duration rainfall rates peaked at close to 2"/hour for a brief period (5-10 minutes) around 1730 PDT. Rainfall rates then averaged around a quarter inch per hour or less during the remainder of the event (after about 1800 PDT).

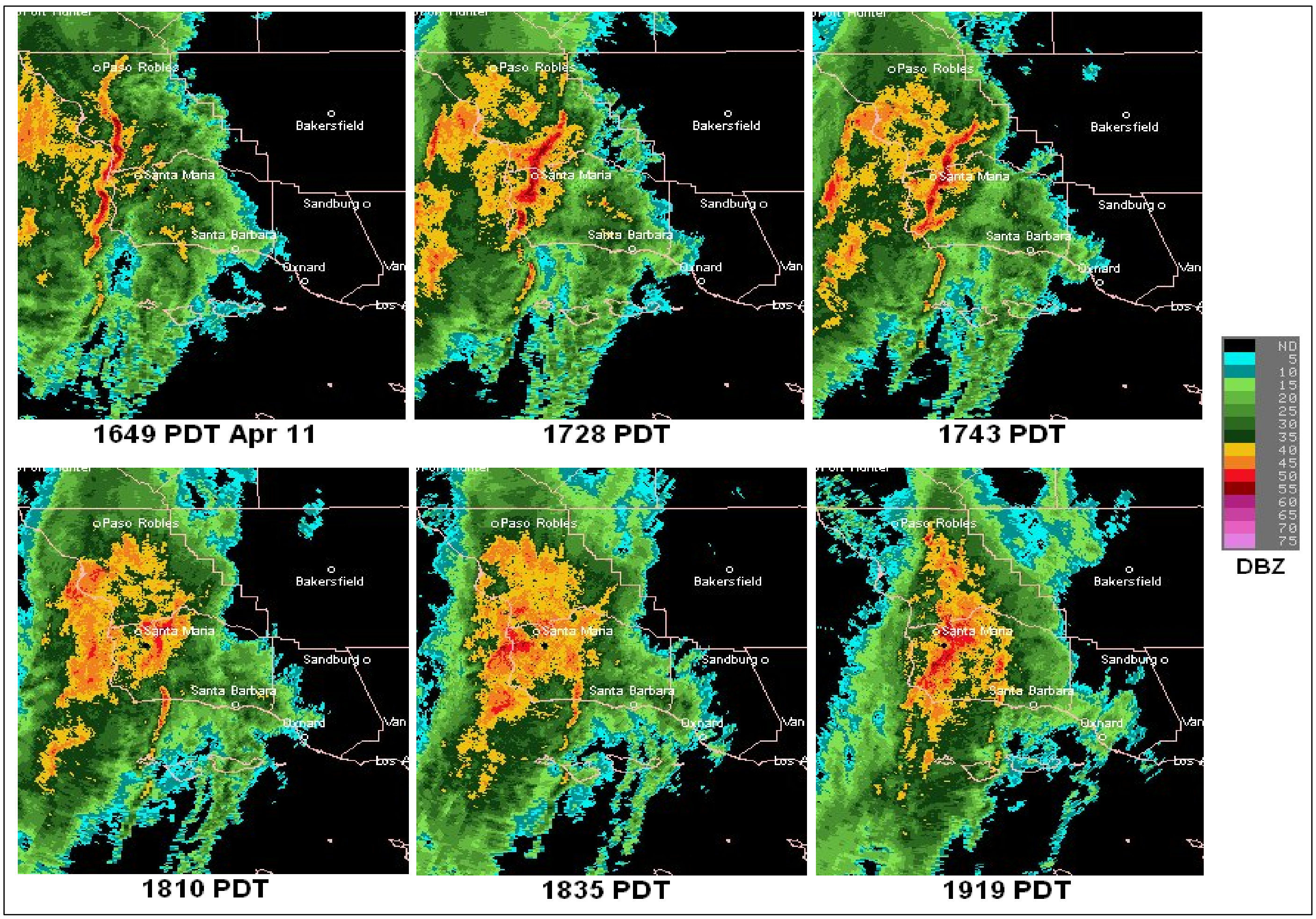


Figure 2.6 Frontal Convection Band passing over San Luis Obispo on April 11, 2010.

Table 2-1
Short Duration Rainfall Amounts at Orcutt During Storm Event in Figure 2.6

Time Period (PDT)	1630 - 1700	1700 - 1730	1730 - 1800	1800 - 1830	1830 - 1900	1900 - 1930	1930 - 2000
Precipitation (in)	0.03	0.26	0.35	0.12	0.10	0.12	0.02

In summary, earlier research conducted in Santa Barbara County indicated that convective bands are a common feature of winter storms that affect the Central Coast and southern California. They are the predominate feature in San Luis Obispo County, which contribute significant proportion of the winter season precipitation. In addition, research has indicated that these bands contain supercooled liquid cloud droplets, the target of most modern day cloud seeding activities (Elliott, 1962). Seeding these bands with silver iodide either from the ground or air increases the amount of precipitation received at the ground. These bands are typically oriented in a general north to south fashion (e.g., northeast to southwest, northwest to southeast) as they move from west to east. It is common to have at least one convective band per winter storm with as many as three or four per storm on occasion. One band is usually associated with cold fronts as they pass through the county. Frequently, these frontal bands are the strongest, longest-lasting bands during the passage of a storm. Other bands may occur in either pre-frontal or post-frontal situations. The duration of these bands over a fixed location on the ground can vary from less than one hour to several hours.

3.0 PROJECT DESIGN

The winter cloud seeding program was conducted over portions of San Luis Obispo County. The target area was the Lake Lopez Target area (Lake Lopez drainage). This target area is depicted in Figure 3.1. The objective of the program was to seed all suitable storm systems affecting the target area that contained organized convective bands, unless precluded by previously established suspension criteria, which are listed in Section 5.0.

Figure 3.1 Project Area and Ground-Based High-Output Flare Site Locations

Table 3-1 provides some generalized seeding criteria that NAWC uses to help determine whether an approaching storm contains suitable conditions for seeding.

Table 3-1
Generalized Seeding Criteria

- Organized convective band approaching the area.
- 700-mb (approximately 10,000 feet) temperature < -4 to -5°C for ground seeding operations. If warmer temperatures are present, aircraft seeding may be viable.
- 700-mb wind directions favorable for transport of the seeding materials over the target areas.
- Cloud top temperatures ≤ -5° C.
- No suspension criteria met.

It has always been NAWC's philosophy that the design of our operational programs should be based upon prior research programs that provided positive indications of increases in precipitation, to the extent that the research results are considered to be representative of the operational programs' conditions (e.g., are research results from one location transferable to the operational program's target area?). The San Luis Obispo program has a unique advantage in this respect since a successful winter research program was conducted during the winters of 1967-1973 in Santa Barbara County, which is immediately south of the area. The research program, known as Santa Barbara II, was summarized in Section 2.4.

Even though Santa Barbara II was conducted over 50 years ago, it is NAWC's professional opinion that it offers the most relevant information for the design of precipitation enhancement programs for this area at the present time. There have not been any winter weather modification research programs conducted in representative coastal areas of the United States since Santa Barbara II. This offers a unique opportunity in technology transfer from a research-oriented to an operationally-oriented cloud seeding program.

As a consequence of the above, **NAWC believes the best project design for a winter cloud seeding program in San Luis Obispo County to be one that replicates, as much as possible, the design of the Santa Barbara II Research Program, since it documented the successful results of randomized seeding experimentation and analysis. In fact, the combination of the research program's phase I (ground-based) and phase II**

(airborne) seeding modes should constitute the optimized method for capitalizing on the seeding potential for the area. NAWC's project design was based upon this approach.

An aircraft was stationed at Santa Maria Regional Airport, just south of the Lake Lopez Target area to allow seeding flights to begin quickly when incoming convective bands were forecast. The aircraft was equipped with two racks, one on each wing of the plane with seeding flares mounted on them.

Two automated high-output ground-based (AHOGS) pyrotechnic firing sites were used to seed suitable convection bands as they passed over these sites. These two sites were located at Mt. Lospe and Berros Peak. Particular consideration was given to focusing the effects of seeding over the intended target areas, and also to seeding suspension criteria.

3.1 Seeding Material Information

The basic concept of both the aircraft and ground seeding in the Santa Barbara II research program was to place as much seeding material as possible into the updraft regions of the convective bands with cloud tops colder than freezing (i.e., -4° to -10° or -12°C). High output silver iodide generators were flown on the aircraft and 400-gram output ground flares were fired every 15 minutes during the passage of convective bands over the single seeding site. The 400-gram flares (known as LW-83's) were considered very high output at the time but have been replaced by even more effective (in terms of nuclei production) flares in programs conducted beginning with the 2001-2002 program. The pyrotechnic flares used at the AHOGS sites emit fast-acting silver iodide complexes during a burn time of approximately four minutes. These flares are referred to as 150-gram flares but this weight includes all the components of the flare (e.g., oxidizer, reduction agent, binder etc.). The amount of silver iodide in the flare has been determined to be 16.2 grams. These flares are manufactured by Ice Crystal Engineering (ICE) located in Fargo, North Dakota.

The output of these ICE flares has been tested at the Colorado State University Cloud Simulation Laboratory. Table 3-2 provides the results of this testing. These flares exhibited activity up to temperatures of -4°C, which is desirable since activity at these warm temperatures can result in the creation of more artificially generated ice crystals at lower altitudes in the convective bands. A couple of advantages can result:

1. Ground releases of seeding material can activate more quickly since the -4°C level will

be reached sooner than the -6°to -8°C level which the case with earlier generation flares.

2. Conversion of cloud water droplets to ice crystals at the -4°C level can release additional latent heat of fusion at lower altitudes within the seeded clouds, which should enhance the dynamic response of the clouds to seeding (refer to Section 2.0 for a discussion of this dynamic response).

A second important outcome of the testing of these flares at the Cloud Simulation Laboratory was that, when the seeding material was introduced into the cloud chamber, 63% of the ice crystal nucleation was produced within the first minute of introduction of the material into the chamber. It was therefore concluded that nuclei produced by these flares were operating by the condensation-freezing mechanism as discussed in Section 2.0. This is also considered to be an advantage over the earlier-generation flares that likely operated by the contact nucleation process, which is much slower, and implies that nearly all of the seeding material that reaches temperatures of -4°C within target clouds should quickly produce ice crystals. Use of the contact nucleation flares, due to the slow nature of the process, could mean that some of the seeding material would not be activated in time to produce a seeding effect in the intended target areas. In fact, this characteristic may partially explain the extended downwind effects shown in southwest Kern County during the conduct of Santa Barbara II, Phase I (see Figure 2.2).

Table 3-2
CSU Cloud Chamber Test Results for Ice Crystal Engineering Flare

Pyro type	Temp (°C)	LWC ($g\ m^{-3}$)	Raw Yield (g^{-1} Agl)	Corr. Yield (g^{-1} Agl)	Raw Yield (g^{-1} pyro)	Corr. Yield (g^{-1} pyro)	Yield (per pyro)
ICE	-3.8	1.5	3.72×10^{11}	3.87×10^{11}	4.01×10^{10}	4.18×10^{10}	6.27×10^{12}
	-4.0	1.5	9.42×10^{11}	9.63×10^{11}	1.02×10^{11}	1.04×10^{11}	1.56×10^{13}
	-4.2	1.5	1.66×10^{12}	1.70×10^{12}	1.80×10^{11}	1.84×10^{11}	2.76×10^{13}
	-4.3	1.5	2.15×10^{12}	2.21×10^{12}	2.32×10^{11}	2.39×10^{11}	3.53×10^{13}
	-6.1	1.5	6.01×10^{13}	6.13×10^{13}	6.49×10^{12}	6.62×10^{12}	9.93×10^{14}
	-6.3	1.5	5.44×10^{13}	5.56×10^{13}	5.87×10^{12}	6.00×10^{12}	9.00×10^{14}
	-6.4	1.5	6.22×10^{13}	6.34×10^{13}	6.72×10^{12}	6.85×10^{12}	1.03×10^{15}
	-10.5	1.5	2.81×10^{14}	2.85×10^{14}	3.03×10^{13}	3.07×10^{13}	4.61×10^{15}
	-10.5	1.5	2.34×10^{14}	2.37×10^{14}	2.87×10^{13}	2.91×10^{13}	4.37×10^{15}
	-4.2	0.5	1.41×10^{12}	1.45×10^{12}	1.53×10^{11}	1.57×10^{11}	2.36×10^{13}
	-6.0	0.5	7.42×10^{13}	7.73×10^{13}	8.01×10^{12}	8.34×10^{12}	1.25×10^{15}
	-10.5	0.5	2.38×10^{14}	2.41×10^{14}	2.91×10^{13}	2.96×10^{13}	4.44×10^{15}

The current ICE flare was compared to the earlier LW-83 flare based upon tests conducted at the CSU Cloud Simulation Laboratory. Figure 3.2 provides a visual comparison of the nucleating characteristics of the ICE and the LW-83 flares. The figure demonstrates that the ICE flare is more effective in the warmer temperature regions of -4°C to -10°C. This temperature region is of prime importance to seeding-induced increases in precipitation in San Luis Obispo County. Freezing supercooled water droplets in the upper (colder) portions of the bands may not necessarily contribute substantially to the production of increased rainfall at the ground. Some information concerning the flare manufacturer ICE is as follows:

- ICE was incorporated in 1999. ICE primarily manufactures three types of flares an ejectable 20-gram silver iodide flare, a burn in place 150-gram silver iodide flare and a burn in place 1000-gram hygroscopic flare.
- ICE supplies flares to 20 different countries on five continents.
- Over 90% of ICE sales are to customers outside the United States.

4.0 EQUIPMENT, PROCEDURES AND PERSONNEL

Each operational cloud seeding program relies upon a mix of suitable equipment, customized procedures, and qualified personnel in order to conduct a successful program. These elements were blended into a comprehensive Operations Plan that was customized specifically for operations of the Lake Lopez program for the 2019-2020 winter season. Various components of this plan are discussed below.

4.1 Weather Radar

The radar used for the project is located at Vandenberg AFB, providing excellent coverage of the project areas. This radar site provides information on precipitation location and intensity, as well as wind speed and direction within the precipitation echoes and a large array of additional products. The radars step-scan through 14 different elevation angles in a six minute period. The maximum range for the detection of precipitation echoes is 143 miles from each site. The National Weather Service provides all the necessary support for these systems: operation, calibration, and maintenance.

An upgrade to the Vandenberg AFB radar that was completed in recent years was a dual polarization capability. This upgrade greatly enhances radars by providing the ability to collect data on the horizontal and vertical properties of hydrometeors (e.g., rain, hail) and non-weather (e.g., insect, ground clutter) targets. Four new products were provided from this upgrade: Correlation Coefficient, Differential Reflectivity, Specific Differential Phase and Hydrometeor Classification. In the context of the San Luis Obispo seeding program this upgrade provided the opportunity for a project meteorologist to be able to determine if supercooled liquid water (SLW) was present using these specialty products, and compare it to icing reports from the pilot.

4.2 Piper Cheyenne II Seeding Aircraft

A twin-engine Piper Cheyenne II served as the seeding aircraft for the project. This aircraft was equipped with two wing-mounted, 38-position silver iodide flare racks. The same high output seeding flares used in the ground sites were used for seeding with this aircraft. It was based at the Central Coast Jet Center, Santa Maria Public Airport, Santa Maria, California during the 2020 winter season. Figure 4.11 provides a photograph of the aircraft. This aircraft was equipped with radios that allowed for communication with the project meteorologist. A device referred to as a phone patch was attached to the radio in the office in order to provide radio communication with the aircraft during seeding operations via phone from NAWC's offices in Sandy, Utah. The aircraft was also equipped with a Garmin 360 navigation system. This system allowed the pilot to see his location with underlying ground terrain and aircraft restricted zone boundaries. The latest weather radar image from the nearest NEXRAD radar site was also depicted on the display. This allowed the pilot to see his location with reference to the location of the convection bands that he was seeding. The Spidertracks tracking system was used for all seeding flights during the aircraft operational period. An image of the Spidertracks flight tracking unit is shown in Figure 4.12. This information was available via the internet to the project meteorologist in real time. The aircraft was on lease to NAWC from the Western Kansas Groundwater District office located in Scott City, Kansas.

Figure 4.1 Piper Cheyenne II cloud seeding aircraft

Figure 4.2 Spidertracks S6 flight tracking unit

4.3 Operations Center and Field Project Office

NAWC's corporate headquarters in Sandy, Utah served as the operations center for the operational period during the 2020 winter season. The project meteorologist's computer contained the LoggerNet software necessary to control the two AHOGS sites that were used in addition to aircraft.

A field office was established at Central Coast Jet Center at the Santa Maria Public Airport during the 2020 winter season, where both the project pilot and aircraft were stationed (Figure 4.15). A 10-watt VHF radio (122.85 or 122.90) and a 25-watt FM radio (151.625 or 151.955) were in this office for communications with the seeding aircraft. In addition to the FM radio, a device referred to as a phone patch was attached to the radio to provide radio communication with the aircraft during seeding operations via phone from NAWC's offices in Sandy, Utah.

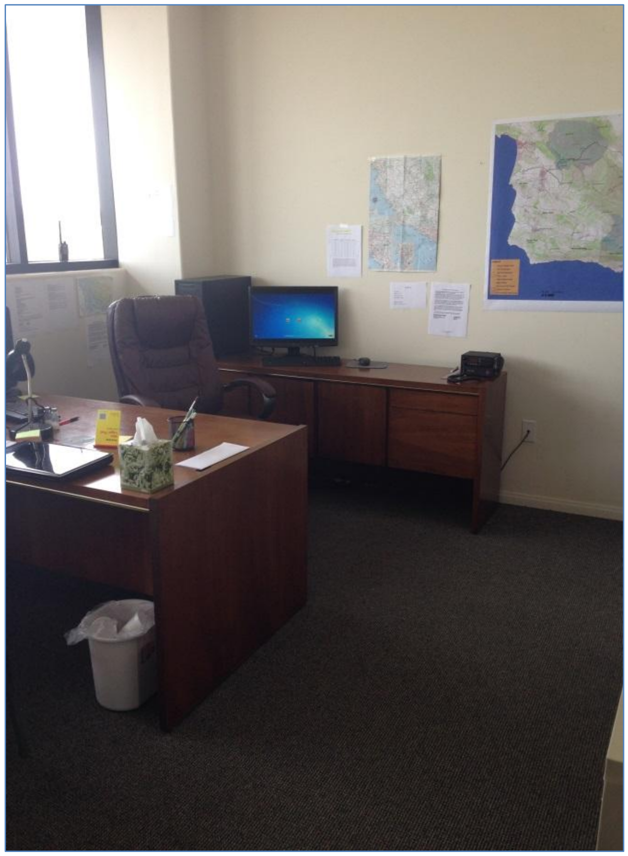


Figure 4.3 NAWC field office at the Central Coast Jet Center

4.4 AHOGS Ground-Based Seeding Systems

The Automated High Output Ground Seeding Systems (AHOGS) allow automated, focused, high-output seeding releases from strategic ridgeline locations under program control from the project operations center with the proper computer software and password. These systems give the project meteorologist the ability to conduct intensive seeding of convection rain bands as they track into and across the project area under different wind flow regimes.

Each site is controlled via a modem-equipped personal computer at the operations center, running custom software to manage the flare seeding operations. The project meteorologist has the option of firing flares individually in real time, or to order batch firing of any number of flares at selectable intervals at each site, e.g., three flares at 15-minute intervals, beginning at any selected time. The software allows monitoring and reporting of AHOGS site status information, such as flare inventory and battery voltage.

NAWC utilized two custom-designed (AHOGS) sites for the 2020 winter season, to affect the Lake Lopez target area. These sites had been pre-established and used for the Santa Barbara Cloud Seeding program but were also used to assist in seeding of the Lake Lopez target area. Both AHOGS sites were previously selected by considering site elevation and geographic location. NAWC believes higher elevation sites to be more effective since the base of the convective bands may not reach lower elevations during their passage over the target area. Such conditions could result in the lack of transport of the seeding agent into effective regions within the bands. Location is important since the effects of seeding will generally occur to the east through north of the site location. Locations are shown in Figure 3.1 of the previous section. The two sites were selected as ones that would offer potential targeting of seeding effects in the Lopez Lake target area under different lower-level wind flow regimes commonly experienced with the passage of convective bands over San Luis Obispo County. Table 4-1 provides location and elevation information for the AHOGS sites.

Table 4-1
AHOGS Site Locations

Location	Latitude (N)	Longitude (W)	Elevation (ft.)
Mt. Lospe	34.897	120.595	1570
Berros Peak	35.062	120.437	1610

These systems were designed for intensive seeding of convection bands using high output pyrotechnic flares. Incorporation of the AHOGS into the project design helps replicate the seeding systems used to achieve the strongly positive results shown in NAWC's Santa Barbara II cloud seeding research program.

Each AHOGS consists of the following primary onsite components:

- Two flare masts, which hold a total of 32 fast-acting seeding flares.
- Spark arrestors that enclose each flare.
- A control mast with an environmentally sealed control box containing a cellular phone communications system, digital firing sequence relays/controller, data logger and system battery.
- A solar panel/charge regulation system to maintain site power.

- Cellular phone antenna.
- Lightning protection.

NAWC installed the Berros Peak site in November 2019 to further help targeting of the Santa Barbara County cloud seeding project, but it also served a dual purpose of helping to seed clouds for the Lake Lopez target area under certain wind regimes. Figures 4.1 and 4.2 provide photos from one of the video cameras of seeding flares burning in daytime and nighttime conditions.

Figure 4.4 Flare Burning at an AHOGS Site During Daytime Conditions

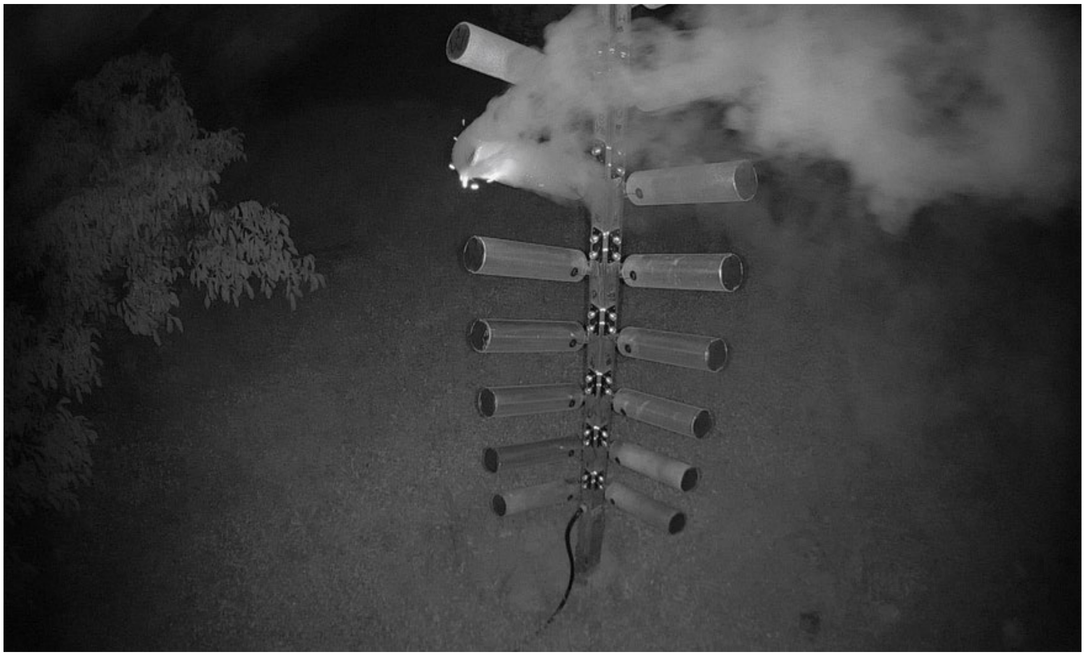


Figure 4.5 Flare Burning at an AHOGS Site During Nighttime Conditions

The video cameras are very useful during seeding operations since they allow the project meteorologist to verify that a flare programmed to fire actually fired. If not, the project meteorologist could program another flare to fire.

The pyrotechnic flares used at the AHOGS sites produce high output, fast-acting silver iodide complexes during a burn time of approximately 3-4 minutes (additional details regarding these flares are provided in Section 3). NAWC upgraded the AHOGS sites for the 2005-2006 rainy season through the addition of spark arrestors placed over each flare. The spark arrestors were developed during the fall of 2005. They are stainless steel cylinders with a large number of small holes drilled through the cylinders' walls. The spark arrestors were designed to eliminate any concerns about sparks, produced during flare combustion, falling to the ground. Even though the cloud seeding program is conducted during the rainy season, there can still be periods when the ground cover can be dry (e.g., at the start of the program in the fall, or during a dry spell that occurs during the operational period). Figure 4.4 is a picture of the Berros Peak site and Figure 4.5 shows a flare burning inside a spark arrestor.

Figure 4.6 Photo of the Mt. Lospe AHOGS Site

Figure 4.7 Photo of the Berros AHOGS Site

Figure 4.8 Flare Burning Inside a Spark Arrestor

4.5 <u>Weather Forecasts and Meteorological Data Acquisition</u>

NAWC project meteorologists were responsible for the determination of when seedable conditions were present and whether seeding suspension criteria were met. Coordination between NAWC's project meteorologist and Ms. Jill Ogren and Mr. David Spiegel of the San Luis Obispo County Public Works Department typically occurred before and after each potential seed event and sometimes during these events. NAWC's project meteorologists archive all weather data pertaining to seeding operations, including time(s) and locations(s) of all seeding material dispensed. Examples are shown in Section 5.0, which discusses last winter's operations.

A variety of weather information is available via the internet that was used to forecast approaching storms, forecast and observe weather conditions during storms as they passed through Santa Barbara County and document conditions of interest like criteria relating to suspension criteria. Some of these useful products include:

- Upper-air data, including important levels at 850, 700, 500 and 250mb.

- Rawinsonde data: pressure, temperature and wind observations which are plotted throughout the atmosphere.
- Radar and surface data which allow the meteorologists to view important parameters before and during seeding operations.
- Hourly observed precipitation data from ALERT networks in San Luis Obispo County, including streamflow data.
- Satellite imagery: visible, infrared, and water vapor presentations updated at intervals ranging from 15 minutes to one hour.

4.6 Seeding Procedures

NAWC's conceptual model of the dynamics of the convection bands is that they are similar to summer squall lines in the Great Plains. NAWC believes that the primary low to mid-level inflow to these bands is along the leading edge of the bands. The inflow regions are thought to be the likely accumulation zones of supercooled liquid cloud droplets water, which are the targets of the seeding. Consequently, this is the desired region for the introduction of the seeding material. Low-level winds are considered in terms of targeting of effects as well as the avoidance of seeding over suspension areas. The HYSPLIT model, discussed in Section 6.0 was also used in real time to help predict the plume dispersion from flares burned.

4.7 Suspension Criteria

Suspension criteria were developed jointly between the Agency and NAWC personnel to serve as safeguards to avoid seeding during situations of extreme weather or adverse hydrologic conditions. Previously, special criteria have been developed and implemented following large fire events within the target area. Cloud seeding suspension criteria include a suspension whenever the National Weather Service (NWS) issued a flood warning that affects any part of the project area. Appendix B contains the suspension criteria for the 2020 winter season. Seeding suspension criteria were monitored during some of the heavier precipitation events, but ultimately, the heavier precipitation event periods did not coincide with seeding operations since they did not meet NAWC's generalized seeding criteria (Table 3-1), thus no seeding suspensions occurred during the operational season.

4.7 Personnel

The following agencies and personnel were responsible for the conduct of the 2019-2020 cloud seeding program.

San Luis Obispo County Public Works
Jill Ogren, Project Administrator
David Spiegel, Assistant Project Administrator

North American Weather Consultants
Ms. Stephanie Beall[1], Project Meteorologist/Program Manager - Sandy, Utah
Mr. David Yorty[2], back-up Project Meteorologist - Sandy, Utah
Mr. Tom Segura, Local Equipment Technician - Lompoc, California

[1] Ms. Stephanie Beall is a Certified Operator by the Weather Modification Association.
[2] Mr. David Yorty is a Certified Manager and Operator by the Weather Modification Association.

5.0 OPERATIONS

The location of the Lake Lopez seeding target area is shown in Figure 5.1. Aerial and ground operations were conducted for the three-month period from January 7, 2020 through April 15, 2020. Ground seeding sites were operational at Mt. Lospe and Berros Peak during the 2020 winter season.

All operations were conducted in accordance with established suspension criteria, which have been developed for a variety of situations, such as high intensity rainfall, flood warnings, forecasted high streamflow and high intensity rainfall for burn areas. These suspension criteria can be found in Appendix B, along with the rest of the suspension criteria for the 2020 winter season.

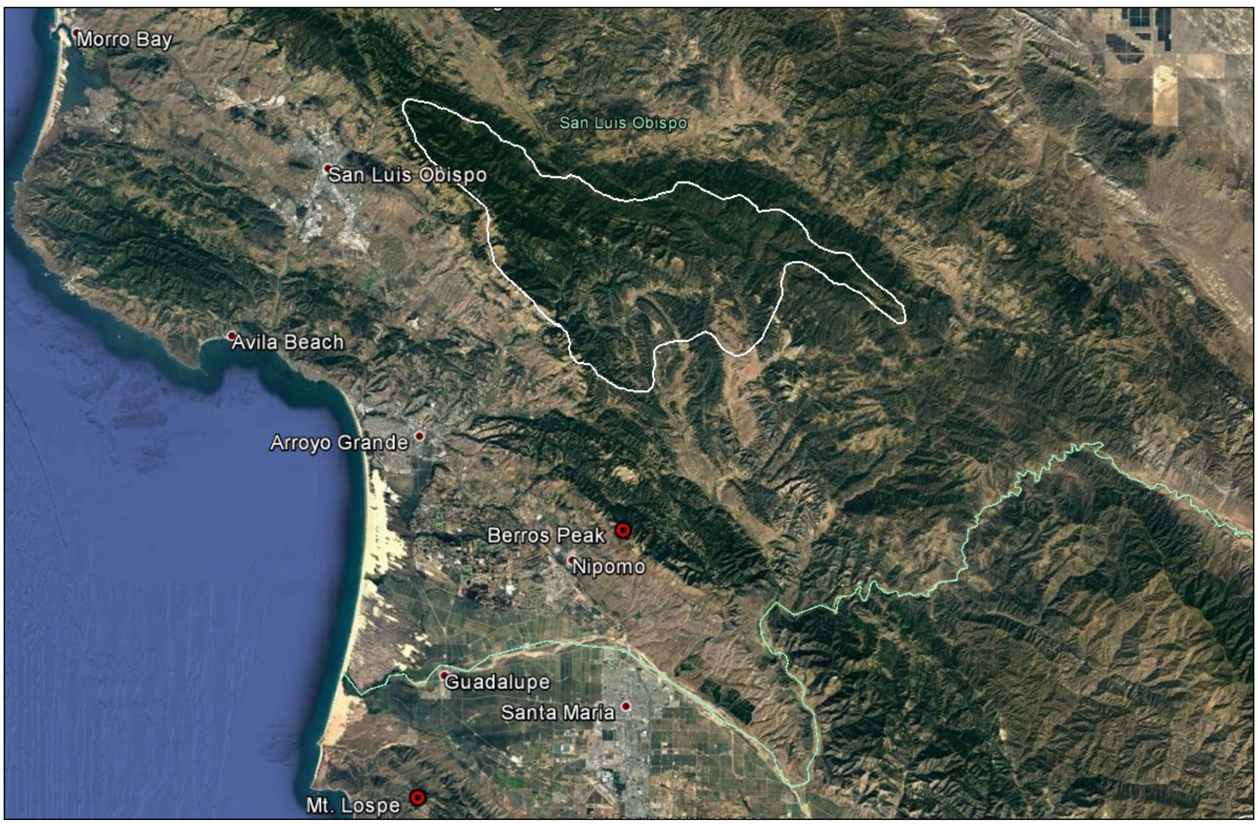


Figure 5.1 Project Area, Topographic Features and Ground Based High-Output Flare Site Locations.

The 2020 winter season was characterized by neutral El Nino Southern Oscillation (ENSO) conditions. The ENSO neutral pattern makes it difficult to distinguish a clear precipitation pattern, i.e. it does not favor either an above or below normal Water Year. Figure 5.2 shows the precipitation percent of average for November 2019 through April

2020 for the contiguous United States. Near-normal precipitation was observed along the Central Coast into coastal Los Angeles County, with 125 to 175 percent of normal precipitation observed over far southwestern California. This precipitation pattern can be tied to a more southerly storm track during November and December and again during the March through April time period. Table 5-2 shows the evolution of the ENSO 3.4 region index throughout the 2019-2020 winter season. A value of -0.5 or less indicates La Nina conditions present and a value of +0.5 or more indicates that El Nino conditions are present. Anything between -0.5 and +0.5 is considered a neutral condition.

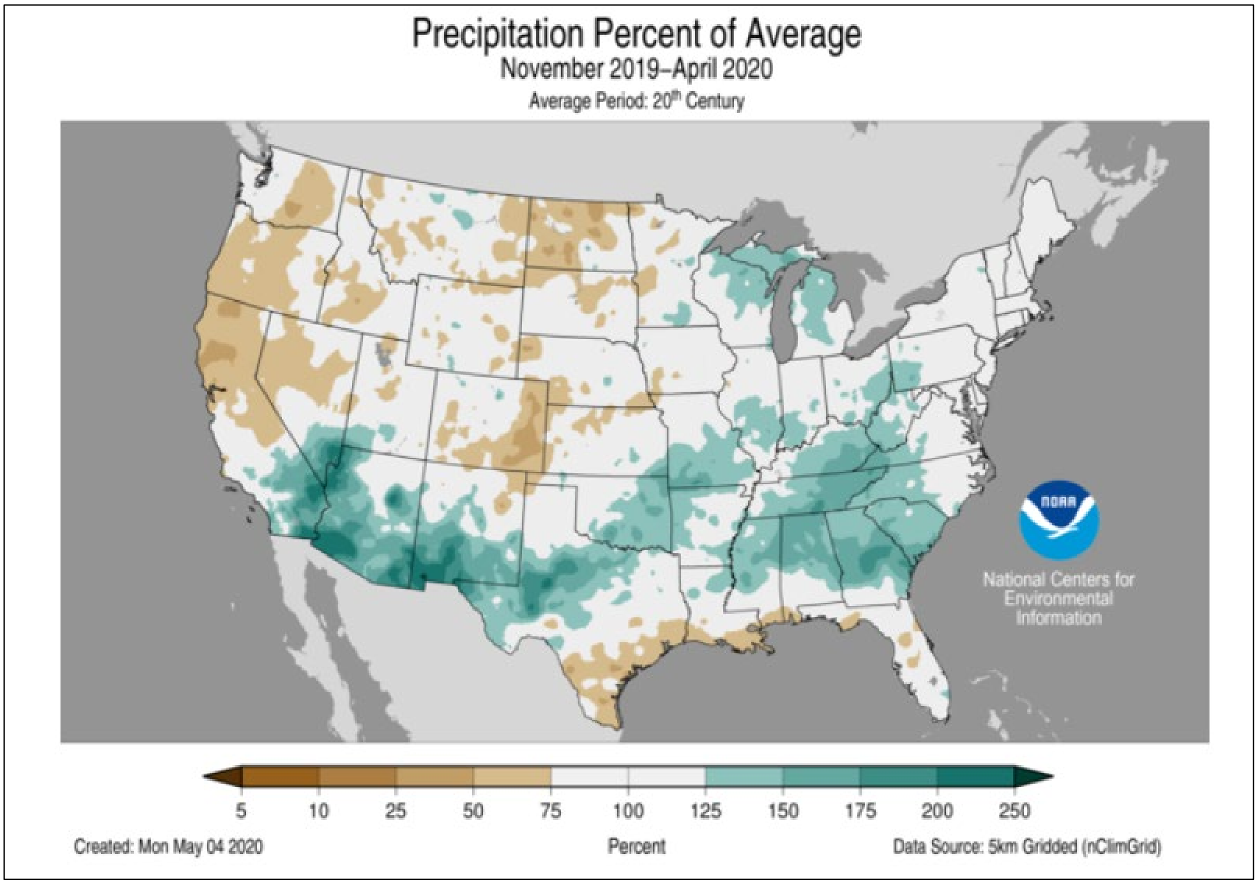


Figure 5.2 Percent of Average Precipitation November 2019 – April 2020 for the contiguous United States

Table 5-1
November 2019 – April 2020 ENSO Values

November - January	December - February	January - March	February - April
0.5	0.5	0.6	0.5

5.1 Summary of the 2019-2020 Winter Season Rainfall

San Luis Obispo County rainfall amounts for the 2019-2020 winter season were right around normal, which contrasts with the 2018-2019 winter season, where the county saw above normal precipitation Countywide percent of normal precipitation as of May 1 was 149% of normal during the 2019 Water Year and 97% of normal during the 2020 Water Year. January and February saw record dry conditions, while March and April saw above normal rainfall values. The months of November and December will be discussed in this section, as they are important pieces of the 2020 Water Year, even though cloud seeding operations did not begin until January.

November precipitation was slightly above normal, with a rain gauge near Lake Lopez at 116% of normal for the month. In discussions of the other months, percent of normal values are countywide-average values as reported on the Agency website. In December, the precipitation producing weather pattern usually improves with a more active storm track moving further south in California. This was the case in December 2019, which turned out to be the Water Year's wettest month to date, with 204% of normal at the gauge. January and February brought considerable dryness to the area. January 2020 monthly precipitation was near 15% of normal and February brought no precipitation at this gauge location. Several other sites in southern San Luis Obispo County were completely dry in February. The combined January through February period was one of the driest on record for many locations across southern California.

March was above normal in terms of precipitation, with the storm track dipping further south, into the southern part of the state. As a result, many locations in northern California were below normal for the month. This resulted in monthly precipitation reaching 170 percent of normal. April offered up another wet month for the county, with 174% of normal precipitation observed at the Lake Lopez gauge. It should be noted that almost all of the observed precipitation fell at the beginning of the month with a very slow-moving low that developed in the Pacific and moved over the Central Coast and southern California, taking nearly a week to completely exit the area.

Figures 5.3-5.8 show a month by month depiction of percent of normal precipitation maps for the county of San Luis Obispo.

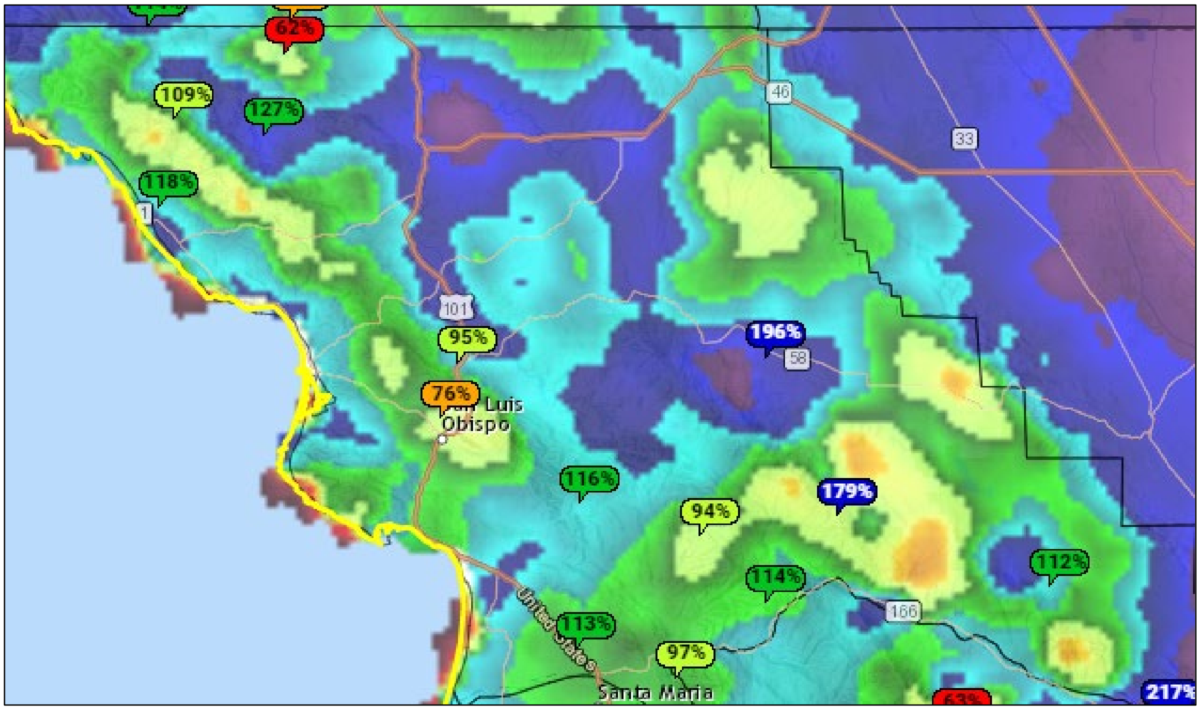


Figure 5.3 November 2019 Percent of Normal Precipitation

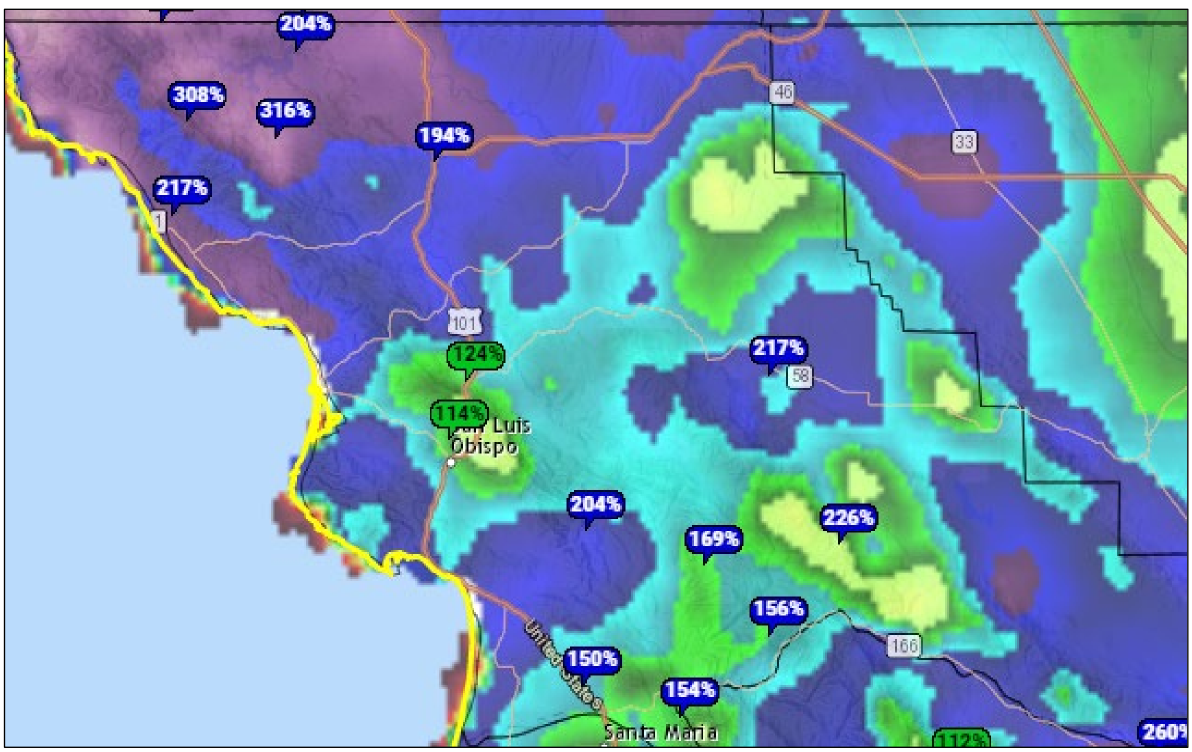


Figure 5.4 December 2019 Percent of Normal Precipitation

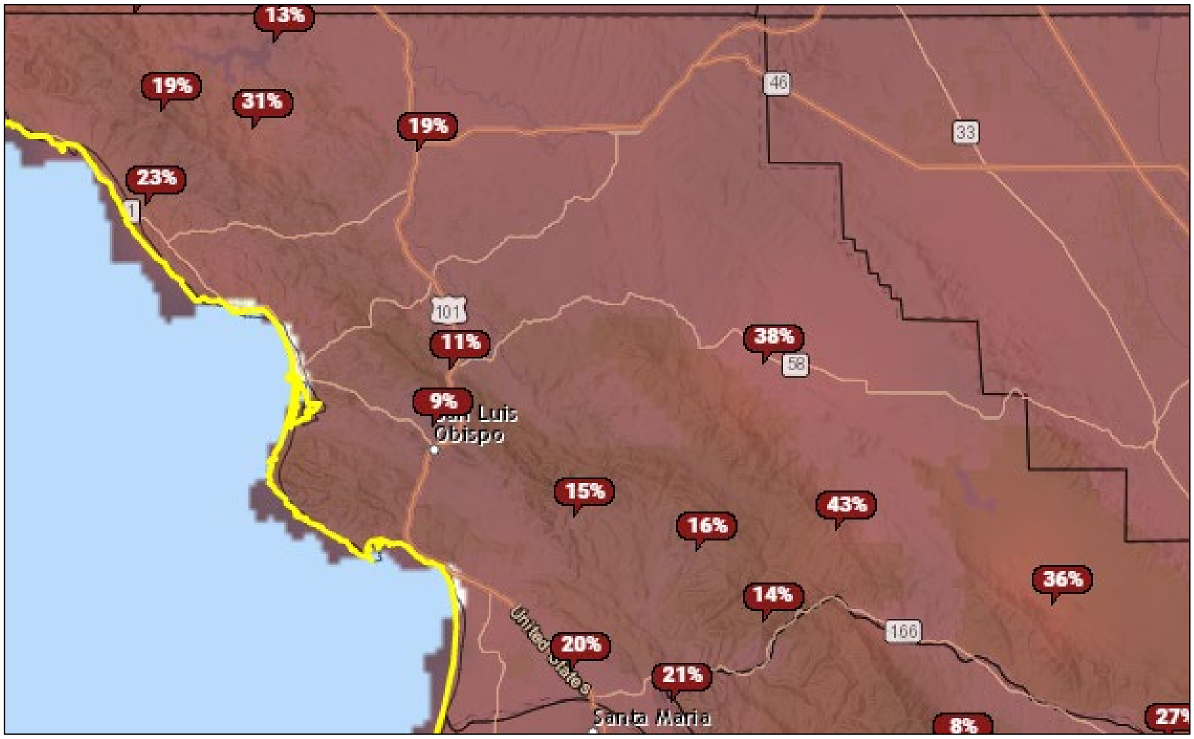


Figure 5.5 January 2020 Percent of Normal Precipitation

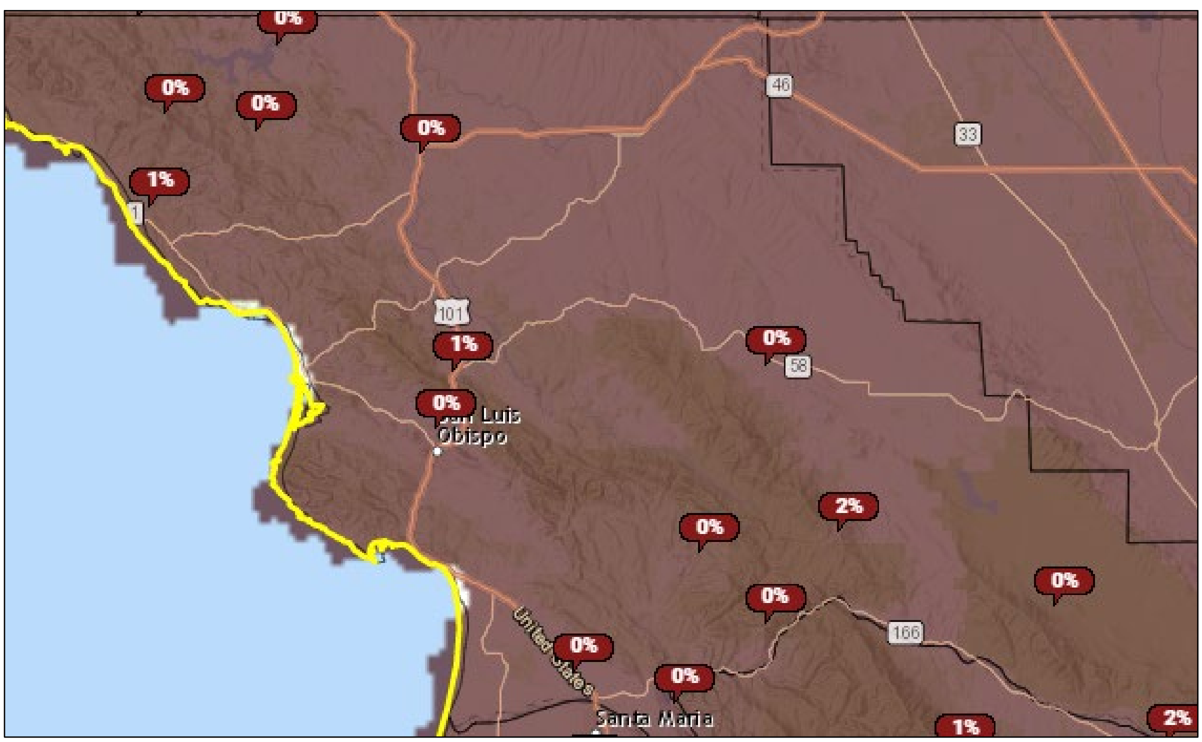


Figure 5.6 February 2020 Percent of Normal Precipitation

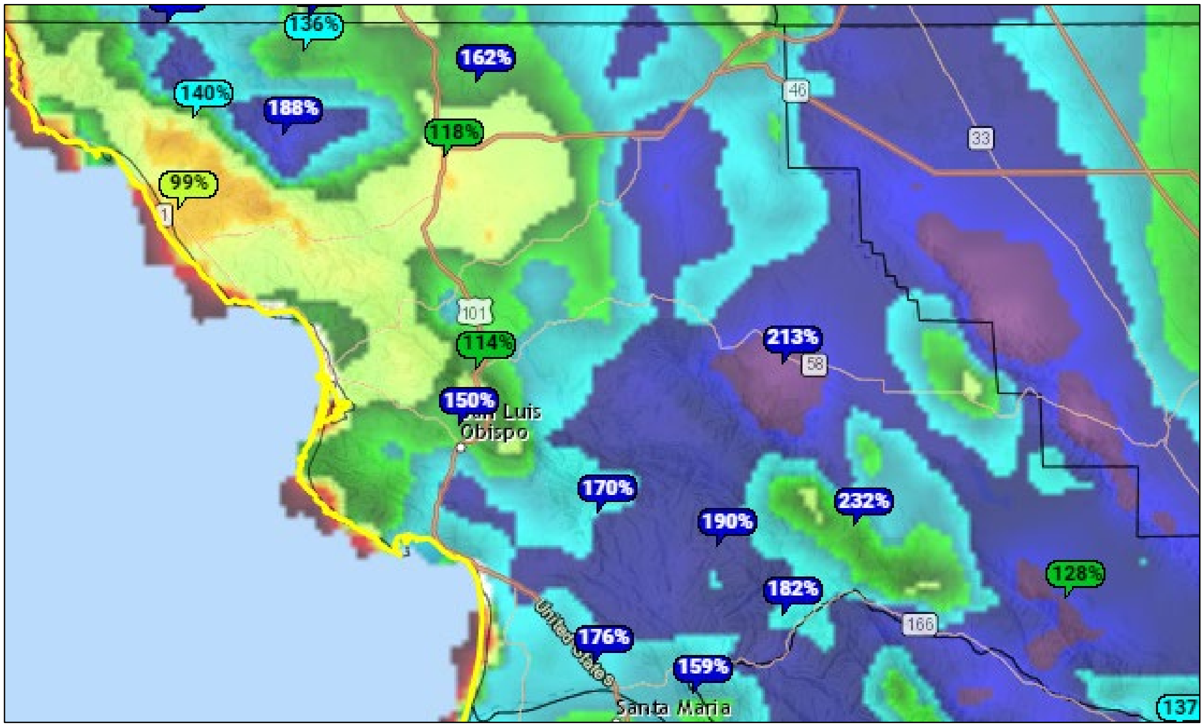


Figure 5.7 March 2020 Percent of Normal Precipitation

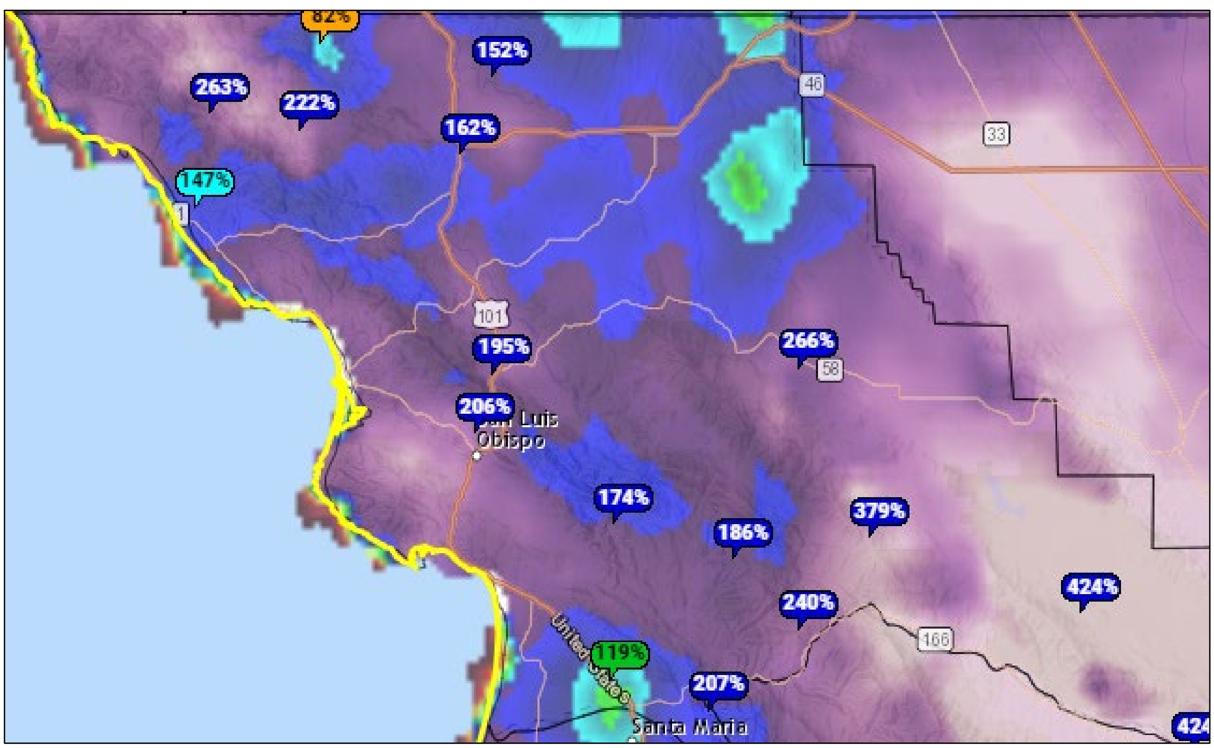


Figure 5.8 April 2020 Percent of Normal Precipitation

Figures 5.9-5.11 provide graphical depictions of rainfall events for the period of November 1, 2019 through April 15, 2020 for two sites in and near the Lake Lopez target area. Again, rainfall amounts were shown prior to the beginning of the operational season in order to depict the entire wet season for San Luis Obispo County. Note that the scale on the x-axis of each site is different, depending on how much rainfall was received during the given period.

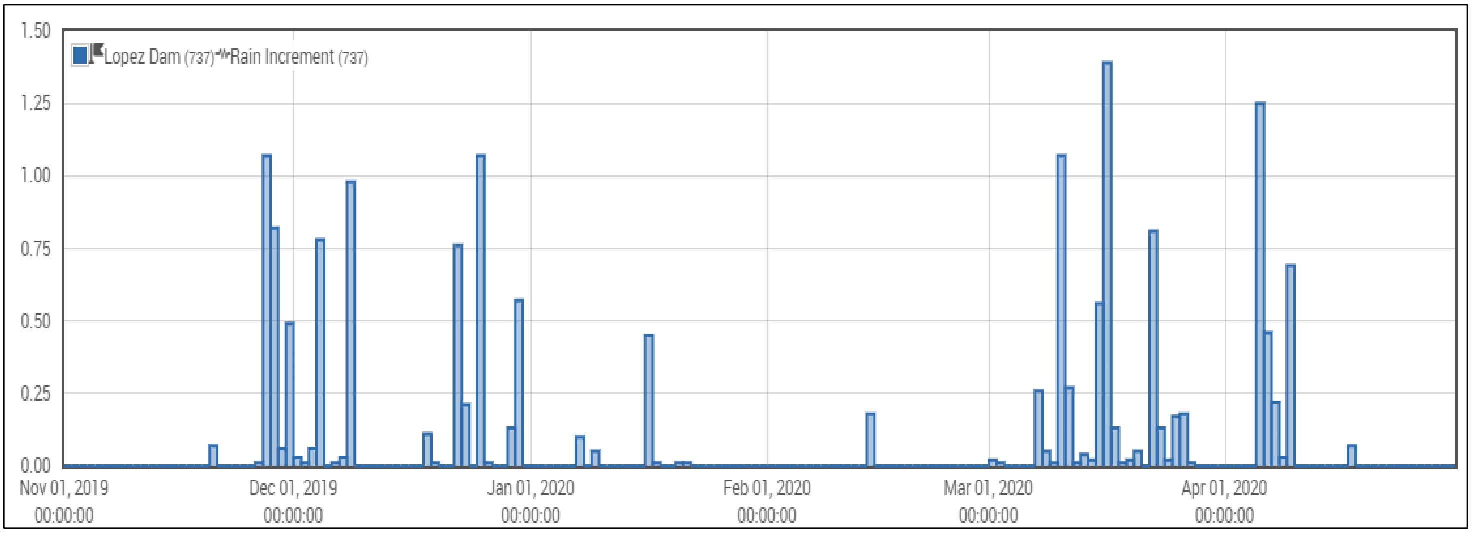


Figure 5.9 Lopez Dam Daily Rainfall (8 am to 8 am), November 1, 2018 to April 15, 2019

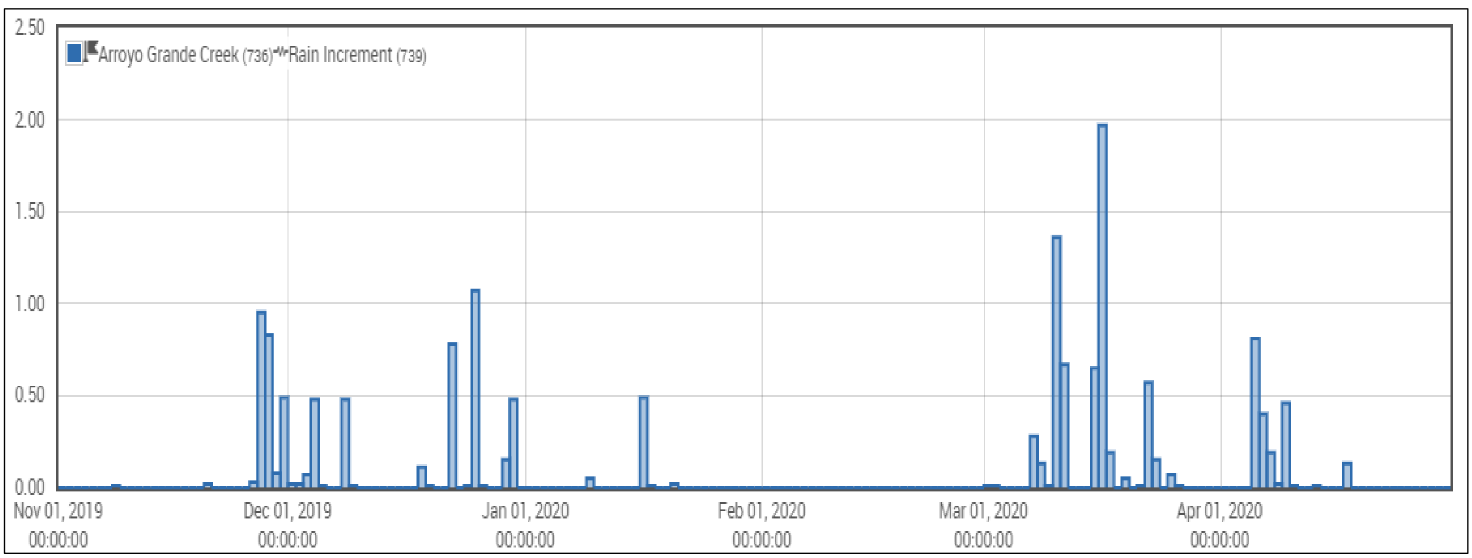


Figure 5.10 Arroyo Grande Creek Daily Rainfall (8 am to 8 am), November 1, 2019 to April 30, 2020

5.2 <u>Hydrologic Conditions During the 2019-2020 Winter Season</u>

Some runoff did occur during the rainy season with increased rainfall in March and April. Figure 5.12 provides data from a stream gauge that represents discharge from Lopez Lake. This gauge site is located close to the Lake Lopez target area. The most notable increases in discharge were observed in mid-March and in early April and were attributed to a very active, wet pattern during these periods. Early season rainfall moistened the soil which allowed later season rainfall to produce surface runoff. More information regarding this active period can be found in Section 5.4. The blue line in Figures 5.11 and 5.12 is representative of when peak discharge typically occurs in San Luis Obispo County.

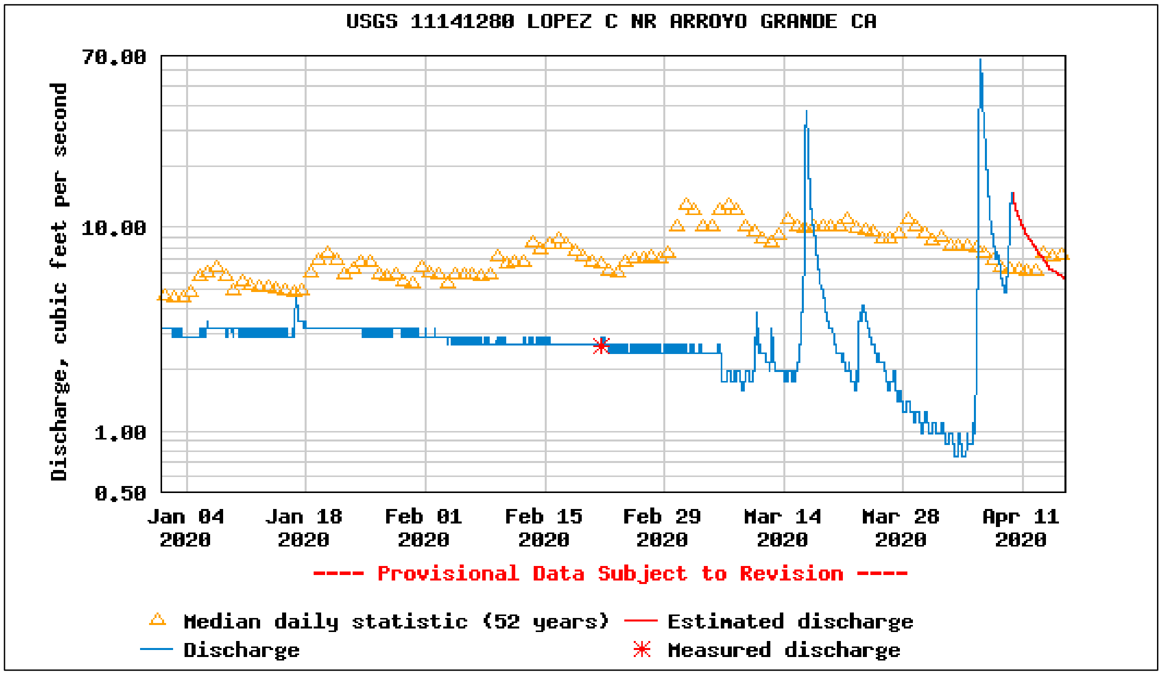


Figure 5.11 Streamflow at the Lopez Creek from January 1 to April 15, 2020

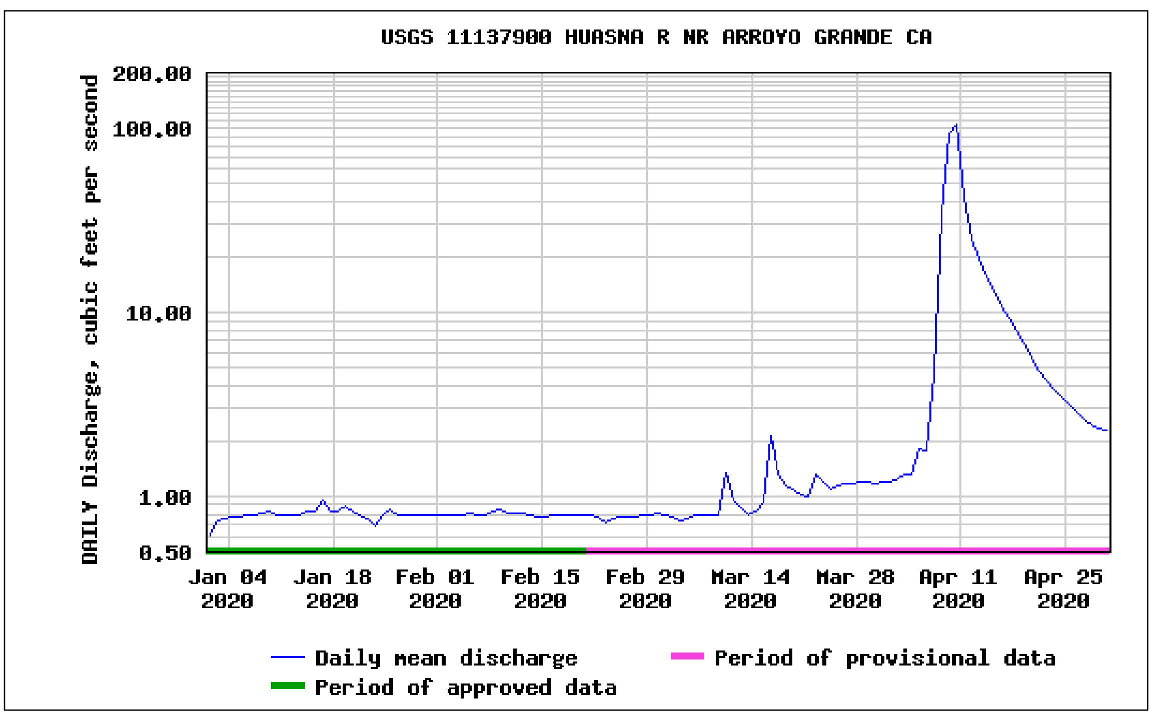


Figure 5.12 Streamflow at the Huasna River from January 1 to April 30, 2020

5.3 Summary of Seeding Operations

The contract period ran from January 7, 2020 – April 15, 2020 for the Lake Lopez target area. Table 5-4 summarizes the aerial and ground-based seeding operations for the season. Seeding opportunities occurred on six days during the 2020 operational season. A total of 30 flares were successfully burned at the two ground sites, releasing an estimated 486 grams of seeding material. In addition, one seeding flight occurred totaling 1.25 hours of seeding time, dispensing a total of 151.2g of AgI. Individual operational periods are discussed in more depth in Section 5.4.

Table 5-2
2020 Aerial and Ground-Based Seeding by Location and Firing Time

Date	Mt. Lospe	Berros Peak	Aircraft Seeding
March 9	0845(2), 0953		
March 10			1300-1345
March 16		0524 (2), 0532 (2), 1015(2), 1030(3), 1100(2)	
March 22[1]	1755	1720(2), 1735 (2), 1745 (2), 1840 (2)	
April 5[1]		2020 (2), 2025, 2035, 2050 (2)	
April 6[1]		1010	

[1] Flare firing times are in PDT.

5.4 Storm Events of the 2020 Season

This section describes the storm events that affected the Lake Lopez project area during the 2020 operational period. A general discussion of the meteorology accompanying each event is given, followed by a description of the seeding operations. Wind directions, when provided, are always reported in the direction from which the wind is blowing (e.g., a southerly wind means the wind is blowing from the south toward the north). Wind speeds are usually reported in nautical miles per hour (knots), with 1 knot equal to 1.15 miles per hour. Figures shown in the storm summaries may include the following:

1) Satellite images; infrared, water vapor or visible. Infrared images provide information during the day and night on cloud top temperatures. Water vapor images can show moist or dry airmasses and visible satellite images can help determine cloud and storm structure.

2) National Weather Service NEXRAD radar images, showing reflectivity values associated with precipitation near the times when seeding occurred. These images give an indication of the type, intensity, and extent of precipitation during seeding periods. Wind direction and velocity are also observed by the NEXRAD radars through the Doppler feature, which is part of the NEXRAD design. Plots of winds with height in 1000-foot increments are available with a 6-minute time resolution from NEXRAD radars. These displays are called Velocity Azimuth Displays (VAD).

3) Skew-T upper-air soundings from Vandenberg AFB. The skew-T sounding is a plot of temperature, dew point, and winds vs. height, observed by a radiosonde (balloon borne weather instrument). This sounding information is useful for analyzing various parameters of the atmosphere, providing temperature and moisture profiles, and convection potential. Soundings are available twice daily at 0400 and 1600 PST. The sounding information allows us to identify the height of the -5°C level. The closer the height of the -5°C level is to the ground seeding, the quicker a seeding effect will begin to be produced in the convection elements embedded in the convective bands. These convective elements transport the seeding material vertically from the ground seeding sites to colder temperatures aloft. The height of the -5°C level is not a factor when conducting aerial seeding since the seeding aircraft can fly at this level regardless of its height.

January 2020

The project became operational on January 9, 2020 for the Lopez Lake Watershed. The aircraft and pilot arrived in early January. A local operations center was established at the Central Coast Jet Central, located at the Santa Maria Public Airport. This operations center was equipped with radio equipment to enable the meteorologist to talk with the pilot remotely during cloud seeding operations. Unfortunately, there were no seeding events for the month of January due to very dry conditions developing over the Central Coast and Southern California. This pattern is described in the operations summary.

February 2020

The weather pattern throughout the month was very inactive with only one very minor storm system affecting San Luis Obispo County and the Lake Lopez Watershed. Except for this one weak system, the area remained abnormally dry throughout most of the month of February. Unfortunately, there were no seeding opportunities for the month of February due to very dry conditions developing over the Central Coast and Southern California.

March 2020

March was not only a better month operationally, but a number of systems that were not seedable still provided additional rainfall across San Luis Obispo County and the Lake Lopez target area. Every week during the month yielded at least one operational period, except for the last few days of the month. Table 1 shows the amount of ground flares fired and the amount of seeding flight time that occurred.

March 9-10, 2020

Two seeding periods occurred during this storm event. Seeding operations occurred on the 9th with a trough/cut off low pressure system off the coast of California. This system was similar to the one at the beginning of the month, in terms of temperatures and moisture values. On the 9th, a pre-frontal trough moved through the area, providing enough lift and instability to yield a weak convective band between 0800 and 1000 PDT (Figure 5.13). Temperatures were -7°C at 700 mb and winds were southeasterly throughout most of the column. The band was moving from southwest to northeast, so even though the ambient winds were from the southeast (Figure 5.14), the storm motion vector would carry the seeded band downwind into the target area. A total of three flares were dispensed from one ground site on the 9th.

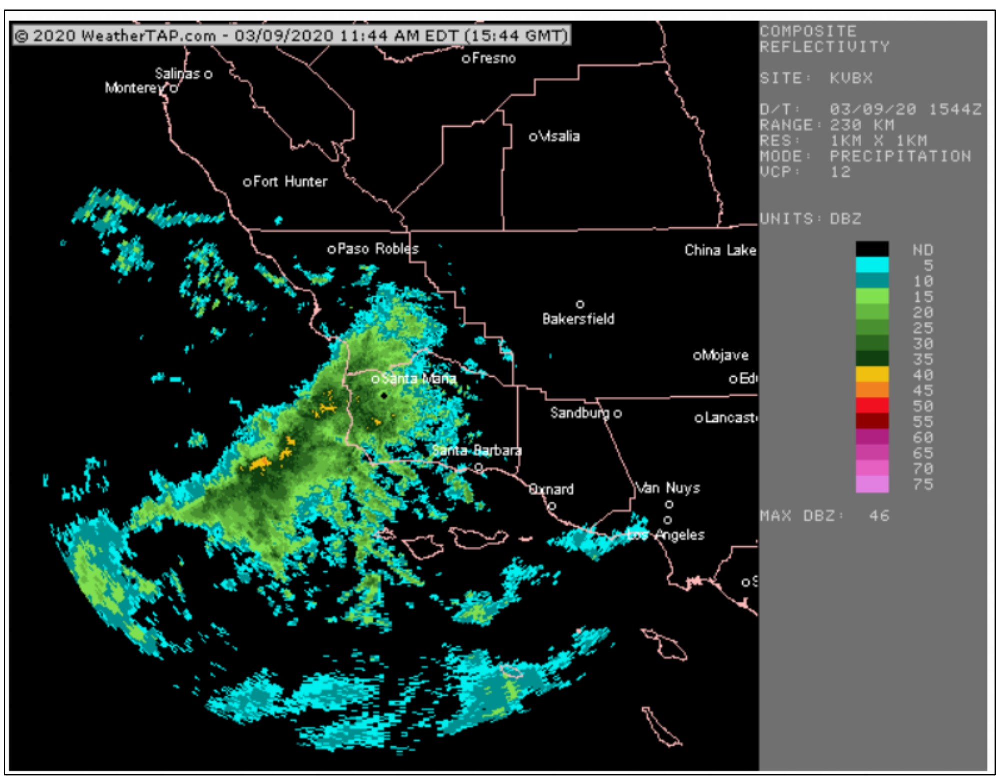


Figure 5.13 Composite Reflectivity on March 9, 2020 at 0840 PDT

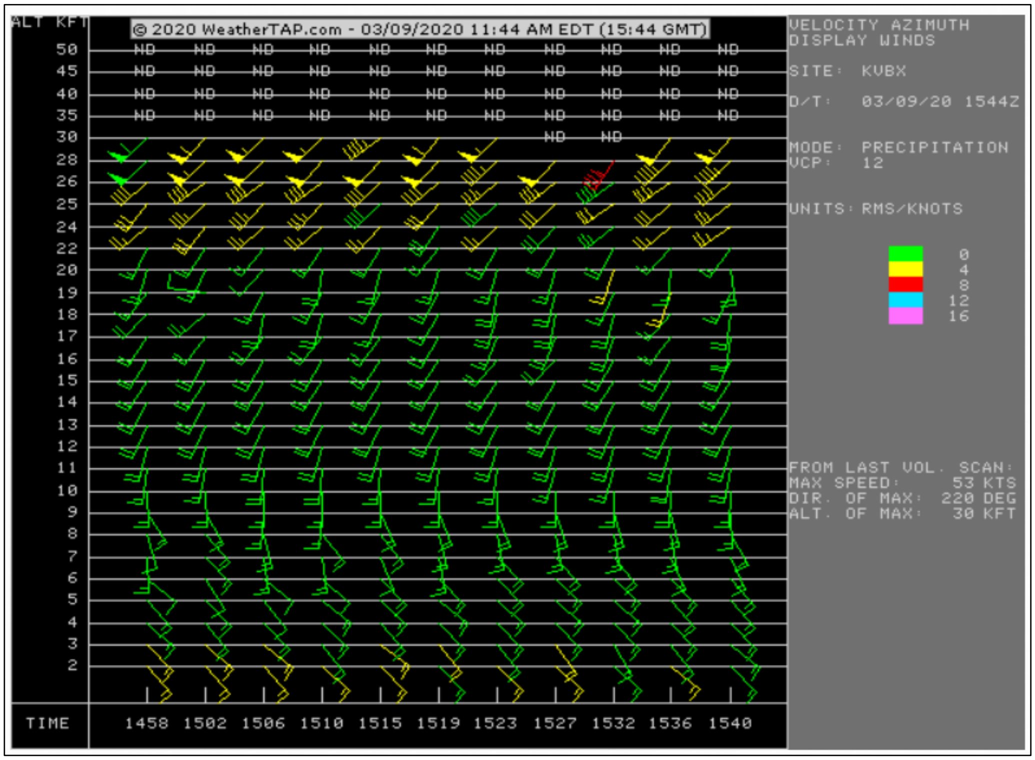


Figure 5.14 VAD wind display on March 9, 2020 at 0844 PDT

A more defined band formed during the afternoon hours of the 10th. This band moved into the area from the south. Temperatures were -5°C at 700 mb (10,000 feet) but, more importantly, echo tops (Figure 5.15) were reaching up to about 25,000 feet. This suggested that a large portion of the cloud might have potentially contained supercooled liquid water (SLW). A seeding flight was launched.

A useful product derived from the NEXRAD radar data is Vertically Integrated Liquid. This parameter allows the meteorologist to estimate how much SLW may be in the cloud. Figure 5.16 shows very high VIL values associated with the band that was seeded during the afternoon hours. Since the band was moving from the southeast to the north/northwest, seeding in southeasterly flow was appropriate for optimal targeting (Figure 5.17). The band was very robust (Figure 5.18) intensity-wise and contained a fair bit of lightning. Airborne seeding was conducted as this band moved into northern Santa Barbara County and prior to the band moving into southern San Luis Obispo County. The flight track can be seen in Figure 5.19. Moderate rain occurred as this band passed over the county. Total seeding time was 1.25 hours, dispersing 150g of AgI.

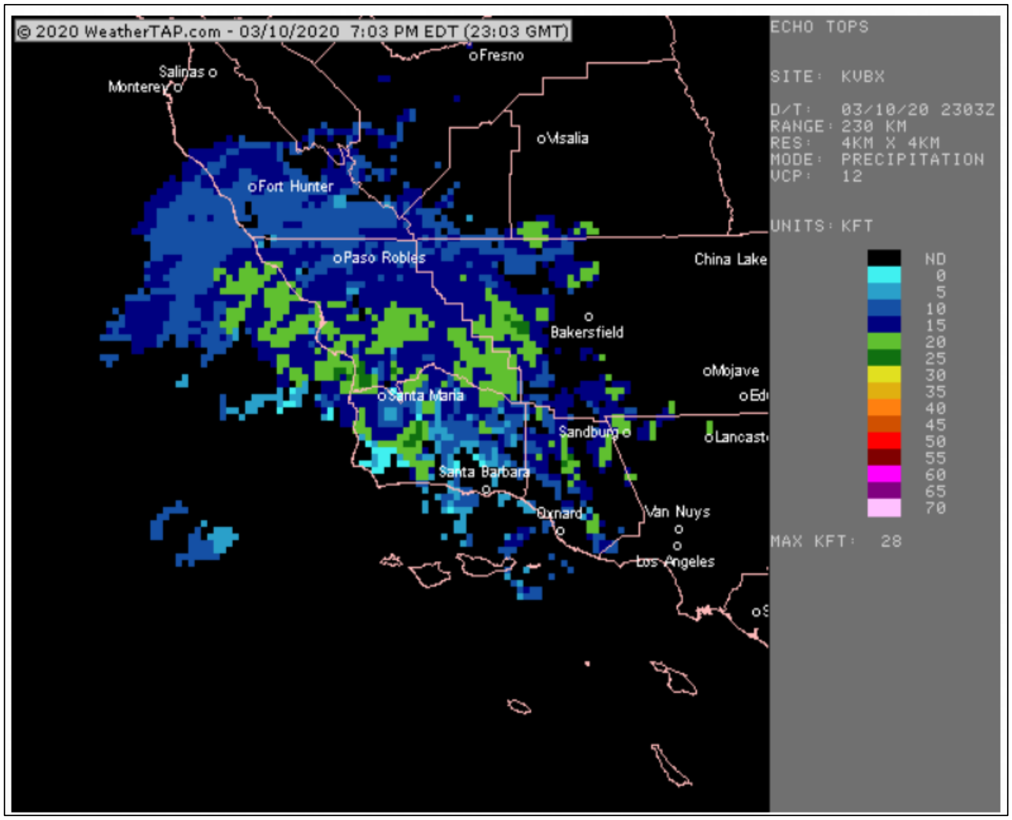


Figure 5.15 Echo tops on March 10, 2020 at 1603 PDT

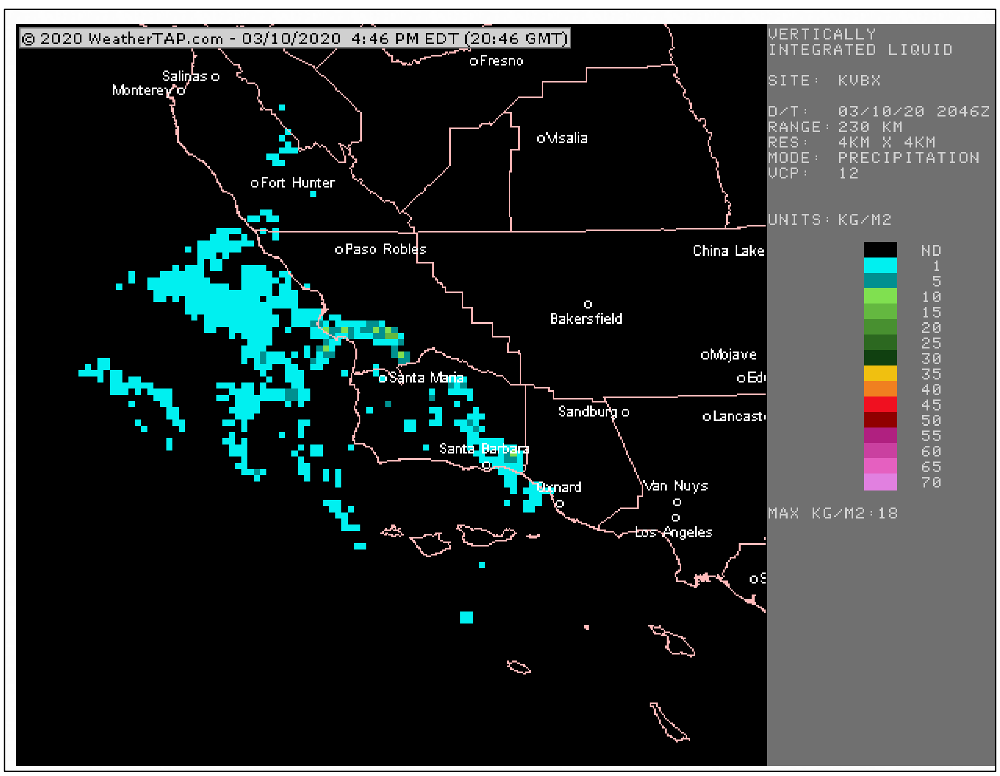


Figure 5.16 Vertically Integrated Liquid on March 10, 2020 at 1346 PDT

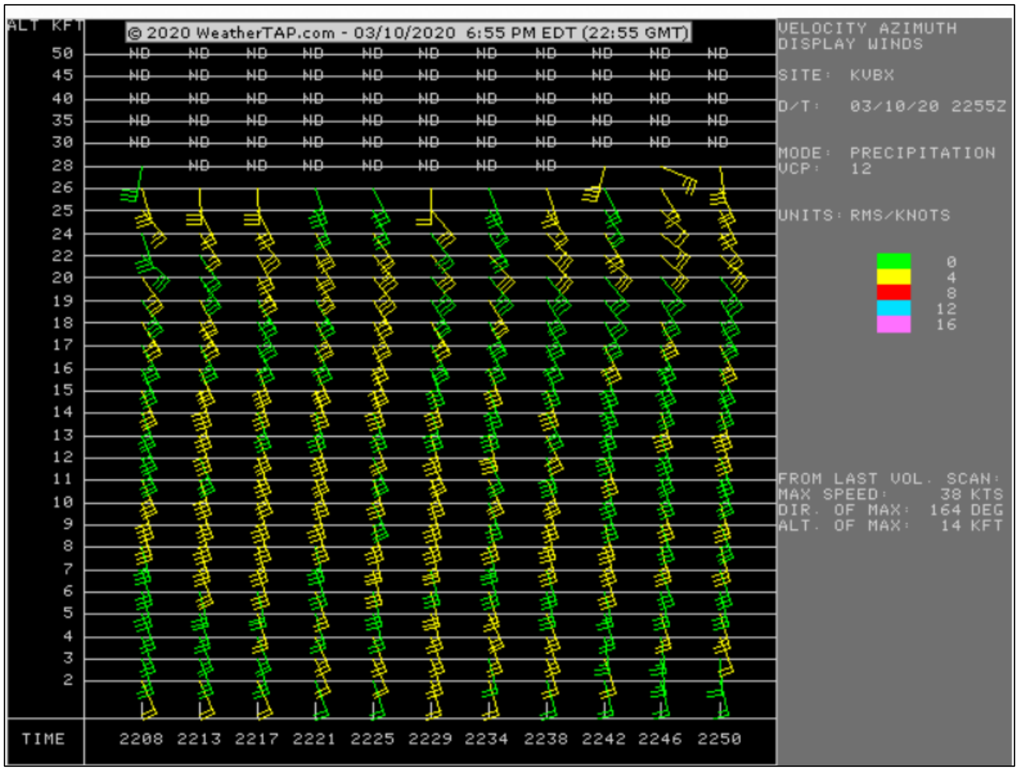


Figure 5.17 VAD wind display on March 10, 2020 at 1550 PDT

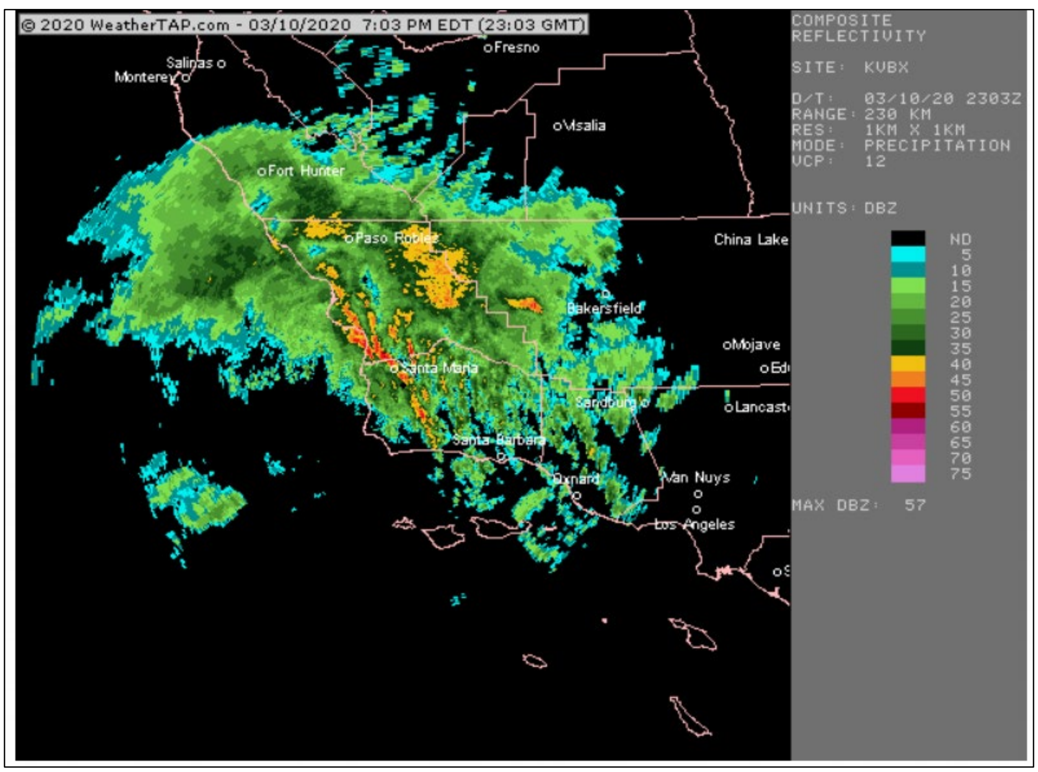


Figure 5.18 Composite Radar on March 10, 2020 at 1603 PDT

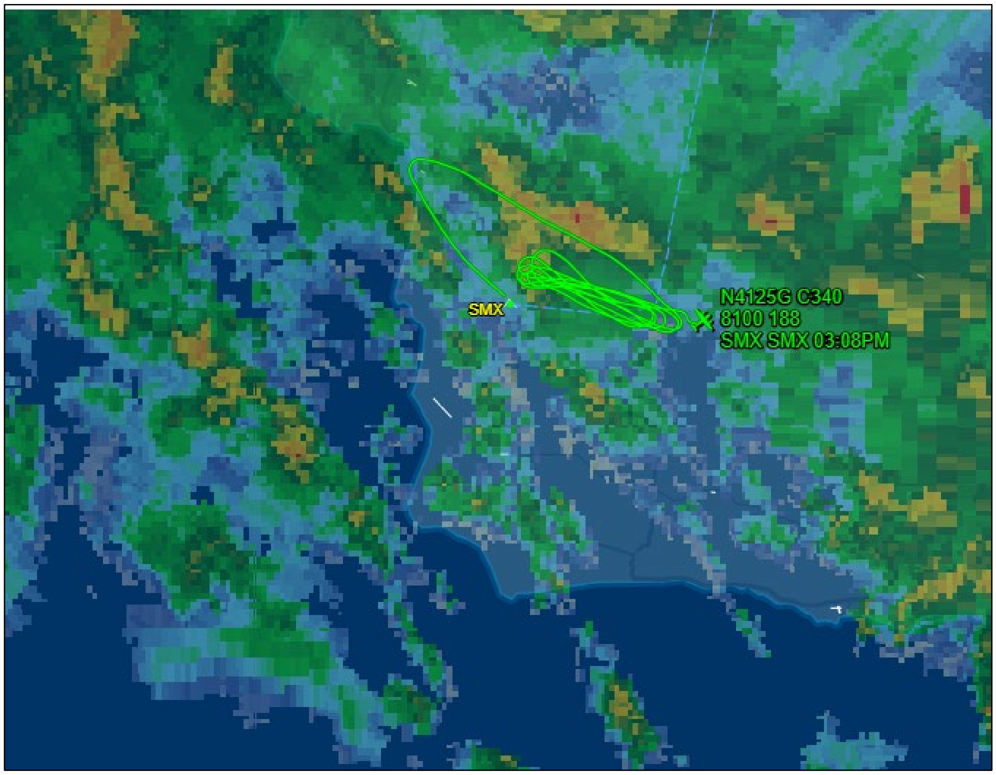


Figure 5.19 Seeding flight track on March 10, 2020

March 16, 2020

A closed low moved down from the Pacific Northwest coast into the central California coast early on the 16th. 700 mb temperatures were around -8°C and the freezing level was near 800 mb or about 6,000 feet. This setup was ideal for two convective bands to be seeded, with the first one being more robust (Figure 5.20) which impacted the county between 1000 and 1200 PDT. Radar imagery determined echo tops (Figure 5.21) to be around 10,000 feet which suggested that a substantial portion of the cloud contained supercooled liquid water. Winds were southerly at the surface with a shift to south/southwest winds as the band moved through (Figure 5.22). Seeding occurred on two separate bands with only light precipitation amounts. A total of 11 flares were dispensed from one ground site during this seeding period.

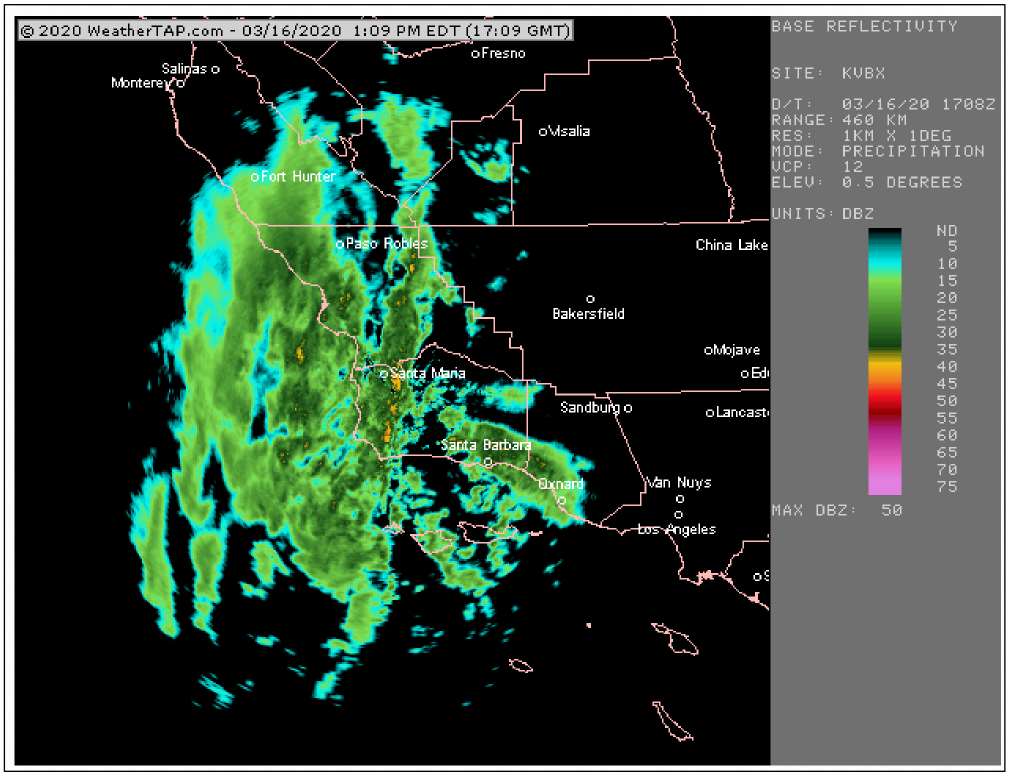


Figure 5.20 Composite Radar on March 16, 2020 at 1000 PDT

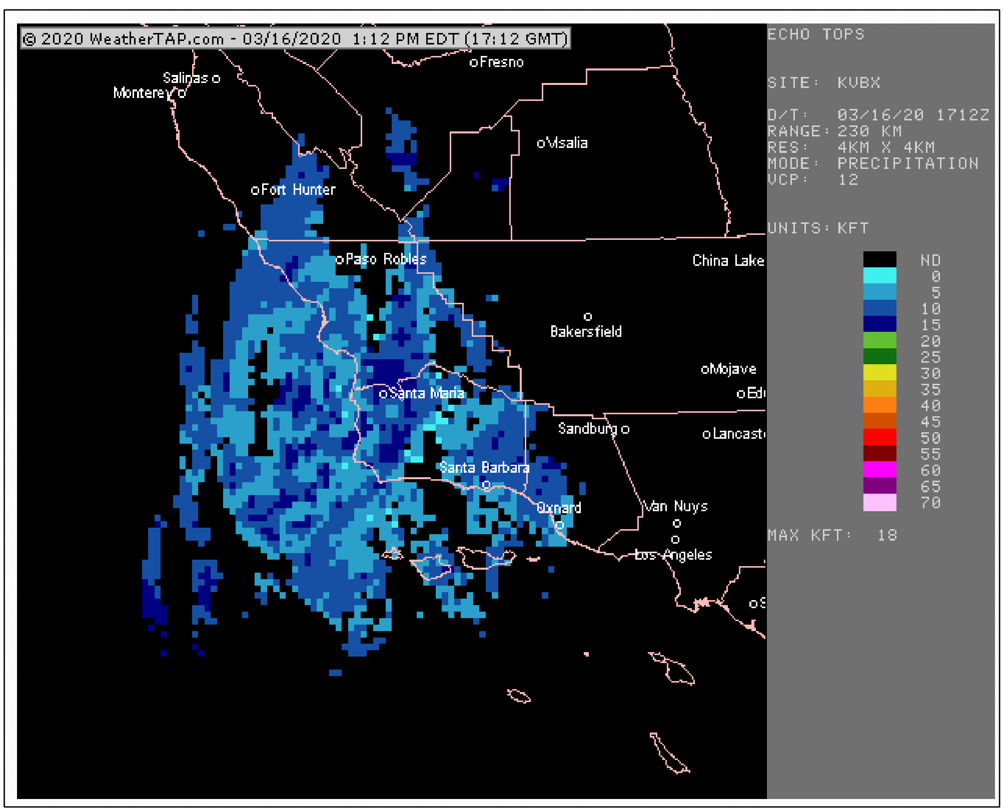


Figure 5.21 Echo tops on March 16, 2020 at 1012 PDT

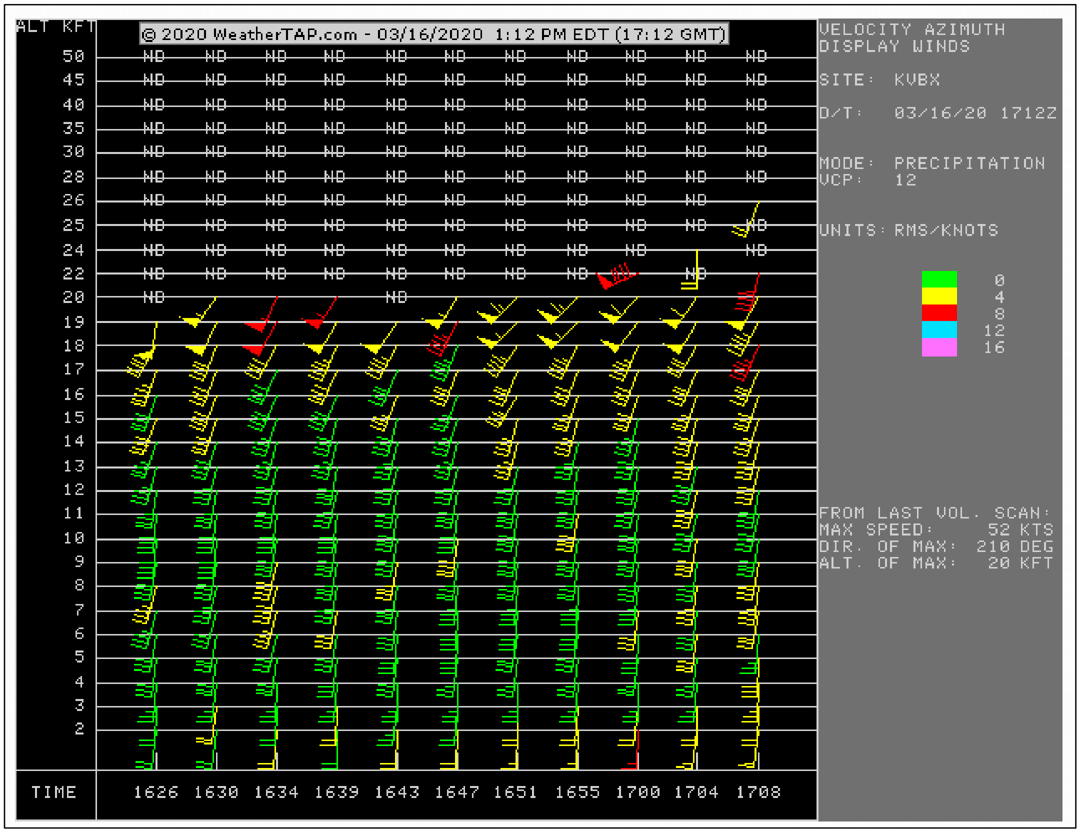


Figure 5.22 VAD wind display on March 16, 2020 at 1012 PDT

March 22, 2020

A closed low located off the California coast was noted on satellite (Figure 5.23) and caused a convective band to form offshore and move through the County between 1500 and 1800 PDT (Figure 5.24). The band was moderately strong in terms of intensity and favorable for seeding operations. 700 mb temperatures were around -8°C at 700 mb and winds were southeasterly at the surface, becoming southerly around 5,000 feet (Figure 5.25). A total of eight flares were dispensed from two ground sites during this storm period.

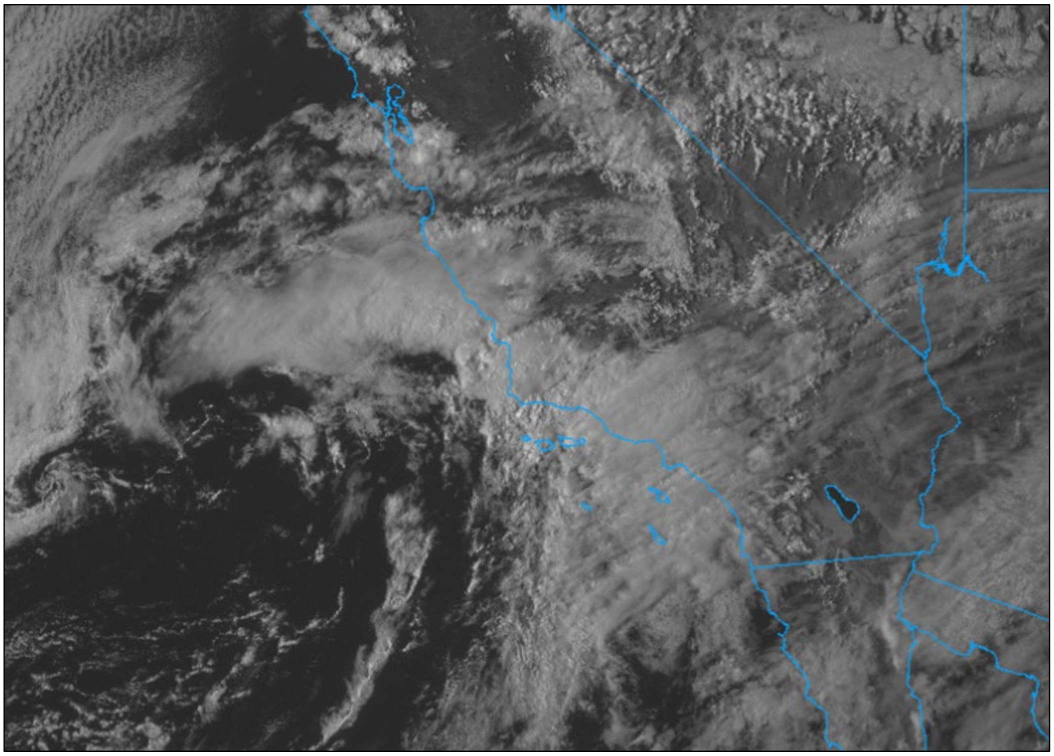


Figure 5.23 Visible satellite image on March 22, 2020 at 1600 PDT

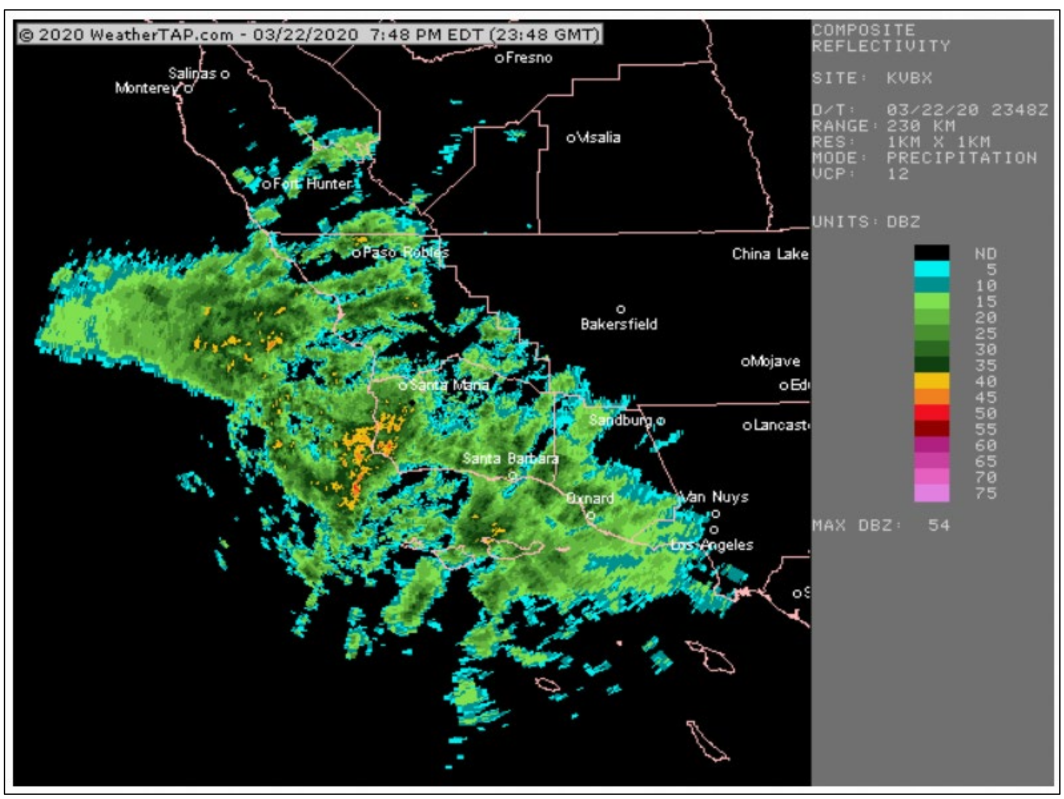


Figure 5.24 Composite radar on March 22, 2020 at 1648 PDT

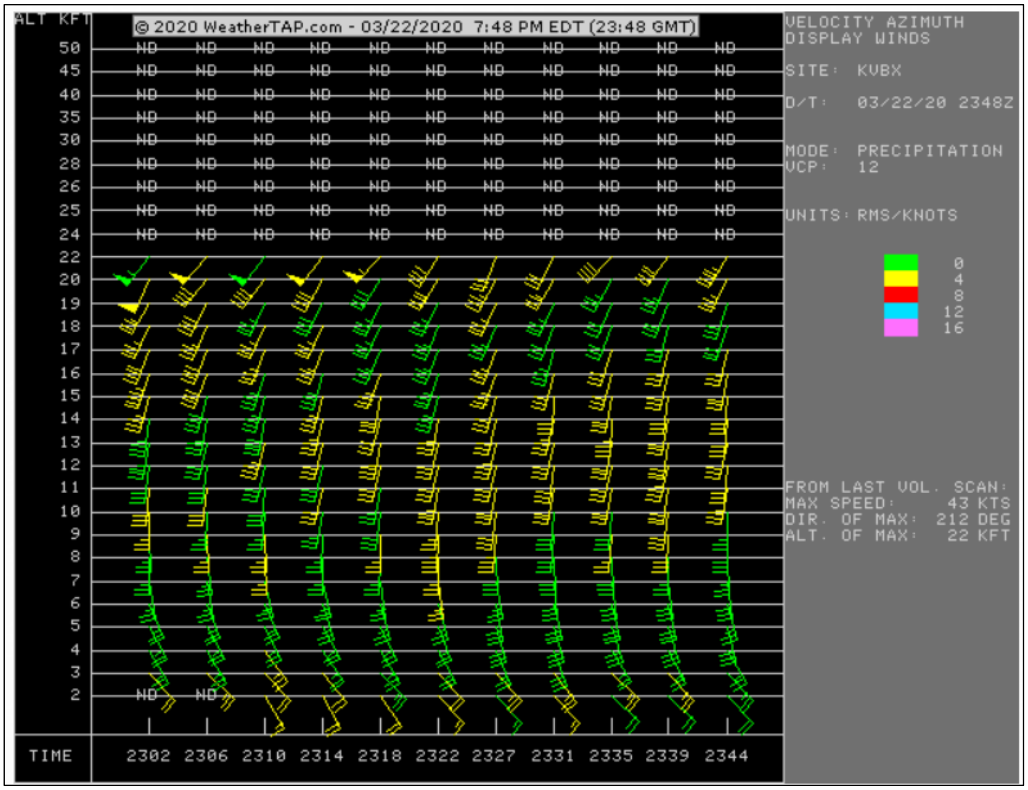


Figure 5.25 VAD wind display on March 22, 2020 at 1648 PDT

April 2020

The first half of April brought a couple of seeding opportunities to the Lake Lopez target area. A low pressure system that moved towards the area on the 5th of the month brought measurable precipitation to the region for several days. The first part of the event, during the April 5-6th period, allowed for two seeding opportunities to occur. The low then moved east of the area on the 6th, creating a northeasterly flow regime that allowed for precipitation to impact the area through the 10th. Decent precipitation amounts were measured, but northeasterly flow was not favorable for the transport of seeding material from existing ground sites into the target area.

April 5, 2020

A cold-core low located off the California coast over the past several days had finally moved closer to the Santa Barbara coast. This system brought periods of rainfall prior to and after the seeding periods. A weak band moved through around 1545 PDT and seeding operations were conducted as it passed. Later in the day, a larger area of precipitation developed, which contained another band that impacted the County and the Twitchell target area (Figure 5.26). Seeding was also conducted with this feature as it moved across the county. Winds were southerly at the surface and southwesterly above that (Figure 5.27). Temperatures were near -5°C at 10,000 feet and the freezing level was located at roughly 6,500 feet. Echo tops ranged between 10,000 and 15,000 feet so a large portion of the cloud was colder than -5°C, which implied adequate amounts of SLW for seeding operations. A total of six flares were dispensed as the bands passed through the county.

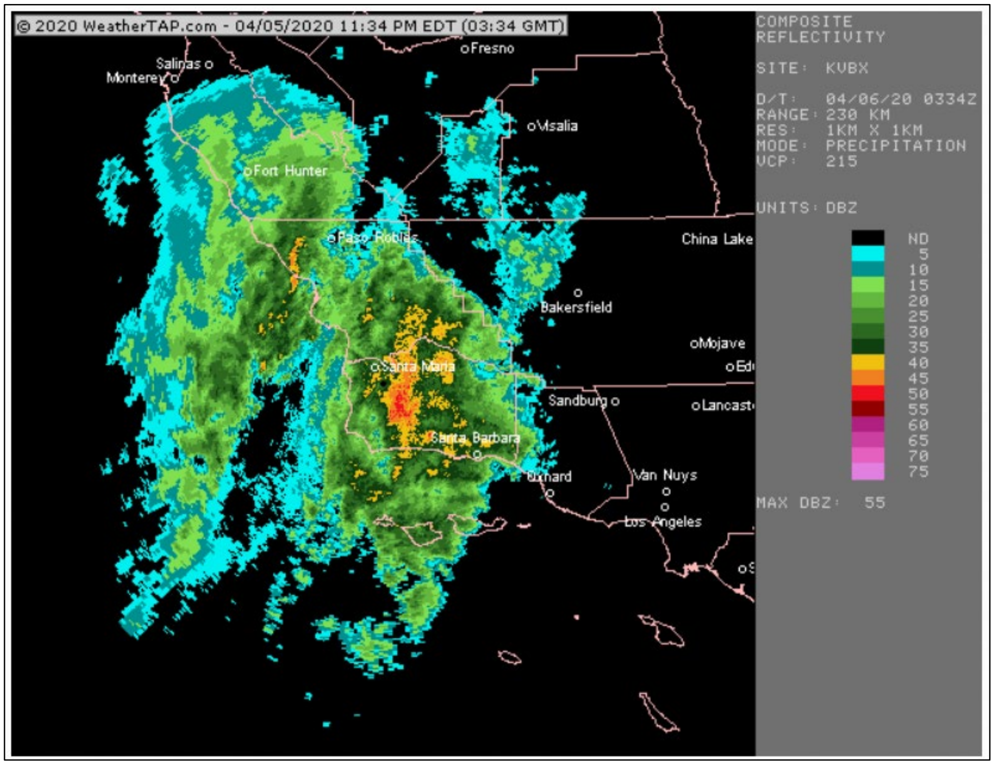


Figure 5.26 Composite radar on April 5, 2020 at 2040 PDT

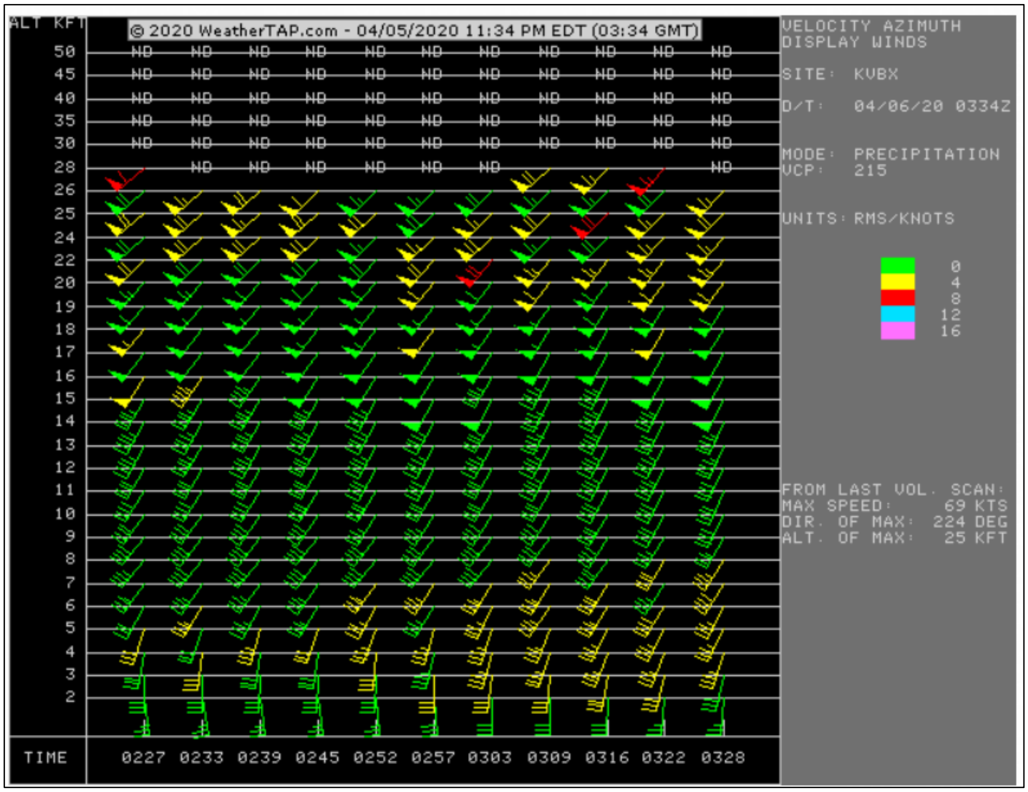


Figure 5.27 VAD wind display on April 5, 2020 at 0844 PDT

April 6, 2020

The closed low that brought rainfall to the area on the 5th continued to be nearly stationary. A weak convective band moved into the area around 0530 PDT with yet another weak band between 1000-1100 PDT (Figure 5.28). Winds with both bands were southerly at the surface, becoming southwesterly with height (Figure 5.29). Temperatures had cooled some at 10,000 feet from the previous day and were at -6°C as measured on the morning sounding from Vandenburg. Seeding occurred with both bands as the cloud/precipitation layer was in a good location relative to the freezing level and -5°C level for SLW formation to occur. One flare was dispensed today.

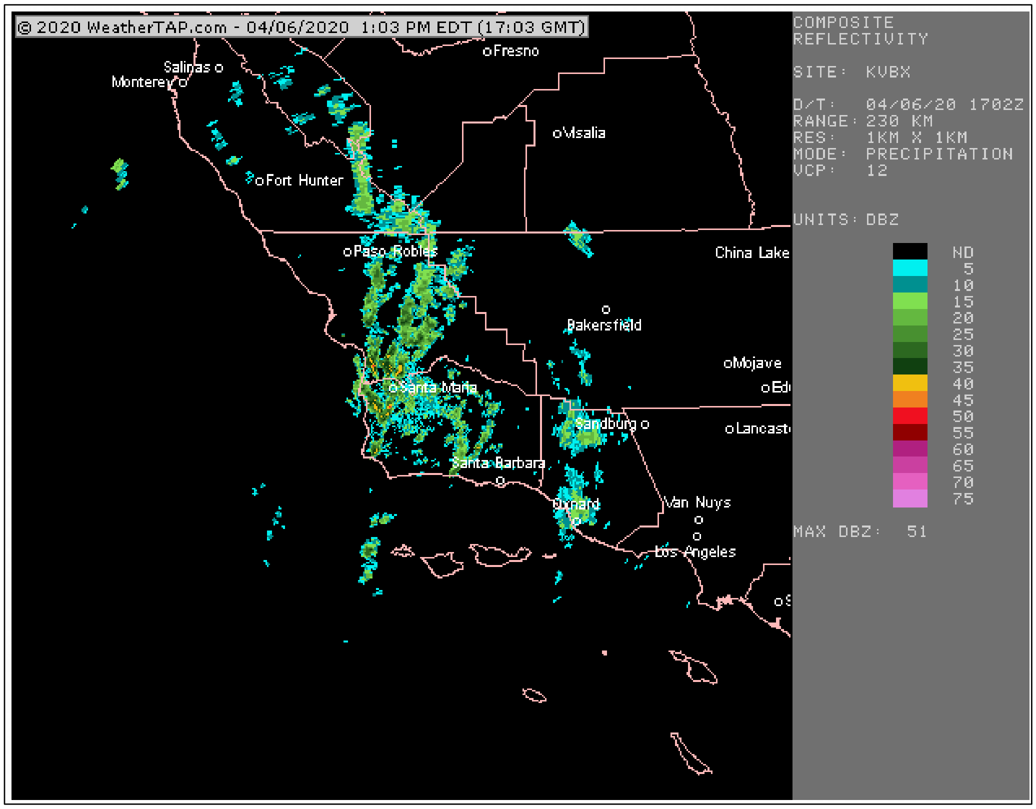


Figure 5.28 Composite radar on April 6, 2020 at 1000 PDT

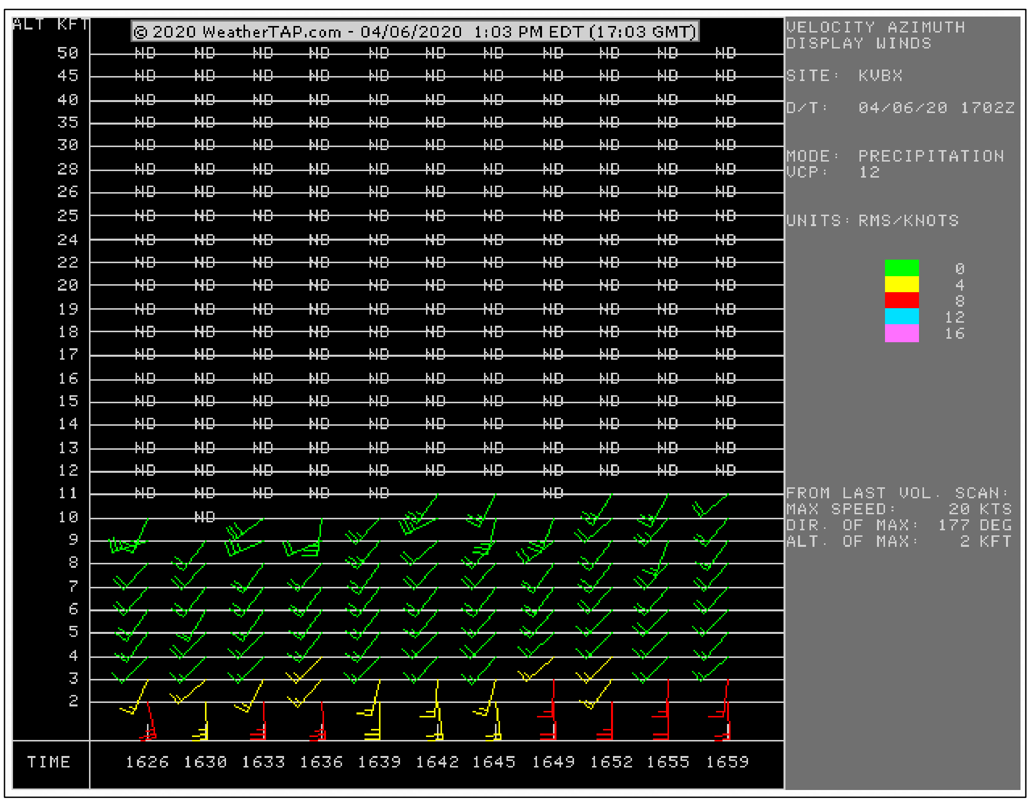


Figure 5.29 VAD wind display on April 6, 2020 at 1002 PDT

6.0 COMPUTER MODELING

NAWC utilized various computer models in the conduct of this program. These models were of two basic types: 1) those that forecast a variety of weather parameters useful in the conduct of the cloud seeding program (e.g., NAM or WRF) and 2) those that predict the transport and diffusion of seeding materials (e.g., HYSPLIT). Some model data was archived on NAWC computers while significant amounts of other data are archived and available on the internet.

In previous winter seasons, NAWC had used the standard National Oceanic and Atmospheric Administration (NOAA) atmospheric models: NAM, HRRR and GFS in forecasting seedable events and associated parameters of interest such as temperatures, winds, precipitation. NAWC continued to use the NAM and GFS models, especially for longer range forecasts. A more sophisticated model was used for shorter range forecasts, the Weather Research and Forecasting (WRF) model developed by the National Center for Atmospheric Research (NCAR) and NOAA. Recently this model has shown considerable skill in predicting precipitation, pressure fields, wind fields, convection bands and a variety of other parameters of interest in conducting the cloud seeding operations.

The HYSPLIT model, developed by NOAA, provides forecasts of the transport and diffusion of either ground or aerial releases of a material, which in our case would be silver iodide particles. NAWC first utilized predictions from the HYSPLIT model to assist in making seeding decisions during the 2012-2013 rainy season. NAWC has continued its use of the HYSPLIT model since that time. The WRF and HYSPLIT models will be discussed separately in the following sections.

6.1 WRF Model

The Weather Research and Forecasting (WRF) Model is a mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores, a 3-dimensional variational (3DVAR) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers.

The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL), the Air Force Weather Agency

(AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. WRF provides operational forecasting in a model that is flexible and efficient computationally, while offering the advances in physics, mathematics, and data assimilation contributed by the research community.

NAWC again utilized NOAA's Earth Systems Research Laboratory's HRRR version of the WRF model during the 2019-2020 winter season. This model has a 3 km grid spacing compared to the more standard grid model spacing of 12 km (e.g., NAM model), plus it is re-initialized every hour using the latest radar observations. The NAM and GFS models are currently re-initialized every six hours. Hourly forecast outputs from the HRRR model are available for a variety of parameters out to 15 hours.

Figure 6.1 is a ten-hour forecast from the HRRR model of composite radar reflectivity over the southwestern U.S., valid at 1600 PDT, March 25, 2012. This model predicted a west-east oriented convective band over the Central Coast associated with an upper closed low located off the coast of Santa Barbara County. This HRRR forecast agrees well with the radar image in Figure 6.2, which is the Vandenberg AFB composite radar reflectivity display valid at 1530 PDT March 25. Figure 6.3 provides a ten-hour forecast of the one-hour accumulated precipitation over California valid from 1500-1600 PDT March 25, 2012. This forecast also seemed to verify. For example, the HRRR forecast indicated approximately 0.10 inches of precipitation in the Sudden Peak vicinity. Figure 6.4 provides hourly precipitation values from Sudden Peak, which indicates 0.20 inches of precipitation fell from 1400-1500 PDT, about an hour earlier than forecast. Examination of the rainfall at Santa Maria indicated that the band apparently rotated northward with 0.11 inches from 1500-1600 PDT being observed there, about an hour earlier than predicted (Figure 6.5). More comparisons like this, conducted in future seasons, will help determine how well this model is performing. The precipitation that was forecast to occur over Santa Barbara County during this period was associated with a convective band that did develop and that was seeded from between 1400 and 1500 PDT.

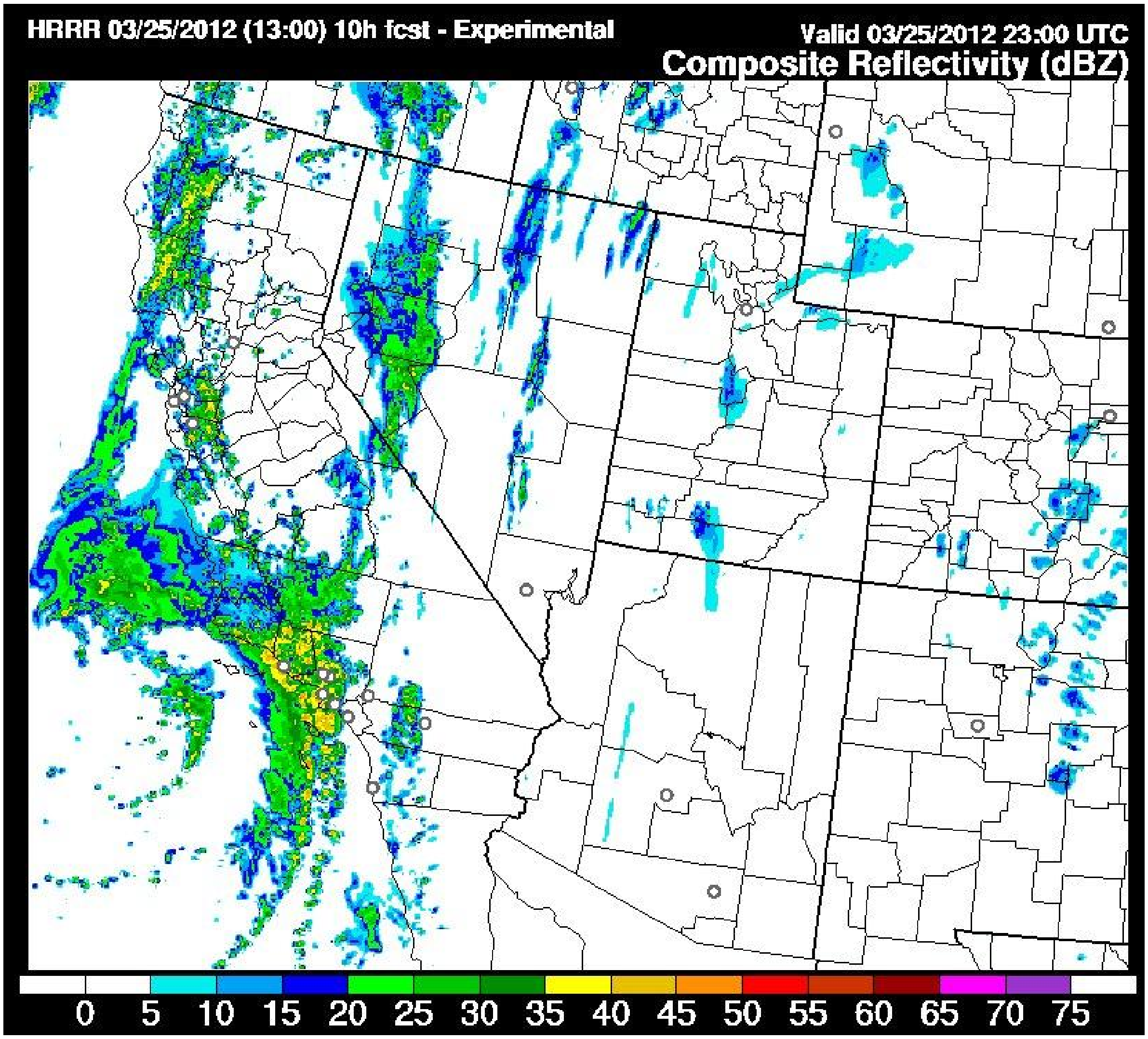


Figure 6.1 HRRR Model Ten-Hour Forecast of Composite Radar Reflectivity

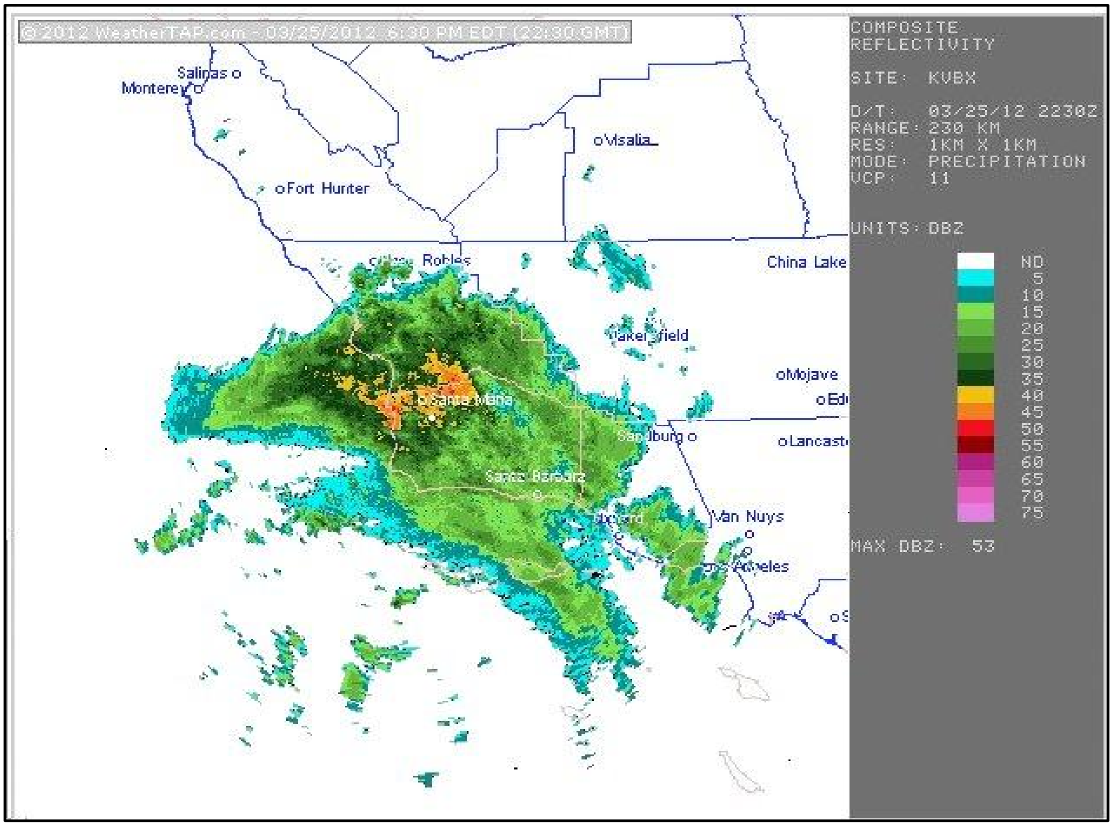


Figure 6.2 Composite Radar Reflectivity valid at 1530 PDT, March 25, 2012

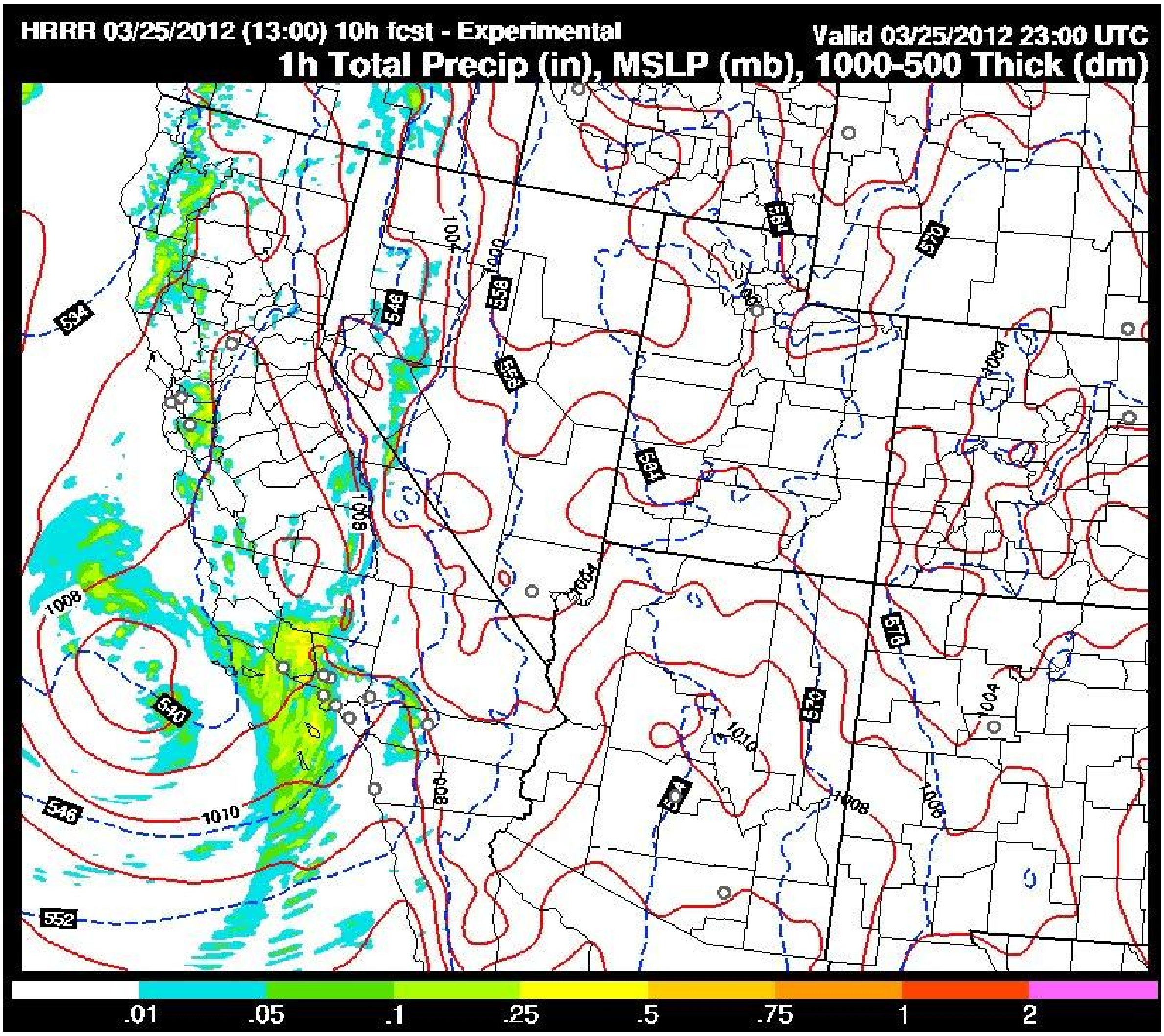


Figure 6.3 HRRR Model Ten-Hour Forecast of One-Hour Precipitation from 1500-1600 PDT March 25, 2012

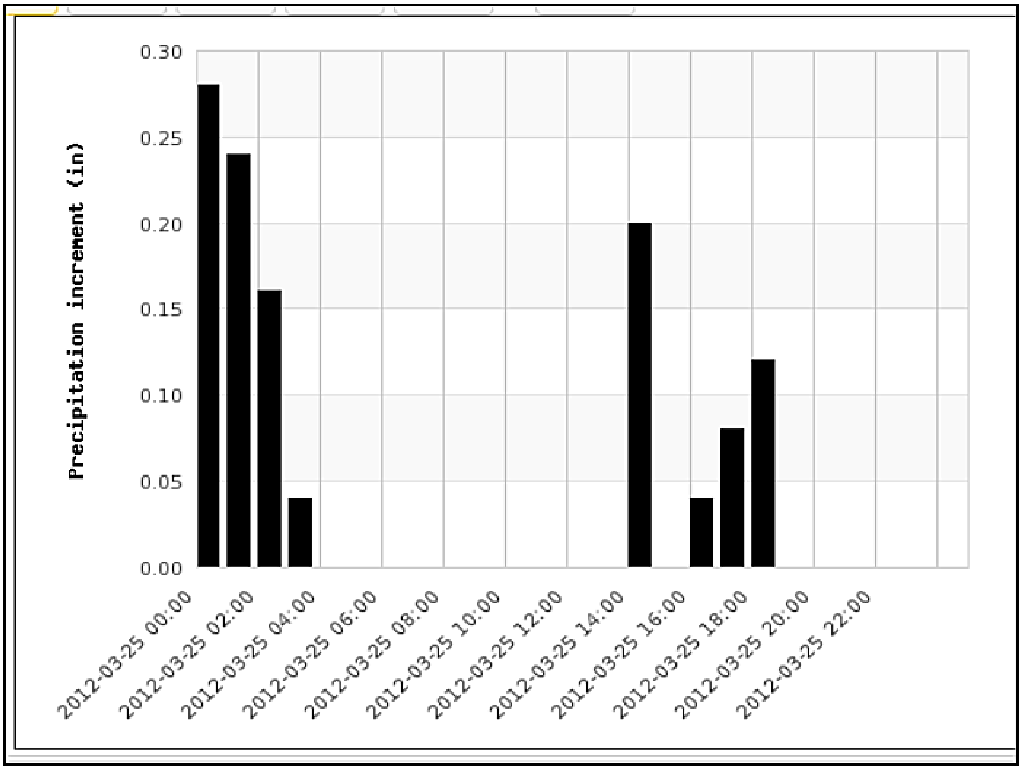


Figure 6.4 Observed Hourly Precipitation at Sudden Peak – March 25, 2012

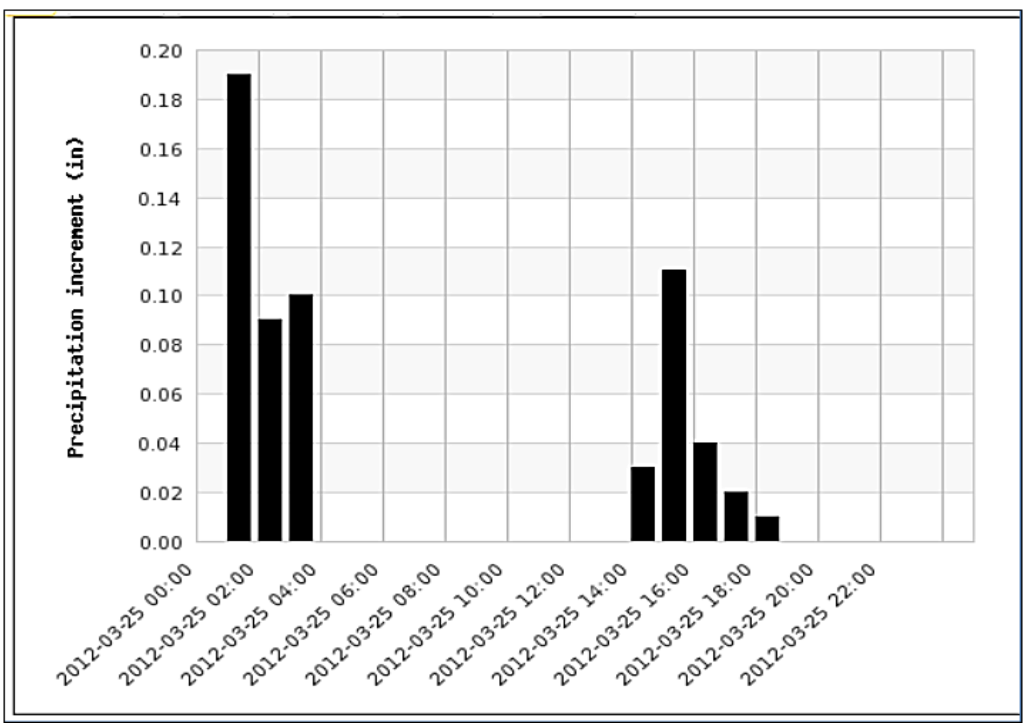


Figure 6.5 Observed hourly precipitation at Santa Maria –March 25, 2012

Based on the design of the program (Section 3.0), which is focused on seeding convective bands, and the seeding techniques as described in Section 4.6, it can be seen that forecasts of convective band locations are useful when using the ground-based seeding sites. Final seeding decisions for ground-based sites can be made using real-time radar information indicating when a convective band is approaching a particular seeding site. These convective band forecasts become more useful in airborne operations in order to provide lead time in filing flight plans and subsequent seeding aircraft take-off times to coincide with convective band passages. The precipitation type forecasts (e.g., Figure 6.3) are also useful when considering suspension criteria.

6.3 HYSPLIT Model

The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model is the newest version of a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations.

The dispersion of particles released into the atmosphere is calculated by assuming either puff or particle dispersion. In the puff model, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into several new puffs, each with its share of the pollutant mass. In the HYSPLIT particle model, a fixed number of initial particles are advected about the model domain by the mean wind field and a turbulence component. The model's default configuration assumes a puff distribution in the horizontal and particle dispersion in the vertical direction. In this way, the greater accuracy of the vertical dispersion parameterization of the particle model is combined with the advantage of having an ever-expanding number of particles representing the material distribution.

NAWC has utilized the HYSPLIT model to predict the transport and diffusion of silver iodide seeding material in real-time during potentially seedable storm situations in Santa Barbara County during the past four seasons of operations. The model can also be run after the fact using archived NAM model data, which is available back to 2007. Figure 6.14 provides HYSPLIT model output for one ground seeded event during the 2018-2019 season.

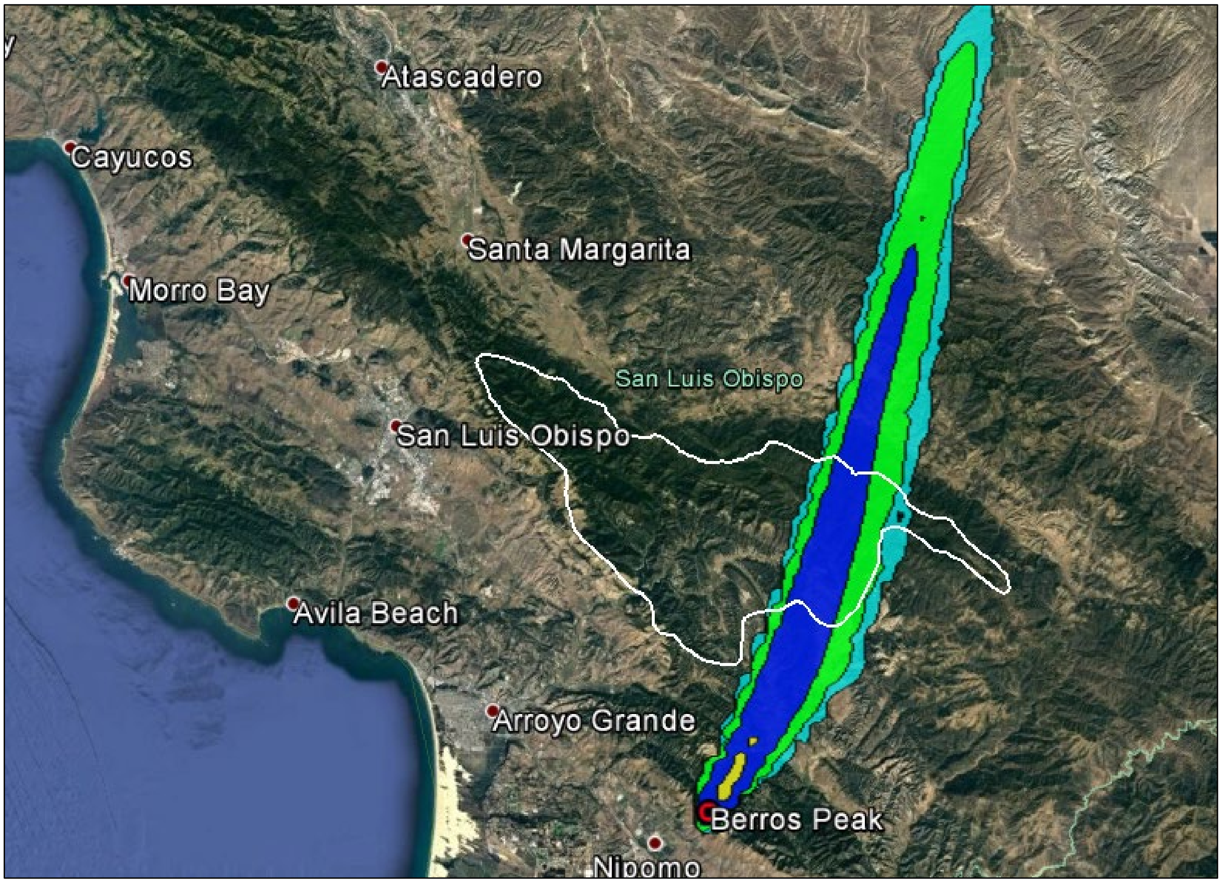


Figure 6.6 HYSPLIT Model output for seeding operations on March 16, 2020 for a one hour time period

The depiction provided in Figures 6.13 is of the transport of the seeding plumes during a seeding day during the season for an hour duration. The seeding material needs to interact with the convective bands forming ice crystals which grow into snowflakes and melt into rain drops as they pass through the freezing level. These processes occur as the band moves downwind in time. Consequently, these depictions are of the initial transport and diffusion phase of the plumes while the resultant fallout of augmented precipitation would occur downwind of these plume depictions (typically to the east or northeast of these plume depictions). Seeding for the storm period featured in Figure 6.13 took place from the Berros Peak seeding site. The HYSPLIT model data were used in making seeding decisions when the winds were questionable. The different shading colors in Figure 6.13 represent the concentration of the seeding material that is being dispersed. Stronger concentrations are indicated in blue and yellow with weaker concentrations depicted in green.

Another very useful tool in avoiding seeding impacts in areas identified in the suspension criteria is the vertical wind displays from the Vandenberg AFB NEXRAD radar. Figure 6.14 provides an example. The vertical distribution of winds at 1,000 foot intervals are displayed over approximately a one hour period in six minute time steps. NAWC has frequently used the winds at the 850-mb level (approximately 5,000 feet) as an indicator of the mean direction that a seeding plume would initially be transported. For example, in Figure 6.14 winds were southerly at the surface, becoming slightly west of south above 6,000 feet. In addition, the flow was rather strong at the surface, so this is depicted fairly well in the HYSPLIT model run in Figure 6.13. The ground-based seeding site at Berros Peak was chosen for seeding on this day as the southerly winds would clearly transport the material into the Lake Lopez target area.

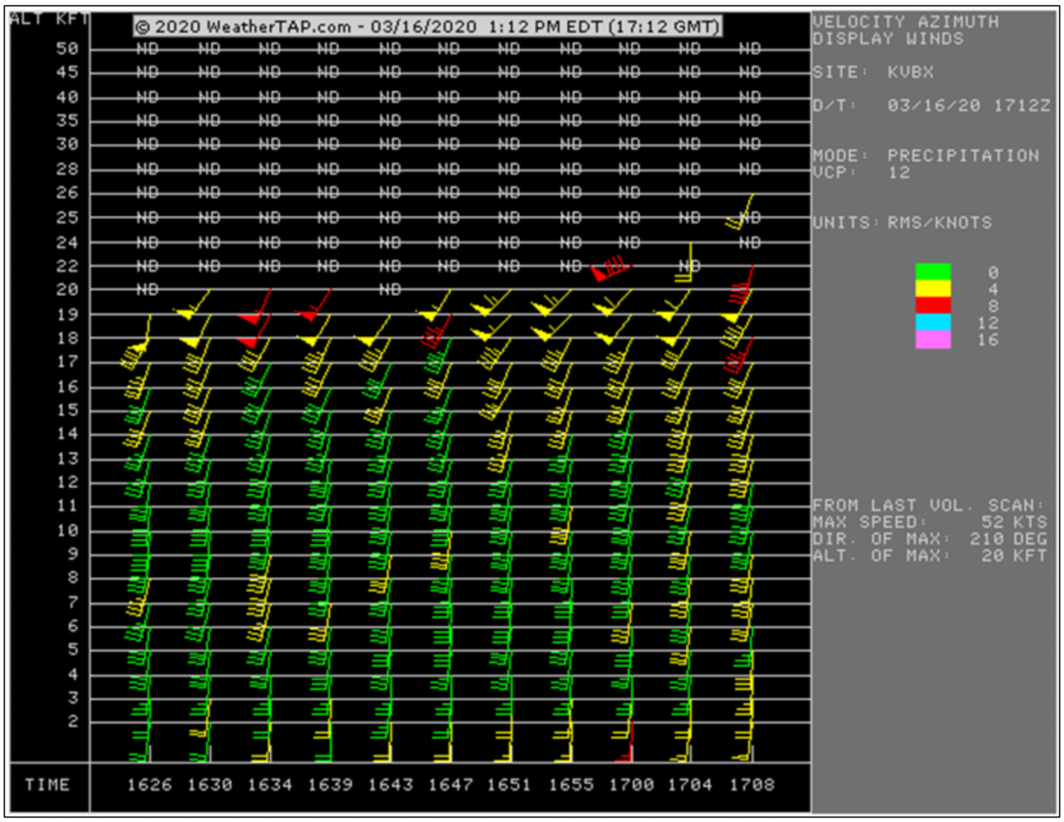


Figure 6.7 VAD wind profiler data during seeding operations on March 16, 2020

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APPENDIX B

2020 CLOUD SEEDING PROGRAM SUSPENSION CRITERIA

1. Whenever the National Weather Service (NWS) issues a severe storm, precipitation, flood warning or flash flood warning that affects any part of the project area, the project meteorologist shall suspend operations, which may affect that part. Operations will be suspended at least for the period that the warning is in effect.
2. Both the Project Meteorologist and District personnel shall each retain independent authority to suspend cloud seeding operations for any part, or all of the project area in the event that unforeseen conditions develop during storm events which in their best judgment have the potential to cause flooding or other adverse conditions anywhere within the project area.
3. Seeding operations shall not target the urbanized areas of the South County area – including but not limited to Arroyo Grande, Oceano, Grover Beach, Avila Beach, Pismo Beach, and Nipomo.
4. If there are any burn scars from recent wildfires within the Lopez watershed or nearby watersheds that would cause severe runoff, seeding operations shall be immediately suspended.
5. Prior to and during each storm event, if any of the stream gauges within the District ALERT system listed in table below are at the following full storm stage levels, seeding operations may be immediately suspended.

Steam Gauge Suspension Criteria Thresholds

Stream Gauge	Level (feet)
Valley Road Bridge	61.50
22nd Street Bridge	27.0
Pier Ave	9.0
Arroyo Grande Lagoon	10.2
Meadow Creek	9.0

6. Should it be predicted that Lopez Lake entirely fill and/or spill based on the District calculations or at or above 90% capacity, seeding operations will be suspended for the remainder of the season.

7. If the District is notified of impacts to agricultural harvest conditions within the Lopez watershed or the areas near Arroyo Grande Creek, seeding operations may be halted.

Note: All suspension criteria are subject to revision should hydrologic conditions warrant it. All revisions must be documented in writing and be approved by District representatives with notification provided to the project meteorologist.

APPENDIX B

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

2015 WMA JOURNAL OF WEATHER MODIFICATION

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 upwind 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.

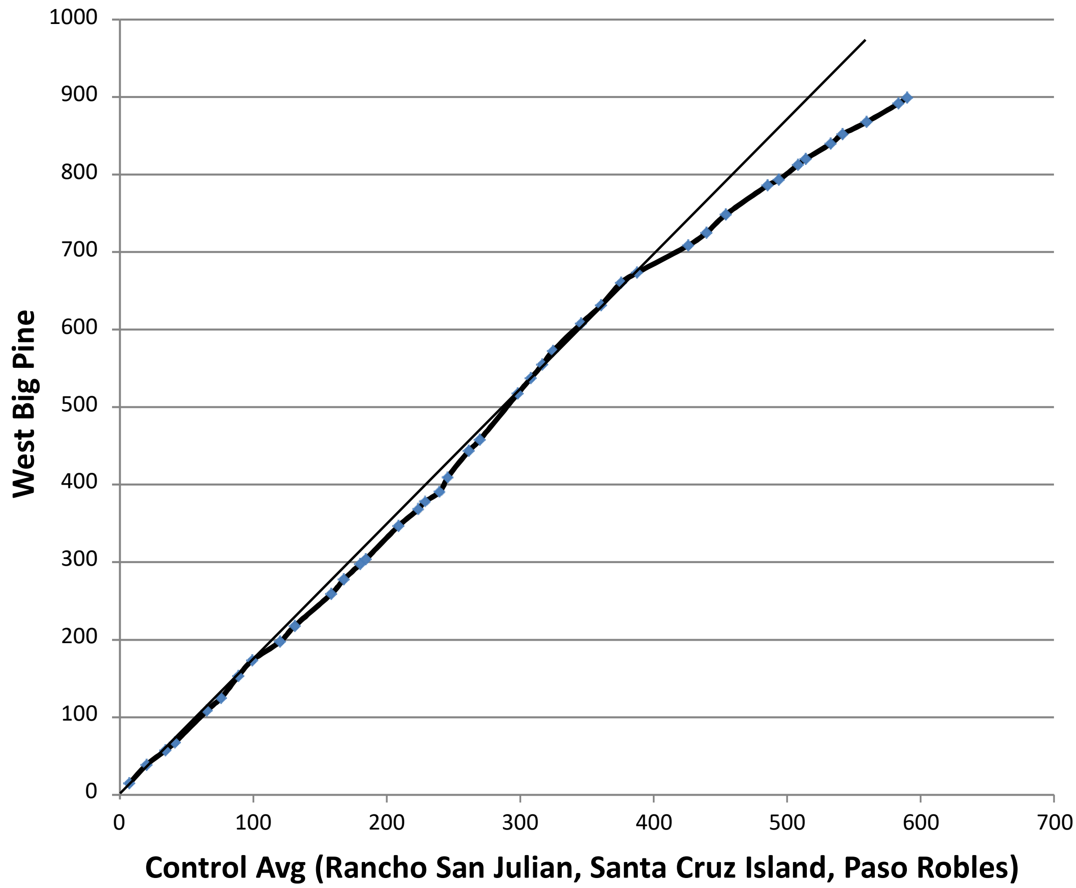

Figure 2: Double Mass Plot of West Big Pine December to March Precipitation versus the Average December to March Precipitation from Three Control Sites. A trend line has been added to illustrate the break in the plot.

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.

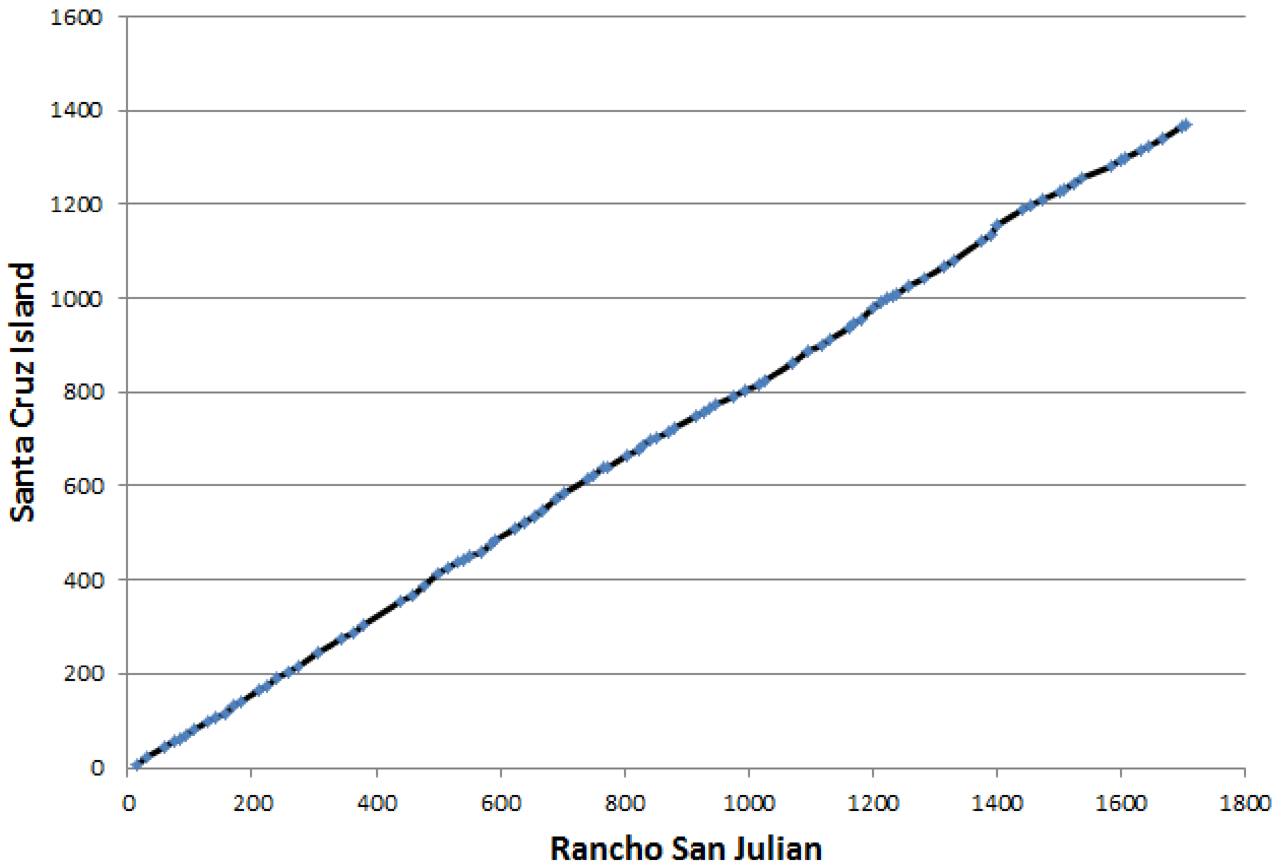

Figure 3: Double Mass plot of December to March Precipitation at Santa Cruz Island versus December to March Precipitation at Rancho San Julian.

3. SELECTION OF CONTROL AND HUASNA-ALAMO YNEZ 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 orogaraphic 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) $y = + 0.71(\text{Rancho San Julian}) + 0.62 (\text{Paso Robles}) - 0.03 (\text{Santa Cruz}) + 0.19$

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**

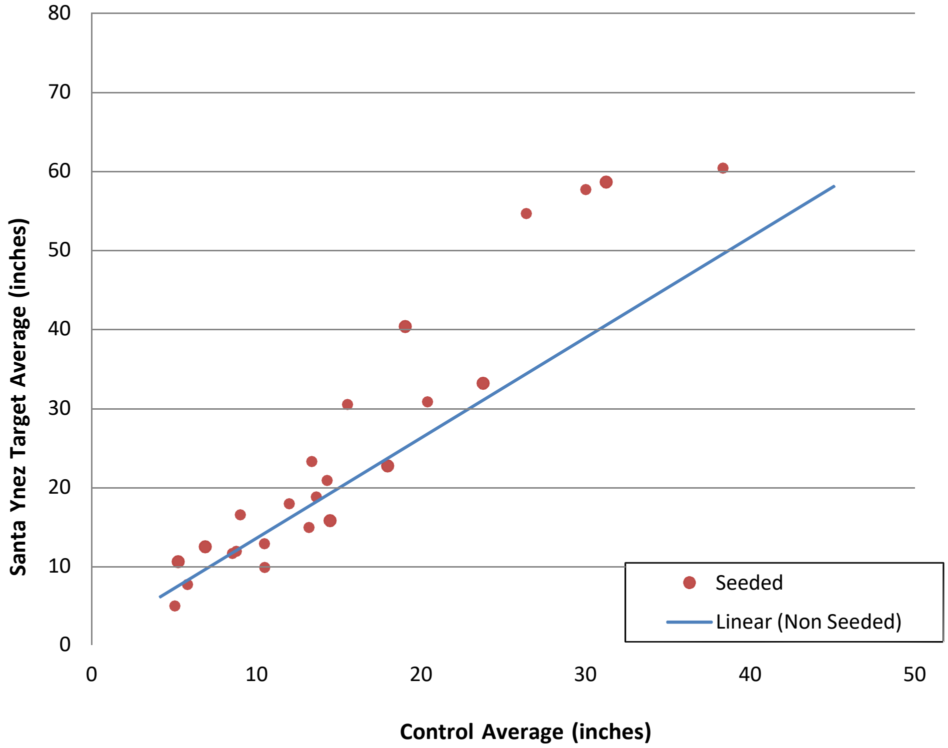

Figure 4: Plot of the Average Upper Santa Ynez Target Area Precipitation versus the Average Control Area Precipitation for the December-March Seeded Seasons. The diagonal blue line is the best fit linear regression line for the not-seeded seasons.

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**

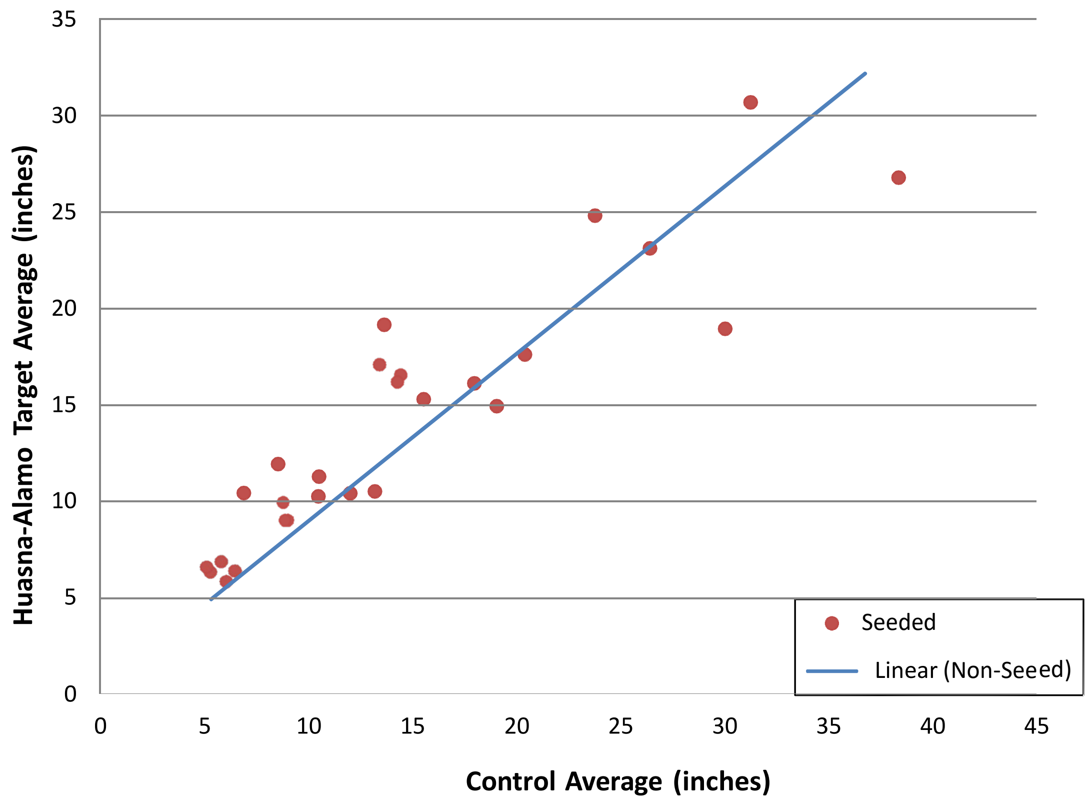

Figure 5: Plot of the Average Huasna-AlamoTarget Area Precipitation versus the Average Control Area Precipitation for the December-March Seeded Seasons. The diagonal blue line is the best fit linear regression line for the not-seeded seasons.

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).

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