State of California,
Department of Water
Resources

Feb. 1960.

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SANTA BARBARA WEATHER MODIFICATION PROJECT

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES

SANTA BARBARA WEATHER MODIFICATION PROJECT

INTERIM REPORT

OF

THE BOARD OF DIRECTORS

This report has been prepared as a joint effort by North American Weather Consultants; Statistical Laboratory, University of California; Meteorology Research, Inc.; and the California Department of Water Resources

EDMUND G. BROWN
Governor

HARVEY O. BANKS
Director of Water Resources

FEBRUARY, 1960

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STATE OF CALIFORNIA
Department of Water Resources
SACRAMENTO

February 1, 1960

Honorable Edmund G. Brown, Governor, and
Members of the Legislature of the
State of California

Gentlemen:

I have the honor to transmit herewith an interim report of an investigation co-sponsored by the Department of Water Resources entitled "Santa Barbara Weather Modification Project - Interim Report of the Board of Directors," dated February, 1960. This report is published pursuant to the provisions of Senate Concurrent Resolution No. 46, 1957.

The Department of Water Resources has participated jointly with other agencies in the operation of the randomized cloud-seeding project in the Ventura-Santa Barbara County area. These agencies include the National Science Foundation, United States Weather Bureau, United States Forest Service, the Counties of Santa Barbara and Ventura, University of California Statistical Laboratory, North American Weather Consultants, Meteorology Research, Inc., and other agencies contributing funds, equipment, or personnel to the project.

The report has been prepared at this time in response to the demonstrated local, national, and international interest in the Santa Barbara Weather Modification Project. The report is a joint effort of the cooperating agencies. However, Chapters III through VI consist of contributions from individual agencies indicated in the chapter titles.

The Department of Water Resources is publishing the report in accordance with the agreements previously reached between the cooperating agencies.

Very truly yours,

Harvey O. Banks

HARVEY O. BANKS
Director

ACKNOWLEDGEMENTS

The Project Board of Directors acknowledges with thanks the contributions and assistance of the many persons and agencies, both public and private, who have aided the Project during the past three years.

Special mention is made of the efforts of the Boards of Supervisors of the Counties of Santa Barbara and Ventura, who supported the cloud seeding operations; the National Science Foundation, which supported many of the statistical and physical studies reported here; the U. S. Weather Bureau, which made available several recording rain gages without which the Project could not have succeeded; and last, but not least, the many individuals and agencies who operated rain gages and supplied records. Unfortunately, space here does not permit listing all those who assisted in this research project. The Board of Directors, however, takes this opportunity to convey their thanks and appreciation.

FOREWORD

This report represents an effort on the part of the Board of Directors of the Santa Barbara Weather Modification Project to present to the public and interested persons and agencies the results of three years' operations of a randomized cloud seeding project. This Project was conceived in 1956 and commenced operations in January, 1957. It has operated during the four-month period, January through April, each year since 1957.

In order to accomplish the desired objective of making this report available at an early date, each of the primary contributors to the Project has prepared a chapter covering his own activities. The authorship is indicated at the beginning of each chapter. These separate chapters have been assembled into a common report. The summarizing chapter has been prepared as a joint effort.

Because of its belief that this Project has wide appeal and interest, the California Department of Water Resources has agreed to publish the report. However, such publication should not be construed to constitute agreement with all of the conclusions and statements made herein. The Department is making a continuing study of weather modification activities in California and has not yet formulated conclusions respecting the effect of such activities.

During its early stages, the Project was known as the Santa Barbara Weather Modification Project. Because this title did not express the true extent of the Project, the Board of Directors decided to rename the investigation "The Santa Barbara-Ventura Weather Modification Project" and this will be its title henceforth. However, because early published reports on the Project have referred only to the "Santa Barbara Project" the Board felt it would be confusing to use the revised title in the present report. It is planned that any ensuing reports will use the complete title, however.

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CHAPTER I

SUMMARY

In January, 1957, the Santa Barbara Project, a cooperative effort among several participants, was initiated in Santa Barbara County, California, to test the effectiveness of weather modification operations. The third year of operation of that project has been completed and this report constitutes a presentation of the results of the three years of operation.

Chapter I, "Summary" presents a summary of the five following chapters which are entitled "Project History and Design", "Cloud-Seeding Operations", "Precipitation Data Collection Program", "Statistical Evaluation", and "Physical Studies of Santa Barbara Storms". Each of the five chapters is authored by and presents the results of studies by one of the several major project cooperators.

1. <u>Project History and Design</u>

Field operations on the Santa Barbara Project commenced in January, 1957, after considerable prior work of organization and preparation. The project is the result of the initiative of Mr. Robert D. Elliott, President of the North American Weather Consultants, Inc. At a conference on weather modification organized by the Statistical Laboratory, University of California, Berkeley, on May 8, 1956, Mr. Elliott announced that his organization would be willing to submit to a randomized cloud-seeding experiment and was of the opinion that the Board of Supervisors of Santa Barbara County might agree to resume, on a randomized basis, the County's cloud-seeding program. The Department of Water Resources agreed to accept the responsibility of collecting the basic data, and the Statistical Laboratory expressed its willingness to participate in the design of the experiment and to perform the statistical evaluation.

Project Objective. The primary objective of the Santa Barbara Project is to evaluate the effect of weather modification operations on precipitation. This primary objective is achieved by scheduling the actual seeding operation on a randomized basis.

Project Participation and Direction. No single agency sponsors the Santa Barbara Weather Modification Project. The project is a cooperative undertaking among several major cooperators, with a number of other agencies furnishing consulting advice and occasional assistance to the project. The major cooperators are the County of Santa Barbara, the County of Ventura, which joined the project in the third year, the National Science Foundation, the Statistical Laboratory of the University of California, the California Department of Water Resources, the United States Weather Bureau, and the United States Forest Service. In addition, the National Science Foundation and the Department of Water Resources support the activities of a major participant, Meteorology Research, Incorporated, a private meteorological research firm. The Counties of Santa Barbara and Ventura support the work of another major participant, North American Weather Consultants, which performs the actual cloud seeding. Direction of the Santa Barbara Project is by a Board of Directors composed of representatives of the various organizations involved in the project.

Project Area. The original area to be included consisted of three control areas (the Channel Islands, the San Simeon-Cape San Martin Area, and the San Luis Obispo-Morro Bay Area) and three target areas (that portion of Santa Barbara County which is drained by the Santa Ynez River above Cachuma Dam, that portion of the Santa Barbara Coastal strip immediately south of the area just described, and the rest of the County).

Topographically, the target and control areas are similar in that they are all precipitous mountains covered with grass, low brush, and sparse timber. For example, in the coastal target area, elevations range from sea level to about 4,000 feet only a few miles inland.

As the project progressed, new areas were added to the original investigation. The principal addition was Ventura County, which is adjacent to Santa Barbara County on the east, and which became a target area in 1958.

2. Cloud Seeding Operations

The cloud-seeding operations were carried out in the manner of a normal cloud-seeding project. A network of ground-based silver iodide smoke generators was employed as the source of artificial nucleant. The seeding was carried on under winter storm conditions in an area of relatively low but rugged terrain. Orographically accentuated convective instability was a feature of the air mass during much of the seeding.

In order to provide fixed units of rainfall observation, a 12-hour schedule was imposed. At the start of each 12-hour period a forecast was made as to whether or not seedable conditions would develop over the target area during the ensuing 12-hour period. A statistical decision was then made by random selection on a 50 per cent probability basis to indicate whether or not seeding should actually be conducted. In this way, a number of seedable storms were selected over a period of time which were nearly equally divided into seeded and non-seeded cases.

There were cases in which the forecast was in error for one reason or another. These errors occurred with sufficient frequency to be a factor of concern in the statistical evaluation.

A summary of weather factors associated with the seeding indicates that conditions were quite different in the different years. In particular, 1958 was a very wet year and 1959 a record dry one.

3. Precipitation Data Collection Program

In order to provide the necessary precipitation data for the statistical analyses for the Santa Barbara Project, there was undertaken what is believed to be the most intensive data collection program ever associated with a weather modification project.

As a result of the decision to divide each day into two 12-hour units of observation, the only type of precipitation data that could be used was that obtained from continuous, recording gages. At the time of inception of the Project, there were only nine acceptable recording gages in the entire original area of investigation. As the area of interest grew, additional existing gages were incorporated. However, in the areas of primary interest, it was necessary to install and maintain many recording gages.

Over a period of three years, recording gages were made available by the United States Weather Bureau, and these were installed at times and places that appeared suitable to the Board of Directors by personnel of the Department of Water Resources. Ultimately, the Weather Bureau loaned a total of 50 gages to the project, all but one of which were installed.

The job of preparing hourly rainfall values for the 165 gages associated with the Santa Barbara Project was accomplished by six agencies. The United States Weather Bureau made special, advanced copies of their data available for 57 gages. Los Angeles County Flood Control District prepared similar tabulations for 23 gages under their jurisdiction, as did Ventura County Flood Control District for their 22 gages. The City of Los Angeles made available the recorder charts for the seven gages they operate, and the Statistical Laboratory, University of California, reduced these charts to tabular form. The United States Forest Service worked up the records for three special-design gages in their area. All remaining records, 53 in number, were prepared by personnel of the Department of Water Resources.

4. Statistical Evaluation

The joint distributions of precipitation amounts in the Santa Barbara target and in one of the control areas, observed over the three years for the four categories of seeding opportunities, viz. (i) with no seeding either in Ventura or in Santa Barbara, (ii) with no seeding in Ventura and seeding in Santa Barbara, (iii) with seeding in Ventura but no seeding in Santa Barbara and (iv) with seeding going on in both counties, exhibit differences corresponding to the level of significance 0.06. Therefore, the authors are prepared to act on the hypothesis that there were real differences among the four distributions of precipitation amounts.

Granting the reliability of data, the above differences can be attributed to two factors. One is the possible effect of seeding and the other is the difference in the pattern of weather in 1957 and in 1958. In 1957 there was no seeding in Ventura. In 1958 the silver iodide generators meant to increase rain in Ventura were acting at every opportunity. In 1959 the operations in the two counties were factorially randomized. However, 1959 was an exceptionally dry year with only nine seeding opportunities. Therefore, the evaluations were dominated by the data of 1957 and 1958 so that practically all the observations referring to groups (i) and (ii) reflect the weather pattern of 1957 with no contribution from 1958 and practically all the observations referring to groups (iii) and (iv) reflect the weather pattern of 1958 with no contribution from 1957. Thus, the possible effect of seeding is partly confounded with the possible effect of weather pattern.

The findings are best illustrated graphically. Figure I-1 refers to one of the subtargets, Santa Barbara N.W., for which the results are more spectacular than for others. In each of the four panels the curves represent the precipitation in the target to be expected without seeding.

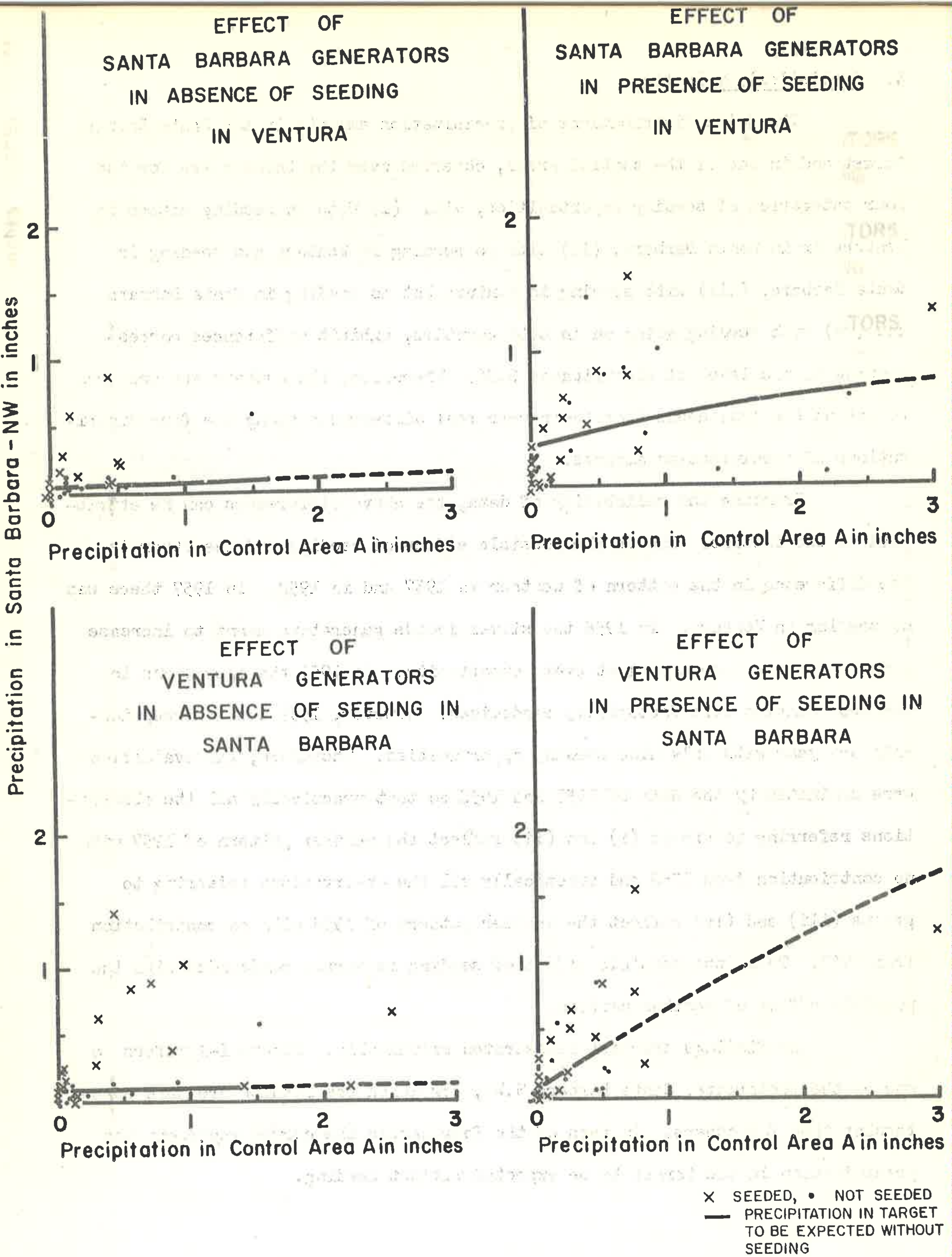


FIG. I-1 EFFECT OF GENERATORS ON PRECIPITATION IN NORTHWEST SANTA BARBARA COUNTY.

The two upper panels of Figure I-1 illustrate the effect of silver iodide generators meant to increase rain in Santa Barbara. Taken by themselves these panels are not affected by confounding and, therefore, granting the reliability of data, the noticeable effects are ascribable directly to seeding. The left upper panel, referring mostly to 1957 when there was no seeding in Ventura, indicates a very low level of unseeded target precipitation and a substantially larger, by a factor of about 3, precipitation during those seeding opportunities which were seeded. The upper right panel, referring predominantly to 1958 when there was seeding in Ventura, indicates higher levels of target precipitation, both with seeding and with no seeding in Santa Barbara, and no noticeable difference between the two.

In the lower panels of the figure the possible effect of seeding by the generators in Ventura County is confounded with the possible effect of a change in the weather pattern; the expectations stem mostly from data of 1957, while the data for seeded seeding opportunities refer, mostly, to 1958. As a combined effect of seeding and weather pattern the lower left panel indicates seeded target precipitation exceeding the expectation by a factor of about 5. In the lower right panel this effect is nil.

The remarkable difference in the apparent effect of seeding in 1957 (when there was no seeding in Ventura) and in 1958 (when seeding went on in Ventura at every opportunity) represents an outstanding result of the experiment. It calls for a meteorological explanation and for further experiments to establish the reproducibility of the effects.

The analysis of the precision of the experiment indicated that, if the true effects of seeding amount to 10-20 per cent of the corresponding unseeded precipitation, then the duration of the experiment of the same precision needed to have a reasonable chance of establishing this effect is probably prohibitive. The same analysis indicated certain ways of redesigning the experiment so as to achieve greater accuracy. Further means of improving the experiment is to have it connected with a comprehensive theory of precipitation and combined with physical measurements other than of the amount of precipitation.

5. Physical Studies of Santa Barbara Storms

Physical studies of Santa Barbara storms have been carried out to investigate the varying reactions of different storms to the seeding process. Such studies should help to refine statistical analyses by improving correlations and eliminating potentially unfavorable seeding situations, should lead to improved seeding techniques and should permit extrapolation of the results of the seeding program to other areas where similar storm structures may be observed.

Adequate quantitative models of the precipitation process do not exist. Additional basic work in cloud physics is required before there will be any hope of detecting seeding effects by observing deviations from a precipitation model. However, semi-quantitative models of precipitation initiation have been constructed. These can be used to define conditions where seeding might initiate precipitation while natural precipitation processes are inoperative. These marginal conditions have been observed on a number of occasions in Santa Barbara storms. For more complex situations where both seeding and natural processes may operate, detailed storm structure analyses are needed. These can be used qualitatively to describe relative seedability of various storms.

Use of the precipitation initiation model in 1958 Santa Barbara storms indicated that seeding might initiate the ice crystal process earlier in about 50 per cent of the precipitation hours than could be expected under natural conditions. It also indicated that ice crystal seeding is frequently carried out naturally from higher cloud layers in the Santa Barbara area. The advantage of seeding under these latter conditions is not clear.

Several examples of precipitation initiated under marginal conditions when seeding might have contributed to the precipitation process were observed. In these instances no other substantial natural precipitation was formed in the area. Positive and undisputed evidence of a direct seeding effect is not possible under these conditions due to the substantial contribution of the island orography to initiating precipitation under these same marginal conditions.

The physical measurements made during the Santa Barbara program included radar with PPI (horizontal) and RHI (vertical) scanning, atmospheric potential gradient, raindrop size distributions, freezing nuclei concentrations and assorted wind and temperature measurements. An additional valuable source of information was radiosonde measurements of upper air temperature and humidity made every 12 hours at Santa Maria and Los Angeles. Combining this information into a coherent picture has made it possible to describe qualitatively a number of examples of natural mechanisms of precipitation formation. An excellent network of recording rain gages in Santa Barbara County is available for use in these studies.

For example, an analysis of the storm of April 2-3, 1958, indicates that precipitation started as a result of ice crystals falling from high clouds into a lower level cloud mass. From the initially patchy nature of the natural ice crystal seeding, it is concluded that additional artificial seeding might have been beneficial at this stage of the storm. Precipitation structure as viewed by the radar was cellular and its convective characteristics caused the largest amounts of rain to fall along the 4000-foot coastal ridge north of Santa Barbara.

The storm of February 24-25, 1958, was stable instead of convective. Radar precipitation structure showed patches, bands and flat sheets of rain. This type of air motion results in maximum precipitation along the immediate coast and along the windward slope of the coastal ridge. Numerous natural ice crystals were provided from high clouds. Whether additional ice crystals would have been beneficial is an unknown factor.

The storm of January 25-26, 1958, was stable early in the storm and then became convective. The precipitation pattern showed the coastal strip rainfall as being maximum during the stable portion of the storm and the ridge rainfall as being maximum during the convective portion. Numerous ice crystals were again provided from high levels throughout the storm.

Additional physical measurements are needed to describe the storms in more detail. These include more information on cloud tops, extent of natural ice crystal seeding from high level clouds, and a measure of liquid water or vertical velocity distribution within the cloud systems. Also needed are better developed hypotheses concerning the relative advantages of seeding during various portions of the storm.

It is concluded that the future development and growth of cloud seeding, and the refinement of seeding techniques to obtain more effective control over the precipitation process, require a continuing and expanding physical study of storm structures together with appropriate laboratory and theoretical studies.

CHAPTER II

PROJECT HISTORY AND DESIGN

In January, 1957, the Santa Barbara Project, a cooperative effort among several participants, was initiated in Santa Barbara County, California, to test the effectiveness of weather modification operations. The third year of operation of that project has been completed and this report constitutes a presentation of the results of the three years of operation.

The project is the result of a number of developments and circumstances over a period of years. In 1946, the State Water Resources Board recommended to the Legislature that a state-wide investigation of California's water resources and water requirements be conducted with the aim of formulating a physical plan to meet these requirements as they would occur in the future. All existing and potential water resources were studied, including surface and underground waters, the conversion of saline and brackish waters, and, since coincidentally the possibilities had been raised about the same time, increased water supplies by weather modification techniques. Studies of these latter techniques were conducted with the assistance and advice of the Statistical Laboratory of the University of California. The results were published in State Water Resources Board Bulletin No. 16, "Weather Modification Operations in California", June, 1955.

This early investigation of weather modification operations had two major phases. One phase involved the collection of complete records of all weather modification operations that had been conducted in California. A continuing program has kept these records up to date. The second phase involved the collection of reports of evaluations of such operations, a review of the methods of evaluation and critical analysis of those methods, and the development of an objective method of evaluation. This method was developed by the Statistical Laboratory of the University of California, whose services were secured to assist in the investigation. The method was used in evaluation studies for three separate weather modification projects in California. Several years were spent by the Laboratory in carefully analyzing precipitation records obtained in the three project areas. For one project the evaluation indicated a large excess of seeded precipitation over the expectation derived from non-seeded storms. For another project the indicated significant effect was less pronounced, but negative. For the third project the results were inconclusive.

On the basis of such analysis it appeared strongly probable that weather in California had been modified by cloud-seeding operations. However, it was not possible to state without qualification that the cloud-seeding operations produced the differences. There is a possibility that the storms, which were divided, at the suggestion of the Laboratory, into classes for the analysis, could be further divided with some of the subclasses favoring the target areas and others the control areas. Undetected changes could have taken place in the frequency of storms of such subclasses between the unseeded period and the seeded period. Such changes could have resulted in a natural favoring of the target areas during the seeded period.

In evaluations which are performed using historic data, one also must take into account the following possible circumstances. According to professional meteorologists, not all storms are suitable for seeding. Furthermore, examination of records of project operations indicates that only a part of the storms are actually seeded. Also, in order to judge whether the seeding is effective, one must have some comparison such as, for example, the amount of rain from the same storm in a comparison area presumably not affected by the seeding. In these conditions, even if the comparison between the rain in the target and in the comparison area appears favorable to the conclusion that seeding is beneficial, there is always a question whether the observed excess of rain in the target is the effect of seeding or the result of a fortuitous selection of storms. In fact, a meteorologist engaged in cloud seeding could possibly identify among the approaching storms those that will deposit in the target relatively more rain than the others. Thus, if only the more promising storms were seeded, the comparison with any pre-assigned standard would tend to indicate a positive effect from seeding.

Based upon the foregoing objections, which would always be valid when seeded storms were compared with any historical non-seeded storms, the Laboratory concluded that none of the evidence produced in the investigation or in any of the other evaluations constituted documentary evidence of effectiveness in cloud seeding.

The Statistical Laboratory suggested,* and Bulletin No. 16 recommended, a procedure for solving the foregoing difficulties. This procedure would consist of pre-arranging a schedule of cloud-seeding operations under which roughly half of the seeding opportunities would be accepted and seeded while the others would be left unseeded in accordance with the dictates of chance. Such a procedure conducted over a suitable period would provide a sizeable number of storms, some of which would be seeded and some unseeded, for which the amounts of precipitation would be compared and subjected to statistical tests. These tests would be able to measure very accurately the probability that seeding was effective. Such a procedure would make it unnecessary to compare present seeded storms with historical storms, the relationships for which, as was pointed out, may change.

As a result of the Laboratory's evaluation and of the widespread and continued interest in evaluation of weather modification operations, Mr. Robert D. Elliott, President of North American Weather Consultants,

* This was first done in a mimeographed report by Professor J. Neyman to the Division of Water Resources under the title "Methodology of Statistical Evaluation of Rain Making Operations" dated December 15, 1951.

persuaded the supervisors of the County of Santa Barbara to carry out the County's cloud-seeding program on a randomized basis. In addition, North American Weather Consultants, which had been conducting the program for the County, indicated their willingness to submit to a randomized cloud-seeding experiment.

In order to complete arrangements whereby the County would conduct the project and the University would evaluate the project, it was necessary that some third agency collect the basic data. Consequently, the Department of Water Resources undertook this responsibility. In January, 1957, the cooperative project was initiated in Santa Barbara County, California, for the purpose of testing the effectiveness of weather modification operations.

1. Project Participation and Direction

No single agency sponsors the Santa Barbara Weather Modification Project. The project is a cooperative undertaking among several major cooperators, with a number of other agencies furnishing consulting advice and occasional assistance to the project. The major cooperators are the County of Santa Barbara, the County of Ventura, which joined the project in the third year, the National Science Foundation, the Statistical Laboratory of the University of California, the California Department of Water Resources, the United States Weather Bureau, and the United States Forest Service. In addition, the President's Advisory Committee on Weather Control, the National Science Foundation, and the Department of Water Resources have supported the activities of another major participant, Meteorology Research, Incorporated, a private meteorological research firm. The Counties of Santa Barbara and Ventura support the work of another major cooperator, North American Weather Consultants, which performs the actual cloud seeding. The Office of Naval Research provided funds to the Statistical Laboratory to aid in the early stages of the project. Technical advice has also been furnished to the project by the Munitalp Foundation and the Institute of Atmospheric Physics of the University of Arizona.

Direction of the Santa Barbara Project is by a Board of Directors composed of representatives of the various organizations involved in the project. This board meets periodically to review the over-all progress of the project and to assign the responsibilities of each of the cooperators. Since the Board of Directors is somewhat too large a body for efficient action, the project operation is directed by an executive committee consisting of four persons. The chairman of the Board of Directors is also the chairman of the executive committee. The four members of the executive committee are: Mr. R. D. Elliott, president of North American Weather Consultants, Inc.; Dr. J. Neyman, director of the Statistical Laboratory of the University of California; Dr. Paul Mac Cready, president of Meteorology Research, Inc.; and Robin R. Reynolds, California Department of Water Resources. Mr. Reynolds is chairman of the Board of Directors and chairman of the executive committee. Dr. Elizabeth L. Scott of the Statistical Laboratory, University of California, is secretary of the Board of Directors and the executive committee.

2. Project Area

When the project was originally conceived, the area to be included consisted of three widely separated control and three contiguous target areas. The entire area was about 200 miles long and extended from the eastern Santa Barbara County line along the coast as far north as San Simeon in Monterey County (See Plate IV-I).

The three control areas, which were given the respective code letters of A, B, and C, consisted of the Channel Islands, the San Simeon-Cape San Martin Area, and the San Luis Obispo-Morro Bay Area. The three target, or "T", areas consisted of (1) that portion of Santa Barbara County which is drained by the Santa Ynez River above Cachuma Dam (2) that portion of the Santa Barbara coastal strip immediately south of the area just described and extending west to Gaviota, and (3) the rest of the County.

Topographically, the target and control areas are similar in that they are all precipitous mountains covered with grass or low brush and some trees. For example, in the coastal target area, elevations range from sea level to about 4,000 feet only a few miles inland.

As the Project progressed, new areas were added to the original investigation. The principal addition was Ventura County, which is adjacent to Santa Barbara on the east. In 1958, Ventura County undertook a non-randomized cloud-seeding Project. In 1959, it joined the Santa Barbara Project and sponsored cloud-seeding operations on a randomized basis.

The topography of Ventura County is similar to that in Santa Barbara County, although some mountain peaks reach elevations above 8,000 feet.

One peculiarity of the Santa Barbara--Ventura area is that this is one of the few places in California where the mountain ranges trend east and west. Elsewhere, most ranges run northwest-southeast.

3. Project Operations

The primary objectives of the Santa Barbara Project are to obtain documentary evidence whether, and to what extent, the seeding of clouds with silver iodide nuclei from ground-based generators alters precipitation, and to obtain evidence as to the conditions in which seeding tends to increase or decrease precipitation. In addition, the general mechanism of natural and artificially induced precipitation has been studied.

The Santa Barbara Project is unique in that it is a research program specifically designed, with scientific control and instrumentation, to test the efficiency of the widely used method of cloud seeding to increase precipitation, using ground-based, silver iodide smoke generators. Earlier research programs in this field, sponsored by the Federal Government, were usually concerned with special phases of cloud seeding by other techniques intended to produce particular effects. Cloud-seeding programs, sponsored privately or by local government agencies, invariably have been designed to produce maximum additional precipitation, without the expensive instrumentation and reduction in seeding opportunity which is inherent in a program designed for maximum information.

As noted above, the actual cloud seeding is conducted by a commercial meteorological firm, North American Weather Consultants, and financed by the Counties of Santa Barbara and Ventura. All decisions regarding the seedability of a given storm situation are made by the North American Weather Consultants based on their analysis of the synoptic situation.

In order to facilitate analysis, calendar time was divided into "units of observation", each extending over 12 hours, from 10 a.m. to 10 p.m., and from 10 p.m. of one day to 10 a.m. of the next. Some time before the beginning of each unit of observation, the North American Weather Consultants decided whether the forthcoming unit was or was not a promising seeding opportunity. This diagnosis, accompanied by an indication as to which of three selected control areas are appropriate for comparison with the target, was then communicated by teletype to the Statistical Laboratory. Thereafter, the Statistical Laboratory communicated to the North American Weather Consultants its randomly attained decision whether to seed or not to seed. The cloud-seeder adhered to the Laboratory's decision. The cloud-seeding techniques and methods used by North American Weather Consultants are described in detail in the next chapter.

Rainfall data from over 160 recording rain gages were available for evaluation of this Project. About 50 of these gages were installed especially for this Project. Collection and reduction of the rainfall records was accomplished primarily by personnel of the California Department of Water

Resources, the United States Weather Bureau, the Los Angeles County Flood Control District, and the Ventura County Flood Control District. Insofar as possible, those persons engaged in working up the rainfall records were unaware of which storm periods were seeded. The data collection program is described in Chapter IV.

The Statistical Laboratory of the University of California is responsible for the evaluation of the precipitation data resulting from the operations. The National Science Foundation supports the activities of the Statistical Laboratory in accordance with the terms of the Foundation's grant to the Laboratory. With respect to the precipitation data, the evaluation of the success of seeding is based solely upon precipitation recorded during those units of observation which the North American Weather Consultants diagnosed as seeding opportunities. Also, in each case the precipitation in the target is compared with that in those control areas which the North American Weather Consultants recognized as appropriate, but not with others. The reason for this detail is that, depending upon air currents, the precipitation in some control areas may be influenced by seeding over the target. However, the decision as to which areas are appropriate for a given seeding opportunity is reached by the North American Weather Consultants before learning the randomized decision whether to seed or not. The statistical evaluation of the precipitation data is described in Chapter V.

Concurrently with the statistical evaluation, the Board of Directors have encouraged physical studies of the winter storms affecting Santa Barbara. These physical studies have been conducted primarily through the use of a weather radar, but have also included measurements of rain drop-size, cloud-electrification, and wind. The physical studies and their evaluation are reported in Chapter VI.

CHAPTER III

CLOUD SEEDING OPERATIONS

By Robert D. Elliott, President

North American Weather Consultants

1. Introduction

Cloud seeding on the Santa Barbara Project can be classified as being of the orographic-convective type. Because height of the -5°C air-temperature level seldom lies below the mountain crests during storm periods, there are no appreciable number of cases which would fall into the category of the simple orographic type. This suggests that there is a distinct difference between seeding in Santa Barbara County, which is representative of conditions along much of the immediate west coast, and that in the Sierra Nevada or other high western mountain ranges where the -5°C level lies below crest line much of the time. However, the difference is not at all striking when one considers that in both cases the convective instability is normally released and/or accentuated by the orography, and that hence each is primarily a convective-orographic seeding situation.

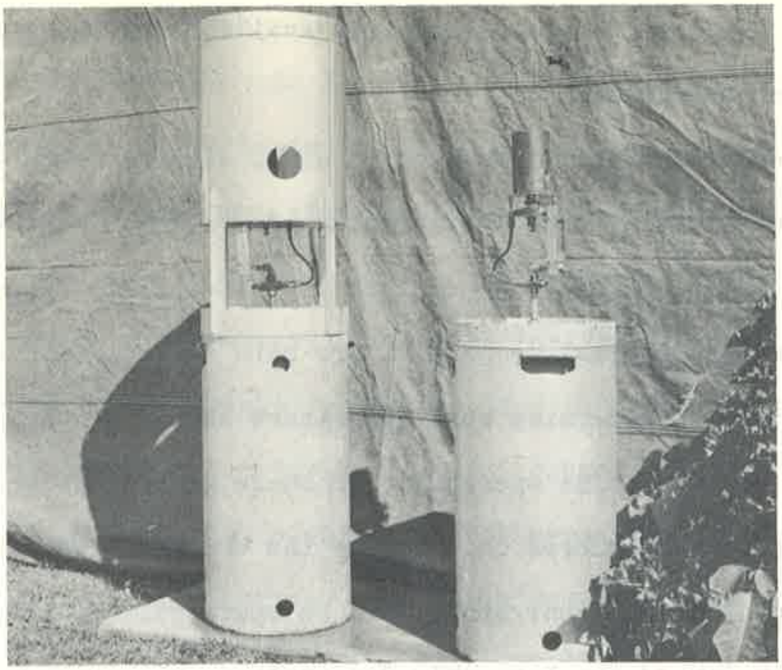
On the other hand, relief varies somewhat in both Santa Barbara and Ventura Counties with relatively flat plains in northwest Santa Barbara and in southwest Ventura County in contrast to rugged mountains elsewhere. Thus, some of the subtargets may be considered only mildly affected by the terrain and therefore comparisons between subtargets is of interest on this basis.

2. Procedures and Equipment

The method of seeding employed during the three years of the project has been essentially the same as that which had been employed previously in Santa Barbara County and elsewhere. It consists basically of seeding from ground-based silver iodide smoke generators located at strategic sites throughout the target area and somewhat upwind therefrom. The theory of artificial nucleation has been treated extensively elsewhere; suffice it to say at this point that the smoke emitted by the generators spreads downwind at low levels some distance, then is either entrained within a convection cell updraft and carried rapidly up to the nucleation level or is blown directly up mountain slopes, then entrained in such a cell. In either case the air mass must be thermodynamically unstable for the appropriate lifting mechanism to exist.

After reaching the nucleation level, ten or twenty minutes elapses before precipitation particles are grown, and resultant fallout to ground level may require a similar time. During these time intervals the nucleant or precipitation particles are carried downwind. Therefore, the ultimate precipitation resulting from release of smoke at map point A falls to the ground at some other point B some distance (on the order of 20 miles) away. The direction of the line AB depends, among other things, upon the surface and the upper wind pattern. The generators are so oriented with respect to the target area as to permit targeting under a variety of wind flow conditions.

The smoke generator employed consists of a nozzle for mixing aspirated silver iodide in acetone solution with propane gas, a flame holder in which the burning commences, a silver iodide solution storage tank, a wind screen, and the necessary plumbing including regulators of gas pressure and of silver iodide solution flow. The flame temperature is around 1200°C which insures vaporization of the silver iodide. Rapid quenching in the environmental air leads to direct deposition in the form of small (.01μ) smoke particles.



SILVER IODIDE GENERATORS WITH AND WITHOUT WINDSCREEN

Figure III-1

Figure III-1 is a picture of the generator with and without windscreen. As used in the Santa Barbara Project the generators burned a 2 per cent solution at the rate of 0.10 gallon per hour. The total output of crystals at this burning rate is around 10^{15} per second. The number effective as ice-forming nuclei varies with temperature, being 10^{10} per second at -10°C, $2x10^{12}$ per second at -15°C, and 10^{13} per second at -20°C.

Plates III-1, -2, -3, and -4 display the arrangement of generators during 1957, 1958, and 1959 in Santa Barbara County and during 1958 (not randomized) and 1959 in Ventura County. Beside each generator appears a figure which represents the total number of hours of operation of that generator during the year. It is seen that in each year the center of gravity of generator operations lay south of the target area center. This results from the fact that the prevailing flow during seeding is southeast at the surface and southwest aloft.

Summaries of generator operations by day and by generator appear in the appendix. Complete generator logs are available in the files of the Department of Water Resources.

The procedure normally employed in cloud seeding is to watch the synoptic situation carefully upon the approach of a storm. Weather teletype data and local observations are both employed at this point. When cloud conditions and air mass thermal properties are both suitable for seeding, a computation is made to determine what generators should be turned on under the existing wind pattern. The operators for these generators are then called and the generators ordered on. During the course of the storm, winds may shift and then different generators will be operated. Finally, when cloud conditions no longer are favorable for seeding, all generators are turned off.

In the Santa Barbara Project it was desirable for test purposes to work with a definite, fixed unit of seeding time. Twelve hours were chosen for this, partly because it would then be possible to analyze day and night-time seeding effects separately. Accordingly, between 8:30 a.m. and 9 a.m., and again between 8:30 p.m. and 9 p.m. each day a meteorological decision was made as to whether there would or would not be a seedable condition at any time during the ensuing 12-hour period. Just before 9 a.m. and 9 p.m. each day this decision was transmitted by teletype to a representative of the University of California Statistical Laboratory and a statistical decision to seed or not to seed was returned. The statistical decisions were made by chance, but in such a way that over a long period of time approximately half of them would be to seed. Therefore, approximately equal numbers of seeded-seedable and not seeded-seedable cases were established in a given year.

In cases where both the meteorological and statistical decisions were to seed, the seeding was commenced as early as 9 a.m. or 9 p.m. but could not be continued for more than 12 hours after the start. The precipitation data were analyzed on the basis of 10 a.m. - 10 p.m. and 10 p.m. - 10 a.m. intervals. Thus, a one-hour time lag was permitted for seeding to take effect.

Various supplementary items were included in the message sent from Santa Barbara to Berkeley which provided information of interest to the project. This included a priority list for control areas. This provided a meteorological judgment as to which control areas would be most secure against possible downwind contamination, especially under unusual wind conditions. Also included was an estimate of the "seedability" of the storm on a scale of 4, with Class 1 being most seedable. The meteorological basis for this was largely air mass temperature and thermal structure; the colder and the more unstable the air mass, the more favorable the situation for seeding. The criteria used in selecting storm seedability and appropriate control areas are given in the following tabulation.

Height of $-5^{o}C$ Level	Low Pressure Center Aloft More Than 200 Miles Away and Wind Direction at $-5^{o}C$ Level From				Low Pressure Center Aloft Within 200 Miles
	West to south sector	South to east sector	East to north sector	North to northwest sector	
12,000	Not seedable	Not seedable	Not seedable	Not seedable	Class 3 control area depends upon wind direction
8 - 12,000'	Class 2 / Controls B&A	Class 2 / Control A	Class 3 / Control B	Class 3 / Controls B&C	Class 2 Control area depends upon wind direction
8,000'	Class 1 / Controls B&A	Class 1 / Control A	Class 2 / Control B	Class 2 / Controls B&C	Class 1 Control area depends upon wind direction

Class 4 - No seeding because of hazardous watershed conditions

Control Area A: Channel Islands.
Control Area B: San Simeon - Cape San Martin Area.
Control Area C: San Luis Obispo-Morro Bay Area.

It is clear that the meteorological decision involves a 12-hour forecast. There is a very appreciable chance for an erroneous forecast to be made, particularly when there arises a question as to whether seedable conditions are to occur near the end of the 12-hour period. Thus, there may arise a case in which no seeding is forecast but seedable conditions develop before the end of the 12-hour period. In this case seeding is permitted if the statistical forecast is for seeding, otherwise it is not. Conversely, the case may arise in which seeding is forecast but the seeding conditions do not develop during the 12-hour interval. In this case no seeding may be done even though both the meteorological and statistical decisions were for seeding.

Table III-1 is a log of all cases where either the meteorological decision was to seed or where a forecast error occurred and the decision should have been to seed. In this log there also appears the category number (to be explained below) and the predominant wind velocity and direction at the $-5^{\circ}C$ level.

TABLE III-1

LOG OF DATES AND PERTINENT
DATA FOR SEEDABLE CASES
SANTA BARBARA WEATHER MODIFICATION PROJECT

Date	Unit of observation 1/	NAWC forecast 2/	NAWC forecast correction to: 2/	Berkeley decision 2/	Actual operation 2/	Category 3/	Avg. wind direction at -5°C level deg. 4/	Avg. wind velocity at -5°C levels, knots	Avg. height of -5°C temp, feet above mean sea level
SANTA BARBARA COUNTY 1957									
1/11	P	S		NS	NS	2	230	40	11,900
1/12	A	NS	S	ND	NS	6	230	50	12,800
1/12	P	S		S	S	1	220	50	11,600
1/20	A	S	NS	NS	NS	4	280	35	9,100
1/22	P	S		S	S	1	240	15	10,000
1/23	A	S		S	S	1	250	25	9,600
1/23	P	S		NS	NS*	2	290	25	9,800
1/25	P	S		S	S	1	290	30	8,500
1/27	A	S		S	S	1	290	5	4,100
1/28	A	NS	S	S	S	5	240	10	5,500
1/28	P	S		NS	NS	2	220	25	6,000
2/ 7	A	S		NS	NS	2	240	25	12,500
2/ 7	P	S		S	S	1	230	35	12,100
2/ 8	A	S		S	S	1	240	40	12,400
2/ 8	P	S		NS	NS	2	250	30	12,900
2/22	P	S		NS	NS	2	250	30	10,000
2/23	A	S		S	S	1	250	30	11,800
2/24	A	S	NS	NS	NS	4	260	35	11,600
2/27	P	NS	S	S	S	5	230	20	11,700
2/28	A	S		NS	NS	2	210	15	9,800

* One generator overran time until 0700 next morning, another until 0215.

1/ A unit of observation is a 12-hour period beginning at (A) 10 a.m. or (P) 10 p.m.
2/ S-seed, NS-no seed, ND-no decision.
3/ See Table III-2 for explanation.
4/ Direction from which wind blowing measured from north.

TABLE III-1

LOG OF DATES AND PERTINENT
DATA FOR SEEDABLE CASES
SANTA BARBARA WEATHER MODIFICATION PROJECT
(continued)

Date	Unit of observation 1/	NAWC forecast 2/	NAWC forecast correction to 2/	Berkeley decision 2/	Actual operation 2/	Category 3/	Avg. wind direction at -5°C level deg. 4/	Avg. wind velocity at -5°C levels, knots	Avg. height of -5°C temp, feet above mean sea level
SANTA BARBARA COUNTY 1957 (Cont'd)									
3/8	P	S		S	S**	1	240	25	12,500
3/15	P	S	NS	NS	NS	4	230	15	8,500
3/17	A	S		S	S	1	150	15	7,800
3/18	P	S		S	S	1	090	10	9,900
4/17	A	S		S	S	1	240	40	11,200
4/18	A	S		S	S	1	300	15	9,800
4/20	A	S		NS	NS	2	250	10	7,000
4/20	P	S		NS	NS	2	330	15	7,200
SANTA BARBARA COUNTY 1958									
1/ 9	P	NS	S	S	S	5	230	25	11,900
1/24	A	S		S	S	1	280	50	12,000
1/25	A	NS	S	S	S	5	250	40	12,400
1/25	P	S		S	S	1	240	40	10,400
1/26	A	S		NS	NS	2	270	35	9,000

** "One generator overran until 1330 March 9. The March 9 a.m. decisions were: NAWC - NS, Berkeley - S, Operation NS."

TABLE III-1

LOG OF DATES AND PERTINENT
DATA FOR SEEDABLE CASES
SANTA BARBARA WEATHER MODIFICATION PROJECT
(continued)

Date	Unit of observation 1/	NAWC forecast 2/	NAWC forecast correction to 2/	Berkeley decision 2/	Actual operation 2/	Category 3/	Avg. wind direction at -5°C level deg. 4/	Avg. wind velocity at -5°C levels, knots	Avg. height of -5°C temp, feet above mean sea level
SANTA BARBARA COUNTY 1958 (Cont'd)									
2/1	A	S	NS	S	NS	3	190	35	12,000
2/2	A	S		NS	NS	2	210	45	11,200
2/2	P	S		NS	NS	2	230	40	10,300
2/3	A	S		NS	NS	2	210	35	10,300
2/3	P	S		S	S	1	190	30	9,900
2/4	A	S		NS	NS	2	220	30	10,000
2/7	A	S		NS	NS	2	250	30	11,800
2/7	P	NS	S	S	S	5	250	30	11,500
2/12	A	S		S	S	1	270	35	13,000
2/18	P	S		S	S	1	190	35	12,600
2/19	A	S		S	S	1	160	15	10,800
2/24	P	NS	S	S	S	5	270	35	9,000
3/6	A	S		S	S	1	310	20	7,000
3/10	P	S		NS	NS	2	100	20	6,900
3/12	A	NS	S	S	S	5	300	15	6,300
3/13	A	NS	S	S	S	5	260	15	7,500
3/14	A	S		S	S	1	240	25	8,800
3/14	P	S		NS	NS	2	230	30	10,900
3/15	A	S		NS	NS	2	220	25	11,500
3/15	P	S	NS	NS	NS	4	240	35	10,600

TABLE III-1

LOG OF DATES AND PERTINENT
DATA FOR SEEDABLE CASES
SANTA BARBARA WEATHER MODIFICATION PROJECT
(continued)

Date	Unit of observation 1/	NAWC forecast 2/	NAWC forecast correction to 2/	Berkeley decision 2/	Actual operation 2/	Category 3/	Avg. wind direction at -5°C level deg. 4/	Avg. wind velocity at -5°C levels, knots	Avg. height of -5°C temp, feet above mean sea level
SANTA BARBARA COUNTY 1958 (Cont'd)									
3/20	A	S		NS	NS	2	240	40	12,200
3/21	A	NS	S	NS	NS	6	220	40	10,300
3/21	P	S		S	S	1	240	35	8,800
3/23	A	S	NS	NS	NS	4	230	20	9,000
3/27	A	NS	S	S	S	5	240	20	8,800
3/30	A	S		S	S	1	260	30	9,500
3/31	A	S		S	S	1	260	25	9,800
3/31	P	S		NS	NS	2	250	20	9,700
4/ 1	A	S		NS	NS	2	270	25	8,700
4/ 2	P	S		S	S	1	230	40	9,600
4/ 3	A	S		S	S	1	250	40	8,200
4/ 3	P	NS	S	NS	NS	6	280	20	6,700
4/ 4	A	S	NS	NS	NS	4	290	25	6,500
4/ 5	A	S	NS	S	NS	3	240	25	9,400
4/ 5	P	S		NS	NS	2	240	30	9,500
4/ 6	A	S		S	S	1	230	40	9,600
4/ 6	P	S		S	S	1	240	25	7,900
4/ 7	A	S		S	S	1	310	15	8,500

TABLE III-1

LOG OF DATES AND PERTINENT
DATA FOR SEEDABLE CASES
SANTA BARBARA WEATHER MODIFICATION PROJECT
(Continued)

Date	Unit of observation 1/	NAWC forecast 2/	NAWC forecast correction to 2/	Berkeley decision 2/	Actual operation 2/	Category 3/	Avg. wind direction at -5°C level deg. 4/	Avg. wind velocity at -5°C levels, knots	Avg. height of -5°C temp, feet above mean sea level
1/ 5	A	S		S	S	1	230	25	11,200
1/ 5	P	S		S	S	1	240	25	10,500
2/ 7	A	S		S	S	1	270	15	9,600
2/ 9	P	NS	S	NS	NS	6	260	20	8,100
2/10	A	S		NS	NS	2	230	30	8,500
2/10	P	S		NS	NS	2	240	25	8,100
2/15	P	S		S	S	1	230	50	13,100
2/16	A	S		NS	NS	2	230	45	12,500
2/18	A	NS	S	S	S	5	260	20	8,600
2/20	P	NS	S	S	S	5	210	20	8,600
2/21	A	S		S	S	1	250	20	7,400
None in March									
4/25	A	S		NS	NS	2	230	30	11,500
Ventura County 1959									
1/ 5	A	S		S	S	1	230	25	11,200
1/ 5	P	S		NS	NS	2	240	25	10,500
1/ 6	A	NS	S	NS	NS	6	280	20	11,100

TABLE III-1

LOG OF DATES AND PERTINENT
DATA FOR SEEDABLE CASES
SANTA BARBARA WEATHER MODIFICATION PROJECT
(continued)

Date	Unit of observation 1/	NAWC forecast 2/	NAWC forecast correction to 2/	Berkeley decision 2/	Actual operation 2/	Category 3/	Avg. wind direction at -5°C level deg. 4/	Avg. wind velocity at -5°C levels, knots	Avg. height of -5°C temp, feet above mean sea level
VENTURA COUNTY 1959 (Cont'd)									
2/ 7	A	S		NS	NS	2	270	15	9,600
2/ 8	A	NS	S	S	S	5	340	20	6,800
2/ 9	P	NS	S	NS	NS	6	260	20	8,100
2/10	A	S		S	S	1	230	30	8,500
2/10	P	S		S	S	1	240	25	8,100
2/15	P	S		S	S	1	230	50	13,100
2/16	A	S		NS	NS	2	230	45	12,500
2/18	A	NS	S	S	S	5	260	20	8,600
2/20	P	NS	s	NS	NS	6	210	20	8,600
2/21	A	S		S	S	1	250	20	7,400
None in March									
4/25	A	S		NS	NS	2	230	30	11,500

Table III-2 presents an annual summary for data of Table III-1. The two contingencies evolving from the two types of statistical decision plus the four contingencies resulting from forecast error possibilities are assigned category numbers and their frequency in each year and county presented. This is the category number referred to in Table III-1. It is clear that forecast errors constitute a considerable percentage of all cases.

TABLE III-2

ANNUAL SUMMARIES
OF LOGS OF SEEDABLE CASES
SANTA BARBARA WEATHER MODIFICATION PROJECT

Category no.	NAWC forecast 1/	Berkeley decision 1/	Actual operation 1/	Forecast correction 1/	Number cases
			SANTA BARBARA - 1957		
1	S	S	S	NONE	13
2	S	NS	NS	NONE	9
3	S	S	NS	S---NS	0
4	S	NS	NS	S---NS	3
5	NS	S	S	NS---S	2
6	NS	NS or ND	NS	NS---S	1
			SANTA BARBARA - 1958		
1	S	S	S	NONE	16
2	S	NS	NS	NONE	13
3	S	S	NS	S---NS	2
4	S	NS	NS	S---NS	3
5	NS	S	S	NS---S	7
6	NS	NS	NS	NS---S	2
			SANTA BARBARA - 1959		
1	S	S	S	NONE	5
2	S	NS	NS	NONE	4
3	S	S	NS	S---NS	0
4	S	NS	NS	S---NS	0
5	NS	S	S	NS---S	2
6	NS	NS	NS	NS---S	1

TABLE III-2

ANNUAL SUMMARIES
OF LOGS OF SEEDABLE CASES
SANTA BARBARA WEATHER MODIFICATION PROJECT
(continued)

Category no.	NAWC forecast 1/	Berkeley decision 1/	Actual operation 1/	Forecast correction 1/	Number cases
			VENTURA - 1959		
1	S	S	S	NONE	5
2	S	NS	NS	NONE	4
3	S	S	NS	S---NS	0
4	S	NS	NS	S---NS	0
5	NS	S	S	NS---S	2
6	NS	NS	NS	NS---S	3

1/ S - seed, NS - no seed, ND - no decision.

3. Weather Summary

A summary of wind conditions at the height of the -5°C level appears in Figures III-2, -3, -4 on Plate III-5. It is seen that with respect to wind direction, the seeding cases show no marked differences from the non-seeded cases and, furthermore, that there is little difference from year to year. The over-all frequency is of course greater in 1958 than in the other years. The isolated group of west winds are connected with post-frontal seeding and the occasional southeast winds with low centers passing inland south of Santa Barbara. Although differences between years and between seeded and non-seeded cases are not marked, there is a difference in the storm paths during each year which fully accounts for the widely different frequencies of seedable conditions in the different years.

Plates III-6, -7, and -8 show the tracks of the low pressure centers of each seedable storm. It must be remembered that the seeding occurs as a rule in the cloud system in advance of a front which extends southward from the low pressure center. This is illustrated by the front appearing in Figure III-6 which is for the indicated observed case. The wide scatter of paths in the N-S direction during 1957 and 1959 is markedly different from the grouping to the north of Santa Barbara in 1958. This suggests that not only was the storm frequency considerably higher in 1958 but that a more uniform type occurred. A method for categorizing storms by types for the purpose of refining evaluation procedures has been developed by Vernon. In application (see Bulletin No. 16, California Water Resources Board) a marked difference in target-control regressions was shown for different storm types.

APPENDICES TO CHAPTER III

APPENDIX III-A

HOURS OF GENERATOR OPERATION

SANTA BARBARA 1957

DATE	JANUARY	FEBRUARY	MARCH	APRIL
1				
2				
3				
4	124:20			
5	168:15			
6				
7		16:00		
8	6:00	114:05	15:15	
9			67:15	
10				
11				
12	19:00			
13	54:00			
14				
15				
16				
17			106:00	84:45
18			9:15	18:15
19			22:45	
20				
21				
22				
23	102:05	15:15		
24	9:15			
25	23:15			
26	58:20			
27	63:45			
28	41:45	19:20		
29				
30				
31				
TOTAL HRS.	670:05	164:40	220:30	103:00
TOTAL DAYS	11	4	5	2

APPENDIX III-A

HOURS OF GENERATOR OPERATION

SANTA BARBARA 1958
(continued)

DATE	JANUARY	FEBRUARY	MARCH	APRIL
1				
2				21:15
3		32:45		90:00
4		70:15		
5				
6			100:00	43:30
7		21:00		45:15
8		89:00		
9	7:00			
10	40:00			
11				
12		75:45	84:00	
13			99:00	
14			115:45	
15				
16				
17				
18		28:00		
19		128:45		
20				
21			29:30	
22			30:45	
23				
24	72:15	15:30		
25	89:30	67:30		
26	71:30			
27			89:45	
28				
29				
30			75:30	
31			58:00	
TOTAL HRS.	280:15	528:30	682:15	200:00
TOTAL DAYS	5	9	9	4

APPENDIX III-A

HOURS OF GENERATOR OPERATION

SANTA BARBARA 1959
(continued)

DATE	JANUARY	FEBRUARY	MARCH	APRIL
1				
2				
3				
4				
5	102:00			
6	69:15			
7		26:30		
8				
9				
10				
11				
12				
13				
14				
15		37:30		
16		106:30		
17				
18		71:45		
19				
20				
21		165:00		
22				
23				
24				
25				
26				
27				
28				
29				
30				
31				
TOTAL HOURS	171:15	407:15		
TOTAL DAYS	2	5		

APPENDIX III-A

HOURS OF GENERATOR OPERATION

VENTURA 1958
(continued)

DATE	JANUARY	FEBRUARY	MARCH	APRIL
1				157:00
2		89:00		24:00
3		98:30		110:45
4		157:00		9:45
5		6:00		
6			47:45	
7		27:45		
8				
9				
10	28:00		42:00	
11			93:30	
12		29:00	40:30	
13			53:30	
14			89:45	
15			163:15	
16			50:00	
17			22:00	
18		55:30		
19		111:45		
20			66:00	
21			54:30	
22			14:30	
23			55:15	
24	54:45	13:00	19:30	
25	75:45	101:00		
26	87:00			
27			76:45	
28				
29				
30			41:30	
31			42:00	
TOTAL HOURS	245:30	688:30	972:15	301:30
TOTAL DAYS	4	10	17	4

APPENDIX III-A

HOURS OF GENERATOR OPERATION

VENTURA 1959
(continued)

DATE	JANUARY	FEBRUARY	MARCH	APRIL
1				
2				
3				
4				
5	36:30			
6				
7				
8		45:45		
9				
10		119:45		
11		76:15		
12				
13				
14				
15		28:00		
16		77:00		
17				
18		80:15		
19				
20				
21		117:00		
22				
23				
24				
25				
26				
27				
28				
29				
30				
31				
TOTAL HOURS	36:30	544:00		
TOTAL DAYS	1	7		

APPENDIX III-B

GENERATOR HOURS

SANTA BARBARA 1957

GENERATOR	JANUARY	FEBRUARY	MARCH	APRIL	TOTAL
Goleta Airport	76:05	30:45	20:15	13:45	140:50
Santa Rosa Island	38:15	28:20	20:15	10:10	97:00
Refugio	75:30	25:00	21:15	13:15	135:00
Bulito	52:50	24:50	22:00	13:00	112:40
Lompoc 3W	34:30	4:30	12:00	3:00	54:00
Los Alamos 6ENE	45:00		10:00	3:05	58:05
Zaca Lake	47:00	2:45		3:10	52:55
Santa Ynez	50:50	2:45	9:15	9:35	72:25
Cachuma	56:05	3:00	9:15		68:20
Montecito	64:00	25:50	25:30	12:00	127:20
Pitas Point	45:05				45:05
Matilija	12:40		20:00		32:40
Ventucopa 6S			11:00		11:00
Buckhorn	10:00				10:00
Cuyama			10:15		10:15
Nipomo	10:00				10:00
Sisquoc					
Casmalia					
Santa Cruz Island	52:15	16:55	20:15	11:00	100:25
Punta Gorda			9:15	11:00	20:15
TOTAL	670:05	164:40	220:30	103:00	1,158:15

APPENDIX III-B

GENERATOR HOURS

SANTA BARBARA 1958
(continued)

GENERATOR	JANUARY	FEBRUARY	MARCH	APRIL	TOTAL
Goleta	30:15	36:30	54:45	1:00	122:30
Santa Rosa Island		24:30	28:00		52:30
Refugio	37:00	52:00	47:00	11:30	147:30
Bulito Canyon			35:00	12:15	47:15
Lompoc 3W	35:45	62:00	63:00		160:45
Los Alamos 6 ENE	27:00	21:45	61:00	37:30	147:15
Zaca Lake			19:15	16:30	35:45
Santa Ynez	35:15	46:30	60:15	49:45	191:45
Paradise	21:00	34:45	25:30	50:30	131:45
Montecito	33:30	61:00	53:00	12:00	159:30
Punta Gorda	31:15	43:45	56:00		131:00
Matilija Canyon	22:45	64:30	46:00		133:15
Ventucopa 6 S		33:15	19:15	9:00	61:30
Buckhorn			18:00		18:00
Cuyama			5:30		5:30
Sisquoc			25:30		25:30
Casmalia	6:30	20:15	56:00		82:45
Santa Cruz Island		27:45	7:15		35:00
TOTAL	280:15	528:30	680:15	200:00	1689:00

APPENDIX III-B

GENERATOR HOURS

SANTA BARBARA 1959
(continued)

GENERATOR	JANUARY	FEBRUARY	MARCH	APRIL	TOTAL
Goleta	18:30	42:45			61:15
Santa Rosa Island	9:00				9:00
Refugio	23:00	34:00			57:00
Bulito Canyon	17:00	9:45			26:45
Lompoc 3W'	2:00	15:00			17:00
Zaca Lake	9:30	21:00			30:30
Santa Ynez	15:00	28:45			43:45
Paradise		40:00			40:00
Montecito		35:45			35:45
Punta Gorda	13:45	16:45			30:30
Matilija Canyon					
Ventucopa 6S					
Buckhorn					
Cuyama					
Sisquoc					
Casmalia		2:00			2:00
Santa Cruz Island					
Carpenteria	19:45	35:45			55:30
Santa Barbara	15:15	34:45			50:00
Dos Pueblos	15:30	12:00			27:30
Gaviota		23:00			23:00
City of Ventura		16:45			16:45
Point Mugu		12:45			12:45
El Rio		12:30			12:30
Los Alamos 6 ENE	13:00	14:00			27:00
TOTAL	171:15	407:15	00:00	00:00	578:30

APPENDIX III-B

GENERATOR HOURS

VENTURA 1958
(continued)

GENERATOR	JANUARY	FEBRUARY	MARCH	APRIL	TOTAL
Ventura	36:45	110:30	85:30	25:30	258:15
El Rio	37:00	112:00	142:15	17:45	309:00
Santa Paula	31:30	73:45	117:00	48:00	270:15
Camarillo	27:30	86:15	131:00	48:15	293:00
Point Mugu	17:00	74:00	80:00		171:00
Camarillo 5SE	22:00	33:45	76:45	13:00	145:30
Solromar	30:45	69:00	85:45	34:00	219:30
Malibu		52:45	30:30	13:30	96:45
Moorpark	14:45		33:00	34:00	81:45
Simi			11:30		11:30
Fillmore		7:00	37:30		44:30
Thousand Oaks	5:30	29:30	30:00	21:00	86:00
Santa Paula 8N		36:00	67:30	46:30	150:00
Calabasas		4:00			4:00
Gorman 7S			5:30		5:30
Matilija Canyon	22:45		38:30		61:15
TOTAL HOURS	245:30	688:30	972:15	301:30	2207:45

APPENDIX III-B

GENERATOR HOURS

VENTURA 1959
(continued)

GENERATOR	JANUARY	FEBRUARY	MARCH	APRIL	TOTAL
Calabasas		34:15			34:15
Camarillo	3:45	64:45			68:30
Camarillo 6SSE		38:00			38:00
City of Ventura	5:30	19:15			24:45
El Rio	5:45	25:45			31:30
Fillmore					
Malibu	5:45	34:15			40:00
Matilija Canyon		21:30			21:30
Moorpark		56:15			56:15
Point Mugu	5:45	25:15			31:00
Punta Gorda		15:00			15:00
Santa Cruz Island		20:45			20:45
Santa Monica		35:00			35:00
Santa Paula		21:30			21:30
Santa Paula 8 N		26:15			26:15
Simi		36:00			36:00
Solromar	5:00	21:00			17:00
Thousand Oaks	5:00	58:15			63:15
TOTAL	36:30	544:00			580:30

APPENDIX III-C

SEEDED DAYS PER SEASON

SANTA BARBARA AND VENTURA

	Santa Barbara			Ventura	
	1957	1958	1959	1958	1959
January	11	5	2	4	1
February	4	11	5	10	7
March	5	12	0	17	0
April	2	5	0	4	0
TOTAL	22	33	7	35	8

PLATE III-1

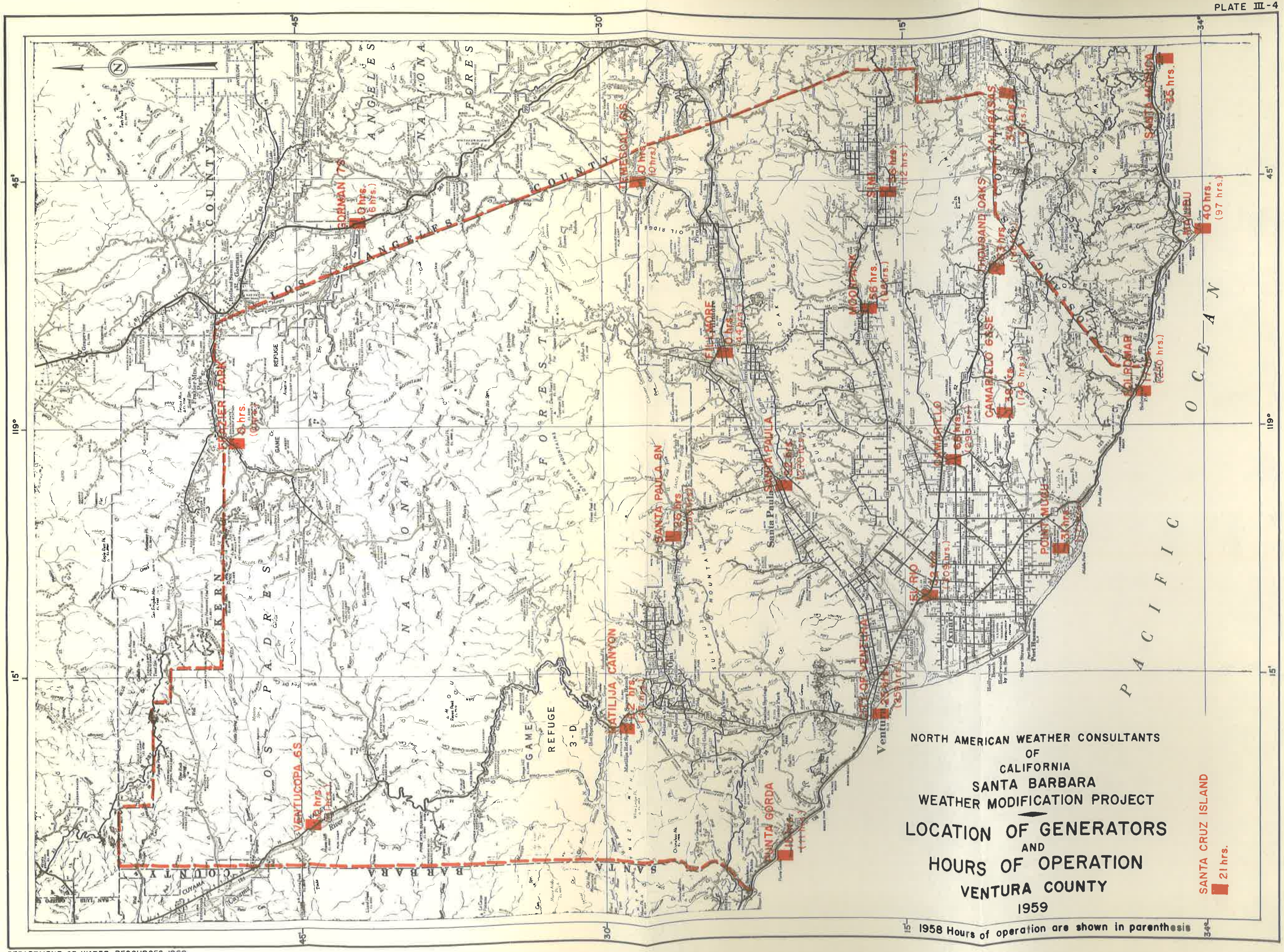
DEPARTMENT OF WATER RESOURCES 1960

NORTH AMERICAN WEATHER CONSULTANTS
OF
CALIFORNIA
SANTA BARBARA
WEATHER MODIFICATION PROJECT

LOCATION OF GENERATORS
AND
HOURS OF OPERATION
SANTA BARBARA COUNTY
1958

DEPARTMENT OF WATER RESOURCES 1960

DEPARTMENT OF WATER RESOURCES 1960


NORTH AMERICAN WEATHER CONSULTANTS
OF
CALIFORNIA
SANTA BARBARA
WEATHER MODIFICATION PROJECT
LOCATION OF GENERATORS
AND
HOURS OF OPERATION
VENTURA COUNTY
1959
1958 Hours of operation are shown in parenthesis
SANTA CRUZ ISLAND
21 hrs.
PACIFIC OCEAN
LOS PADRES NATIONAL FOREST
LOS ANGELES COUNTY
SANTA BARBARA COUNTY
KERN COUNTY
GAME REFUGE 3-D
GORMAN 7S
FRAZIER PARK
VENTUCOPA 6S
MATILIJA CANYON
SANTA PAULA 8N
SANTA PAULA
FILLMORE
PIRU
MOORPARK
SIMI
CAMARILLO
CAMARILLO 6SSE
THOUSAND OAKS
CALABASAS
SANTA MONICA
MALIBU
SOLROMAR
POINT MUGU
EL RIO
PUNTA GORDA
VENTURA
40 hrs.
(97 hrs.)
35 hrs.

		<170°	170°	180°	190°	200°	210°	220°	230°	240°	250°	260°	270°	>270°<360°
AVG. HEIGHT -5°C LEVEL (FEET)	SEEDED	8850						11,600	12,100	11,550	10,700			7466
	NON-SEEDED						9800	6000	11,900	12,500	9000			8500
AVG. WIND STRENGTH -5°C LEVEL (KNOTS)	SEEDED	12.5						50	35	30	27.5			16.7
	NON-SEEDED						15	25	40	25	35			20

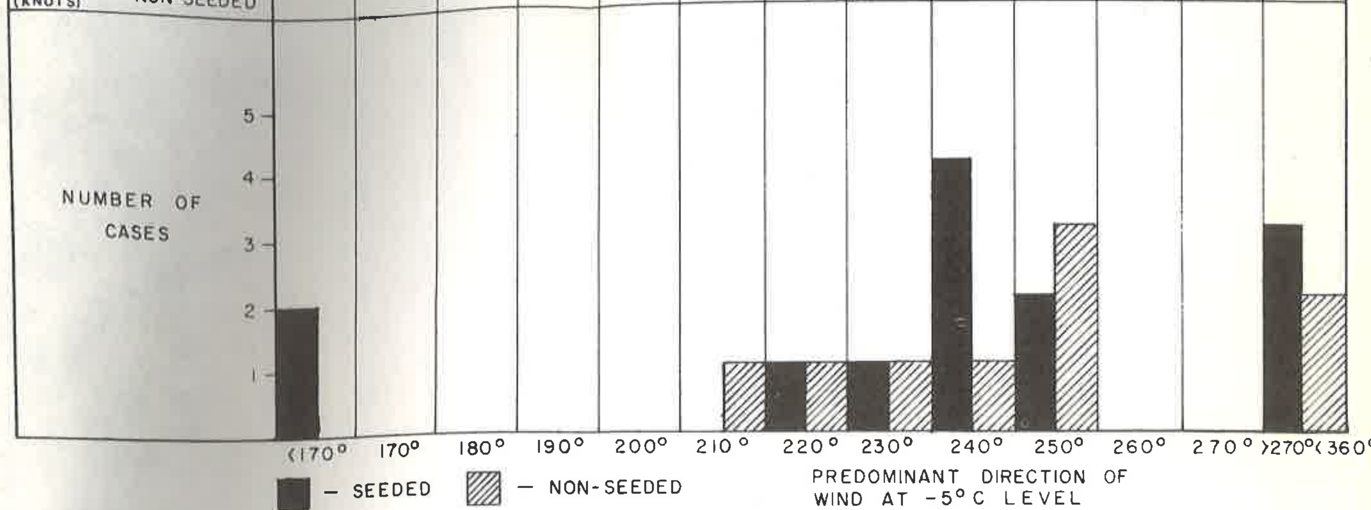


Fig. III-2 WIND DIRECTION AND STRENGTH AT THE -5°C LEVEL (1957)

		<170°	170°	180°	190°	200°	210°	220°	230°	240°	250°	260°	270°	>270°<360°
AVG. HEIGHT -5°C LEVEL (FEET)	SEEDED								12,150	10,500	7400		9600	
	NON-SEEDED								10,830	8100				
AVG. WIND STRENGTH -5°C LEVEL (KNOTS)	SEEDED								37.5	25	20		15	
	NON-SEEDED								35	25				

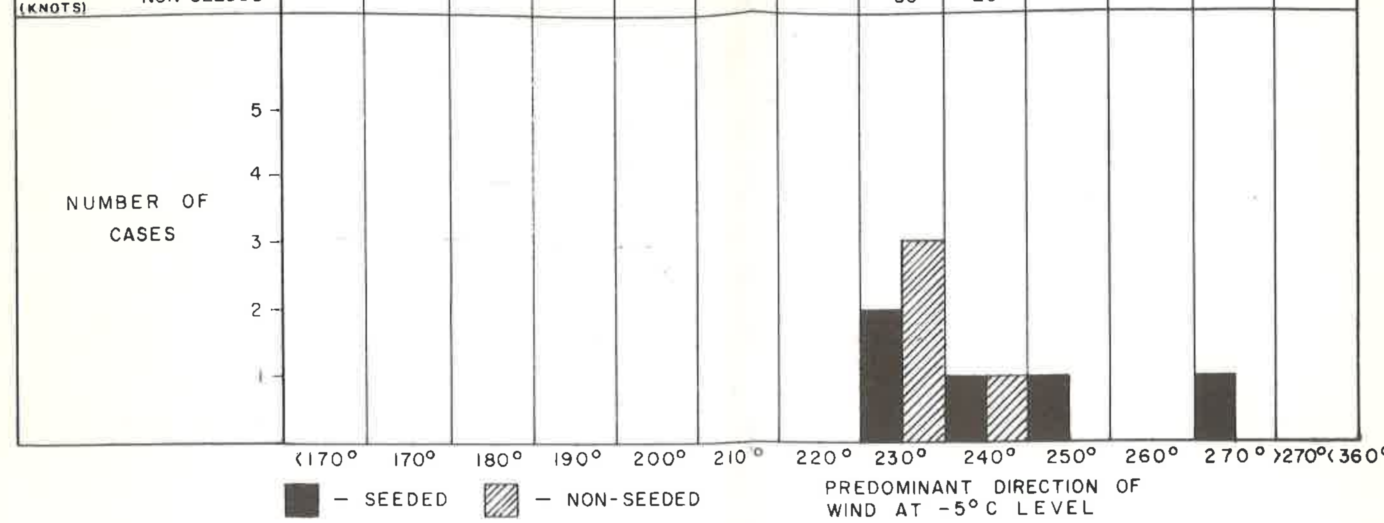


Fig. III-4 WIND DIRECTION AND STRENGTH AT THE -5°C LEVEL (1959)

		<170°	170°	180°	190°	200°	210°	220°	230°	240°	250°	260°	270°	>270°<360°
AVG. HEIGHT -5°C LEVEL (FEET)	SEEDED	10,800			11,450				9600	8850	8200	9650	13,000	9160
	NON-SEEDED	6900					10,750	10,750	10,600	10,760	10,400		8850	
AVG. WIND STRENGTH -5°C LEVEL (KNOTS)	SEEDED	15			32.5				40	33	40	27.5	35	28.3
	NON-SEEDED	20					40	27.5	35	35	25		30	

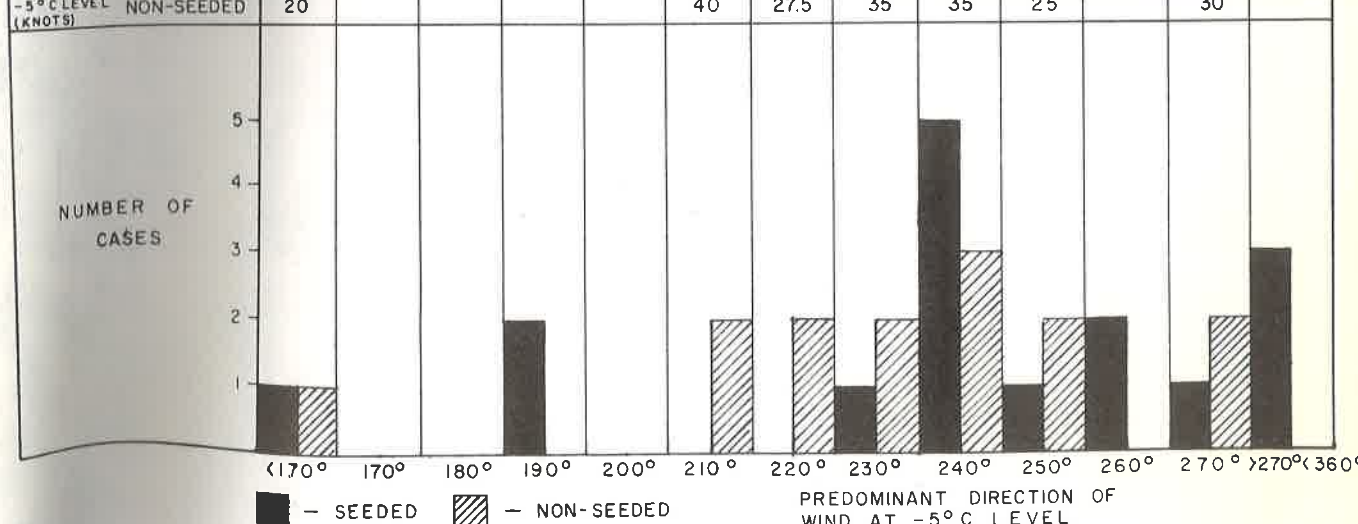
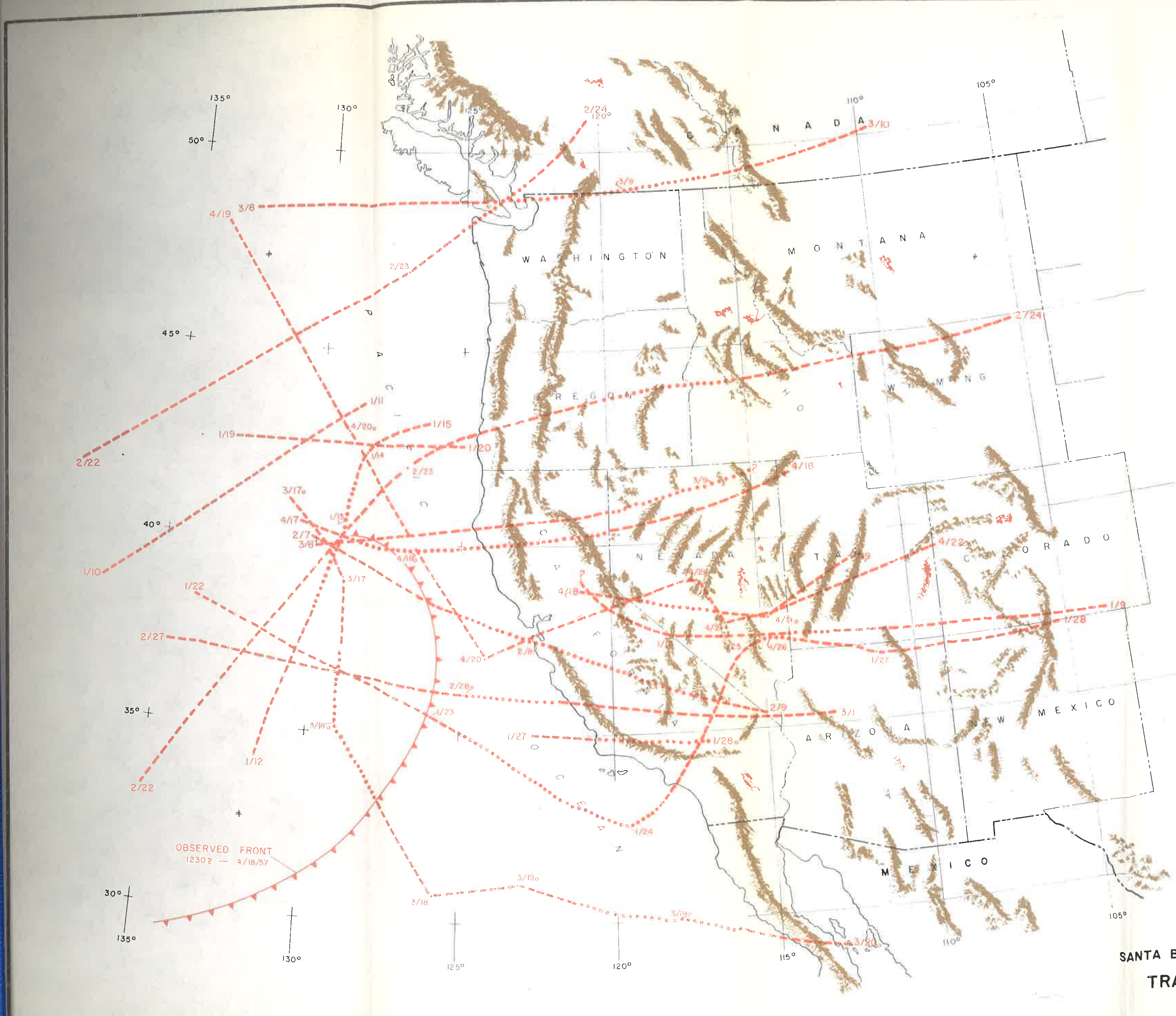


Fig. III-3 WIND DIRECTION AND STRENGTH AT THE -5°C LEVEL (1958)

NORTH AMERICAN WEATHER CONSULTANTS
OF
CALIFORNIA

SANTA BARBARA WEATHER MODIFCATION PROJECT

SUMMARY OF WIND CONDITIONS



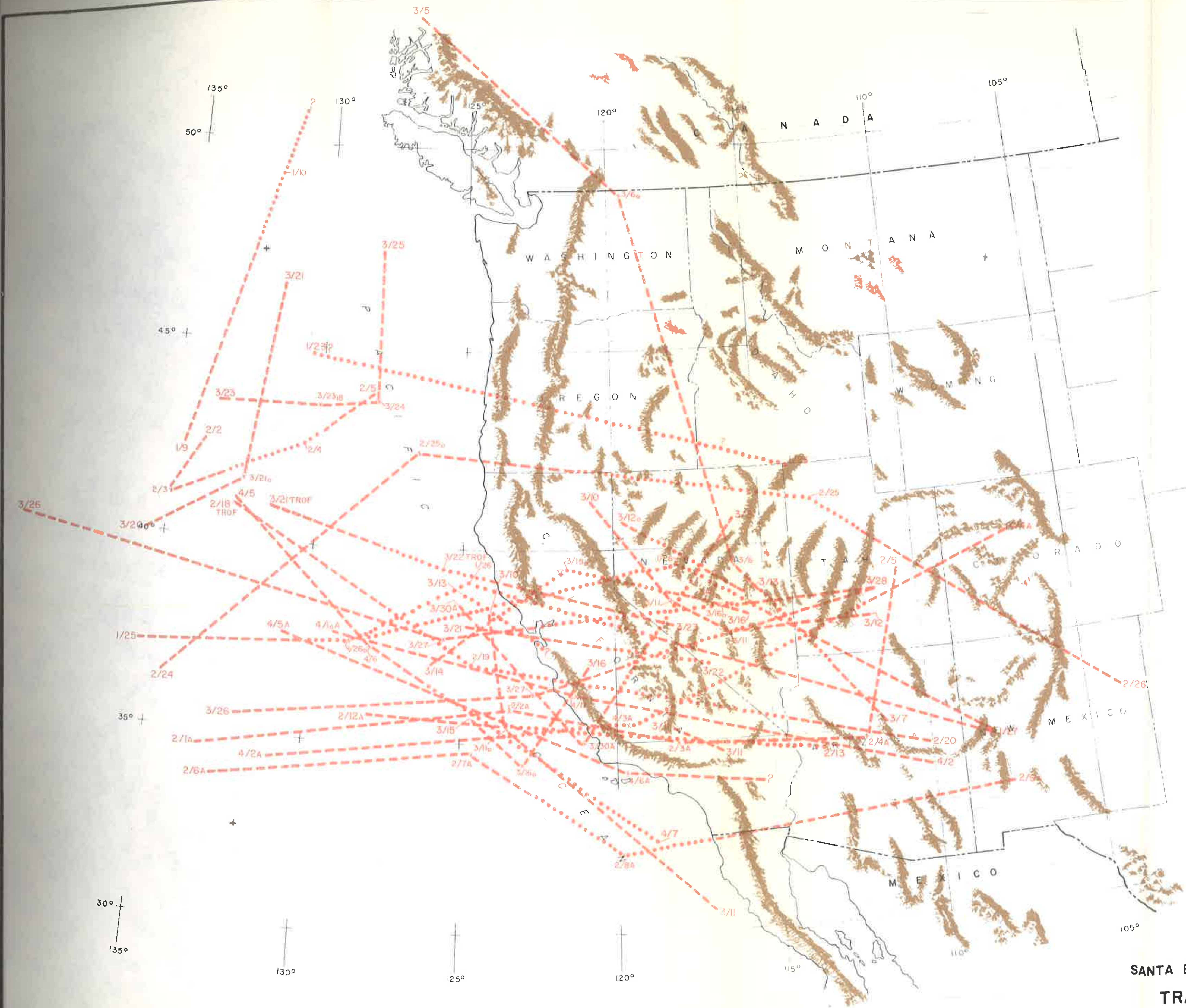
LEGEND

······	TRACK OF LOW PRESSURE CENTER DURING TIME SEEDING OCCURRED.
- - - -	TRACK OF LOW PRESSURE CENTER DURING TIME NO SEEDING OCCURRED.
TROF	INDICATES POSITION OF TROUGH INSTEAD OF LOW PRESSURE CENTER.
A	INDICATES POSITION OF APEX, OR PEAK, OF WARM SECTOR INSTEAD OF LOW PRESSURE CENTER.
12/18	POSITION OF LOW PRESSURE CENTER AT 1230 GREENWICH MEAN TIME ON DECEMBER 18
$12/18_0$	POSITION OF LOW PRESSURE CENTER AT 0030 GREENWICH MEAN TIME ON DECEMBER 18
$12/18_6$	POSITION OF LOW PRESSURE CENTER AT 0600 GREENWICH MEAN TIME ON DECEMBER 18
$12/18_{18}$	POSITION OF LOW PRESSURE CENTER AT 1800, GREENWICH MEAN TIME ON DECEMBER 18.

NORTH AMERICAN WEATHER CONSULTANTS
OF
CALIFORNIA

SANTA BARBARA WEATHER MODIFCATION PROJECT

TRACKS OF SEEDABLE STORMS
JAN. — APRIL, 1957



LEGEND

······	TRACK OF LOW PRESSURE CENTER DURING TIME SEEDING OCCURRED.
– – – –	TRACK OF LOW PRESSURE CENTER DURING TIME NO SEEDING OCCURRED.
TROF	INDICATES POSITION OF TROUGH INSTEAD OF LOW PRESSURE CENTER.
A	INDICATES POSITION OF APEX, OR PEAK, OF WARM SECTOR INSTEAD OF LOW PRESSURE CENTER.
12/18	POSITION OF LOW PRESSURE CENTER AT 1230 GREENWICH MEAN TIME ON DECEMBER 18
$12/18_0$	POSITION OF LOW PRESSURE CENTER AT 0030 GREENWICH MEAN TIME ON DECEMBER 18
$12/18_6$	POSITION OF LOW PRESSURE CENTER AT 0600 GREENWICH MEAN TIME ON DECEMBER 18
$12/18_{18}$	POSITION OF LOW PRESSURE CENTER AT 1800 GREENWICH MEAN TIME ON DECEMBER 18.

NORTH AMERICAN WEATHER CONSULTANTS
OF
CALIFORNIA

SANTA BARBARA WEATHER MODIFCATION PROJECT

TRACKS OF SEEDABLE STORMS
JAN. — APRIL, 1958

NORTH AMERICAN WEATHER CONSULTANTS
OF
CALIFORNIA

SANTA BARBARA WEATHER MODIFCATION PROJECT

TRACKS OF SEEDABLE STORMS
JAN. — APRIL, 1959

CHAPTER IV

PRECIPITATION DATA COLLECTION PROGRAM

By C. G. Wolfe, Senior Hydraulic Engineer
California Department of Water Resources

In order to provide the necessary precipitation data for the statistical analyses which are the crux of the Santa Barbara Project, the California Department of Water Resources undertook the most intensive data collection program ever associated with a weather modification project. This chapter describes this program, the problems encountered, and the results obtained. In addition to its data collection activities, the Department also partially supported the statistical and physical studies associated with the Project. These studies are reported in the appropriate chapters.

1. Background Information

As described briefly in a previous chapter, the original area included in the investigation covered about 1200 square miles and extended about 200 miles along the California coast from Carpinteria in the south to Cape San Martin in the north. It also included the Channel Islands that lie about 25 miles off the Santa Barbara coast. Except for narrow plains along some portions of the coast, the entire area from which records were desired consists largely of rugged, brush-covered mountains. Only a small number of roads that can be used in winter extend more than a few miles inland. Most of the area is uninhabited.

One of the early decisions of the Project was to divide each day into two 12-hour seeding opportunities, beginning at 10 a.m., and 10 p.m., in order to evaluate day and night effects separately. As a consequence of this decision, the only type of precipitation data that could be used was that obtained from weighing-type, continuous recording gages. At the time of inception of the Project, there were only 9 acceptable recording gages in the original area of investigation.

2. Data Collection Program

Because of this paucity of available records, it was evident that many gages would have to be installed and operated. As its contribution to the Project, the Department of Water Resources undertook this task, and in the late fall of 1956 started preliminary planning and operating.

The Department does not maintain a large supply of recording rain gages, nor does it have funds to purchase many of these expensive pieces of equipment. Fortunately, the United States Weather Bureau was in a position to loan to the Project 37 weighing-type, recording gages, and on December 27, 1956, the first shipment was received in Santa Barbara. Also, the Weather Bureau assigned one of its Substation Inspectors to the Project for two days, in order to instruct State personnel in the standard techniques of gage calibration and maintenance. Insofar as possible, these techniques were adhered to throughout the period of the Project.

The original objectives in instrumenting the area were to obtain the most complete areal coverage, and at the same time, a representative sampling of rainfall at varying elevations. With these objectives in mind, a tentative grid was laid out, and on December 31, 1956, the first gage was installed and placed in operation.

It soon became apparent that the rugged topography of the area would not permit the placement of gages at all of the most desirable locations due to restricted access and poor sites available for installation. As a result, several compromises were necessary, but the network as finally evolved is believed adequate for the original objectives.

Another problem occurred during the first year of operation, when it became physically impossible to install all gages by January 1, 1957, the proposed beginning date of the Project. As funds and personnel became available, however, the gages were installed as rapidly as possible, and by March 27, 1957, all gages were in operation within the original limits of the Project.

As the Project expanded and as new information on the rainfall pattern was developed, additional gages were made available by the Weather Bureau during the second and third years of the Project, and these were installed at times and places that appeared suitable to the Board of Directors. Ultimately, the Weather Bureau loaned a total of 50 gages to the Project.

As originally designed, the Project consisted of three control areas (the Channel Islands, the San Simeon-Cape San Martin Area, and the San Luis Obispo-Morro Bay Area) and target areas in Santa Barbara County. For convenience, these four areas were given the code letters A, B, C, and T, respectively. Throughout the three-year history of the Project, as emphasis shifted and expanded in various areas, records from more and more areas were collected and utilized in the analyses. These new areas also have been assigned letter codes, but without special significance.

All gages of interest to the Project have been assigned a two-part identification number. This number consists of the area code letter described above and an arbitrary serial number. All gages installed and operated specifically for this Project, together with all known recording gages of other agencies in the area from which records were available, are indexed in Table IV-1 and their location indicated on Plate IV-1. In total, records from 165 gages have been available to this Project. However, records from many of these gages were not continuous for the entire period of the Project.

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959

Map Number	Station	Agency	Location: Latitude Deg.	Latitude Min.	Longitude Deg.	Longitude Min.	Elevation above mean sea level, in feet	Remarks
A-1	South Point	DWR	33	54.1	120	06.6	355	
A-2	Middle Ranch	DWR	33	59.7	119	42.9	240	
A-3b	Gherini Ranch	DWR	34	02.9	119	33.5	20	Station moved 2 mi. NNW November 20, 1957, to be accessible, to observer. Base raised 27" above ground November 8, 1958, due to flooding conditions.
A-4	Vail Ranch	DWR	34	00.5	120	03.0	60	
A-5	Santa Cruz Island	DWR	33	59.7	119	38.0	1,470	
A-6	Anacapa	DWR	34	01.2	119	21.9	250	
A-7	San Nicolas Island	USWB	33	14	119	28	502	
B-1	Lucia Willow Springs	USWB	35	53	121	27	340	
B-2	Melville Consolidated Mines	DWR	35	53.2	121	23.9	2,920	
B-3	Salmon Creek Guard Station	DWR	35	48.9	121	21.8	360	
B-4a	Piedras Blancas	DWR	35	40.0	121	17.0	25	Station moved 0.2 mi. S. November 29, 1957, due to cattle in area.
B-5	Sunical Hilltop	DWR	35	41.2	121	10.5	1,400	
B-6	San Simeon	DWR	35	38.4	121	11.6	15	
C-1	Cordoza Ranch	DWR	35	30.6	120	50.7	1,415	
C-2	Toro Creek	DWR	35	26.7	120	49.7	340	
C-3	Cerro Alto Guard Station	DWR	35	25.5	120	44.3	1,050	
C-4	Cayucos	DWR	35	26.3	120	53.2	20	
C-5	Perry Ranch	DWR	35	21.5	120	46.6	125	

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

Map Number	Station	Agency	Location				Elevation above mean sea level, in feet	Remarks
			Latitude		Longitude			
			Deg.	Min.	Deg.	Min.		
C-6	Tassajera Creek	DWR	35	23.2	120	40.4	1,400	
C-7a	Morro Bay	DWR	35	18.1	120	52.1	150	Station moved 0.1 mi. SE November 28, 1957, due to vandalism.
C-8	San Luis Obispo Poly	USWB	35	18	120	40	300	
C-9	Perfumo Canyon	DWR	35	15.5	120	45.8	500	
C-10	Avila	DWR	35	10.8	120	43.3	100	
D-1	Figueroa Mountain	USWB	34	44	120	00	3,150	
D-2	Sisquoc S. F. Camp	USWB	34	46	119	46	2,500	Six-month recorder.
D-3	Santa Barbara Potrero	USWB	34	47	119	39	5,200	Six-month recorder.
D-4	Cuyama R.S.	USWB	34	51	119	29	2,749	
D-5	Ozena Guard Station	VCFCD	34	41.0	119	21.2	3,600	
D-6	Wheeler Springs 7N	USWB	34	36	119	20	4,150	
D-7	Wheeler Springs 2SW	USWB	34	29	119	18	850	
D-8	Santa Ynez	USWB	34	37	120	06	600	
D-9	Stewart Canyon	VCFCD	34	27.6	119	14.8	920	
D-10	Hall Canyon Reservoir	VCFCD	34	16.8	119	15.5	190	
D-11	Selby Ranch	VCFCD	34	25.5	119	21.2	660	
D-12	Raymond Ranch	VCFCD	34	28.5	119	11.9	1,300	
D-13	Ferndale Ranch	VCFCD	34	25.7	119	05.4	960	
D-14	Saticoy Fire Station	VCFCD	34	17.2	119	09.3	190	
D-15	Ventura County Equipment Yard	VCFCD	34	12.1	119	12.4	35	
D-16	County Water Works District No. 6	VCFCD	34	09.8	118	50.2	900	

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

Map Number	Station	Agency	Location: Latitude Deg.	Location: Latitude Min.	Location: Longitude Deg.	Location: Longitude Min.	Elevation above mean sea level, in feet	Remarks
D-17	Fillmore State Fish Hatchery	VCFCD	34	23.6	118	53.1	470	
D-18	Camulos Ranch	VCFCD	34	24.3	118	45.3	720	
D-19	Piru Canyon	VCFCD	34	30.8	118	45.5	1,150	
F-1	Huasna	USWB	35	05	120	22	710	
F-2	La Panza Ranch	USWB	35	23	120	10	1,560	
F-3	Taft	USWB	35	09	119	28	1,025	
G-1	Santa Maria WBAP	USWB	34	54	120	27	238	
G-2	Surf 2 ENE	USWB	34	41	120	34	105	
G-3	Lompoc Airport	DWR	34	38.5	120	27.4	90	
G-4	Wasioja Patterson Ranch	USWB	34	59	119	54	2,175	
G-5	Cuyama Ranch	USWB	34	59	119	40	2,150	
G-6	Manzanita Mountain	USWB	34	54	120	05	3,125	
G-7	Apache Camp	USWB	34	52	119	21	4,600	
J-46d	Big Tujunga Dam	LACFCD	34	17.5	118	11.2	2,315	
J-47c	Clear Creek School	LACFCD	34	16.8	118	10.4	3,125	

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

Map Number	Station	Agency	Location				Elevation above mean sea level, in feet	Remarks
			Latitude		Longitude			
			Deg.	Min.	Deg.	Min.		
J-52c	Waterman G. S.	LACFCD	34	16.0	118	08.6	3,290	
J-57be	Opids Camp	USWB	34	15	118	06	4,250	
J-470	Tujunga Mill Creek	USWB	34	23	118	05	740	
J-471	Little Tujunga	USWB	34	19	118	18	2,750	
J-1013B	Tujunga Canyon above Gold Canyon	LACFCD	34	18.0	118	16.1	1,650	
K-1	Cholame Hatch Ranch	USWB	35	41	120	12	1,975	
K-2	Lost Hills	USWB	35	37	119	41	285	
K-3	Bakersfield WBAP	USWB	35	25	119	03	493	
K-4	Chuchupate RS	USWB	34	48	119	00	5,250	
K-5	Coalinga ISE	USWB	36	08	120	20	663	
K-6	Corcoran ID	USWB	36	06	119	34	200	
K-7	Tehachapi RS	USWB	35	08	118	27	3,975	
L-1	Camarillo 2 SE	VCFCD	34	12.3	119	00.8	123	
L-2	Camarillo 4 NNW	VCFCD	34	16.4	119	04.6	352	
L-3	Moorpark 3 NNW	VCFCD	34	19.5	118	53.7	1,050	

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

Map Number	Station	Agency	Location: Latitude Deg.	Location: Latitude Min.	Location: Longitude Deg.	Location: Longitude Min.	Elevation above mean sea level, in feet	Remarks
L-4	Moorpark 3 SE	VCFCD	34	15.4	118	50.9	635	
L-5	Newbury Park 2 WNW	VCFCD	34	11.3	118	56.4	685	
L-6	Santa Paula 3 SE	VCFCD	34	19.9	119	01.2	2,240	
L-7	Santa Susana 4 NNE	VCFCD	34	19.7	118	41.9	1,520	
L-8	Simi 3 E	VCFCD	34	16.3	118	44.4	920	
L-9	Somis 2 NNW	VCFCD	34	17.0	119	00.4	510	
L-10	Somis 5 WNW	VCFCD	34	17.1	119	04.4	520	
M-2b	Escondido Patrol Station	LACFCD	34	02.9	118	46.4	1,050	
M-6	Topanga Patrol Station	LACFCD	34	05.0	118	36.0	747	
M-352b	Lechuza Patrol Station	USWB	34	05	118	53	1,530	
M-434	Malibu Headquarters	LACFCD	34	08.1	118	45.1	800	
M-435	Monte Nido Patrol Station	LACFCD	34	04.7	118	41.6	600	
M-443b	Latigo Canyon Beach Ranch	LACFCD	34	05.6	118	48.9	1,700	
N-33ae	Pacoima Dam	LACFCD	34	19.8	118	24.0	1,500	
N-357	San Fernando P.H. No. 3	USWB	34	19	118	30	1,248	

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

Map Number	Station	Agency	Location: Latitude Deg.	Latitude Min.	Longitude Deg.	Longitude Min.	Elevation above mean sea level, in feet	Remarks
N-407e	Newhall R.S.	USWB	34	22	118	31	1,342	
N-446	Aliso Canyon	USWB	34	19	118	33	2,367	
N-466b	Pacoima Canyon	LACFCD	34	21.1	118	20.6	3,225	
N-493b	Sand Canyon	LACFCD	34	23.2	118	25.0	1,780	
N-801	Magic Mountain	USWB	34	24	118	17	4,450	
P-755	Griffith Park-Little Canyon	SL	34	07.5	118	17.0	900	
P-756	Griffith Park-Upper Spring Canyon	SL	34	07.8	118	17.6	1,200	
P-757	Griffith Park-Fern Dell	SL	34	07.2	118	18.3	750	
P-758	Griffith Park-Lower Spring Canyon	SL	34	08.0	118	17.4	600	
P-779	Griffith Park-Lower Mineral Wells	SL	34	08.8	118	17.8	625	
P-780	Griffith Park-Upper Mineral Wells	SL	34	08.6	118	18.1	950	
Q-124b	Bouquet Canyon Res.	SL	34	35.2	118	21.8	3,050	
Q-128b	Elizabeth Lake Canyon-Warm Springs Camp	LACFCD	34	36.4	118	33.7	2,075	
Q-261b	Acton Escondido	USWB	34	30	118	17	2,920	
Q-372	San Francisquito P.H. No. 2	LACFCD	34	32.0	118	31.4	1,585	

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

Map Number	Station	Agency	Location Latitude Deg.	Location Latitude Min.	Location Longitude Deg.	Location Longitude Min.	Elevation above mean sea level, in feet	Remarks
Q-451b	Castaic Patrol Station	LACFCD	34	27.9	118	37.0	1,066	
Q-747	Sandberg	USWB	34	45	118	44	4,517	
S-1	Arroyo Seco	USWB	36	14	121	29	800	
S-2	Lockwood	USWB	35	58	121	05	1,104	
S-3	Bryson	USWB	35	48	121	05	925	
S-4	King City	USWB	36	12	121	08	320	
S-5	Valleton	USWB	35	53	120	42	950	
S-6	Paso Robles 3 NNW	USWB	35	40	120	43	815	
T-1	Gaviota	DWR	34	28.3	120	12.8	120	
T-2	Alegria Ranch	DWR	34	30.0	120	03.8	420	
T-3	Dos Pueblos	DWR	34	26.8	119	57.0	160	
T-4	Goleta AP	DWR	34	26.0	119	50.1	15	
T-5	Santa Barbara	USWB	34	26	119	42	100	
T-6	Carpinteria	DWR	34	23.6	119	31.2	10	
T-7	T. V. Peak	DWR	34	31.5	119	57.5	3,990	

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

Map Number	Station	Agency	Location				Elevation above mean sea level, in feet	Remarks
			Latitude		Longitude			
			Deg.	Min.	Deg.	Min.		
T-8	San Marcos Pass Oaks	DWR	34	30.4	119	49.0	2,020	
T-9a	La Cumbre	DWR	34	29.8	119	42.8	3,925	Station moved 0.2 mi. NW; weighing gage replaced Stevens float gage January 15, 1958, due to vandalism.
T-10	Romero Saddle	USFS	34	28.6	119	35.6	3,100	Stevens float gage.
T-11	Juncal Dam	DWR	34	29.4	119	30.4	2,200	
T-12	Cachuma Dam	USWB	34	35	119	59	781	
T-13	San Marcos Ranch	USWB	34	33	119	52	800	
T-14	Los Prietos Ranger Station	USFS	34	32.7	119	47.1	900	Stevens float gage.
T-15	Gibralter Dam	DWR	34	31.4	119	41.3	1,560	Station moved 0.4 mi. E to dam tender's new residence summer of 1957.
T-16	Pendola Guard Station	USFS	34	30.6	119	34.5	1,625	Stevens float gage.

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

Map Number	Station	Agency	Location: Latitude Deg.	Latitude Min.	Longitude Deg.	Longitude Min.	Elevation above mean sea level, in feet	Remarks
T-17	Horse Canyon #2	DWR	34	37.1	119	51.1	1,465	
T-18	Horse Canyon	USWB	34	37	119	51	1,550	Six-month recorder
T-19	Little Pine Mountain	DWR	34	36.0	119	44.4	4,290	
T-20	Hildreth	DWR	34	34.8	119	34.1	3,180	
T-21	Monte Arido	DWR	34	36.1	119	28.0	5,345	
T-22	H. D. 29	DWR	34	37.0	119	39.0	3,975	
T-23	Cachuma Saddle	DWR	34	43.4	119	55.1	3,100	
T-24	Bluff Camp	DWR	34	40.4	119	39.9	4,450	
T-25	Don Victor	DWR	34	40.2	119	30.8	3,510	
T-26	Brubaker Canyon	DWR	34	44.7	119	26.7	3,770	
T-27	Potrero Seco #2	DWR	34	38.3	119	25.6	4,840	
T-28	Potrero Seco	USWB	34	38	119	26	4,860	Six-month recorder
T-29	Divide Peak	DWR	34	28.5	119	26.8	4,600	
T-30	Santa Cruz Peak	DWR	34	40.7	119	48.8	5,030	
T-31	T. V. Peak #2	DWR	34	31.5	119	57.5	3,990	
T-32	Romero Saddle #2	DWR	34	28.6	119	35.6	3,100	
T-33	Los Prietos	DWR	34	32.7	119	47.1	900	
T-34	Pendola Guard Station	DWR	34	30.6	119	34.5	1,625	
T-35	Horse Canyon #3	DWR	34	37.1	119	51.1	1,465	
T-36	Cachuma Saddle #2	DWR	34	43.4	119	55.1	3,100	

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

Map Number	Station	Agency	Location				Elevation above mean sea level, in feet	Remarks
			Latitude		Longitude			
			Deg.	Min.	Deg.	Min.		
T-37	Potrero Seco #3	DWR	34	38.3	119	25.6	4,840	
T-39	Piedra Blanca Guard Station	DWR	34	33.6	119	09.9	3,060	
T-40	Amargosa Creek	DWR	34	45.0	119	05.1	5,190	
T-41	Ridge Route Maintenance Station	DWR	34	40.6	118	46.8	2,500	
V-X6	Encino	LACFCD	34	08.2	118	31.0	747	
V-15	Van Nuys City Whse	LACFCD	34	10.8	118	27.0	695	
V-23	Chatsworth Reservoir	USWB	34	14	118	37	865	
V-259C	Chatsworth Patrol Station	LACFCD	34	16.6	118	36.2	1,254	
V-465B	Sepulveda Dam	USWB	34	10	118	28	740	
V-725	Birmingham Hospital	USWB	34	11	118	30	722	
W-280B	Flintridge Fire Station	LACFCD	34	11.0	118	11.8	1,345	
W-338B	Mt. Wilson	USWB	34	14	118	04	5,709	
W-367	Haines Canyon Upper	LACFCD	34	16.3	118	15.1	3,450	
W-373	Briggs Terrace	LACFCD	34	14.3	118	13.7	2,310	
W-433C	Fair Oaks Debris Basin	LACFCD	34	12.2	118	08.4	1,580	
X-10	Bel Air	USWB	34	05	118	27	540	
X-415	Signal Hill	USWB	33	48	118	10	100	
X-715B	Los Angeles City	USWB	34	03	118	14	312	
X-734B	Los Angeles Airport	USWB	33	56	118	23	99	

TABLE IV-I

RECORDING RAIN GAGES OF INTEREST
IN THE SANTA BARBARA WEATHER MODIFICATION PROJECT

1959
(continued)

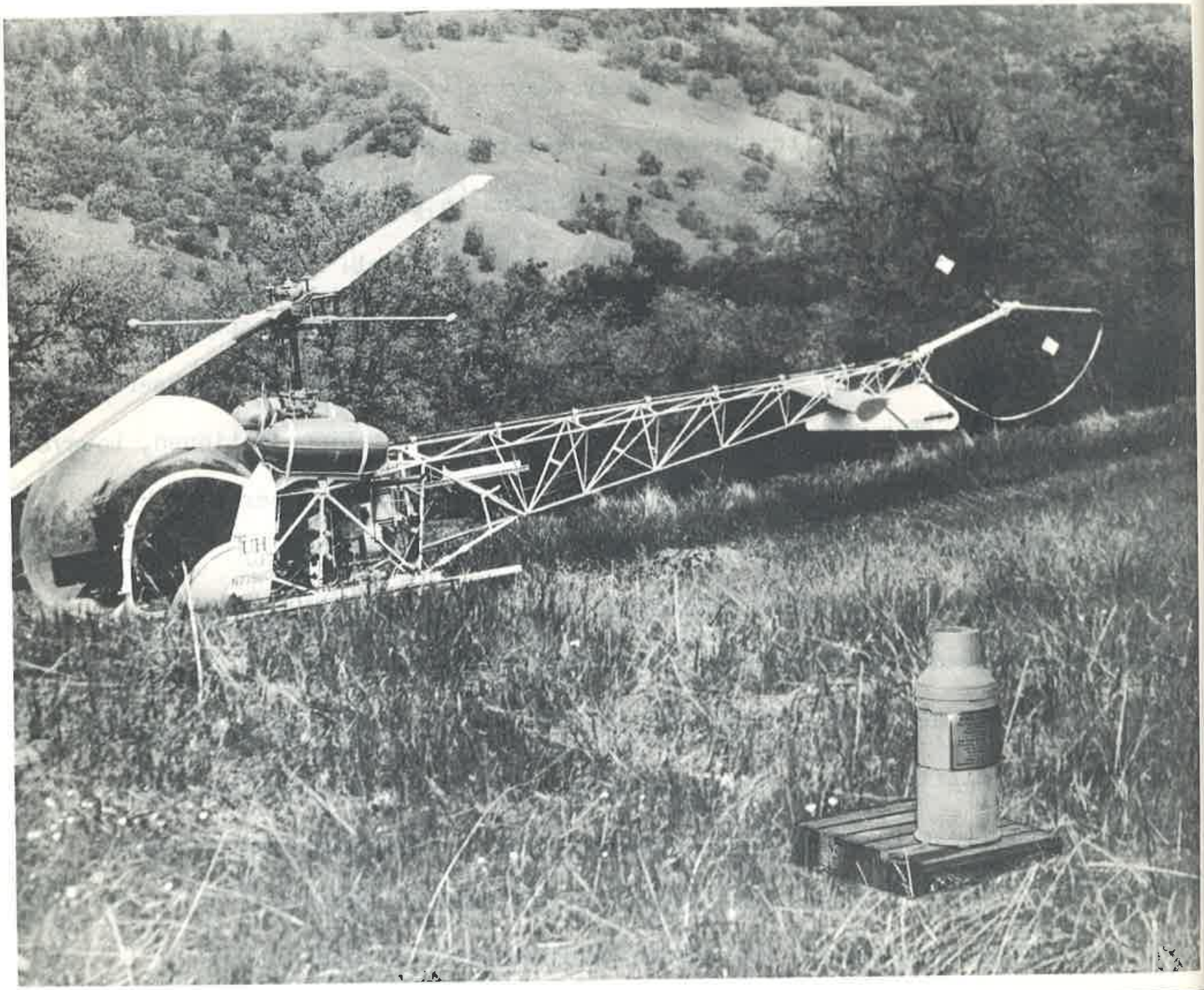
Map Number	Station	Agency	Location: Latitude Deg.	Latitude Min.	Longitude Deg.	Longitude Min.	Elevation: above mean sea level, in feet	Remarks
Y-436B	Hansen Dam	USWB	34	15	118	24	975	
Y-749	Burbank	USWB	34	12	118	22	699	
Y-1107B	Latuna Canyon	LACFCD	34	14.3	118	20.4	1,225	

* Agency refers to organization reducing recorder charts to tabular data, although in some cases other agencies acutally are responsible for gage operation and maintenance. The following abbreviations are used: DWR - Department of Water Resources, USWB - U. S. Weather Bureau, VCFCD - Ventura County Flood Control District, LACFCD - Los Angeles County Flood Control District, SL - Statistical Laboratory, University of California.

In the Department's field activities in the target and control areas, the difficulties of gage installation were minor compared with the continuing difficulties associated with gage operation. It was apparent early in the planning that if the target area were to be instrumented at all, it would be necessary to make the weekly service visits by helicopter. Since most of the target area lies in Los Padres National Forest, the Department contracted with that agency to service 17 gages in the Target. This arrangement continued during the first two years of the Project. During the third year, personnel of the Department operated all gages installed specifically for the Project, with the exception of those located where a local observer could be found. The necessity for helicopter transportation continued, however, and all gages in the remote portions of the target area were serviced by helicopter. Figure VI-1 shows a typical rain gage installation.

Based on experience gained during this investigation, there is considerable need for development of a dependable recording rain gage which will accurately measure all forms of precipitation for considerable periods. Considerable difficulty was encountered in obtaining continuous, reliable records from those gages installed and operated by the Department of Water Resources in remote areas. The standard model weighing-type rain gage was never designed, apparently, to operate unattended under adverse weather conditions. Clock stoppages, chart expansions, snow splashes, bucket overflow, and pen-arm linkage changes due to ice formation were a few of the problems encountered.

The target was not the only area presenting special problems of accessibility. The Channel Islands, although only 25 miles offshore, in some respects were even more remote than the target area. All but one of the islands on which gages were operated are in private ownership and are devoted mainly to cattle-grazing. There is no regular transportation to these



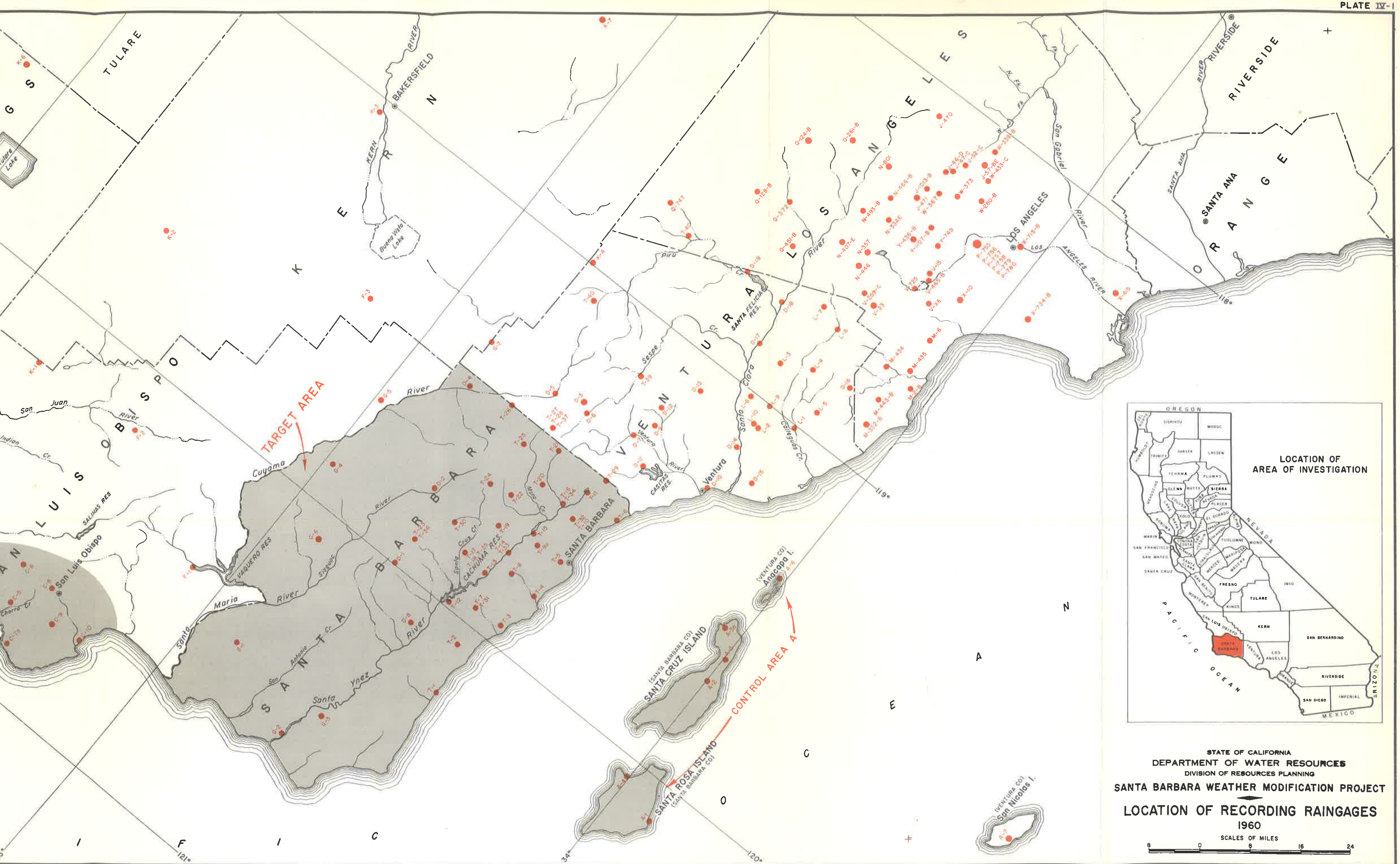
TYPICAL RAIN GAGE INSTALLATION

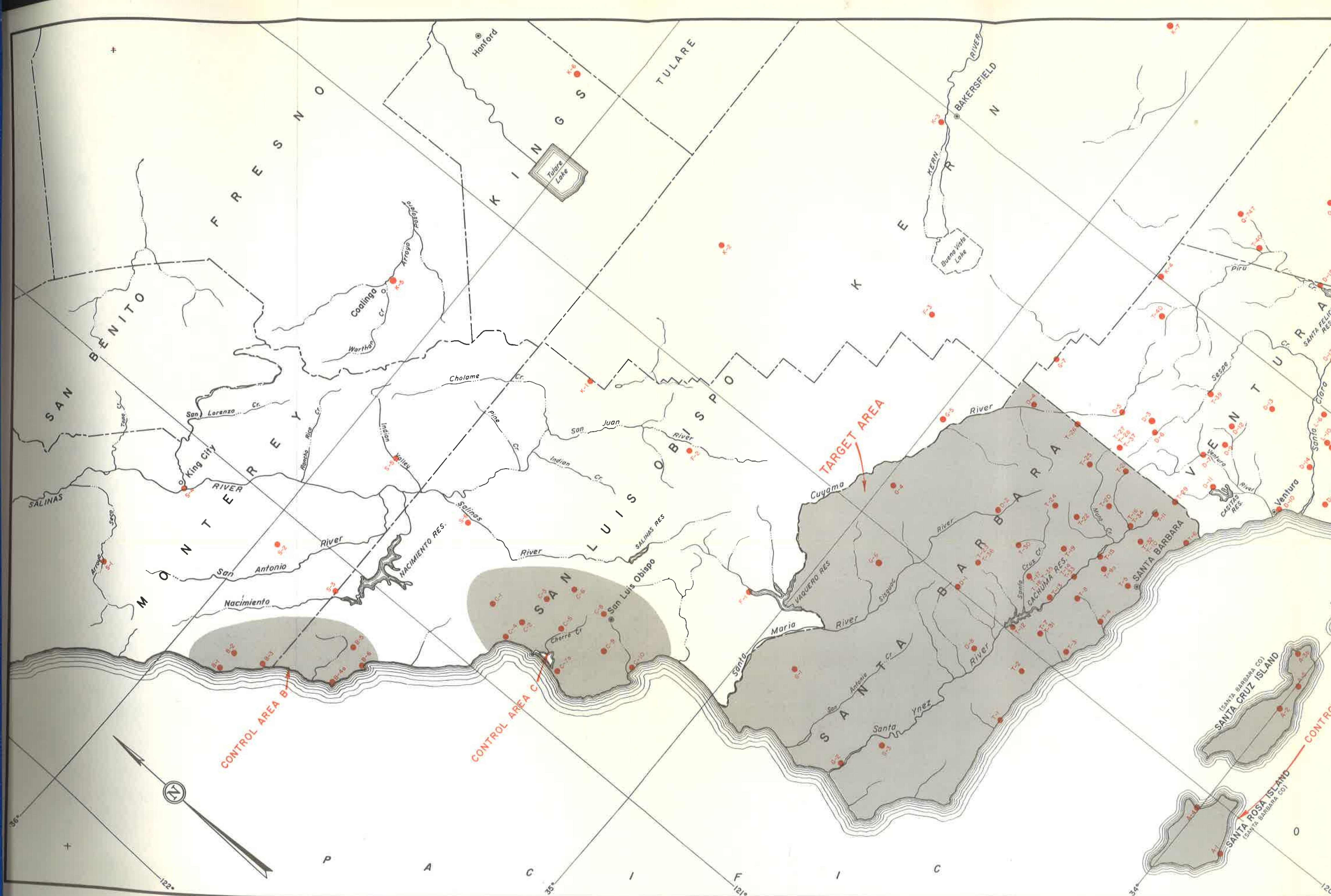
Fig. IV -1

Islands, and all visits by Department personnel had to be arranged through the landowner at his convenience, or through use of a California Department of Fish and Game patrol boat when it was available. In all cases, it was necessary to depend on residents of the Islands to operate the gages.

In order to insure accuracy of the basic data, all gages of concern to this Project, other than those under the jurisdiction of the United States Weather Bureau and Los Angeles County Flood Control District, were visited at least twice during each operating season by Department personnel and calibrated by standard techniques. Those gages in the study area which were the responsibility of the Weather Bureau and the Flood Control District were maintained by those agencies through their regular programs.

Collection of the weekly charts showing the record of precipitation is only a part of the job of supplying rainfall data. Each chart, which contains about 168 hours of record, must be analyzed in such detail as to determine and tabulate the hour-by-hour precipitation. The tedious job of preparing these hourly values for the 165 gages associated with the Santa Barbara Project was accomplished by six agencies. The United States Weather Bureau made special, advanced copies of their data available for 57 gages. Los Angeles County Flood Control District prepared similar tabulations for 23 gages under their jurisdiction, as did Ventura County Flood Control District for their 22 gages. The City of Los Angeles made available the recorder charts for 7 gages they operate, and the Statistical Laboratory, University of California, reduced these charts to tabular form. The United States Forest Service worked up the records for three special-design gages in their area. All remaining records, 53 in number, were prepared by personnel of the Department of Water Resources, using standard Weather Bureau Techniques. The agency which supplied the tabulated data to the Statistical Laboratory is indicated in Table IV-1 for each gage.


STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SANTA BARBARA WEATHER MODIFICATION PROJECT
LOCATION OF RECORDING RAINGAGES
1960
SCALES OF MILES
8 0 8 16 24
LOCATION OF AREA OF INVESTIGATION
TARGET AREA
CONTROL AREA A
TULARE
KERN
SAN LUIS OBISPO
SANTA BARBARA
VENTURA
LOS ANGELES
ORANGE
RIVERSIDE
BAKERSFIELD
LOS ANGELES
SANTA ANA
SANTA BARBARA
Ventura
San Luis Obispo
CACHUMA RES.
VAQUERO RES.
SANTA FELICIA RES.
CASITAS RES.
Buena Vista Lake
Tulare Lake
SANTA CRUZ ISLAND (SANTA BARBARA CO)
SANTA ROSA ISLAND (SANTA BARBARA CO)
Anacapa I. (VENTURA CO)
San Nicolas I. (VENTURA CO)
PACIFIC OCEAN
118°
119°
120°
121°
34°



FRESNO
KINGS
TULARE
KERN
SAN BENITO
MONTEREY
SAN LUIS OBISPO
SANTA BARBARA
VENTURA
Hanford
Tulare Lake
Bakersfield
Kern River
Buena Vista Lake
Coalinga
Warthan Cr.
Arroyo Pasajero
Cholame Cr.
San Lorenzo Cr.
Rancho Rico Cr.
King City
Salinas River
Indian Valley
Pine Cr.
San Juan River
Indian Cr.
San Antonio River
Nacimiento
Nacimiento Res.
Salinas Res.
San Luis Obispo
Chorro Cr.
Cuyama River
Vaquero Res.
Santa Maria River
Sisquoc River
San Antonio Cr.
Santa Ynez River
Santa Cruz Cr.
Cachuma Res.
Mono Cr.
Santa Barbara
Sespe Cr.
Piru
Santa Felicia Res.
Santa Clara River
Ventura River
Casitas Res.
Ventura
Santa Cruz Island (Santa Barbara Co.)
Santa Rosa Island (Santa Barbara Co.)
TARGET AREA
CONTROL AREA B
CONTROL AREA C
CONTROL
P A C I F I C O
36°
35°
34°
122°
121°
120°

TABLE IV-I

CHAPTER V

EVALUATION OF SEEDING OPERATIONS IN SANTA BARBARA AND VENTURA COUNTIES IN 1957, 1958 and 1959*

By Jerzy Neyman, Elizabeth L. Scott and Marija Vasilevskis
Statistical Laboratory, University of California, Berkeley

Abstract, Conclusions and Recommendations

A. Summary and Conclusions

1. The joint distributions of precipitation amounts in the Santa Barbara target and in one of the control areas, observed over the three years for the four categories of seeding opportunities, viz. (i) with no seeding either in Ventura or in Santa Barbara, (ii) with no seeding in Ventura but seeding in Santa Barbara, (iii) with seeding in Ventura but no seeding in Santa Barbara, and (iv) with seeding going on in both counties, exhibit differences corresponding to the level of significance 0.06. Therefore, the authors are prepared to act on the hypothesis that there were real differences among the four distributions of precipitation amounts.

2. Granting the reliability of data, the above differences can be attributed to two factors. One is the possible effect of seeding and the other is the difference in the pattern of weather in 1957 and in 1958 as reflected in the precipitation data and as confirmed by the analysis of the North American Weather Consultants, see Chapter III. In 1957 there was no seeding in Ventura. In 1958 the silver iodide generators meant to increase rain in Ventura were acting at every seeding opportunity. In 1959 the operations in the two counties were factorially randomized. However, 1959 was an exceptionally dry year with only nine seeding opportunities. Therefore, the evaluations were dominated by data of 1957 and 1958 so that practically all the observations referring to groups (i) and (ii) reflect the weather pattern of 1957 with no contribution from 1958 and practically all the observations

* Prepared with the partial support of the National Science Foundation.

referring to groups (iii) and (iv) reflect the weather pattern of 1958 with no contribution from 1957. Thus, the possible effect of seeding is confounded with the possible effect of weather pattern.

3. If one decides to ascribe the differences in the distribution of rainfall in the target and in the controls to the effect of seeding, then the figures obtained would indicate unexpectedly high* (of order of magnitude of 100 per cent per seeding opportunity) increase in rain over Santa Barbara, ascribable to generators in Santa Barbara, when there is no seeding in Ventura, and also to generators in Ventura when there is no seeding in Santa Barbara. On the other hand, when there is seeding in Ventura, the effect of Santa Barbara generators both on rain in Santa Barbara and in Ventura appears nil. When seeding is going on in Santa Barbara, the indicated effect of Ventura generators is negative but far from significant.

Unfortunately, the lack of complete randomization of the experiment over the three years results in the confounding of the effects of seeding and of weather pattern and in an unresolvable ambiguity of interpretation.

4. The unexpected difficulties of terrain in Santa Barbara and difficulties of communications with control area A (Channel Islands) resulted in a regrettably small number of rain gages having continuous usable records over the three years. For example, while since 1958 there have been five rain gages in area A, the evaluations had to be based on records of a single gage A-2. However, there was a steady improvement in the collection of data and in 1959 practically all the gages had continuous records.

5. Calculations of power indicate that, if the effect of seeding is expected to amount to something of the order of 20 per cent increase per seeding opportunity, then, in order to have a reasonable chance of finding this effect significant while the precision of the experiment is comparable to that in 1957-1959, the requisite number of years of further experimentation

* See Addendum, p. V-55.

is likely to be prohibitive. In this respect the Santa Barbara-Ventura project appears to be in a position comparable to that of other similar ventures.

If the expected percentage increase of 10-20 per cent refers not to a single seeding opportunity but to a season during which only a fraction of days with rain are seeded, then, with some improvement, the Santa Barbara-Ventura experiment may bring definitive results within a reasonable time. The improvements contemplated include continued reliability of data from all the six gages in control area A and perhaps also of the seventh gage on San Nicolas Island, thus far ineffective. Also, they include certain changes in design and the availability of certain physical measurements.

6. The main weakness of the present Santa Barbara-Ventura experiment is the lack of stability of basic conditions. In 1957, there was just one target, Santa Barbara County, and just one network of generators meant to influence the precipitation over that target. In 1958, the sudden decision of the Board of Supervisors of Ventura County to seed continuously in its territory, just next to Santa Barbara, created a change in conditions which ruined the original design. In 1959 there were two targets, with a two way factorial randomization and similar conditions are expected for 1960.

Because of the inherent variability of precipitation, in order to have any hope for definitive results of the experiment, it is imperative to arrange that the basic conditions of the experiment remain unchanged over a reasonable period of years. It seems probable that this goal will be easier to achieve if the cost of seeding operations is covered not by counties, in which the decisions in this respect are bound to be shaky and be subject to various uncertain influences, including the rainfall in the preceding year, but by a governmental agency.

7. The other weakness of the Santa Barbara-Ventura experiment is its detachment from a comprehensive theory of precipitation and from physical measurements, other than the amounts of precipitation.

The current technique of seeding is based on hypotheses of uncertain validity. The inclusion in the experiment and in its evaluation of actual measurements of a few meteorological parameters may lead to the verification of these hypotheses and thus may contribute to the understanding of the effects of seeding. In addition, if the hypothesis tested proves valid, the measurements of the same parameters will improve the precision of the experiment.

For example, seeding is expected to be successful only under certain physical conditions and, in particular, if the $-5^{\circ}C$ temperature level is not too high. The diagnosis of a seeding opportunity involves a forecast of the $-5^{\circ}C$ temperature level. In these circumstances, the inclusion in the experiment and in its evaluation of actual measurements of the $-5^{\circ}C$ temperature level prevailing at the beginning of each seeding opportunity would provide evidence about the validity of the underlying hypothesis. Also, if the hypothesis proves true, the same measurements would serve as an efficient predictor of success of seeding and their use will contribute to the reduction of the residual variance.

B. Recommendations

1. On the assumption that the Santa Barbara-Ventura experiment is to continue, it is recommended to consider the operations in 1957, in 1958 and, perhaps also, in 1959 as a uniformity trial (a device used in many domains of experimentation, meant to explore the general conditions) and to embark on a novel design of the experiment, based on records of a substantial number of rain gages which were active in 1959 and on some supplementary data.

2. On the same assumption, it is recommended that most energetic efforts be made to insure (i) the stability over several years of the general design of the experiment and (ii) the continuity of records from a number of gages, particularly in control Area A.

The preferred general arrangement of the experiment is the factorially randomized seeding in both present targets, Santa Barbara and Ventura. Other possibilities are to randomize seeding in just one target, say Santa Barbara, and to keep unchanged the conditions in the other. These unchanged conditions may be either no seeding at all or continuous seeding.

In deciding this point it is necessary to keep in mind that definitive results are more easily obtained if the experiment involves just one target rather than two. On the other hand, factorially randomized seeding over two targets extended over a sufficient period of time will answer more questions about the mechanism of the seeding effect.

3. If the experiment is to continue then it is recommended to modify its design so as to decrease the residual variance in the regression analysis. Specifically, it is recommended that the North American Weather Consultants be allowed to diagnose seeding opportunities not at just two appointed times 9 a.m. and 9 p.m. but at more frequent intervals, which may result in a decrease in the errors of forecasting. Also, the North American Weather Consultants should be given the freedom of diagnosing the duration of the seeding oppotunities, some of which may be short and some others long. Finally, the North American Weather Consultants should be given the opportunity to designate, for each diagnosed seeding opportunity, the "corresponding" periods of precipitation in the appropriate control areas. These corresponding periods need not be simultaneous with the seeding opportunity and need not be of the same duration.

All the above determinations by the North American Weather Consultants should be made <u>prior</u> to receiving the randomized decision whether to seed or not. The subsequent "official" evaluation of the experiment will be made using the data on precipitation in the target occurring during the diagnosed seeding opportunity and on precipitation in the control areas during the diagnosed "corresponding" time intervals.

4. It is recommended that prior to, or early during, each seeding opportunity some relevant physical measurements be made of atmospheric conditions, perhaps using radiosondes. For example, the height of the $-5^{\circ}C$ temperature level may be measured. Another possibility occurring to the authors is to measure the "precipitable water". The nature of the measurements and their timing will have to be determined on meteorological considerations. Their purpose is to provide one or two extra predictors for the estimation of target rain to be expected without seeding and to serve for the verification of the relevant meteorological hypotheses.

5. It is recommended that, in parallel with the Santa Barbara-Ventura project or, perhaps, independently, a new kind of study be instituted leading to the establishment of stochastic-dynamic theory of normal precipitation. This theory should combine the thermodynamical and hydrodynamical considerations developed by the Scandinavian School (Bergeron, Bjerknes) with the stochastic-descriptive theory initiated by LeCam and Morlat. Facilities should be provided for numerical verification of particular sections of this theory by comparing its consequences with the observations. It is expected that work of this kind, best conducted in close cooperation between meteorologists and statisticians, will create the possibility of judging effects of seeding not merely on the total amounts of rain but in relation to the different parts of a storm's "anatomy".

Evaluation

1. Introduction

The present evaluation combines two points of view. One, to be labeled substantive, is concerned with the evidence of the effects of seeding accumulated during the first three years of operations of the Santa Barbara Project. The other point of view, to be labeled prospective, is concerned with the future and, specifically, with the question of whether the Santa

Barbara-Ventura experiment should be continued, for how long, etc. Both points of view require a historical sketch of the operations. Such a sketch is given in Sections 3 and 4. Section 2 outlines the general design of the experiment and defines certain terms.

2. Design of the Experiment.

In the experiment we contemplate two main target areas, one the County of Santa Barbara and the other the County of Ventura, with certain subdivisions into subtargets, and three control areas: A--the Channel Islands, B--the San Simeon-Cape San Martin area, C--the San Luis Obispo-Morro Bay area. Because of the small number of rain gages in area B active in 1957 it was found desirable to combine the records of these gages with those located farther east, in the Salinas Valley. As a result, this report deals with comparisons of target rain not with the originally defined area B but with a combination symbolized by the letters BS.

Following repeated urgings of the Statistical Laboratory, going back to 1951 (1), the original Santa Barbara cloud seeding experiment of 1957 and, subsequently, the combined Santa Barbara-Ventura experiment, started in 1959, are randomized. The season of operations of each year, January 1st to April 30th, is divided into 12 hour "units of observation," from 10 a.m. to 10 p.m. of one day and from 10 p.m. of one day to 10 a.m. of the next day. Prior to the beginning of each unit of observation, the North American Weather Consultants, Inc., (N.A.W.C. for short) decide whether this unit offers good prospects for seeding and communicates this decision to the Statistical Laboratory. In the favorable case, the unit of observation is called a "seeding opportunity". In addition, for each seeding opportunity the N.A.W.C. indicate which of the three comparison areas A, BS and C, are "suitable" for comparison with the target, that is, depending upon the prevailing air currents, are expected to be unaffected by seeding.

According to the agreement of the Board of Directors made at the outset of the Project, the evaluation of the experiment is based only on precipitation records for seeding opportunities and on all such records. Also, according to the same agreement, the basic evaluation is based on records of so-called "simultaneous" precipitation. That is, the target precipitation recorded from 10 a.m. to 10 p.m. of a given date is compared with the amounts recorded in the control areas also from 10 a.m. to 10 p.m. of the same date, etc. Some exploratory evaluations have been made based on nonsimultaneous precipitation. Also an effort was made to evaluate the difference between the effects of seeding during daytime and at night. However, the results of such evaluations are not reflected in the present report.

In 1957, when the experiment was strictly confined to the Santa Barbara target, the 12 hourly message of the N.A.W.C. to the Statistical Laboratory referred to the Santa Barbara target only. Subsequently, with the extension of the experiment to Ventura County, the message of the N.A.W.C. contained two sets of information, one for Santa Barbara and the other for Ventura. However, overwhelmingly, these two sets coincided.

Upon receiving the message of the N.A.W.C., the Statistical Laboratory communicated to the N.A.W.C. a randomized decision whether to seed or not to seed, with probability of one-half for each. When the randomization was extended to Ventura County, there were two independent randomized decisions whether to seed, one for the Santa Barbara and the other for the Ventura targets. This randomization procedure divided the seeding opportunities into categories "seeded" and "not seeded", separately for each target.

The terms "units of observations," "seeding opportunities," "seeded" and "not seeded" in either target and "suitable" control areas A, BS or C are constantly used in the present Chapter.

The number of cases where area C was "suitable" is so small that no evaluations are reported using C as control. As to areas A and BS, in a number of cases both were suitable. The evaluations based on both these areas are marked with the letters ABS. However, in a substantial number of cases only one of the controls A or BS was diagnosed as suitable. Because of the general paucity of data, separate evaluations were made covering all seeding opportunities in which either area A or BS was suitable. The results are marked with the corresponding letters A or BS. Because of the considerable overlap in data, the three evaluations are not independent.

3. Historical Sketch of Operations Over the Three Years 1957-1959.

General arrangements. One of the basic principles of experimentation with any material showing substantial variation from one unit to the next is that the experiment needs replication. This means that, whatever treatments are studied, they must be applied a number of times so that the variation inherent in the material can be averaged out. Another basic principle is that the units of experimental material to which a given treatment is to be applied must be selected effectively at random. Only by this method can the observed differences in the average effects of treatments be attributed to treatments themselves rather than to some other causes, perhaps to subconscious selection. From the point of view of these two basic principles of experimentation, the first three years of operation of the Santa Barbara Project, contemplated from the substantive point of view, were disappointing. On the other hand, from the prospective point of view, they provide a considerable amount of information likely to be most useful in the possible continuation of the experiment and also in setting up new experiments of the same kind.

Essentially, the three years of operation of the Santa Barbara Project represent not one but three different experiments which, with the notorious variability of weather phenomena and the relatively few seeding opportunities per year, results in a paucity of substantive information.

During the first year of operation, January 10 to April 30, 1957, there was, essentially, just one target, the County of Santa Barbara, with a subdivision into three subtargets indicated on the map (see Plate IV-1). At that time there was no seeding done in any of the adjoining areas that might have been suspected of exercising any influence on the precipitation in the target. The seeding operations in Santa Barbara, to be described below, were randomized and, granting the reliability of the data and a substantial time of experimentation in the same conditions, the results would have produced unambiguous indications as to the possible results of seeding.

However, in the next season (1958), there occurred a change in the experiment brought about by the decision of the Board of Supervisors of Ventura County, adjoining Santa Barbara, to conduct seeding operations in its own area. Fortunately, the company contracted for seeding in Ventura was the North American Weather Consultants, Inc. which performs the seeding in the Santa Barbara Project, and this promised a cooperative arrangement. The decision of the Ventura Board of Supervisors opened a broad possibility of expanding the Santa Barbara Project. The questions as to how far the hypothetical influence of silver iodide plumes extends beyond the target and as to whether a change in precipitation caused by seeding in one area is accompanied by a counterchange in some adjoining area are important not only from the practical point of view but also from the point of view of understanding the general phenomenon of precipitation. By properly adjusting the operations in Ventura County some of these questions could be given at least a partial answer. The adjustment needed for this purpose is simple: the operations in Ventura County should be randomized so that, combined with the randomization in Santa Barbara, the experiment includes seeding opportunities of four different categories:

(i) no seeding in either county,

(ii) seeding in Santa Barbara but no seeding in Ventura,

(iii) no seeding in Santa Barbara, seeding in Ventura and

(iv) seeding in both counties.

A design such as this is technically called a factorial design. It was invented by R. A. Fisher and is widely used in many domains. The comparisons symbolized by (iv)-(iii) and (ii)-(i) would provide information on the effect of seeding in Santa Barbara both in the presence and in the absence of seeding in Ventura. The comparisons of the type (ii)-(i) and (iii)-(i) would indicate whether the seeding in one county has any effect on the rain in the other, etc. In short, the inclusion of the Ventura area into a broader randomized cloud seeding experiment, with the strict observance of the principles of randomization and with a sufficient length of the experiment would contribute a considerable amount of important information.

For this reason, the news of the possible inclusion of Ventura County into the Santa Barbara Project was received by the Statistical Laboratory with a considerable amount of enthusiasm. Also, the Laboratory was outspoken in its recommendation that the operations in Ventura be randomized as described above. Unfortunately, partly because of the pressure of drought experienced by the Board of Supervisors of Ventura County, this recommendation was not followed. As a result, in the season of 1958,every seeding opportunity was seeded in Ventura.

On general principles, the observations of 1958 either in Santa Barbara or in Ventura are not comparable to those in 1957 (or 1959) and should not be combined with them in any but exploratory evaluations. The particular reason for this regrettable situation is the notorious fact of serial change in the general pattern of weather conditions from one year to the next, and the fact established by the Statistical Laboratory (2) that the relation between target and control precipitation depends upon the type of storm. In the presence of changes in weather patterns, the process of randomization would pick representative samples of each of the succeeding patterns and assign them to the four categories enumerated, (i) to (iv). As a result, comparisons between these categories would give reliable answers to questions as to the various effects of seeding averaged over the totality of the different successive patterns of weather. As things are, the year 1957 provided data referring to categories (i) and (ii) of the classification with reference to the weather pattern of 1957. On the other hand, the observations of 1958 contributed nothing to categories (i) and (ii) but referred to (iii) and (iv), with reference to the weather pattern of 1958. The weather pattern of 1958 happened to be very different from that of 1957. Also, as seen in tables in subsequent sections of this Chapter, the general picture of apparent seeding effects on rainfall in the two counties is very different in the two years. Because of the lack of any overlap in the operations it is impossible to determine whether this difference in the apparent effects is attributable to the seeding in Ventura or to the change in the pattern of weather. Technically the situation is described by saying that in the operations of 1957 and 1958 the effect of seeding in Ventura is "confounded" with the effect of weather patterns. Non-technically, one might perhaps say that the two sets of observations lack a "common denominator."

The season of 1959 brought about a salutary change in the situation. The seeding operations in Ventura became randomized as indicated above. Unfortunately, the year in question proved to be very dry (still another pattern of weather), with only nine seeding opportunities, thus providing about two observations per category. Two of these categories, corresponding to no seeding in Ventura, can be combined with the data of 1957 in order to obtain evaluation of the effect of seeding in Santa Barbara averaged, with very unequal weights, over the weather patterns of 1957 and 1959. Similarly, the other contributions of 1959 can be combined with the data of 1958 and used to evaluate the effects of the Santa Barbara seeding in the presence of seeding in Ventura, averaged, again with very unequal weights over the years 1958 and 1959. However, no combination of the three years' data in one coherent set is possible other than on the doubtful a priori assumption that, whatever the weather pattern, the effects of seeding are always the same.

4. Historical Sketch

Availability of Data. The above difficulties connected with the general arrangement of the project are somewhat aggravated by limitations on data. These limitations affect the two earlier years, 1957 and 1958.

Although the intended beginning of the seeding season was January 1st, the organizational difficulties connected with the beginning of the experiment forced postponement of the start of the experiment to January 10, 1957. However, even after that date a number of rain gages freshly installed especially for the project were not active over all seeding opportunities. Table V-1 gives the number of gages in Santa Barbara County, separately those run by the U. S. Weather Bureau and separately those installed and serviced by the Department of Water Resources, classified according to the number of seeding opportunities in 1957 over which these gages had usable continuous records up to the end of the season. It must be explained that "usable record" means not only clear-cut record on the chart determining the rainfall over the desired 12 hour period, but also a less satisfactory record representing the accumulation of rainfall in a given gage over a longer period of time which it was possible to "distribute" convincingly between several adjoining units of observation, using clear-cut data from some neighboring gages.

TABLE V-1

Classification of rain gages in Santa Barbara County according to the number of seeding opportunities of 1957 for which the gages have continuous usable records ending with the last seeding opportunity of that year. In 1957 there were 25 seeding opportunities

Data received from	Number of seeding opportunities of continuous record								Totals
	0	4	6	7	8	9	12	25	
	Number of rain gages								
U.S.W.B.	0	1	0	1	0	0	0	7	9
D.W.R.	4	5	1	1	1	1	3	6	22
Totals	4	6	1	2	1	1	3	13	31

The meaning of the table is as follows. The figures in the first column indicate that four gages, serviced by the Department of Water Resources, had continuous records ending with the last seeding opportunity of 1957 of duration zero. In other words, for these four gages, the precipitation records for the last seeding opportunity of 1957 were not "usable". The next column in Table V-1 indicates that there were six gages with usable records over the last four seeding opportunities of 1957, that is, for the 22nd, the 23rd, the 24th, and the 25th seeding opportunity. However, the records of these gages for the 21st seeding opportunity were not usable. The last two columns indicate that, out of a total of 31 gages only 13 had usable records extending over all the 25 seeding opportunities of 1957. Table V-1 illustrates the difficulties in deciding on which period of the experiment to use in performing the evaluation.

The date at which to place the effective beginning of the experiment is to a certain extent arbitrary, except that, in order to avoid bias in the results, the determination of the period for which an evaluation is to be made must not depend on the amounts of rain fallen either in the target or in the control. Early in 1957 a number of gages were still being installed for the experiment, some with inherent defects requiring immediate repairs and others in places with unanticipated difficulties in servicing. Therefore, the fact that several gages were inactive during a number of the early seeding opportunities of 1957 may be attributed to factors other than weather and, if it is found essential, an evaluation of the 1957 results could cover a shorter period than the first four months of the year. In the earlier evaluations by the Statistical Laboratory this actually was done. However, as indicated by the columns in the right side of Table V-1, in order to gain a very moderate increase in the number of gages, one has to sacrifice a considerable number of seeding opportunities. Thus, in order to increase the number of gages from 13 to 15, it is necessary to reduce the number of seeding opportunities from 25 to 12. About one-half of these 12 opportunities were seeded and the other half non-seeded and it is obvious that the regression analysis based on something like six observational points subject to notoriously high variability cannot give very valuable results. For this reason the present paper gives only the evaluation based on 13 gages for which usable data are available for all the 25 seeding opportunities of 1957.

From the prospective point of view it is important to examine the availability of data over the two subsequent years. It is a pleasure to report a marked steady improvement in the situatuion, which in 1959 reached near perfection, with almost 100 per cent availability of data for the whole season.

However, in 1958 there were several weak spots in the data collecting picture. One of them was the Channel Islands, the very important control area A close to both Santa Barbara and Ventura Counties. In 1958 there were five gages on the Channel Islands. Of these only two gages had continuous record over the whole seeding period. Unfortunately, these two gages, A2 and A5 are located one near the other and, therefore, provide a poor representation of rain falling over the whole area. In addition to A2 and A5 one other gage, A1, provided data which, after some interpolation, may be treated as "usable".

Fortunately, in 1959 all six gages in the Channel Islands provided continuous record, promising similar performance for the future.

From the substantive point of view, the situation is much less satisfactory. In fact, during the season of 1958, which was a year with a generous number of 34 seeding opportunities, there was a long period of heavy rains in April containing eight seeding opportunities, for which none of the gages located in the interior Santa Barbara County has a usable record. It is understood that, because of bad weather, these gages were not accessible even by a helicopter, and overflowed.

It must be realized that an evaluation performed on the data of 1958, with the omission of those seeding opportunities in April for which the data are lacking, is subject to bias of unknown nature. This incident, combined with lack of randomization of seeding in Ventura, diminishes the substantive value of the observations during the year 1958.

From the prospective point of view, the same incident indicates a problem of instrumentation: if projects similar to the one in Santa Barbara-Ventura are contemplated for the future, then it seems imperative to develop recording rain gages which could operate throughout long periods of heavy rain without being serviced.

5. Selection of Seeding Opportunities

During the three years of operation, beginning with January 10, 1957, there were 701 units of observation (that is, 701 twelve-hour periods). Table V-2 gives a classification of these units according to the average rainfall per gage in the four coastal gages T1, T2, T5, and T6 (see Table IV-1 for listing of gages) and according to whether or not they were recognized as seeding opportunities.

TABLE V-2
CLASSIFICATION OF UNITS OF OBSERVATION ACCORDING TO AVERAGE RAIN IN TARGET-COAST AND SUITABILITY FOR SEEDING

Average precipitation, in inches	Units of observation	Seeding opportunities No.	%	Units of observation	Seeding opportunities No.	%	Units of observation	Seeding opportunities No.	%	Units of observation	Seeding opportunities No.	%
	Season 1957			Season 1958			Season 1959			Total		
Exactly zero	179	4	2	168	3	2	216	0	0	563	7	1
0.00-0.03	14	5	36	18	4	22	4	1	25	36	10	28
over 0.03	28	16	57	54	27	50	20	8	40	102	51	50
over 0.10	20	12	60	39	22	56	16	8	50	75	42	56

The table exhibits something like a decreasing tendency in the number of units of observation diagnosed as seeding opportunities. However, the figures in this table are distinctly of the same order of magnitude as those obtained for nine commercial seeding operations conducted in California in 1951-52 for which the Laboratory has easily accessible data. The combined number of days with average rain in the target of over 0.03 inches and covered by a contract for seeding was 305. Of these there were 167 days with some seeding, which is about 55 per cent of the total.

Apart from the mere number of units of observation diagnosed as seeding opportunities it is interesting to examine the corresponding joint distribution of rain in the target and in one of the comparison areas. This distribution is particularly interesting from the point of view of repeated claims that the evaluation of seeding operations by the historical methods is reliable.

Figure V-1 on Plate V-1 gives the scatter diagram of the precipitation at station T5 (target) and the simultaneous precipitation at station B1 (control) for all the seeding opportunities over the three years of operation of the project. Seeded and not-seeded opportunities are distinguished by different symbols. Figure V-2 also on Plate V-1 gives a similar scatter diagram corresponding to the units of observation diagnosed as not seedable. The optical difference between the two distributions is quite noticeable, not to say striking. On the other hand, the difference between the seeded and not seeded opportunities, in Figure V-1, is much more delicate. It must be clear that, if the historical method of evaluation is used and the seeded storms in one period are compared to regression lines based on all storms of a preceding period, the conclusions drawn from such comparisons are subjected to bias due to the difference between the population of all storms and the subpopulation of those that are selected for seeding.

As a matter of interest, we prepared Figures V-3 and V-4 (Plate V-2) giving scatter diagrams of target and control precipitation for all 12 hour periods: Figure V-3 corresponding to the three seasons of the Santa Barbara Project and Figure V-4 to the six year period 1945-50 when there was no seeding. Thus, Figure V-3 is a combination of the scatter diagrams in Figures V-1 and V-2. In July of 1959, Mr. J. Powers who in 1957-59 was connected with N.A.W.C. and was diagnosing the units of observation as "seedable" or not, reviewed the weather data of 1945-1950. The observations marked in Figure V-4 by dots correspond to those units of observation which Mr. Powers diagnosed as seedable. It will be seen that the distributions in Figures V-3 and V-4 are generally similar.

6. Data Used For Evaluation

As already mentioned, the evaluation given in this report is based on all rain gages in the two targets and in the control areas for which there is a continuous record over all the seeding opportunities in the three years.

In this general rule one exception is made for the seeding opportunities in April, 1958, for which the data from quite a number of gages in the inland part of the Santa Barbara target were missing.

The data, representing the simple average precipitation per gage, separately for three subtargets in Santa Barbara, for the entire Santa Barbara target, for the two controls A and BS and for the three subtargets in Ventura, are given in Table V-3. This table is subdivided into four parts corresponding to categories (i) through (iv) of the seeding opportunities defined earlier. The definitions of the subtargets in terms of the rain gages included is given at the bottom of the table. The last line in each part of the table gives the average amount of precipitation in inches per seeding opportunity.

In Section 3 we mentioned the difficulty with the confounding of the effect of seeding in Ventura and the effect of weather pattern. This difficulty is easily seen in Table V-3. The two parts of the table on the left correspond to conditions of seeding in Santa Barbara. The two parts on the right correspond to no-seeding in Santa Barbara. The upper parts correspond to no-seeding in Ventura and the lower part to seeding in Ventura. Also the data in the upper parts are dominated by those from the year 1957. It will be seen that the differences between the left and right sections are relatively mild. On the other hand, the differences between the upper and the lower parts of the table are striking. If this kind of data resulted from an experiment wholly conducted on a double randomization basis, it would strongly suggest that seeding in Ventura has a very considerable positive effect not only in all the subtargets both in Santa Barbara and Ventura Counties but also in the control areas. Unfortunately, as things are, the differences between the control precipitation amounts between the upper and the lower parts of the table are indicative of a change in the weather

TABLE V-3

SIMULTANEOUS AVERAGE PRECIPITATION IN TARGET
AND COMPARISON AREA
IN INCHES

OPPORTUNITY SEEDED IN SANTA BARBARA

OPPORTUNITY NOT SEEDED IN VENTURA

Date	Unit of observation	Approp. comp. area	T-Coast	T-Valley	SB-NW	SB entire	A	BS	V-North	V-S. C.	V-Calleguas
1957											
1-22	ev	A,B	.460	1.035	.223	.640	.500	.454	.905	1.095	.749
1-22	ev	A,B	.005	.000	.000	.002	.000	.008	.000	.031	.061
1-23	m	A,B	.145	.198	.137	.164	.190	.000	.155	.142	.164
1-25	ev	A,B	.255	.235	.077	.185	.470	.028	.100	.345	.307
1-27	m	B,C	.020	.005	.000	.008	.000	.000	.130	.146	.095
2-7	ev	A,B	.278	.445	.577	.414	.440	.088	.180	.146	.057
2-8	m	B,C	.270	.312	.287	.302	.100	.052	.120	.090	.037
2-23	m	A,B	.000	.070	.007	.027	.000	.150	.025	.027	.010
3-8	ev	A,B	.095	.148	.160	.134	.060	.178	.010	.045	.043
3-17	m	A,B	.000	.000	.000	.000	.000	.000	.030	.010	.000
3-18	ev	B	.070	.062	.070	.067	.430	.000	.060	.085	.061
4-17	m	A,B	1.228	1.728	.867	1.315	.440	.872	.915	1.158	.610
4-18	m	B	.015	.008	.003	.008	.000	.000	.010	.009	.000
1959											
1-5	ev	A,B	.805	1.960	.213	1.074	.520	.316	1.725	1.567	1.064
2-7	m	A,B	.022	.200	.000	.066	.000	.066	.060	.024	.026
		Mean	.245	.427	.175	.295	.190	.148	.295	.328	.219

OPPORTUNITY SEEDED IN VENTURA

Date	Unit of observation	Approp. comp. area	T-Coast	T-Valley	SB-NW	SB entire	A	BS	V-North	V-S. C.	V-Calleguas
1958											
1-24	m	A,B	.308	.775	.623	.518	.730	.326	.095	.333	.265
1-25	ev	A,B	.648	1.232	.660	.814	.250	.760	.535	.578	.740
2-1	m	A	.000	.000	.000	.000	.000	.000	.000	.000	.000
2-3	ev	B,C	.835	1.428	.430	1.019	.090	1.196	2.110	1.135	.882
2-12	m	A,B	.318	.558	.513	.472	.240	.070	.095	.099	.065
2-15	ev	A,B	2.510	2.740	1.257	2.405	2.990	1.226	3.195	2.445	2.086
2-19	m	A,B	.022	.010	.080	.017	.000	.000	.075	.007	.009
3-6	m	B,C	.000	.055	.017	.018	.030	.000	.220	.033	.055
3-14	m	A,B	.370	.948	.290	.567	.010	.946	.210	.361	.171
3-21	ev	A,B	.085	.358	.017	.162	.020	.042	.270	.437	.431
3-30	m	A,B	.208	.320	.057	.205	.150	.046	.220	.430	.379
3-31	m	A,B	.048	.142	.013	.066	.050	.232	.010	.031	.002
4-2	ev	A,B	.788	-	.853	-	.490	.614	1.725	1.756	.994
4-3	m	B,C	.065	-	.160	-	.010	.074	.000	.024	.013
4-5	m	A,B	.000	-	.000	-	.000	.576	.000	.000	.000
4-6	m	A,B	.628	-	.463	-	.430	.476	.465	.367	.378
4-6	ev	A,B	.525	-	.250	-	.790	.052	1.025	.743	.655
4-7	m	B	.022	-	.010	-	.000	.000	.005	.000	.000
1959											
1-5	m	A,B	1.652	2.046	1.553	1.862	.740	1.764	1.995	1.113	.730
2-15	ev	A,B	1.170	1.121	.597	1.050	3.360	1.382	2.040	1.040	.568
2-21	m	A,B	.112	.234	.193	.176	.220	.102	.120	.180	.236
		Mean	.491	.618	.392	.624	.505	.471	.686	.530	.413

OPPORTUNITY NOT SEEDED IN SANTA BARBARA

OPPORTUNITY NOT SEEDED IN VENTURA

Date	Unit of observation	Approp. comp. area	T-Coast	T-Valley	SB-NW	SB entire	A	BS	V-North	V-S. C.	V-Calleguas
1957											
1-11	ev	A,B	.158	.212	.030	.148	.120	.546	.330	.203	.035
1-20	m	A,B	.315	.265	.047	.227	.220	.034	.275	.270	.305
1-23	ev	A,B	.055	.100	.043	.086	.110	.000	.090	.188	.152
1-28	ev	A	.102	.152	.017	.105	.090	.030	.050	.040	.086
2-7	m	A,B	.055	.180	.123	.102	.100	.054	.125	.102	.091
2-8	ev	A,B	.008	.015	.000	.008	.000	.000	.000	.004	.002
2-22	ev	B,C	1.102	1.682	.580	1.150	1.500	.870	1.850	1.720	1.114
2-24	m	B,C	.000	.002	.000	.001	.000	1.094	.000	.000	.000
2-28	m	A	.585	.688	.060	.485	.560	.134	.585	.955	1.881
3-15	ev	A,B	.008	.072	.127	.058	.000	.000	.070	.329	.595
4-20	m	A,B	.188	.302	.100	.192	.440	.180	.065	.252	.379
4-20	ev	B,C	.000	.008	.000	.007	.060	.000	.000	.002	.000
1959											
2-16	m	A,B	.118	.276	.103	.161	.000	.012	.230	.498	.311
4-25	m	A,B	.542	.558	.120	.432	.900	.044	1.170	.807	.408
		Mean	.231	.324	.096	.226	.293	.214	.346	.384	.383

OPPORTUNITY SEEDED IN VENTURA

Date	Unit of observation	Approp. comp. area	T-Coast	T-Valley	SB-NW	SB entire	A	BS	V-North	V-S. C.	V-Calleguas
1958											
1-26	m	A,B	.042	.325	.133	.175	.060	.058	.025	.047	.099
2-2	m	A,B	.778	1.635	.113	.943	1.400	.736	1.120	.685	.431
2-2	ev	A,B	.478	1.128	.883	.795	.690	.340	2.195	.803	.629
2-3	m	A,B	.415	.335	.030	.275	.140	.104	.470	.280	.359
2-4	m	A,B	.382	.785	.223	.467	.030	.154	.460	.545	.185
2-7	m	A,B	.118	.482	.023	.268	.000	.052	.110	.070	.004
3-10	ev	A	.225	.258	.117	.229	.040	.010	.440	.314	.168
3-14	ev	A,B	.915	.972	.667	.818	2.510	.406	.880	1.112	.716
3-15	m	A,B	.882	.765	.100	.607	2.210	.890	.720	1.088	.846
3-15	ev	A,B	.080	.162	.230	.142	.040	.100	.065	.345	.272
3-20	m	A,B	.710	.772	.380	.600	.860	.624	.570	.749	.595
3-23	m	A,B	.002	.022	.060	.013	.000	.346	.000	.051	.019
3-31	ev	A,B	1.338	2.655	1.410	1.888	.430	1.234	2.270	1.626	1.129
4-1	m	A,B	.302	.358	.263	.311	.290	.078	.565	.424	.417
4-4	m	B,C	.005	-	.000	-	.120	.006	.020	.013	.000
4-5	ev	A,B	1.398	-	1.020	-	.950	.328	1.015	1.052	.795
1959											
2-10	m	A,B	.895	2.751	.833	1.665	.540	.970	1.735	.783	.212
2-10	ev	A,B	.538	.921	.613	.723	.300	.262	.940	.892	.815
		Mean	.528	.897	.394	.620	.589	.372	.756	.604	.427

ev - Unit of observation beginning at 10 p.m.
m - Unit of observation beginning at 10 a.m.
T-Coast: T1, T2, T5, T6
T-Valley: T7, T12, T17, T23
SB-NW: E1, G1, G2
SB-entire: T1, T2, T5, T6, T7, T12, T17, T23, D1, D8, G1, G2

Comparison A: A2
Comparison BS: B1, S1, S2, S3, S4
V-North: D5, D6
V-Santa Clara: D7, D9, D10, D11, D12, D13, D14, D15, D17, D18, D19
V-Calleguas: D16, L1, L2, L3, L4, L5, L6, L7, L8, L9, L10

pattern; and the knot confounding the seeding in Ventura and the change in weather cannot be disentangled. This applies not only to the comparison of averages in Table V-3 but also to the regression analysis given in the next section.

7. Estimation of effect of seeding on precipitation in the two targets.

Table V-4 gives the results of regression analysis of precipitation amounts in the various subtargets on those in the control areas. As mentioned previously, in each case only the seeding opportunities that were "suitable" for a given control were used in the evaluation. In order to be able to use the normal theory, assuming independence of the residual variance from the values of independent variables (the amounts of precipitation in the controls) all the raw data of Table V-3 were replaced by their square roots. When calculating for each seeded seeding opportunity the expected amount of non-seeded rain, a suitable correction was applied to avoid bias introduced by the transformation of variables.

One part of Table V-4 gives the evaluation of the effects of silver iodide generators meant to increase rain in Santa Barbara County. The other part gives similar estimates for those generators which are meant to increase rain in Ventura.

Asterisks mark the results of evaluation made on data of 1958 with the omission of eight seeding opportunities in April. As already mentioned, at that time certain gages used in the present evaluation, namely those in the Santa Barbara Target-Valley, had no usable record. In order to see the probable effect of the loss of these eight seeding opportunities, two evaluations were made for Target-Coast and for S.B.-N.W., one using the data for April 1958 and the other leaving these data out. It will be seen that the differences between the two sets of results are inessential.

TABLE V-4

INDICATED EFFECTS OF CLOUD-SEEDING[1]

Target[2]	Comparison area	INDICATED EFFECTS OF SANTA BARBARA GENERATORS — When there is no seeding in Ventura — Avg. Target Precip.: Observed: seeded, inches	Expected if no seeding, inches	Increase ascribable to seeding: per cent	Significance probability: F test	Significance probability: Permutation test	When there is seeding in Ventura — Avg. Target Precip.: Observed: seeded, inches	Expected if no seeding, inches	Increase ascribable to seeding: per cent	Significance probability: F test	Significance probability: Permutation test	INDICATED EFFECTS OF VENTURA GENERATORS — When there is no seeding in Santa Barbara — Avg. Target Precip.: Observed: seeded, inches	Expected if no seeding, inches	Increase ascribable to seeding: per cent	Significance probability: F-test	When there is seeding in Santa Barbara — Avg. Target Precip.: Observed: seeded, inches	Expected if no seeding, inches	Increase ascribable to seeding: per cent	Significance probability: F-Test
T-Valley*	A, BS	.547	.233	+ 130	.03	.	.899	1.115	-19	.74		.939	.413	+ 127	.28	.899	1.704	-47	.05
	A	.547	.246	+ 122	.05	.05	.830	.898	- 8	.61	.57	.897	.427	+ 110	.08	.830	1.337	-38	.25
	BS	.427	.291	+ 47	.03	.08	.876	1.120	-22	.55	.95	.939	.384	+ 145	.03	.876	1.289	-32	.27
T-Coast*	A, BS	(does not apply)					.621	.609	+ 2	.96		.525	.362	+ 45	.48	.621	1.001	-38	.19
	A						.573	.516	+11	.55	.43	.506	.381	+ 33	.14	.573	.830	-31	.31
	BS						.592	.634	- 7	.78	.61	.525	.266	+ 97	.09	.592	.656	-10	.88
T-Coast	A, BS	.299	.170	+ 76	.11		.537	.611	- 4	.82		.580	.372	+ 56	.58	.587	.895	-34	.38
	A	.299	.181	+ 65	.12	.10	.552	.541	+ 2	.54		.559	.393	+ 42	.13	.552	.767	-28	.33
	BS	.245	.200	+ 22	.21	.12	.516	.625	-17	.62		.546	.259	+ 111	.07	.516	.581	-11	.87
SB-NW*	A, BS	(does not apply)					.504	.449	+12	.83		.397	.081	+ 390	.41	.504	.566	-11	.68
	A						.466	.378	+23	.48	.41	.380	.081	+ 369	.05	.466	.461	+ 1	.51
	BS						.464	.449	+ 3	.98	.69	.397	.124	+ 220	.06	.464	.436	+ 6	.85
SB-NW	A, BS	.206	.072	+ 186	.18		.476	.468	+ 2	.76		.436	.082	+ 432	.41	.476	.514	- 7	.84
	A	.206	.069	+ 199	.04	.04	.448	.406	+10	.47		.418	.082	+ 410	.04	.448	.433	+ 3	.56
	BS	.175	.103	+ 70	.10	.10	.412	.454	- 9	.95		.411	.122	+ 237	.04	.412	.389	+ 6	.84
SB-entire	A, BS	.367	.163	+ 125	.02		.694	.758	- 8	.84		.646	.288	+ 124	.25	.694	1.147	-39	.18
	A	.367	.172	+ 113	.04	.05	.640	.622	+ 3	.51	.51	.620	.308	+ 101	.06	.640	.910	-30	.37
	BS	.295	.203	+ 45	.04	.07	.669	.768	-13	.73	.86	.646	.264	+ 145	.03	.669	.852	-21	.65
V-North	A, BS	.373	.267	+ 40	.58		.755	.898	-16	.45		.821	.520	+ 58	.69	.755	1.028	-27	.69
	A	.373	.256	+ 46	.48	.15	.710	.774	- 8	.29	.50	.799	.508	+ 57	.27	.710	.876	-19	.74
	BS	.295	.332	- 11	.43	.23	.720	.888	-19	.61	.75	.774	.424	+ 83	.19	.720	.671	+ 7	.99
V-Santa Clara	A, BS	.417	.274	+ 52	.05		.621	.696	-11	.66		.660	.368	+ 79	.51	.621	1.217	-49	.20
	A	.417	.313	+ 31	.11	.07	.585	.624	- 6	.40	.61	.639	.503	+ 27	.50	.585	1.047	-44	.18
	BS	.328	.356	- 8	.19	.17	.557	.701	-21	.43	.87	.621	.410	+ 51	.14	.557	.761	-27	.60
V-Calleguas	A, BS	.281	.208	+ 35	.06		.483	.469	+ 3	.96		.470	.198	+ 137	.52	.483	.785	-38	.38
	A	.281	.371	- 24	.39	.50	.455	.438	+ 4	.72	.51	.452	.561	- 19	.92	.455	.703	-35	.26
	BS	.219	.284	- 23	.29	.20	.434	.487	-11	.78	.69	.443	.294	+ 51	.21	.434	.474	- 8	.84
	Period	1957: Jan. 10- Apr. 30; 1958: none; 1959: Jan. 1- Apr. 30					1957: None; 1958: Jan. 1- Apr. 30 (*Apr. 1); 1959: Jan. 1- Apr. 30					1957: Jan. 10- Apr. 30; 1958: Jan. 1 - Apr. 30 (*Apr. 1); 1959: Jan. 1 - Apr. 30				1957: Jan. 10- Apr. 30; 1958: Jan. 1- Apr. 30 (*Apr. 1); 1959: Jan. 1- Apr. 30			

1/ Simultaneous precipitation. Regression analysis by square root inches, assuming normality, etc, and ignoring lack of randomization in Ventura in 1957 and 1958. All seeding opportunities for which comparisons are "appropriate". All stations with continuous data, Jan. 10 - Apr. 30, 1957; Jan. 1 - Apr. 30 (*Apr. 1), 1958; Jan. 1 - Apr. 30, 1959.

2/ T-Valley: T7, 12, 17, 23 T-Coast: T1, 2, 5, 6 SB-NW: F1, G1, G2 SB-entire: T1, 2, 5, 6, 7, 12, 17, 23, D1, 3, G1, 2 V-North: D5, 6 V-Santa Clara: D7, 9, 10, 11, 12, 13, 14, 15, 17, 18, 19 V-Calleguas: D16, L1, 2, 3, 4, 5, 6, 7, 8, 9, 10 Comparison A: A 2 Comparison BS: B1, S1, 2, 3, 4

In interpreting Table V-4 it is necessary to keep in mind that it refers to four different groups of observations defined earlier: (i) no seeding in either county, (ii) seeding in Santa Barbara but no seeding in Ventura, (iii) no seeding in Santa Barbara but seeding in Ventura, and (iv) seeding in both counties. There are several comparisons possible among these groups and each evaluates a specific aspect of the effect of seeding, as follows:

(ii)-(i) The comparison symbolized by (ii)-(i) evaluates the effect of Santa Barbara generators in the absence of seeding in Ventura. This is given in the leftmost section of Table V-4.

(iv)-(iii) The comparison symbolized by (iv)-(iii) evaluates the effect of the Santa Barbara generators acting in the presence of seeding in Ventura (second section of Table V-4).

(iii)-(i) The comparison symbolized by (iii)-(i) evaluates the effect of Ventura generators in the absence of seeding in Santa Barbara (third section of Table V-4).

(iv)-(ii) The comparison symbolized by (iv)-(ii) evaluates the effect of Ventura generators in the presence of seeding in Santa Barbara (last section of Table V-4).

Each of these comparisons reflects the hypothetical effect of seeding separately for each of the subtargets. For example, the estimates given in the first line of the table all refer to the same subtarget Santa Barbara Valley. The identification of each subtarget in terms of rain gages is given at the bottom of Table V-4.

It will be noted that the amounts of actual precipitation in each of the subtargets observed during those seeding opportunities which were seeded both in Santa Barbara and in Ventura (group (iv)) are being compared with expectations derived from two different sets of predictors and, therefore, appear in Table V-4 in two different columns. In one case the precipitation of group (iv) is compared with the expectation derived from group (iii) providing estimates of the Santa Barbara generators while there is seeding in Ventura. In the other case, the precipitation of group (iv) is compared with the expectation derived from (ii) and this comparison indicates the effect of the Ventura generators when there is seeding in Santa Barbara.

As emphasized in the earlier sections of this chapter, the lack of double randomization of seeding in the years 1957 and 1958 deprives the results of the experiment of its documentary value concerned with seeding and the evaluation reported in Table V-4 should be treated more or less as an illustration of what would have been possible in the presence of randomization. Nevertheless, with all the limitations mentioned, the table appears interesting.

Similar to the situation reflected in Table V-3, the present table indicates a striking difference between the seeding opportunities that were seeded and those not seeded in Ventura. When there was no seeding in Ventura, the estimated effects of the Santa Barbara generators on precipitation in Santa Barbara are generally very large and some of them significant. Because of the multiplicity of cases where the significance test was applied, a sprinkling of apparently significant cases must be expected even if the true effects are zero. In order to avoid this difficulty an over-all test was applied to the category labeled "Santa Barbara entire" and, separately, to "Ventura-Calleguas." One of these tests, using the control area BS, indicated the existence of real effects for Santa Barbara with the significance level of 0.06. As a result, we are prepared to adopt the attitude that during the three years of the experiment there was a real difference between the joint distribution of rain in Santa Barbara and in the control BS as experienced in the four categories of seeding opportunities, those seeded in both targets those seeded in one of them but not in the other and those left unseeded. Looking at the three middle lines of Table V-4 we see that those differences may have been:

(a) When there is no seeding in Ventura then the Santa Barbara generators tend to increase rain in Santa Barbara to an unexpected extent, with no noticeable effects in Ventura.

(b) When there is no seeding in Santa Barbara, then the Ventura generators tend to increase the rain in Santa Barbara, again to a very high extent, with no noticeable effects in Ventura.

(c) In the presence of seeding in Ventura the effect of Santa Barbara generators on rain in any subtarget appears to be nil.

(d) Similarly, in the presence of seeding in Santa Barbara, the Ventura generators appear to have no effect.

Unfortunately, the conclusions as just formulated must be treated only as an illustration of what would have been legitimate in the presence of double randomization in both counties and absolute certainty of data. As things are, the conservative summary of results is as follows.

The part of Table IV referring to the Santa Barbara generators indicates that:

(i) The records of precipitation in Santa Barbara from seeding opportunities randomly selected for seeding out of those in 1957 and 1959, when there was no seeding in Ventura, exceed the expectation calculated from non-seeded opportunities during the same periods by amounts of the order of magnitude of 100 per cent, and this excess can hardly be attributed to chance alone.

(ii) No such significant increase is noticeable in the records of precipitation in Ventura.

The part of Table IV referring to the Ventura generators indicates that:

(iii) If estimates of expected precipitation in the various targets are based on seeding opportunities at which there was no seeding either in Santa Barbara or in Ventura (most of them in 1957 and a few in 1959) and if one compares with these estimates the amounts of actual target precipitation observed when seeding was going on in Ventura but not in Santa Barbara (mostly in 1958 and a few in 1959) then, in Santa Barbara but not in Ventura, one finds a statistically significant and a very considerable (over 100 per cent) excess of actual precipitation over that expected. Granting the reliability of data, this excess may be due either to seeding in Ventura or to the fact that in the year 1958 the general pattern of weather appeared very different from that in 1957. In order to investigate this point, one might think of using the same predictions for a comparison with target rain during the seeding opportunities with no seeding in Ventura. However, in 1958 the seeding went on in Ventura at every opportunity.

(iv) If estimates of expected precipitation in the various targets are based on seeding opportunities at which there was seeding by the Santa Barbara generators but not by those in Ventura (most of them in 1957, when the indicated effect of Santa Barbara seeding was very high, and a few in 1959), and if one compares with these estimates the amounts of actual target rain for those seeding opportunities for which the generators in both Santa Barbara and Ventura were active, one finds predominantly negative indicated effects, generally far from being statistically significant.

At the outset we mentioned that the three years' experiment, considered from the substantive point of view, was a disappointment. The above difficulties in interpretation illustrates the meaning of this conclusion.

Before concluding this section we must add a warning about a possible confusion which may arise from a casual inspection of Table V-4. A comparison of two columns of estimated effect of seeding in different targets and subtargets, for example those under the general label "Indicated Effects of Ventura Generators," one column corresponding to "no-seeding in Santa Barbara" and the other to conditions of seeding in Santa Barbara, may hypnotize the reader by the prevalence of large positive estimates in one column and a similar prevalence of not so large but substantial negative estimates in the other. By looking at these columns one might be inclined to assert boldly that a large positive effect in one case and a considerable negative effect in the other are a certainty, whatever the statistical tests might say. The reason for this presumption is, of course, the routine of thought established by the many cases of reported experimentation in which the single entries in the relevant columns refer to different experiments performed on different units of experimental material so that the estimates listed are mutually independent. In examining Table V-4 it is essential to remember that the particular entries in each column are not independent because they are all based on essentially the same seeding opportunities. For the above reasons, an attempt to summarize Table V-4 by averaging over the columns the estimated excess of precipitation or by counting positive excess, etc. would not be appropriate.

If a summary result for Santa Barbara County is desired, the relevant figures are given in Table V-4 in the central lines labeled "SB-entire". The figures in the preceding lines in the same column should not be considered as "supporting" the figures for "SB-entire". They are meant to indicate how the presumed effect of seeding estimated for "Santa Barbara entire" is distributed among the several subtargets. Thus, for example, it may be interesting to note that the indicated effect of the Santa Barbara generators in the absence of seeding in Ventura appears strongest in the northwest part of the country, weakest on the coast and intermediate in the inland mountainous region. For a precise meaning of these definitions the reader should take into account the relevant rain gages identified at the bottom of Table V-3 and refer to the map of the target area.

8. Probability of Five Per Cent Significance of a Given Effect as a Function of the Number of Years of Experimentation.

In this section an effort is made to forecast the number of years of experimentation necessary to detect the effect of seeding in the two targets given that this effect exists and has a preassigned numerical value. Of course, however strong the given effect is, we can never be certain that the statistical test will discover its existence. The best we can do is to evaluate the probability, called "power" of the statistical test, that this test will detect the given effect at a preassigned level of significance.

Naturally, the power depends upon the test to be applied. It is intended to base the final evaluation of the Santa Barbara Project on a non-parametric test designed for this purpose, the validity of which does not depend upon any *a priori* assumptions regarding the distribution of rainfall, etc. Unfortunately, the numerical work connected with this test, particularly that needed to compute the power, is very heavy and has to be performed on a high-speed computer. Thus far, all that can be reported in this connection is limited to several significance probabilities exhibited in Table V-4 under the heading "Permutation Test." No identity can be expected between the outcome of this test and the F-test based on normal theory. However, a reasonable correlation between the significance probabilities is apparent. Therefore, one might expect that the values of power given below for the F-test must be indicative of what the corresponding results for the non-parametric test will be. On theoretical grounds one can only say that the non-parametric test is likely to be somewhat less powerful: the generality of cases to which it is applicable is paid for by less sensitivity.

The calculation of power requires the specification of conditions. The details of this are somewhat technical. Roughly speaking, it is assumed in all cases that the regression of square root measure of target precipitation on that in one or in two controls is linear and, in conditions of no seeding, coincides with that computed from the data provided by the first three years of the experiment. Furthermore, it is assumed throughout that the effect of seeding is expressed by a simple multiplication of the regression equation for non-seeded opportunities by the same constant corresponding to a 100p per cent increase in precipitation.

The power of the test depends on a number of other circumstances: on the number of seeding opportunities per year, on the residual variance σ^2 of square root target precipitation about the regression line, on the distribution of the non-seeded target precipitation in the controls, and on the number of control areas used in the evaluation. All the values of power were computed on the assumption that in the years to come all these elements will coincide with the average values observed over the three years 1957-1959.

Two particular elements in the computation of power require special attention. One is the assumption that in the years to come there will be only one target, say Santa Barbara, or there will be two, Santa Barbara and Ventura. In the first case the observations for a given year will be divided into two categories only: seeded and non-seeded in the given target. In the second case, with double randomization, the observations relating to the same number of seeding opportunities will be divided into four categories: seeded in both counties, seeded in one only and non-seeded in both. In the first case, the hypothesis tested, namely that the seeding has no effect, is expressed by fewer equations than in the second and, for this reason, the corresponding test is more powerful. Of course, in the first case the experiment can answer fewer questions about the effects of seeding.

The other element to which we wish to call particular attention is whether or not, in applying the test, we admit the possibility that the regressions of square root target precipitation on that in the control areas change from one year to the next. If we admit this possibility, then this must be reflected in the machinery of the test and this machinery implies less power. One might think that this particular circumstance is an argument in favor of an a priori hypothesis that the regressions mentioned are always the same. Unfortunately, such an argument is superficial. If we assume the identity of regressions from year to year while in actual fact they are different, the unavoidable result will be malfunctioning of the test and, in particular, an increase in the estimate of the residual variance, leading to a decrease in the power. This particular point will be referred to in the section concerned with redesign of the experiment.

Tables of power were computed on four different assumptions regarding the details of the hypothetical effect of seeding, formulated after consultation with Mr. Robert D. Elliott. Identified by symbols $\bar{H}_1$, $\bar{H}_2$, $\bar{H}_3$, and $\bar{H}_4$, these assumptions are as follows:

$\bar{H}_1$: Generators in one target increase the precipitation in that target by 100p per cent, but have no effect on the precipitation in the other target.

$\bar{H}_2$: Generators in one target increase the precipitation in that target by 100p per cent. Also, they increase the precipitation in the other target by one-half of 100p per cent. When the generators in both targets are active, their combined effect on the precipitation in either target is an increase by three halves of 100p per cent.

It will be noticed that the hypotheses $\bar{H}_1$ and $\bar{H}_2$ assume a symmetry of effects of seeding in the two targets, which may be unrealistic. The following hypotheses are asymmetric.

$\bar{H}_3$: In the absence of seeding in Santa Barbara, the Ventura generators increase the precipitation in Ventura by 100p per cent. In the absence of seeding in Ventura, the Santa Barbara generators decrease the rain in Ventura by one-half of 100p per cent. The combined effect of seeding in Santa Barbara and in Ventura on the rain in Ventura is an increase of one-half of 100_p per cent.

$\bar{H}_4$: The effects of seeding estimated for the past three years of operations (Table V-4) are exactly equal to the true effects.

We wish to emphasize that the computation of power for the above four hypotheses was motivated by the desire to investigate a reasonably broad range of possibilities. It is not intended to suggest that any of the hypotheses is regarded as particularly likely.

While the values of power computed for the first three hypotheses are different in detail, the general picture exhibited by the three sets of tables is very much the same. For this reason, and in order not to disperse the attention of the reader, the following table V-5 refers only to the hypothesis $\bar{H}_1$ and refers to just one level of significance, five per cent.

TABLE V-5

PROBABILITY OF OBTAINING FIVE PER CENT SIGNIFICANT RESULT AFTER ν YEARS OF EXPERIMENTATION

Conditions of experimentation	Per cent increase	Evaluation of Santa Barbara-entire ν = 2	3	4	5	6	7	8	9	Evaluation of Ventura-Calleguas ν = 2	3	4	5	6	7	8	9
Two targets.	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Double rancomization.	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Yearly change in	30	-	-	-	-	.57	.66	.72	.79	-	-	-	-	-	-	.51	.56
regressions excluded.	40	-	-	.61	.74	.84	.90	.9	.9	-	-	-	.54	.63	.72	.78	.84
	50	-	.65	.82	.9	.9	.9	.9	.9	-	-	.61	.73	.83	.89	.9	.9
	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Two targets.	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Double randomization.	30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Yearly change in	40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
regressions admitted.	50	-	-	-	-	-	-	.54	.63	-	-	-	-	-	-	-	-
	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
One target.	20	-	-	-	-	-	.51	.56	.61	-	-	-	-	-	-	-	-
Single randomization.	30	-	-	.59	.72	.78	.84	.89	.9	-	-	-	-	.58	.65	.70	.75
Yearly change in	40	-	.67	.85	.9	.9	.9	.9	.9	-	-	.65	.78	.84	.88	.9	.9
regressions excluded.	50	.65	.87	.9	.9	.9	.9	.9	.9	-	.66	.84	.89	.9	.9	.9	.9
	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
One target.	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Single randomization.	30	-	-	-	-	-	-	-	.50	-	-	-	-	-	-	-	-
Yearly change in	40	-	-	.54	.61	.70	.73	.78	.80	-	-	-	-	-	-	.53	.57
regressions admitted.	50	-	.68	.75	.84	.87	.90	.9	.9	-	-	.53	.61	.69	.74	.77	.79

Also, this table is limited to just one assumption regarding the number of comparison areas used, namely that the evaluation is based on both control areas A and BS. Even with these restrictions, Table V-5 has a considerable number of subdivisions according to:

(i) whether there are two targets, with double randomization, or just one target, Santa Barbara or Ventura,

(ii) whether or not the test applied excludes the possibility of a year-to-year change in regression equations.

The computation of power is laborious and, therefore, Table V-5 contains only those entries which are above .50. Also, whenever the power appeared to exceed .9, only one decimal was computed.

It is seen that, if the experiment is continued in exactly the same manner as that providing the data on which Table V-5 was computed, the conclusions regarding its necessary duration are pessimistic. Because of the indicated effect of yearly weather pattern on the target-controls regressions, the forecasts of duration should be based on the second and on the fourth arrays of power values. It will be seen that, with double randomization the chance of obtaining significant results in evaluating Ventura County is below one-half even if the effect of seeding amounts to 50 per cent and even if the experiment is continued for nine years. If the experiment is limited to just one target, namely Santa Barbara, with single randomization the situation is somewhat better but still far from satisfactory. Furthermore, in order to reduce the experimentation to the Santa Barbara target alone, it is necessary to insure a kind of uniformity of conditions in Ventura, either continuous seeding or continuous absence of seeding.

Table V-5 illustrates the expected effect on the power of the test of an increased number of years of experimentation. However, as mentioned earlier, the power also depends upon the residual variance σ_0^2. Finally, the reader will remember that the computations leading to all the tables exhibited thus far, including Table V-5, are based on fewer than one-half of all the gages installed for the experiment. Thus, there is the possibility that, if one discards the first two years of the experiment, treating them more or less as uniformity trials usual in other fields of experimentation, then a new experiment, beginning with the season of 1959, using all the existing gages, might prove more accurate and might promise definitive results after a relatively short period of experimentation.

In order to investigate these possibilities, Table V-6 was computed giving the factor, say $F(\nu,p)$, by which the residual variance as computed from the data of 1957-1959, has to be diminished in order to insure the probability of significant effects equal either to $\beta = .8$ or $\beta = .9$. This factor $F(\nu,p)$ was computed only in the case of two targets, Santa Barbara and Ventura, evaluated using both control areas A and BS. Also the factor applies to the more realistic treatment of the data admitting the possibility of a year-to-year change in the regressions.

TABLE V-6

FACTOR $F(\nu,p)$ BY WHICH THE RESIDUAL VARIANCE HAS TO BE DIVIDED IN ORDER TO ACHIEVE THE PRESCRIBED VALUE OF THE POWER $\beta = .8$ OR $\beta = .9$

Conditions of experimentation	Per cent increase 100p	Evaluation of Santa Barbara-entire: Number of years 3: $\beta = .8$	3: $\beta = .9$	4: $\beta = .8$	4: $\beta = .9$	Evaluation of Ventura-Calleguas: Number of years 3: $\beta = .8$	3: $\beta = .9$	4: $\beta = .8$	4: $\beta = .9$
Two targets	10	57.6	70.1	45.0	59.1	87.8	106.9	68.6	90.0
Double	20	15.3	18.6	12.0	15.7	23.1	28.1	18.1	23.7
randomization	30	7.0	8.6	5.5	7.2	10.8	13.2	8.4	11.1
Yearly change	40	4.1	5.0	3.2	4.2	6.3	7.7	4.9	6.5
in regressions	50	2.8	3.4	2.2	2.8	4.2	5.1	3.3	4.3
admitted									

Because of the small number of seeding opportunities at which a large number of rain gages have complete records (essentially, the nine opportunities of 1959), it is impossible to predict with any kind of precision what the residual variance for various subtargets will be in the years to come if the calculations are based on all the gages available. The best we can do is to judge by analogy. One point of reference is the differnece between the residual variance for the non-seeded precipitation in Santa Barbara-entire computed using alternatively the comparison Area B and its extension BS. Using this extension the original value of residual variance was reduced by a factor of 1.8. This result may be due to the fact that the rain gages in the proper control B are concentrated and, therefore, the sections of storms contributing to the precipitation in the target frequently miss the control B. On the other hand, the diameter of the combined control BS is about 40 miles, a multiple of the diameter of B, and thus not so easily missed. Here is another point, referring to the gages in the Control Area A: Tables V-5 and V-6 were computed using the single gage A2 in this area for which there is a continuous record. However, there are in this area six gages located more or less on a straight line from east to west, presumably across the frequent path of storms delivering precipitation to the two targets. If all these gages, extending over a distance of about 50 miles, are functioning, it is very likely that the correlation between the target precipitation and that in Area A will increase. In 1958 there were three gages with usable records in the Control A. Unfortunately, the distance between the two extremes is equal to about 25 miles. Also unfortunately, only two of the gages, located close to each other, have really good records and that of the third had to be adjusted by an extrapolation from the first two. Thus, essentially, this third gage did not provide much independent information. Yet, the use of these three gages reduced the original residual variance by a factor of 1.7.

As a result, it seems realistic to expect that, if the experiment is continued on the earlier basis but with satisfactory records of all the rain gages, particularly in the Control Area A and, perhaps with a few extra gages installed in the control BS, the residual variances for the particular subtarget will be markedly reduced, perhaps by a factor of 2.

With this in mind we may now examine Table V-6 more closely. In doing so it is essential to take into consideration the anticipated increase in rain due to seeding. The figures frequently mentioned are 10 to 15 per cent. However, we are not sure about the standard to which these percentages refer. If they refer to the amount of rain during a given seeding opportunity which would have fallen without seeding, then Table V-6 combined with the anticipated decrease in the residual variance by a factor of 2 or even much larger, indicates that the present experiment is much too crude to detect such effects within a reasonable period of time. In order to gain an intuitive conviction of the correctness of this result, the reader is referred to Table V-3. It will be seen that the average non-seeded precipitation in Santa Barbara-entire, in the absence of seeding in Ventura, was 0.226 inches per gage per opportunity. Ten per cent of this quantity is 0.023 and, with all the scatter of observational points exhibited in Figure V-1, it must be clear that, in order to have a high probability of distinguishing between the averages of 0.226 and 0.249 inches of precipitation, either the conditions of the experiment must be vastly improved or else the experiment must be continued for a very long time indeed.

However, the percentages 10 to 15 may have a different reference base. In fact, it is likely that they refer to the increase in rain due to seeding conducted over part of the rainy season, January to April, with only about one-half of its rainy days seeded, compared to the total precipitation over the whole season, say from October to April. If this be the case, the same anticipated increase referred to a single seeding opportunity will represent a much greater percentage than 10 to 15 per cent, perhaps 50 per cent. In this case the figures of Table V-6, namely those in the last line, while not too encouraging, do not appear hopeless. For example, in order to attain a 90 per cent chance of detecting a 50 per cent increase in rain in Santa Barbara, with three years of experimentation, the residual variance in the regression analysis has to be divided by 3.4. With four years of experimentation, this factor decreases to 2.8. Taking into account the decrease in the residual variance, by a factor of about 2, expected from the use of all the six gages in Control A, it is seen that the further improvement in the accuracy of the experiment needed to achieve the power $\beta = .9$ is only moderate. The three years of experience with the Santa Barbara Project indicate certain faults in design. It is plausible that, if these faults are removed, the accuracy of the experiment will be increased enough to insure, with a moderate amount of experimentation, a high probability of detecting the effect of seeding if this is as large as 50 per cent per seeding opportunity.

In the next two sections we consider certain ways of redesigning the experiment by which this goal may be achieved.

9. Redesign of the Experiment. Analysis of Sources of Variation.

The data and the various calculations described in the preceding sections indicate that the rainfall in the targets corresponding to any fixed values of the two predictors, namely the amounts of precipitation in the two control areas, is subject to variation (measured by the residual variance σ^2) so strong that, in order to be able to establish the effect of seeding, if this is of the anticipated magnitude, the experiment must be continued for a very long time indeed. In these circumstances it is appropriate to consider whether it is possible to redesign the experiment so as to diminish the residual variance. Any such redesign requires the identification of sources of variation; two possibilities appear.

First, it is possible that the observable quantity serving as an indicator of effects of seeding, namely the target precipitation over the 12-hour "unit of observation" from 10 a.m. to 10 p.m., or from 10 p.m. to 10 a.m., was chosen unluckily. Second, it may be noted that, usually, a high degree of variation in the experimental material results from insufficient effort towards proper classification of the material. This problem is very frequent in many domains of experimentation and, frequently, is solved satisfactorily. Thus, for example, the originally excessive variability in response to treatments of animals was reduced by (i) classifying experimental animals by their weight (that is, by using weight as one of the predictors), (ii) by using particular litters of animals as randomized blocks, that is, by basing the evaluation of treatments on differences between their effects on members of the same litter, and, finally, (iii) by breeding genetically homogeneous strains of animals. While the latter procedure cannot be applied to storms, appropriate modifications of (i) and (ii) may perhaps be useful.

In spite of the fact that the 12-hour unit of observation, always beginning at 10 o'clock, was unanimously adopted at the outset of the experiment, experience shows that this device was not altogether satisfactory. For example, consider a unit of observation beginning at 10 a.m. that is diagnosed as a seeding opportunity. Assume for the moment that this diagnosis is correct in the sense that, at some time or other before 10 p.m., the atmospheric conditions are really favorable to seeding. However, in some cases these favorable conditions may last over the whole duration of the unit of observation, from 10 a.m. to 10 p.m., while in some other cases the same conditions may prevail only over a fraction of this period, perhaps from 8 p.m. to 10 p.m. It is obvious that, even if seeding has a very uniform effect on precipitation, its effect on the amount of rain in the target measured from 10 a.m. to 10 p.m. will be very unequal in the two cases envisaged. Thus, the precision of the experiment will be improved if the rigid "unit of observation" from 10 o'clock to 10 o'clock is abandoned and replaced by a flexible period of time adjusted, as closely as practicable, to the actual duration of conditions believed suitable for seeding.

The above suggestion is made on the assumption that there is no error in forecasting the approach of conditions suitable for seeding. However, it must be clear that such errors are unavoidable and, as indicated by Table V-7, kindly provided by Mr. Elliott, are not infrequent.

TABLE V-7

Number of Corrections to Forecast

Original Forecast		Seedable	Not seedable
Corrected Forecast		Not seedable	Seedable
Number of cases:	1957	3	3
Santa Barbara	1958	5	9
	1959	0	3
Ventura	1959	0	5

In addition to the relatively high frequency of errors of forecast we are impressed by their numerical effect and also by the possibility of redesigning the experiment so as to decrease the frequency of errors. The history of one particular storm is instructive. The storm in question occurred on February 23-24, 1957. During the morning of February 24 there was no rain in Santa Barbara, but the storm approaching from the north was growing in intensity and the North American Weather Consultants expected it to reach Santa Barbara at some time before 10 p.m. of February 24. Hence, at 9 a.m. of that day they diagnosed a "seeding opportunity" reflected in Table V-3 and were prepared to seed at the first appearance of clouds. The randomized decision was "do not seed." As it happened, the storm deposited more than one inch of rain in the Control Area BS but never reached so far south as the Santa Barbara target. As a result of this occurrence, the scatter diagram in Figure V-1 contains a point on the horizontal axis with is abscissa exceeding 1.8 inches. It is obvious that this single point contributes considerably to the residual variance. Also, the presence of this point lowers the regression line for unseeded seeding opportunities and thus contributes to the height of the seeding effects estimated for 1957. Alternatively, if the randomized decision were "seed", the same point would have decreased considerably the apparent positive effect of seeding.

It is obvious that the removal of this particular, and certain other, errors of forecasting, would result in an increased precision of the experiment. However, without exposing the evaluation to the danger of non-objectivity, it is not appropriate to attempt to eliminate forecast errors <u>ex post</u>. If this were done, there could result an evaluation using data which one "likes" with the omission of data that one "dislikes", that is, essentially using "manipulated" data. On the other hand, a redesign of the experiment is indicated whereby the frequency of forecast errors could be diminished. This can be achieved easily by letting North American Weather Consultants diagnose seeding opportunities not at 12-hour intervals but more frequently, say every two hours. With this arrangement, it is plausible that the error of forecast committed at 9 a.m. on February 24, 1957, would have been avoided.

The experience of the three past years of the experiment indicates still another method of increasing its accuracy. By perusing the hourly precipitation data for rain gages arranged in a suitable geographical order, say from north to south, one frequently observes the phenomenon of a storm creeping gradually in a given direction. For example, at the time when there is substantial rain in the north, in the Control BS, there is no rain in Santa Barbara. Several hours later the situation is reversed: it rains in Santa Barbara but not in the Control Area BS. Yet the change in the precipitation pattern is continuous and one has an irresistible impression that the rain in BS occurring say from 2 a.m. to 8 a.m. and the rain in Santa Barbara extending from 10 a.m. to 4 p.m. of the same day are brought down by the same entity, the same storm traveling in a southerly direction. Thus, one has the intuitive feeling that the amount of rain in BS between 2 a.m. and 8 a.m. is a predictor of the amount in Santa Barbara between 10 a.m. and 4 p.m. However, the adopted rule of evaluating the experiment on the amounts of "simultaneous" precipitation in the target and the controls results in excessive scatter of the points in Figure V-1. For example, there are too many points on the vertical axis of coordinates: when there was some rain in the target, the "simultaneous" precipitation in the control was exactly zero.

It seems plausible that, if the rule of using "simultaneous" precipitation in the target and in the controls is abandoned and replaced by appropriately defined "corresponding" periods of precipitation, there will result a considerable decrease in the residual variance. When this circumstance was noticed, strenuous efforts were made to devise an objective ex post method of determining periods of precipitation in the controls "corresponding" to any given seeding opportunity in the target. This was done with the help of meteorological consultants, Dr. Arnold Court and Professor Morton G. Wurtele of the University of California at Los Angeles. Unfortunately, we were advised that the attempts made to determine ex post the identity of a storm passing gradually over different parts of California could not be made with a satisfactory degree of objectivity. Nevertheless, a tentative evaluation of the experiment was performed using target precipitation during the usual units of observation from 10 o'clock to 10 o'clock and the precipitation in the controls over periods of time which Drs. Court and Wurtele defined as "corresponding." This change from "simultaneous" to "corresponding" precipitation in the control areas resulted in a decrease in the residual variance by a factor depending upon the distance between the particular target and the particular control area contemplated. Thus, the distance between the Santa Barbara subtarget "Coast" and the Control Area A is small and, in practically all cases, the "corresponding" period of precipitation in A coincided with the "simultaneous" period. Thus, in this case, there was no real reduction in the residual variance. For the subtarget Santa Barbara N.W., somewhat more distant from the Control Area A, the residual variance was reduced by a factor of 1.4 and similar values were obtained for the Control Area BS and the various subtargets in Santa Barbara County.

It is anticipated that the combined effect of "corresponding" periods of precipitation and the appropriately defined units of observation, not necessarily from 10 o'clock to 10 o'clock but coinciding approximately with the period of real opportunity for seeding, will have a considerably stronger effect on the residual variance.

Turning to the problem of non-homogeneity of experimental material we must recall some of the facts established in our earlier work relating to the evaluation of cloud seeding operations (2). Specifically, we refer to the dependence of the target-control regressions on the type of storm and also to the interesting fact that while for some types of storms the apparent effect of seeding was positive, for some other types it was negative. Still another fact which came out of this earlier study is that the relative frequency of different types of storms varies from year to year. These earlier conclusions appear to be confirmed by the findings of Mr. Elliott in his contribution to the present Report illustrated by maps giving three different patterns of storm paths prevalent in the three years 1957-1959, (Plates III-6, -7, and -8). These sources of variability were entirely left out of consideration in the original design of the Santa Barbara experiment and an effort at their elimination may be expected to be very fruitful. As a first step in this direction we think of the possibility of some actual measurements, somewhat in line with the suggestions of Dr. Roscoe R. Braham, Jr. (3), perhaps some of those contemplated by Meteorology Research, Inc., to be conducted systematically before and/or during each seeding opportunity, whether seeded or not. It may be anticipated that the results of these measurements could serve as predictors in addition to the precipitation in the control areas.

10. Suggested Redesign of Study - First Stage.

In this section we suggest certain modifications of the Santa Barbara-Ventura experiment which are likely to improve the chances of detecting and estimating the effects of seeding with precision. However, the modifications suggested here are adjusted to the main framework of the experiment conducted over the last three years, and are really minor. In the final section and in the subsequent article by Professor LeCam, certain broad modifications of the study are indicated, treating it as fundamental research in atmospheric physics rather than as research directed towards the establishment of an isolated point: whether seeding does or does not affect rainfall.

A successful design of any experiment may be achieved only in consultation between representatives of the substantive domain and statisticians. For this reason, the following suggestions are submitted as very tentative contributions to the discussion.

(i) It is suggested that the fixed duration of units of observation from 10 o'clock to 10 o'clock be abandoned. The North Amercian Weather Consultants should be allowed freedom in determining the beginning and the end of a "seeding opportunity" on a continuous basis, perhaps starting at 11:35 a.m. and ending at 4:20 p.m., etc. It would be most desirable if arrangements could be made for no limitations on the timing of the decision in this respect. Unfortunately, this would require a 24-hour servicing of the teletype machine in the Statistical Laboratory which may prove too costly. However, it seems probable that such a 24-hour service will not really be necessary. For example, one might expect that a very considerable improvement in the situation will be achieved if regular teletype communications between North American Weather Consultants and the Statistical Laboratory were established more or less as follows:

(ii) Each day, at preassigned times (to be termed basic times), say at 9 a.m. and 9 p.m., the North American Weather Consultants will send to the Statistical Laboratory one of the following three messages, to be termed <u>basic</u> messages.

(a) A seedable opportunity already exists.

For Santa Barbara:

Class of opportunity........ Seeding will begin at...... and will continue until....... The relevant period of precipitation in the target will be from ..... to..... The appropriate control areas will be.......... The "corresponding" period of precipitation in control area........ will be from........ to....... The "corresponding" period of precipitation in control area....... will be from....... to ....

For Ventura......... (a similar message).

(If determined by the Board of Directors, these items may be supplemented by other physical data).

(b) A seedable opportunity may develop during the next 12 hours. Situation alert.

(c) No seedable opportunity is expected during the next 12 hours.

Following message (a) the Statistical Laboratory will communicate to the North American Weather Consultants the doubly randomized decision (separate for Santa Barbara and for Ventura): either "seed" or "do not seed". The North American Weather Consultants will abide by this decision.

The "Standard" method of evaluation of the experiment (the one to be agreed upon in advance) will be based on precipitation records (and possibly some other physical data) referring to the "relevant" period of precipitation in the target and the "corresponding" periods in the control areas as determined in the message from the North American Weather Consultants.

If the announced end of the seeding opportunity occurs at night, the next message from the North American Weather Consultants to the Statistical Laboratory will be transmitted at the next basic time, when this message may be either (a) or (b) or (c).

If the announced end of the seeding opportunity occurs during the day, then it will be followed by a period of "alert" as explained below.

Following message (b) situation alert, the North American Weather Consultants will contact the Statistical Laboratory and the Laboratory will be prepared to receive messages at each time of a regular frequent schedule (to be termed secondary times, say every two hours, perhaps at 11, 13, 15, etc., until a reasonable time at night). The message to be transmitted at the secondary times may be one of the following three kinds.

Message α: Same as basic message (a) and will have the same consequences.

Message β: No seeding opportunity yet. Alert continues.

Message γ: Hope for seeding opportunity abandoned. All clear.

Following the secondary message γ the state of alert will be discontinued and the next contact between North American Weather Consultants and the Laboratory will occur at the next basic time, either 9 a.m. or 9 p.m.

Following basic message (c), there will be no communication between North American Weather Consultants and the Laboratory for the next 12 hours and this period will be excluded from the experiment. It is hoped that message (c) will be sent only in those cases when North American Weather Consultants is very sure that no seeding opportunity will arise. Hence, the question of actual seeding will not arise after message (c).

Unfortunately, the above schedule makes a distinction between day and night. There is an obvious advantage in having a uniform arrangement over the 24 hours. The possibility of such an arrangement should be explored, but there are obvious difficulties.

(iii) As a further means of decreasing the residual variance, it is strongly recommended that the plan of the experiment include appropriate measurements of atmospheric conditions. Some of the factors which may be measured may be influenced by seeding. For example, such may be the case of the height of the -5°C level. Measurements of such factors should be performed immediately prior to seeding. If the -5°C level is really relevant, then it appears probable that the effect of seeding must depend on whether this level is at 12,000 feet, at 10,000 or at 8,000 feet and the ascertained actual height is likely to serve as a valuable predictor.

A report of the Arizona Institute for Atmospheric Physics lists a parameter described as "precipitable water." If this term means what it suggests, its determination some time early during each diagnosed seeding opportunity may provide another useful predictor, perhaps independent of the -5°C level. Presumably, if this level is low but there is little precipitable water in the atmosphere, the seeding cannot be very effective.

It should be clearly understood that the above two parameters, the -5°C level and precipitable water, are mentioned here solely as examples. The nature of actual measurements and the method of performing them, including timing, are within the domain of meteorologists. Our own point is that even with the freedom of determining the beginning and the end of each seeding opportunity, the North American Weather Consultants will have to do some forecasting and that an effort to obtain objective data on which to correct the forecasts is highly desirable. Also quite apart from actual errors of forecasting, such objective measurements will provide new predictors. Finally, the degree of correlation between rain and the proposed measurements is likely to lead to a better understanding of the mechanism of precipitation.

Upon examination of the program of work of Meteorology Research, Inc. it appears probable that the measurements contemplated in this program could fill the needs now discussed. If this be the case then the only problem to be faced is that of appropriate coordination and timing of these measurements.*

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* It is a pleasure to record the offer of Mr. J. van de Erve, of the U. S. Weather Bureau, made at the meeting of the Board of Directors of the Santa Barbara Project at which the present report was presented, to make an effort to arrange that a radiosonde be taken on call, say, at the beginning of each diagnosed seeding opportunity. It is hoped that the efforts of Mr. van de Erve will be successful.

11. Suggested Redesign of Study - Second Stage.

The Santa Barbara experiment as conducted thus far, and also as it may be conducted if and when it is redesigned in accordance with the suggestions of Section 10, is a distinct example of what is commonly called "applied research." The reason for our ascribing this particular label is that the central question that we are trying to answer is whether seeding as conducted by North American Weather Consultants using ground generators does increase rain and, if so, by how much. It is true that in the process of trying to answer this fundamental question, particularly when efforts are made to select opportunities for seeding, the mechanism of precipitation comes under frequent consideration. However, the nature of the mechanism is not the primary objective of the study. On the contrary, apart from its size, cost and the novelty of the experimental domain, the Santa Barbara Project is comparable to many tests performed more or less routinely in various testing laboratories in order to establish the effectiveness of a given substance or device.

After some years of contact with the problem, roughly from 1951, we came to the conclusion that the practical question of the effectiveness of seeding, and of conditions in which it may be particularly effective, is likely to be answered satisfactorily if the present study, of an applied research character, is supplemented by another study having the character of basic research. Whether this proposed basic research study is to be conducted within the same framework of the Santa Barbara cooperative venture or by some other institution is a question we would like to leave out of consideration. The following lines are given entirely to the nature of the proposed fundamental study.

As we see it, efforts to determine the possible effects of seeding must be preceded by an effort to understand the "anatomy" and the "physiology" of the meteorological unit variously called a storm, a front, a disturbance, etc. Outlines of this anatomy and physiology are frequently discussed at meteorological meetings and in the literature. For example, at one of the recent meetings Mr. Elliott spoke of turbulent "cells," their evolution, and their contribution to the rain in the target. These cells are elements of what we call the anatomy of the storm. Two storms differ in the number of component cells and, presumably in the intensity of precipitation delivered by each cell. In his instructive talk Mr. Elliott, outlined how, according to his views, the storm cells react to various conditions, such as seeding. However, no quantitative characterization of these cells seems to be available. As we see it, in order to understand the process of precipitation, whether "natural" or seeded, it is unavoidable to develop methods of quantitative characterization of storms as composed of appropriately defined elementary units. This is precisely the subject of the fundamental research study we wish to recommend.

The question arises as to how such a study can be conducted. The answer seems to be: by combining the deterministic methods used by the Scandivian school, symbolized by the names of Bergeron and Bjerknes, with modern statistical methods used in many domains of research.

The Scandinavian school certainly achieved great success in its treatment of atmospheric phenomena by building hydrodynamical and thermodynamical models. In many cases the mechanisms contemplated are very convincing and illuminating. Nevertheless, there is still much room for novel approach. The point is that the Scandinavian studies are chiefly deterministic so that, in most cases, the various characteristics of the atmosphere such as temperature, pressure, etc. are treated as single-valued functions of time. On the other hand, the actual phenomena, such as the development of cells described by Mr. Elliott, show very considerable variation. In fact, this tremendous variation is the essential cause of the indistinctness of the results of the Santa Barbara experiment.

The unavoidable conclusion is that, in order to develop a comprehensive theory of precipitation, it is necessary to combine the dynamical studies of the Scandinavian school with appropriate stochastic methods, that is, taking account of the random variation described above. For example, these methods will introduce explicitly the variability in the number of cells, the variability of what may be called the diameter of a cell, etc. Once such an anatomical theory is developed, there will result methods of empirical determination of the various parameters. For each particular storm, a considerable number of observations from the existing Weather Bureau network and such others as may be determined in the course of theoretical work could be used to estimate the parameters characterizing this storm. With reference to our present study, one might say that, instead of having just two Control Areas A and BS, essentially the same for all storms, each storm will be judged from the observations over its own "control area" comprising a substantial part of the United States. With this approach the year-to-year variation in the weather pattern will become irrelevant. The comparison between sections of Table V-5 corresponding to treatments of the experimental data admitting and excluding year-to-year variation in weather pattern indicates the advantage in power that may be gained.

The feasibility of a given kind of study must always be considered critically. In the present case, it is encouraging that a skeleton of a stochastic theory of precipitation has already been built (4) by Lucien LeCam and, partly, by Georges Morlat (5). Thus far this theory is detached from dynamical considerations. Also it requires confrontation with observational data. Work in these two directions, particularly if it is combined with physical measurements, is likely to create a foundation on which the effectiveness of seeding could be established more easily than by the present Santa Barbara experiment.

12. References

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APPENDIX V-A

On the Application of Statistical Methods To the Study of Meteorological Phenomena

By L. LeCam

1. Introduction

This is a brief outline of a program for studies in statistical meteorology. In short, the application of statistical methods to the investigation of meteorological phenomena requires the construction of suitable simplified stochastic models for these phenomena.

Deterministic models of atmospheric disturbances such as fronts, cyclones, thunderstorms, have already proved their usefulness. However, Bergeron's theory of frontal systems does not by itself provide any information about the frequencies of occurrence of various possibilities. An effort should be made to imbed in this theory enough randomness to account for the observed frequencies and distributions of natural phenomena, while retaining the principle that the evolution of such phenomena may not depart from the laws of hydrodynamics and thermodynamics.

Several years ago the author had the opportunity to try his hand at the stochastic description of precipitation. This was done with the help of G. Morlat and E. Halphen, for very limited purposes and without the benefit of meteorological advice. The model used with its motivation and limitations is sketched in Section 2 below. In Section 3 we discuss the role and place of such a model in a more realistic and more comprehensive study.

2. A Model for the Description of Precipitation

The model sketched below was developed in order to link together several different aspects of precipitation viewed as the source of streamflow. It is to be emphasized that the model was arrived at before we had any knowledge of the existence of fronts and related phenomena so that dynamic considerations are absent from our construction. Essentially, the model may be considered a translation into formulas of visual impressions augmented by the computation of a few correlation coefficients.

It was postulated that at times and places selected by a suitably periodic (period 1 year) random mechanism, certain events occur independently of one another. The occurrence of such an event at time t and place x signals the formation in an ellipsoidal region around (t,x) of a general state of atmospheric instability. In the region of instability, certain places and times, again selected at random and independently of one another, are considered as centers of ellipsoidal systems of convective cells. Inside these ellipsoidal systems, the cells themselves are placed at random, independently of one another. Finally the precipitation from a given cell is distributed evenly on a circular area, the amount of precipitation from each cell being selected at random from a suitable distribution. To obtain a mechanism more in accord with visual observation, the general areas of instability and the systems of cells were given a certain velocity selected in direction and magnitude at random from a suitable population. In a first analysis we postulated independence between the number of cells per system and the amount of precipitation per cell. It was also postulated that our ellipsoidal regions and cell systems were all essentially of the same size. Later, such assumptions were modified to obtain regions of instability and cell systems of different shape and "strength," as well as to make the amount of precipitation per cell dependent on the number of cells per system and the time and place of occurrence.

Such a basically simple scheme can be translated with formulas, from which one can deduce, through cumbersome but not inherently difficult algebra, relations to be compared with actual observations.

At this point, it must be emphasized that we did not at any time consider the possibility of actually isolating cells in nature and counting the number of cells per storm system. Nor did we try to separate the actual observed precipitation at any given point and time into the contribution of various cells. Rather, our investigation, which unfortunately remained very superficial, relied on the estimation of sizes of cells, distribution of the numbers of cells per system, etc., through the use of various correlation coefficients and similar statistics.

The following statistics are particularly informative.

(a) The correlations between amounts of precipitation at the same location but at times separated by various numbers of hours, days and weeks.

(b) The correlations between amounts of precipitation for the same or different periods at locations separated by variable distances.

(c) The correlations between numbers of rainy periods (hours or days) at various places and for different length of time.

3. More Realistic Models

Some time after the elaboration of the model just described, the author became aware of the existence of Bergeron's theory of frontal systems and naturally identified the cell systems discussed above with Bergeron's fronts. Although it happens that the estimated width of our cell systems is in fair agreement with the width of a front other aspects of the whole scheme may need important revision.

In addition, the model does not provide for the use of many available measurements, because the relevant physical quantities are conspicuously absent from the model. For instance, we could not use the information provided by radiosondes because the model does not contain anything about pressure, humidity, temperature, entropy or the like.

One may conceive of a model which, for a given region, would provide joint probability distributions for the essential dynamic and thermodynamic parameters at every point at the atmosphere above this region. Needless to say the construction of such a model cannot be done by a statistician who would not be acquainted with the works of Navier, Stokes, Prandlt, Von Karman, Taylor, Batchelor as well as with thermodynamics. Such a model would, by necessity, assign frequencies to the occurrence, extent and velocities of the masses of air described in the usual classification as continental, maritime, Arctic, Polar, tropical, etc.

The description of the fronts and precipitation formed by the encounter of these masses of air could be achieved by a procedure similar to the one outlined in Section 2.

It is true that the construction of such a comprehensive model will require time and effort. In the meantime, one may try to construct more modest submodels and test them before incorporation into the general scheme. It is apparent that even for the elaboration of such submodels close cooperation between statisticians and meteorologists will be required.

ADDENDUM

By Jerzy Neyman and Elizabeth L. Scott

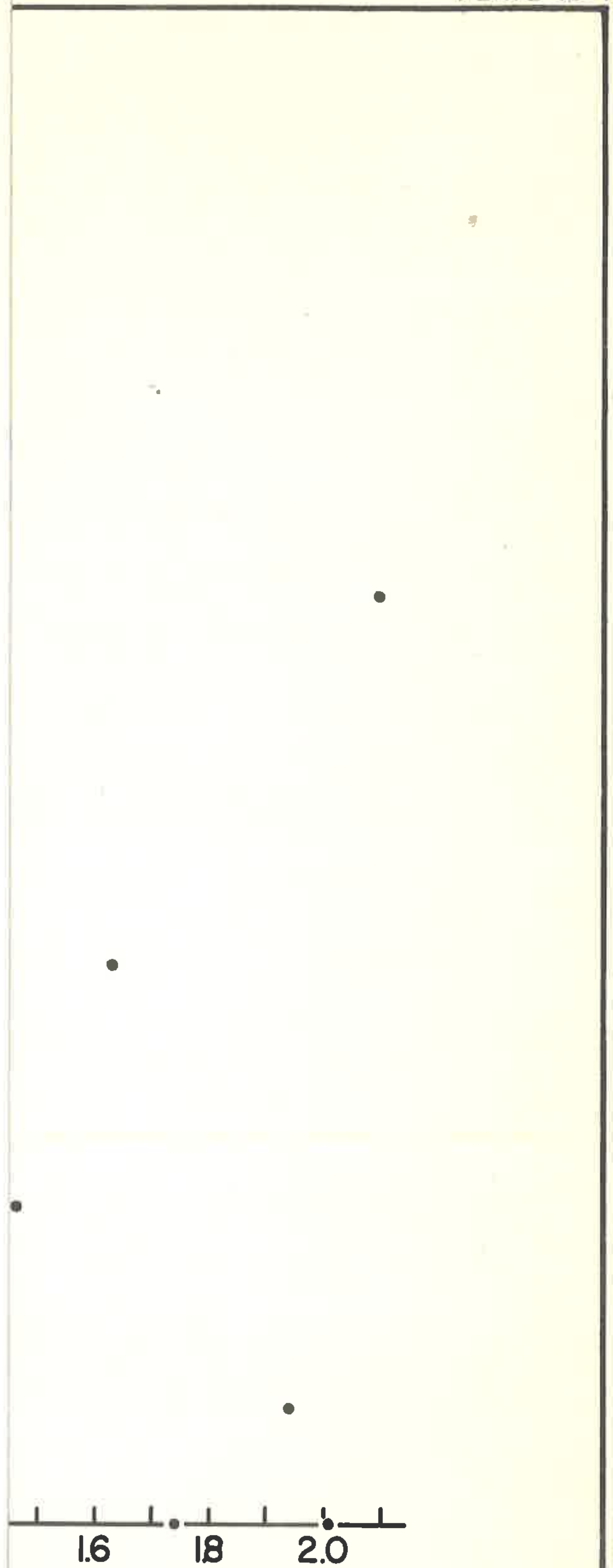
The first evaluation of the results of 1957 was included in the progress report of the Statistical Laboratory, presented to the Board of Directors on September 4, 1957. The estimates of the increase in rain ascribable to seeding were given in Table 4. Although these estimates were based on preliminary data then available, the general picture they presented was very similar to that now given in the first part of Table V-4: increases in precipitation by factors 2 and more.

Several months later there appeared in print an article [6] signed by Robin R. Reynolds, Chairman of the Board of Directors of the Santa Barbara Project. In this article it is stated that the data of 1957 indicate an increase in the target precipitation due to seeding of about 23 per cent. Also, the same estimate of 23 per cent increase appears in a paper bound mimeographed booklet issued by the North American Weather Consultants, dated December, 1957.

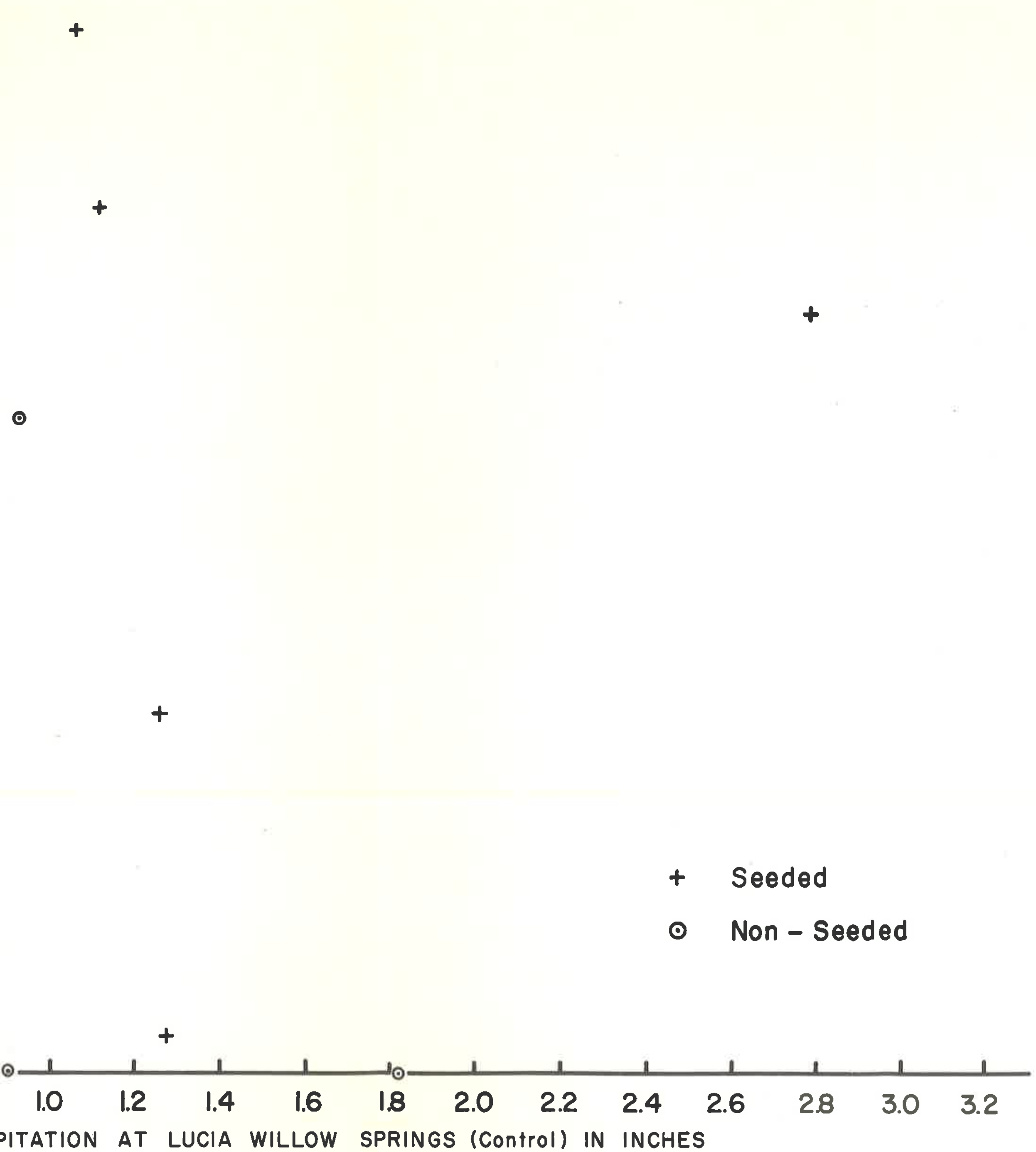
Both publications describe the cooperative character of the Santa Barbara Project, with the Statistical Laboratory as one of the participants, but fail to indicate the authorship of the estimate of 23 per cent. In fact, the relevant sentences collected from page 4 of the booklet of the North American Weather Consultants read as follows: "... the statistical design and analysis is being conducted by the Statistical Laboratory of the University of California at Berkeley, ... The data for the first year have been analyzed,... . The average increase for the first season was 23 per cent, ..."

The present authors wish to make clear that this estimate was reached and published without their knowledge and that it bears no relation to Table V-4 of the present chapter, nor to the preliminary evaluation reported to the Board of Directors of the Santa Barbara Project on September 4, 1957.

The two publications involving the estimate of 23 per cent came to the authors' attention in the Spring of 1959 at which time the present authors registered their regret. At the time of this writing (November, 1959) the authors were informed by Mr. Elliott that, following their protest in March, the NAWC circularized the recipients of the report of 1957 requesting that the estimate of 23 per cent be removed.



CIA WILLOW SPRINGS (B-1)
57-58-59
TUNITIES



SIMULTANEOUS PRECIPITATION AT LUCIA WILLOW SPRINGS (B-1)
AND SANTA BARBARA (T-5) 1957-58-59
ALL SEEDING OPPORTUNITIES

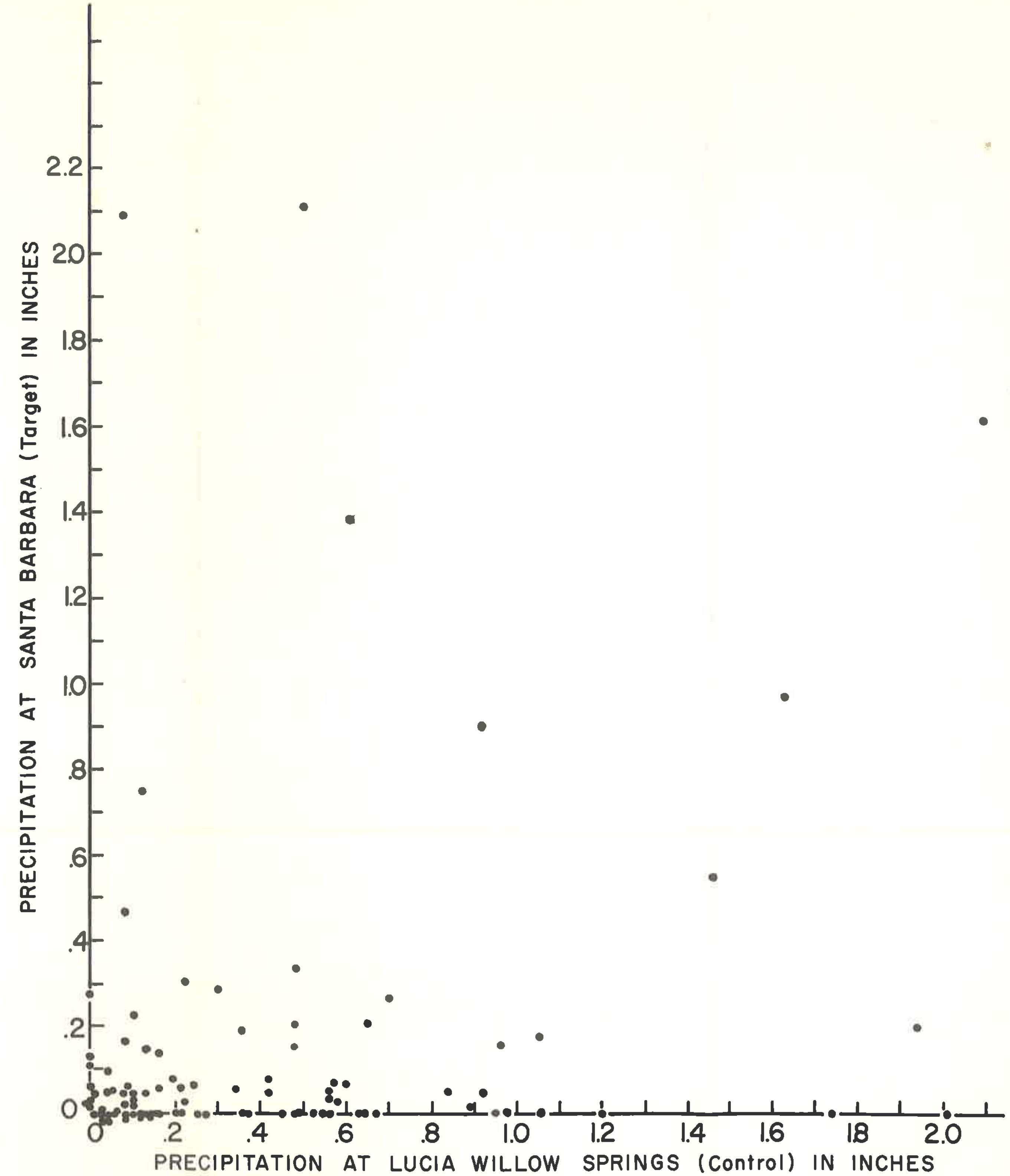


Fig. V-2 SIMULTANEOUS PRECIPITATION AT LUCIA WILLOW SPRINGS (B-1)
AND SANTA BARBARA (T-5) 1957-58-59
ALL NOT - SEEDABLE OPPORTUNITIES

STATISTICAL LABORATORY,
UNIVERSITY OF CALIFORNIA, BERKELEY

SANTA BARBARA WEATHER MODIFICATION PROJECT

COMPARISON OF TARGET AND CONTROL PRECIPITATION 1957-58-59

WEATHER
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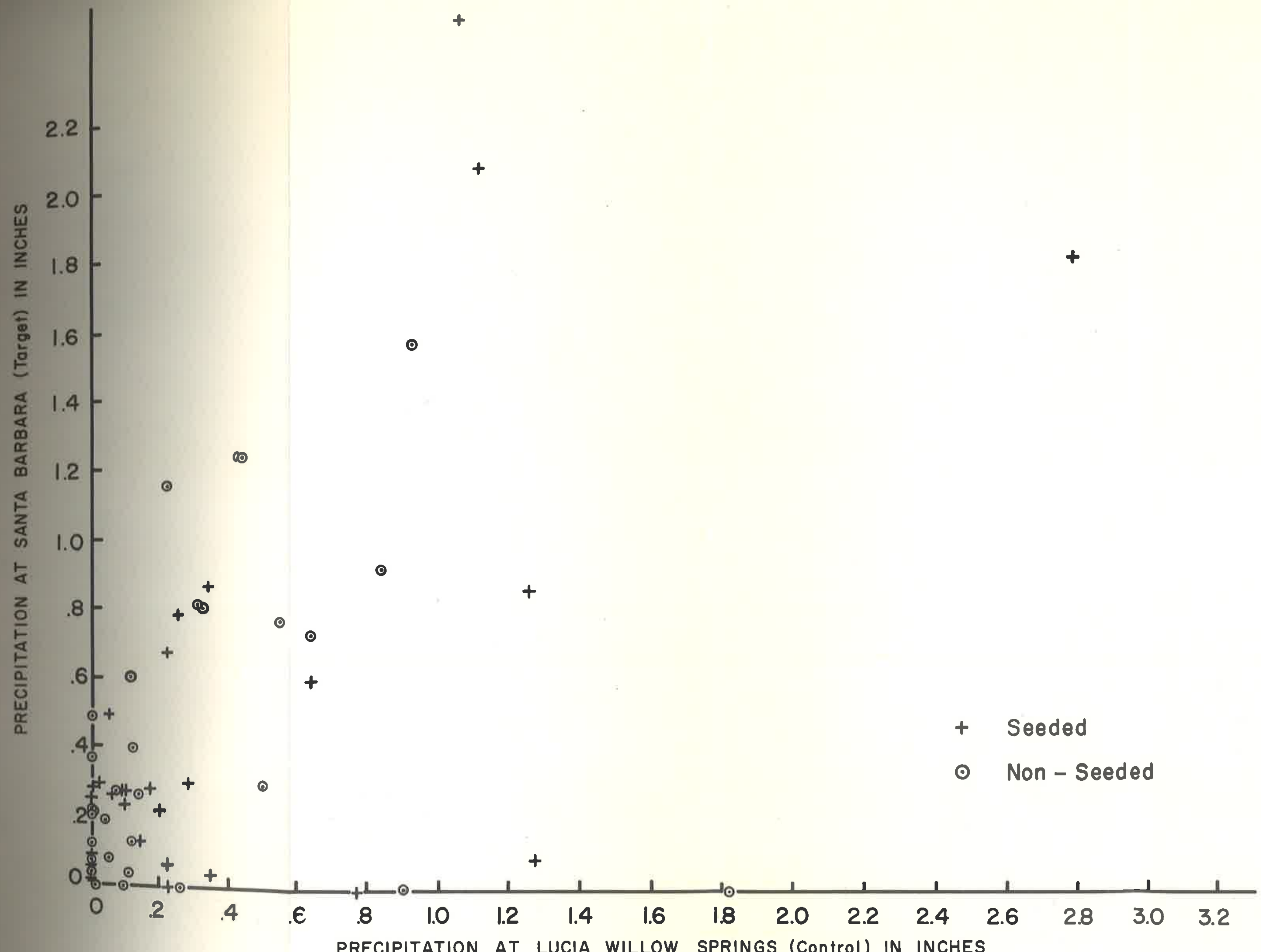


Fig. V-1 SIMULTANEOUS PRECIPITATION AT LUCIA WILLOW SPRINGS (B-1) AND SANTA BARBARA (T-5) 1957-58-59 ALL SEEDING OPPORTUNITIES

STATISTICAL LABORATORY, UNIVERSITY OF CALIFORNIA, BERKELEY

SANTA BARBARA WEATHER MODIFICATION PROJECT

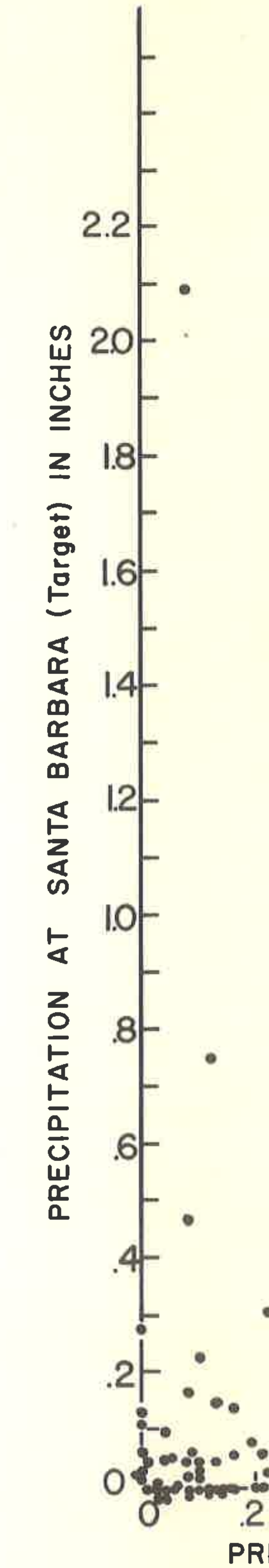


Fig. V

COMPARISON OF TARGET AND CONTROL PRECIPITATION 1957-5

DEPARTMENT OF WATER RESOURCES 1960

A WILLOW SPRINGS (B-I)
7-58-59

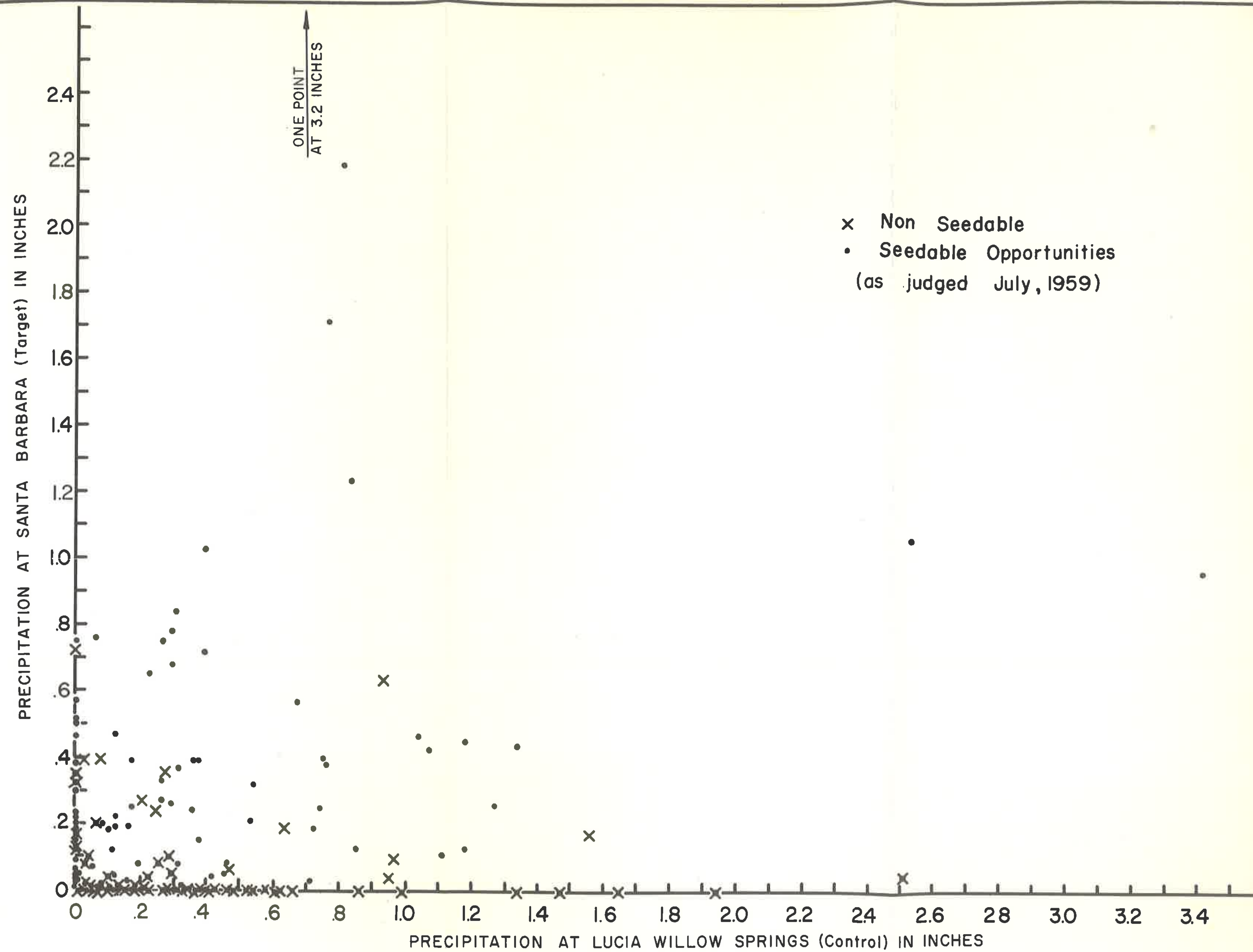


Fig. V-4 SIMULTANEOUS PRECIPITATION AT LUCIA WILLOW SPRINGS (B-I)
AND SANTA BARBARA (T-5) 1945-50
ALL OPPORTUNITIES

STATISTICAL LABORATORY,
UNIVERSITY OF CALIFORNIA, BERKELEY
SANTA BARBARA WEATHER MODIFICATION PROJECT

COMPARISON OF HISTORICAL TARGET AND CONTROL PRECIPITATION

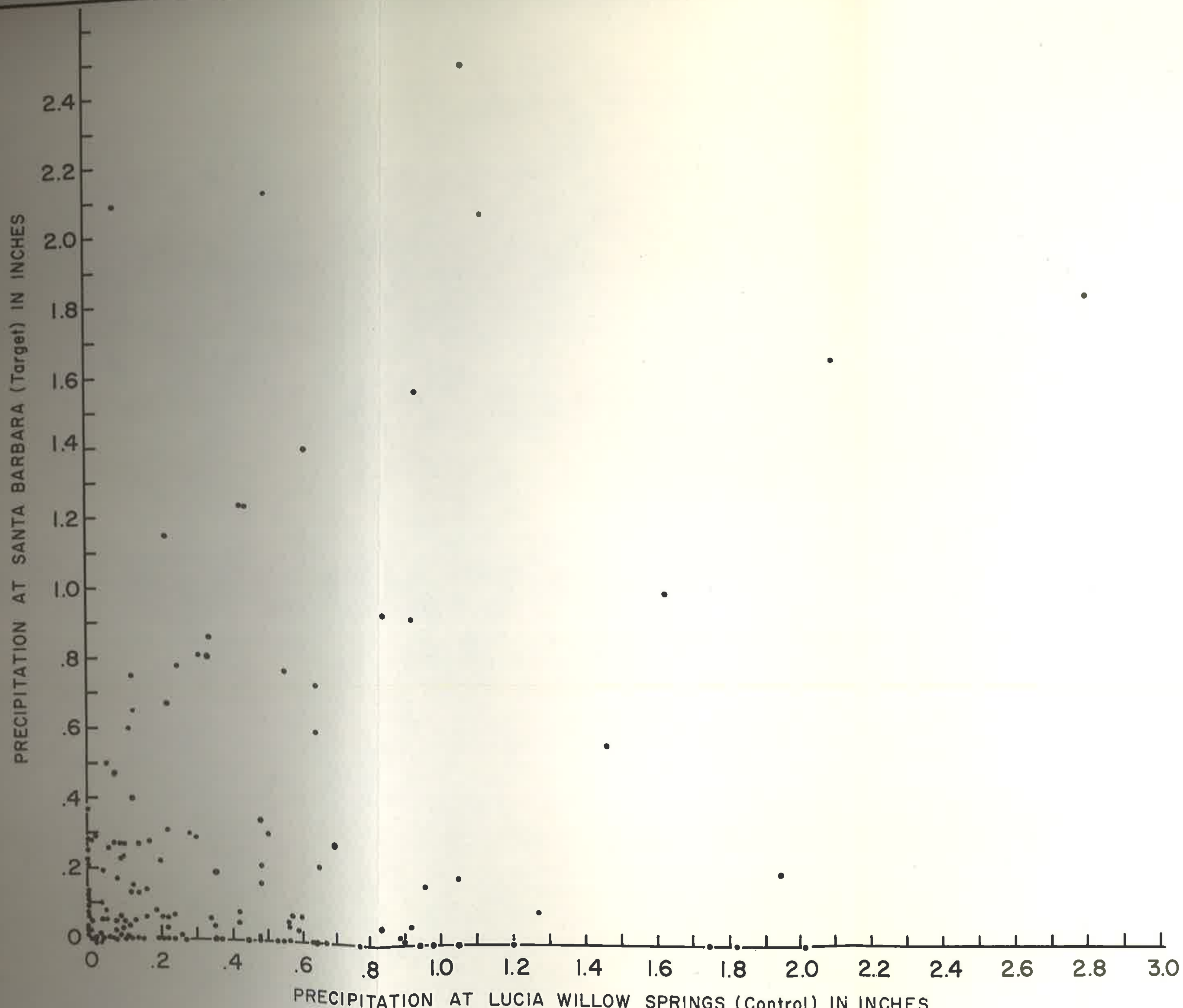
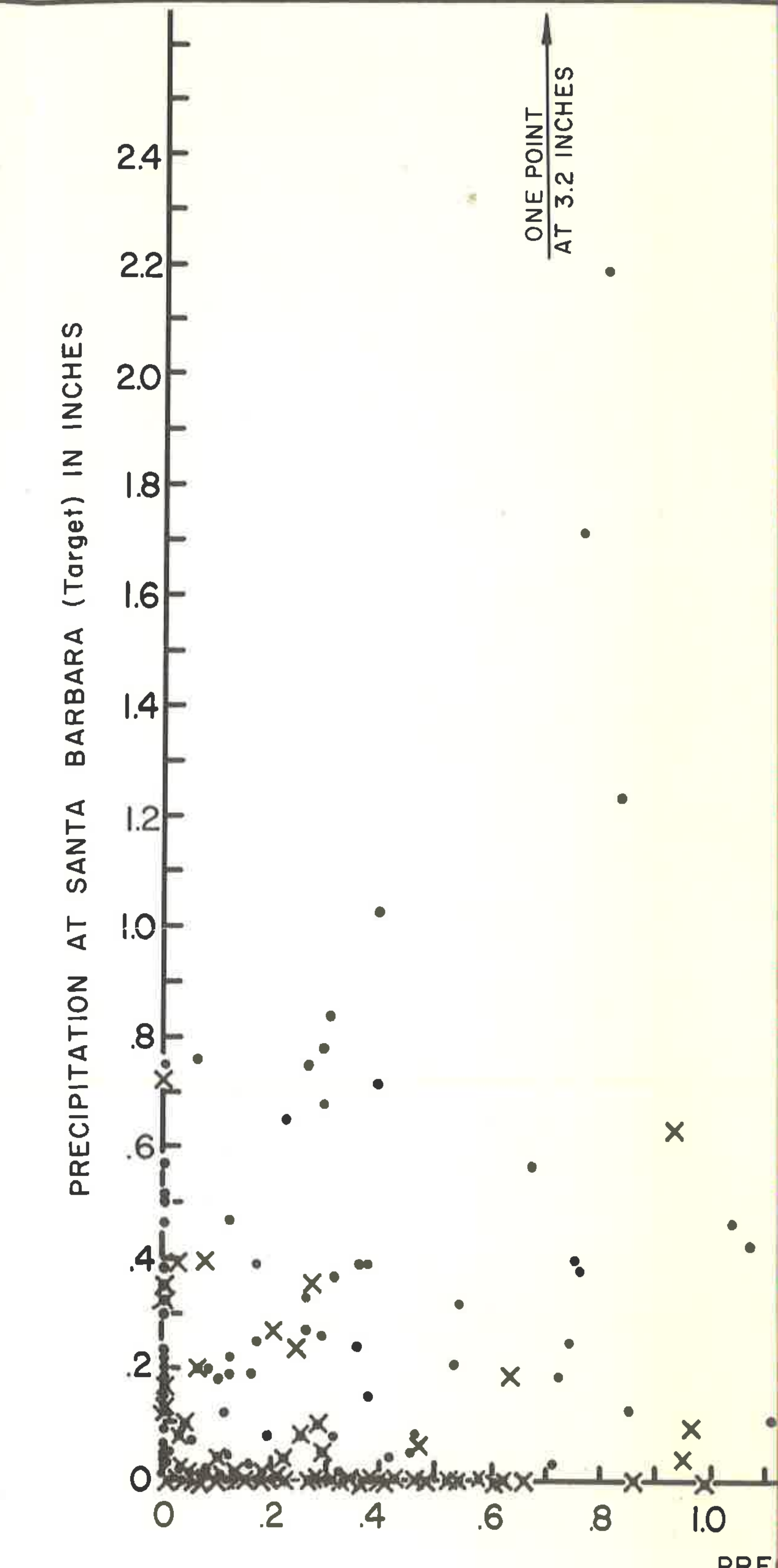


Fig. V-3 SIMULTANEOUS PRECIPITATION AT LUCIA WILLOW SPRINGS (B-1) AND SANTA BARBARA (T-5) 1957-58-59
ALL OPPORTUNITIES



STATISTICAL LABORATORY,
UNIVERSITY OF CALIFORNIA, BERKELEY

SANTA BARBARA WEATHER MODIFICATION PROJECT

Fig. V-4

COMPARISON OF HISTORICAL TARGET AND CONTROL PRECIPITATION

CHAPTER VI

PHYSICAL STUDIES OF SANTA BARBARA STORMS

Meteorology Research, Inc.
Altadena, California

By Theodore B. Smith, Clement J. Todd, Paul B. Mac Cready, Jr.

ABSTRACT

The conduct and evaluation of cloud seeding operations require weather observations on a geographic scale approximating the scale of motions producing the precipitation. Present observing networks are too sparse for an adequate study of the existing precipitation process. In order to understand the physical effects of seeding it is necessary to understand the natural mechanisms of precipitation formation and their variations. Several observing techniques for this purpose have been used during the Santa Barbara Project.

The physical measurements made during the Santa Barbara program include radar with PPI (horizontal) and RHI (vertical) scanning, atmospheric potential gradient, raindrop size distributions, freezing nuclei concentrations and assorted wind and temperature measurements. An additional valuable source of information has been radiosonde measurements of upper air temperature and humidity made every 12 hours at Santa Maria and Los Angeles. Combining this information into a coherent picture has made it possible to describe qualitatively a number of examples of natural mechanisms of precipitation formation. An excellent network of recording rain gages in Santa Barbara County is available for use in these studies.

From 1958 storms for which complete data were available detailed studies are presented of three cases selected as being representative of convective, stable, and mixed conditions. An analysis of the storm of April 2-3, 1958, indicates that precipitation started as a result of ice crystals falling

from high clouds into a lower level cloud mass. From the initially patchy nature of the natural ice crystal seeding it is concluded that additional artificial seeding might have been beneficial at this stage of the storm. Precipitation structure as viewed by the radar was cellular and its convective characteristics caused the largest amounts of rain to fall along the 4,000-foot coastal ridge north of Santa Barbara.

The storm of February 24-25, 1958, was stable instead of convective. Radar precipitation structure showed patches, bands and flat sheets of rain. The result of this type of air motion is a maximum in precipitation along the immediate coast and along the windward slope of the coastal ridge. Numerous natural ice crystals were provided from high clouds. Whether additional ice crystals would have been beneficial is an unknown factor.

The storm of January 25-26, 1958, was stable early in the storm and then became convective. The precipitation patterns showed the coastal rainfall maximum during the stable portion of the storm and the ridge maximum during the convective portion. Numerous ice crystals were again provided from high levels throughout the storm.

Through this type of analysis it is hoped that storms and portions of storms can eventually be categorized according to comparable seedabilities. This refinement is needed for the subsequent growth and improvement of seeding operations and evaluations.

PHYSICAL STORM STUDIES

1. Introduction

Meteorology Research, Inc., has received sponsorship for physical studies of Santa Barbara storms from the President's Advisory Committee on Weather Control in 1957, and from the National Science Foundation and The Department of Water Resources in subsequent years.

The Santa Barbara Project was originally organized to test the ability of standard silver iodide seeding techniques to increase precipitation in California winter storms. Concurrent physical studies of storm characteristics were also required for a balanced research program in weather modification. Information on the physical structure of the storms was needed for 1) refinement of statistical analyses through categorizing of storms and improved correlations, 2) physical explanation of observed statistical results, 3) extrapolation of observed statistical results to other areas and 4) development of improved seeding techniques.

Implicit in the need for such studies is the assumption that the storm reaction to seeding varies substantially from one storm to another and perhaps within a given storm. This is a reasonable assumption intuitively but has not been demonstrated in reality. The extent to which the seeding reaction varies and the physical reasons for the variations are the prime motives for the continuing physical storm studies at Santa Barbara.

Ideally, physical studies of seeding effects should be made in terms of deviations from a quantitative precipitation model, which could be attributed to the seeding action. Since such quantitative models do not exist, it might then be hoped that seeding could be detected by some type of direct observations at least under a limited range of storm conditions. This turns out to be possible occasionally in the marginal case when natural precipitation processes will not operate but seeding is effective due to the production of ice crystals at warmer temperatures than can occur naturally. This portion of the precipitation process - initiation - can be treated by a semi-quantitative model. For more complex situations where both natural and seeding processes might be expected to operate, it is not yet possible to separate by physical measurements the seeding effects from the natural precipitation process.

In these cases, the approach has been to describe the storm structure in some detail and to attempt qualitative estimates of the possible effects of seeding based on the observed storm structure and accepted cloud physics principles. As more is learned concerning the varying details of storm structures more definitive estimates of storm seedability should be possible.

Of the three years included in the program to date, most of the analysis has been concentrated on the 1958 rainfall season. Available data for analysis were more comprehensive than in 1957, the first year of the program, due to increased and improved observations. A relatively large number of storm cases in 1958 provided a variety of precipitation conditions. The 1959 season was quite dry. Opportunities for analysis are considerably more limited and some of the data required for detailed analyses have not yet been received. Consequently the examples and discussions included in this report deal primarily with the 1958 season.

2. Need For Basic Knowledge

Description of the relative seedability of different storms require a model of the method by which seeding acts to increase precipitation in winter storms. For these storms there is nearly universal agreement that precipitation increases due to seeding must originate from cloud moisture sources which would otherwise have evaporated or blown away and become unavailable for the local precipitation process. Bergeron (1949) has discussed an example of this in orographic flow over mountain ridges. In this case, the lifetime of the cloud droplets may be too short for precipitation to develop. Elliott (1958) has discussed California winter storm characteristics in detail and has suggested that moisture transported into altostratus clouds at high altitudes may not participate substantially in the precipitation process. Seeding in the central portion of the storm might thus convert more moisture into the precipitation process with a consequent reduction in moisture amounts lost in the altostratus.

No extensive computations have been made of the moisture budget in winter storms. Due to the complexity of the processes involved, little is known about the amounts of moisture lost in the storm which might be converted by seeding into precipitation. Presumably these amounts will vary considerably from one storm to another as nature operates the precipitation process in varying degrees of efficiency.

There are a number of factors involved in the natural precipitation process which are poorly understood on a quantitative basis. For ice crystal-produced precipitation, Bergeron (1950) has postulated two separate features of the precipitation process, a "releaser" cloud and a "spender" cloud. The spender cloud occurs at low levels and supplies most of the water to the precipitation process. The prime purpose of the higher releaser cloud is to provide ice crystals which fall through the spender cloud, sweeping out the available moisture into the precipitation process. At times, the releaser cloud and the spender cloud may be contiguous or they may be separate cloud systems. The quantitative description of the action of the falling ice crystals -- falling velocity, splintering, clumping of crystals, collection of melted water drops, etc. -- has not been adequately treated. In addition, the numbers of crystals available for the spender cloud are not usually known. Under these circumstances the effect of adding ice crystals on the efficiency of the precipitation process is difficult to evaluate.

Considerable work remains to be done in cloud physics before a quantitative model of the precipitation mechanism can be developed. Another source of natural variations in precipitation amounts is the effect of terrain. As indicated later, substantial variations in precipitation can be caused by terrain-produced, low level wind convergence.

In the absence of quantitative precipitation models which can be used for determining seeding effects, it is necessary to study the physical structure of the storms in as much detail as possible. Information must be collected on source of natural rainfall variability and their physical explanations. Such studies will aid in separating the effects attributable to seeding from those caused by natural variations.

3. Possible Seeding Effects

Direct observations of seeding effects in winter storms are quite difficult to obtain. Many possibilities for observing the seeding influence on precipitation growth in summer cumulus clouds are not possible in winter storms due to a lack of discrete cloud systems and to a longer precipitation cycle in winter.

An obvious possibility for the use of radar in observing seeding effects is the use of quantitative measurement of precipitation rates to distinguish increases due to seeding. Considerable work has been done by the Illinois State Water Survey (1958), Conover and Hiser (1958) and others on the quantitative measurement of precipitation by radar. The measurements are difficult and painstaking because of the need for accurate calibration of the radar equipment. In addition, correction must be made for attenuation of the radar signal due to rain intervening between the set and the area of interest. These problems, together with the frequent non-uniformity in precipitation structure, make it extremely doubtful that precipitation increases of the order of 10-15 per cent could be detected directly by quantitative radar precipitation studies.

On a number of occasions in the Santa Barbara area, marginal precipitation conditions have been observed in which a supply cloud was present in the low levels without any effective releasing mechanism. In some cases when the top of the supply cloud is colder than about -5°C silver iodide could generate ice crystals in the cloud top when no ice crystal releasing mechanism would be possible naturally. Under these conditions long isolated plumes might be expected downwind of the silver iodide generator. Such plumes have been reported by several radar observers under marginal precipitation conditions. This is the most striking opportunity available for direct observational seeding evidence. However, in view of the marginal nature of the situation it is not to be expected that large quantities of precipitation will be released by this process.

Several clear examples of these isolated plumes have been observed by radar in the Santa Barbara storms. Two striking cases occurred on February 4 and March 14, 1958, when long plumes were observed over the Santa Barbara Channel downwind of silver iodide generator sources. These plumes over the channel were observed during the first year of the program and studied in more detail during the second year. It became apparent that the islands themselves occasionally set off such isolated plumes without seeding activity, due to the passage of air over the island ridges. Precipitation was initiated by this orographic flow downwind of the islands when no natural precipitation was visible elsewhere. In view of these instances of plumes occurring without seeding it appears that incontrovertible direct evidence of seeding in these cases will require additional measurements to separate natural from seeded effects.

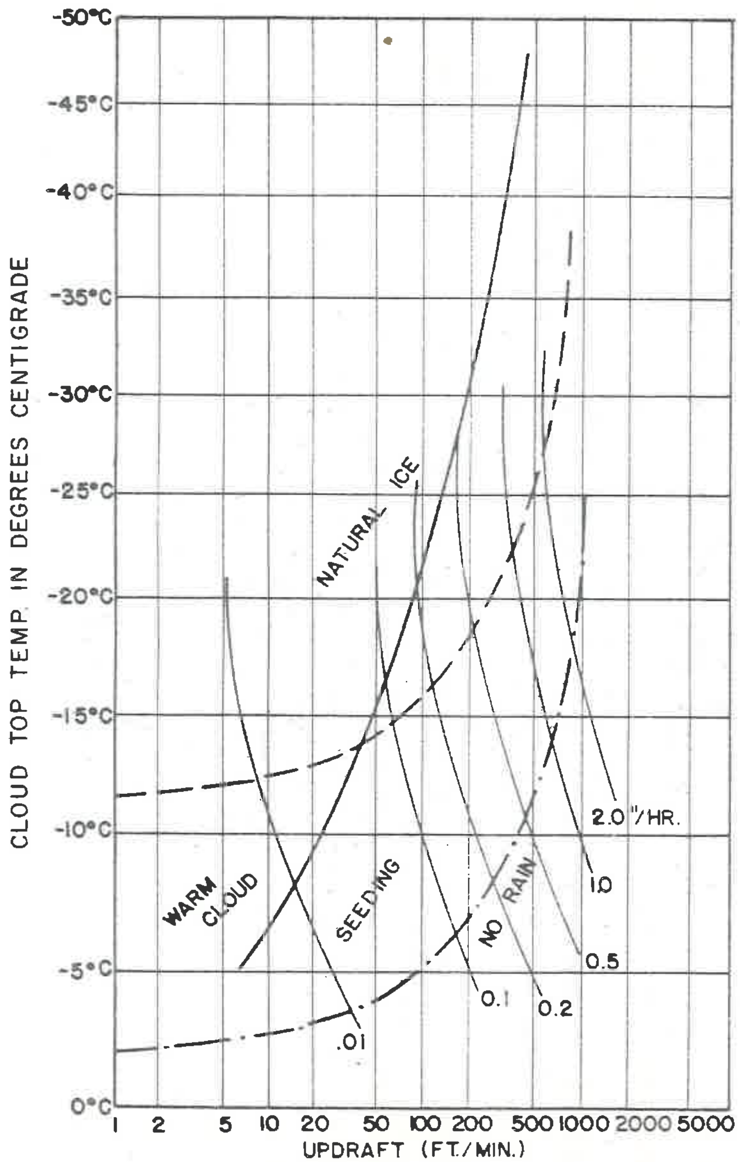
On numerous occasions in the Santa Barbara storms, extensive high level ice sheets are observed. These produce copious ice crystals naturally at cold temperatures, and these crystals fall into the lower supply clouds, sweeping out the existing liquid water. No information is available on the numbers of these crystals or the effectiveness of adding additional crystals during this stage of the precipitation process. The extensive natural precipitation at this time prevents any direct observation of seeding effects.

In summer cumulus clouds, considerable experimental seeding has been possible. On some occasions, a cloud randomly selected from a similar pair of clouds is seeded while the remaining cloud of the pair is left untreated for a control. The effect of seeding on initiation of precipitation can thus be studied under partially controlled conditions. This technique is not compatible with the statistical design of the Santa Barbara Project. In portions of the Santa Barbara storms, when marginal conditions for precipitation prevail in all or part of the area, experimental seeding under radar observation would yield useful information on the ability of seeding to initiate precipitation under the specified conditions.

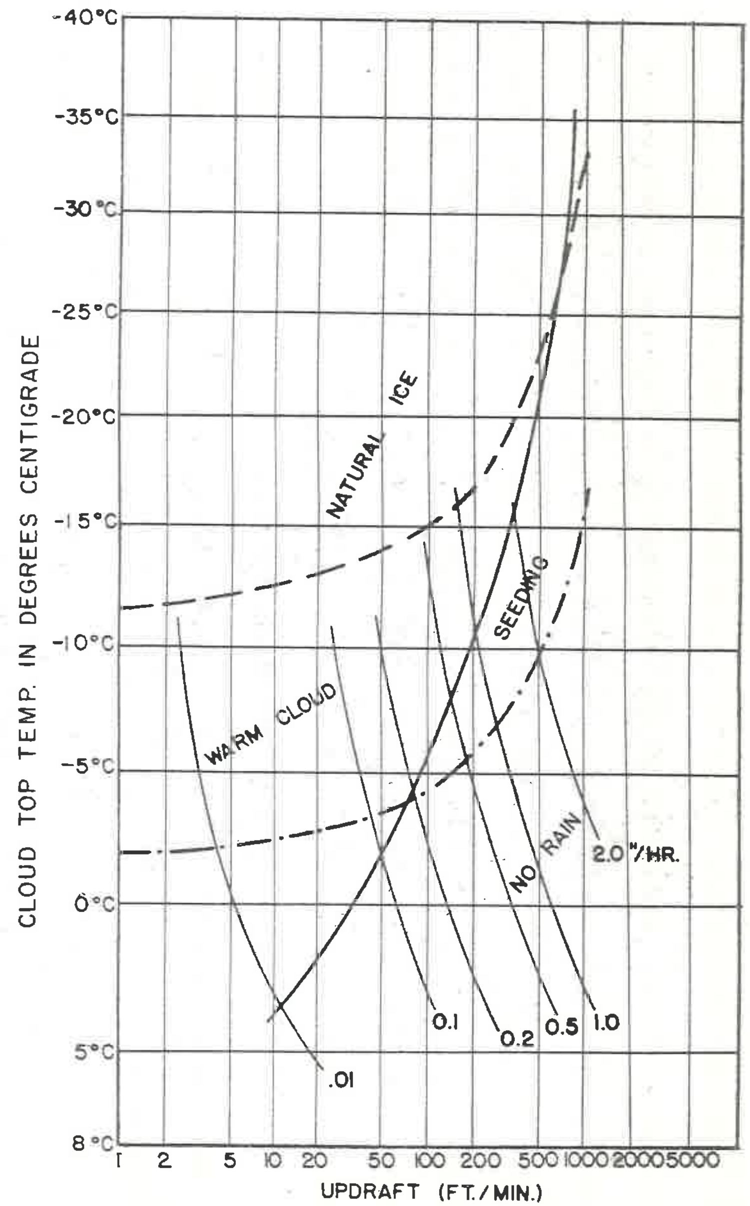
4. Precipitation Initiation

East (1957) and Todd (1957) have shown that a quantitative model of precipitation initiation could be constructed for the case of precipitation growth by the all-water coalescence process. Todd has also constructed an initiation model for ice crystal -- produced precipitation although additional assumptions are required and the model is consequently not as well defined. The model is discussed in detail in the 1958 MRI report on the project (2).

Two examples of the "initiation" model are shown in Figure VI-1 for cloud base temperatures of 0°C and 8°C. Updraft velocities are plotted against height of the cloud top. Points above the "Warm Cloud" line (solid



CLOUD BASE TEMPERATURE 0°C



CLOUD BASE TEMPERATURE 8°C

PRECIPITATION INITIATION MODEL

curve) represent conditions where the condensation-coalescence process can cause precipitation. Points above the "Seeding" line (dot-dash curve) represent conditions where silver iodide seeding can cause precipitation. Points above the "Natural Ice" line (dashed curve) represent conditions where natural nuclei can cause precipitation. Below all the lines is the "No Rain" situation. Also shown are maximum rates of precipitation possible under the conditions indicated, assuming no evaporation or mixing with outside air.

Obviously the different areas in the charts are not mutually exclusive. For some conditions both "Warm Cloud" and "Seeding" precipitation can be initiated -- determining which one comes first or is dominant depends on many factors including what seeding is being performed and is a refinement beyond the scope of the "initiation" model. All the "Natural Ice" area is within the "Seeding Area"; if a cloud is in the joint area and if seeding is taking place, the first precipitation will be caused by the artificially created crystals, and the natural nuclei may or may not have the opportunity to act (the "Initiation" model deals only with timing, not number of nuclei or hydrometeors.) The natural nuclei are here assumed to have a relatively warm threshold temperature, because a low nuclei concentration is assumed. When radar records, visual observations, and/or the "synoptic" situation imply that the cloud is being seeded by ice crystals which are falling from above, such seeding is assumed to cause the first precipitation.

A set of these charts has been constructed for various cloud base temperatures and applied to storms in the Santa Barbara area. Cloud base temperatures are readily obtainable from standard weather observations.* Cloud top temperatures are occasionally available from aircraft pilot reports, and also could be calculated from radar and lapse rate information. No direct information is available on updraft rates in various portions of the storm, and these must be assumed.

For the 1958 rainfall season the following results were obtained from this analysis:

Precipitation Could Be Initiated By	% of Precipitation Hours
"Warm Cloud" process only	4%
"Seeding" only	17%
"Warm Cloud" or "Seeding" process	36%
"Natural Ice" (natural nuclei) or "Seeding"	0%
"Natural Ice" (natural nuclei or "Warm Cloud" or "Seeding" process	14%
Ice crystal seeding from higher clouds	29%

It was concluded from this study that 1) warm cloud precipitation is an important factor in Santa Barbara storms at least from the standpoint of frequency of occurrence, but perhaps not from an intensity standpoint, 2) seeding might initiate the ice mechanism earlier than the natural nuclei process or the warm cloud process in about half of the total hours, 3) ice crystal seeding is frequently done from higher cloud layers, and 4) seeding could provide the only precipitation in about one-sixth of the total hours.

These studies refer only to the initiation of precipitation and not to subsequent developments. Added complications arise when a portion of the liquid water begins to fall out as precipitation. Further extension of the precipitation initiation model to more complex analyses is largely limited by the lack of adequate observational data such as updraft velocities within the cloud systems.

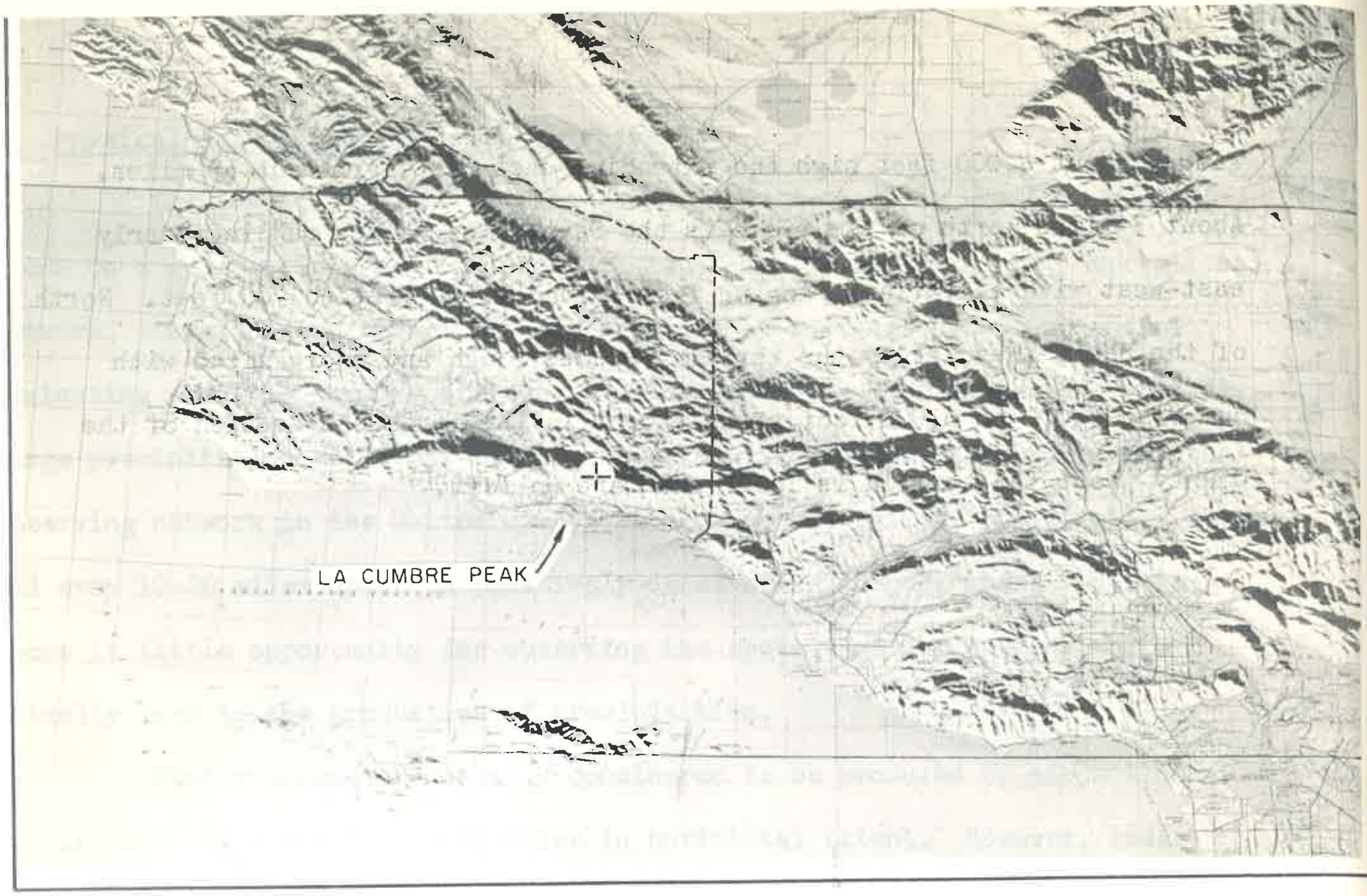
5. Physical Measurements at Santa Barbara

The advent of cloud seeding has created a need for weather observations on a geographic scale not provided routinely by the standard observational network. This applies equally to the problems of seeding operations and of evaluating possible seeding effects. In the case of summer convective activity, large precipitation cells may be only several miles in diameter while the usual observing network in the United States is made up of stations 50-100 miles apart and even 10-20 miles apart in relatively dense areas. Under these conditions there is little opportunity for observing the systems of air motions which actually lead to the production of precipitation.

Winter storms are usually considered to be produced by air motions of the order of several hundred miles in horizontal extent. However, radar echoes from precipitation in such storms reveal considerable non-uniformity in horizontal structure. Precipitation occurs in sheets, bands or cells during these storms depending on air structure and terrain factors. Short distance variability in winter precipitation is particularly pronounced in orographic conditions when rainfall amounts may double or triple within a few miles.

In order to understand how cloud seeding works and how the natural precipitation process may be modified, it is necessary to understand the natural mechanisms of precipitation formation and their variations. This requires reducing the observations to a scale comparable with that of the precipitation process itself. Also required is a concentration of effort on the measurement of those parameters which will yield the most information about the operative precipitation mechanism.

Figure VI-2 shows a map of the Santa Barbara County Area. The principal terrain features of interest in the County are the east-west coast line and coastal plain, about 3-5 miles wide. North of the plain is the coastal ridge, about 4,000 feet high and extending east-west for about 45 miles. About 3 miles north of the ridge is the Santa Ynez Valley running nearly east-west with elevations ranging from around 1,500 feet to 700 feet. North of the Santa Ynez Valley the terrain becomes rough and unorganized with numerous 5,000 to 6,000-foot peaks except in the northwest section of the County where the terrain is lower and more uniform.

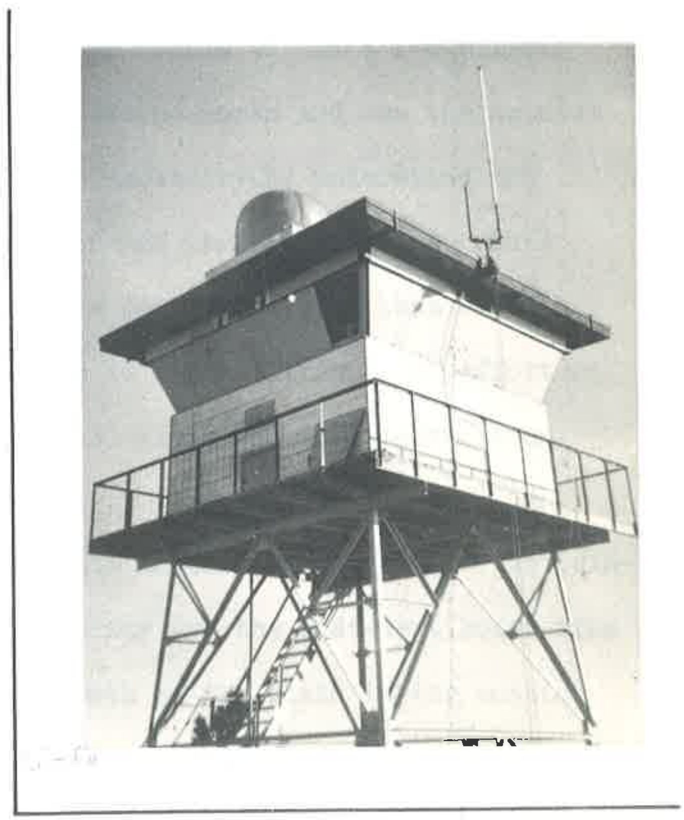


RELIEF MAP OF SANTA BARBARA COUNTY
SHOWING LOCATION OF LA CUMBRE PEAK

Fig. VI-2

RADAR DOME MOUNTED ON
U.S. FOREST SERVICE LOOKOUT,
LA CUMBRE PEAK

Fig. VI-3



Observations made by Meteorology Research, Inc. during the Santa Barbara program include radars with PPI (horizontal) and RHI (vertical) scanning, atmospheric potential gradient, raindrop size distributions, freezing nuclei concentrations and assorted wind and temperature measurements. Most of these observations were made from a U. S. Forest Service Lookout on La Cumbre Peak, at 4,000 feet on the coastal ridge about 6 miles north of Santa Barbara (Figure VI-2.) The 3-cm radar is located on the roof of the lookout (Figure VI-3) and has an uninterrupted view of precipitation approaching the coast from the south and southeast but considerable ground clutter appears from higher mountains to the north of the lookout. An additional source of valuable information comes from radiosonde measurements of upper air temperature and humidity made every 12 hours at Santa Maria and Los Angeles, from hourly airport weather data, and from occasional pilot in-flight reports.

The use of radar in the Santa Barbara program has been confined to semi-quantitative studies of horizontal and vertical precipitation structure. Much can be learned from these studies concerning the type of air motion occurring in the precipitation process. Sheet or layer type precipitation structure is associated with slow, stable, relatively uniform upward motion. When the air becomes unstable, upward motions increase, the areas of upward vertical motion decrease in size and the precipitation structure becomes more cellular.

Natural freezing nuclei concentrations have varied markedly during the observational period at Santa Barbara. Concentrations ranging from one per/liter effective at about -18°C to one per/liter at about -28°C have been observed. At the level of one per/liter at -18°C the air can be considered as comparable to concentrations measured in many other areas. The level of one per/liter at $-28^{\circ}C$ represents an unusually low level of nuclei activity. Thus ample opportunity exists in the Santa Barbara area for silver iodide nuclei to act in a wide range of temperatures where no natural nuclei are formed.

6. Storm Studies

Details of the structures of most of the 1958 storms have been assembled from the data sources mentioned previously. Examples of three of these storms are given in the following section to illustrate the information which can be readily obtained concerning storm structure and to demonstrate the variations in rainfall patterns associated with storm structure changes. From those for which data were available, these three were selected as being representative of the convective, stable, and mixed convective-stable storm situations.

April 2-3, 1958. Figure VI-4 on Plate VI-1 shows a vertical-time cross section made from radiosonde data taken at successive 12-hour intervals at Santa Maria, California. Dashed lines represent air temperatures and solid lines represent moisture values plotted as the difference between temperature and dewpoint in $^{\circ}C$. The shaded area shows the moist air region.

A characteristic feature of winter storms in this area is a low level moist layer during the early portion of the storm. This layer is usually referred to as the marine layer and is topped by the "marine inversion", a region of warmer and drier air. Above the inversion the air is frequently dry except for possible layers of moist air at high levels being advected into the area by the approaching storm. The top of the marine layer is shown in Figure VI-4 as a solid line with an indication that the air is stable at the top of the layer.

Rain began in the Santa Barbara area about 1800 PST on April 2. At this time the top of the marine layer as shown on Figure VI-4, was about 11,000 feet at a temperature of -10°C. Precipitation cells were seen on the radar to approach the coast from the southwest. Top of the precipitation was measured at 10,000 feet or about -7°C. At 2029 an aircraft pilot reported the top of the cloud at 11,500 feet. According to freezing nuclei measurements, no natural nuclei could have operated to produce ice crystal precipitation at the warm temperatures present in the observed cloud mass.

Raindrop size distributions and atmospheric potential gradient were measured during this period and are shown in Figures VI-5, -6, and -7 on Plate VI-2. The times of the 31 raindrop size samples are shown in Figure 7. Eleven samples were taken prior to 2000. The first nine of the samples are plotted as points in Figure VI-5 together with a solid line which has been shown (Mac Cready et al, 1958) to represent a generalized size distribution for raindrops produced by the coalescence, or warm cloud, process which does not involve the presence of any ice crystals. It is suggested by Figure VI-5 that the first nine raindrop samples on April 2 were taken in coalescence-produced rain. Samples 10 and 11 (dashed lines) deviate markedly from the generalized coalescence distribution and Figure 6 shows that these samples correspond to the generalized size distribution found by Marshall-Palmer (1948) (solid line in Figure V-6.) The conclusion is suggested that ice crystal precipitation began abruptly at about 2000 PST.

Further suggestive evidence for this change in precipitation mechanism is shown in Figure VI-7 where an abrupt change to a negative potential gradient is observed beginning with samples 10 and 11. An increasingly popular theory of electric charge generation in clouds (e.g. aufm Kampe, 1957) associates the common formation of negative fields with the presence of ice crystal-produced precipitation.

These sources of information permit the separation of coalescence and ice crystal precipitation processes and indicate that ice crystal precipitation commenced at about 2000 PST on April 2. Since the ice crystals could not have been formed within the cloud mass below 11,500 feet they presumably fell into the mass from a higher ice cloud not seen by the radar or the radiosonde ascent. The patchy character of the precipitation indicates patchy non-uniform concentrations of ice crystals falling from above. This mechanism of ice crystal seeding from above is one of the most effective natural seeding processes observed.

The situation just described is an excellent example of a marginal condition for the formation of precipitation when occasional ice crystals can release the low level moisture which would otherwise remain in the cloud. The patchy seeding in this example suggests that an opportunity exists in this case for artificial seeding to smooth out the irregularities in the precipitation process and make the precipitation more uniform.

After 2000 PST, the top of the marine layer rose until at around 0100 PST on April 3 the radar top had increased to near 14,000 feet or about $-15^{\circ}C$. Peak precipitation occurred between 0100 and 0200 and by 0600 the precipitation had essentially ended. During the peak and later portions of the storm the depth of the marine layer had increased to where ice crystal formation could take place within the cloud mass below the marine layer top.

Horizontal radar cross sections through the storm showed a generally cellular structure, each cell being several miles in width. A summary of the storm would suggest that these cells developed within the marine layer, increasing the height as the marine layer deepened as suggested by the increasing heights of the radar echoes. Early in the storm ice crystal seeding must have been accomplished from higher ice cloud patches. Later in the storm ice crystals could also have developed within the main cloud mass itself. Seeding began at 2200 PST on April 2, several hours after the onset of the first ice crystal precipitation, and continued for 24 hours.

Figure VI-8 on Plate VI-1 shows the hourly precipitation amounts of April 2-3 for various portions of the Santa Barbara area. Each portion represents a nearly east-west line of recording stations beginning with the Islands and extending northward to the San Rafael Ridge. There is a distance of about 30 miles between the Islands line and the Coast, about 4 miles from the Coast to the Coastal Ridge, about 3 miles from the Coastal Ridge to the Santa Ynez Valley and about 5 miles from the Valley to the San Rafael Ridge.

Air flow at the precipitation levels is generally from the south or southwest during storm conditions so that these parallel lines are oriented nearly normal to the wind flow.

As would be expected under the unstable, cellular precipitation regime observed, the Coastal Ridge received the greatest precipitation amounts since instability is usually released principally over the ridge. Due to these vertical motions, total liquid water amounts tends to be highest in the clouds over the ridge and ice crystals falling from above grow by this liquid water and fall as precipitation. It is to be noted that the coastal plain did not receive particularly large amounts of rain during this storm. On the other hand, amounts were substantial in the Santa Ynez Valley in the lee of the Coastal Ridge. This is undoubtedly the result of precipitation processes commenced over the ridge but not completed until the cloud system had been moved downwind over the Valley.

February 24-25, 1958

A different type of storm system is shown in Figure VI-9 on Plate VI-3. The principal characteristic of the storm is a low marine inversion (about 5,000 feet) throughout most of the storm. Considerable moist air was advected into the area at levels above the marine layer but there was no indication that ground level air passed upward beyond about 5,000 feet until very late in the storm.

Precipitation started in the Santa Barbara area about 2000 PST on February 24. At this time storm moisture extended to 20,000-25,000 feet, or to air temperatures below -20°C. Under these conditions numerous ice crystals would be formed naturally at high levels, fall toward the ground and collect whatever liquid water was present at the lower levels.

Tops of the radar echoes were generally around 13,000-14,000 feet early in the storm but increased to 17,000-18,000 feet during the peak rainfall period. An aircraft pilot reported layers of clouds to 23,000 feet (about -25°C) shortly after the precipitation had started. Horizontal radar cross-sections indicated a relatively uniform precipitation structure of sheets, bands and occasional patches. From the structure of the precipitation and the great vertical depth of moisture during the storm it would be concluded that nature was doing a very extensive job of providing natural ice crystals. Whether additional artificially made ice crystals would be beneficial under these conditions is an unknown factor in cloud seeding operations today.

Figure VI-10 shows the hourly rainfall amounts for the storm of February 24-25. The striking feature of the chart is the extensive precipitation received by the coastal plain, only slightly less than occurred on the Coastal Ridge. Elsewhere the precipitation was relatively uniform and considerably less than observed near the coast.

The explanation for this coastal maximum in precipitation has been given by Bergeron (1949.) Under the stable, low level inversion conditions characteristic of the February 24-25 storm, surface air moving northward along the coast cannot flow over the east-west ridge north of Santa Barbara but is turned westward to pass through the Santa Barbara Channel. Winds at Santa Barbara under these conditions are moderately strong from the east with much higher velocities being occasionally reported by ships in the Channel. Frictional slowing down of the air by the coastal plain and convergence produced by the efforts of the air to flow around the Coastal Ridge combine to produce a piling up of air (and liquid water) in the immediate vicinity of the coast. As in the February 24-25 case, ice crystals produced aloft may then collect this liquid water during their descent and substantially higher amounts of rain are produced in the coastal areas.

This phenomenon is essentially a low level one being produced by convergence in the layers near the surface. As seen in Figure VI-10 the effects do not extend to the Santa Ynez Valley due to the stable, low inversion conditions prevailing. In view of these conditions and since moisture from the coastal source does not appear to influence the rainfall in the Valley it is considered probable that silver iodide released from ground generators would not rise to levels in the atmosphere where it could become effective in producing ice crystals. Thus the storm of February 24-25 was characterized by a large supply of natural ice crystals and it is likely that it was relatively unaffected by artificial seeding, even though it was seeded beginning around 2200 PST on February 24.

January 25-26, 1958

The storm of January 25-26 combines some of the features of the two preceding storms. As shown in Figure VI-11 on Plate VI-4 the characteristic marine layer was shallow early in the storm but deepened rapidly during the storm. Rain began at about 1300 PST when the top of the marine layer was only about 8,000 feet or $0^{o}C$. In agreement with the previous cases, natural production of ice crystals could not have taken place in the marine layer by this stage in the storm. However, as in the February 24-25 example, advection of moisture into the area at high levels apparently produced numerous natural ice crystals. This is indicated by a radar precipitation top of 19,000 feet shortly after the precipitation commenced.

The structure of the precipitation as viewed by the radar showed frequent bands and patches during the early part of the storm. Between 1930 and 2000 PST the character of the echoes changed rather abruptly from stratiform, layer type to cellular. This coincided with an increase in the top of the marine layer to about 11,000 feet and thereafter the top continued to rise. Thus, after 2000, in terms of the depth of the marine layer, the January 25-26 storm then became similar to the April 2-3 example which also showed a cellular precipitation structure.

Figure VI-12 shows the hourly precipitation amounts for the January 25-26 storm. The Coastal plain received substantial amounts of precipitation through 1900 but the precipitation rate decreased rapidly thereafter. The Coastal Ridge, however, did not receive its peak precipitation until the hour between 2000 and 2100. Since only about 4 miles separate the coastal stations from the ridge stations it is obvious that the coastal maximum precipitation and the coastal ridge maximum were produced by different processes. It is apparent that the precipitation characteristics of the January 25-26 storm are made up of the coastal maximum patterns described in the February 24-25 storm until 1900 followed by a change in precipitation regime to that characterizing the April 2-3 storm. Indicative of this change in regime is the change in radar echo characteristics from stratiform to cellular between 1900 and 2000 PST. This storm was seeded after 2200 PST.

7. Low Level Control of Precipitation Amounts

The variations indicated above in area distribution of precipitation amounts from one storm to another have important general implications. It is indicated that low level wind flow patterns exert an important influence on precipitation amounts. In those areas where liquid water accumulates due to convergent flow, precipitation amounts increase if a releasing mechanism is provided. The latter usually consists of ice crystals formed at high levels which fall through and sweep out the lower level liquid water. Cloud seeding purports to influence mainly the releasing mechanism. To the extent that the low level flow patterns control the actual precipitation amounts, increases in these amounts due to seeding will be difficult to detect. In some studies of cumulus seeding, indications have been obtained of greater cloud growth during seeding. In this case the seeding has directly influenced the low level liquid water supply and the seeding effect will be more easily observed.

8. Need for Additional Measurements

It has been shown that, using various rather easily obtained measurements, it is possible to reconstruct qualitatively many of the details of the precipitation processes occurring during the course of a storm. This is a step toward a better understanding of how seeding might influence these processes. In the April 2-3, 1958 storm example, a lack of natural ice crystal seeding was apparent during a portion of the storm. Artificial seeding should produce additional precipitation under these conditions. In the case of the February 24-25 storm, it was suggested that seeding from ground generators would probably not be effective due primarily to limited upward transport of the silver iodide nuclei. Further progress requires additional measurements and the formation of better hypotheses on the possible action of the seeding. Some of the problems which require consideration are:

1) To obtain direct measurements of liquid water content or vertical motions within the clouds.

2) To obtain more frequent measurements of cloud tops during the storm.

3) To obtain a measure of the extent of natural ice seeding from high levels as a function of time during the storm.

4) To develop an improved hypothesis concerning the benefits of artificial seeding when numerous natural ice crystals are present.

5) To develop improved hypotheses concerning the relative importance and benefits of seeding various portions of the storm.

If the cloud seeding continues to develop in the future it is likely that seeding operations will eventually be concentrated in those storms or portions of storms where maximum effects can be achieved. Development of new seeding techniques requires a knowledge of the optimum timing and location for introduction of the seeding material which is not available at present. Further progress toward these goals in winter storms will come from physical studies of individual storm characteristics and associated variations in precipitation mechanism.

9. Reports and Papers

The following reports and papers have been prepared by Meteorology Research, Inc. to describe the results obtained during the three years of the Santa Barbara Program.

1) Final Report Advisory Committee on Weather Control, pp. 191-196, 1957.

2) "Radar and Cloud Physics Studies of Santa Barbara Storms", MRI Rept. to National Science Foundation and Calif. Dept. of Water Resources, 15 July, 1958.

3) "The Possibility of Making Quantitative Discriminations between Condensation-Coalescence Rain and Ice Initiated Rain", Proc. 7th Weather Radar Conf., pp. A-17 to A-23, 1958.

4) "Physical Study of Precipitation Processes at the Santa Barbara Cooperative Seeding Project", paper given at Woods Hole Conf. on Physics of Precipitation, June 1959.

5) "Physical Studies of Santa Barbara Storms", paper given at AMS Meeting, San Diego, California, June 1959.

6) "Radar and Cloud Physics Studies of 1959 Santa Barbara Storms", MRI Report to California Department of Water Resources, June 30, 1959.

7) "Physical Studies of Santa Barbara Storms", paper given at joint AMS-ASCE Meeting, Denver, Colorado, August 1959.

Copies of certain of these more detailed reports are available, and Meteorology Research, Inc., or the California Department of Water Resources can provide some of the radar films and other records to qualified interested groups.

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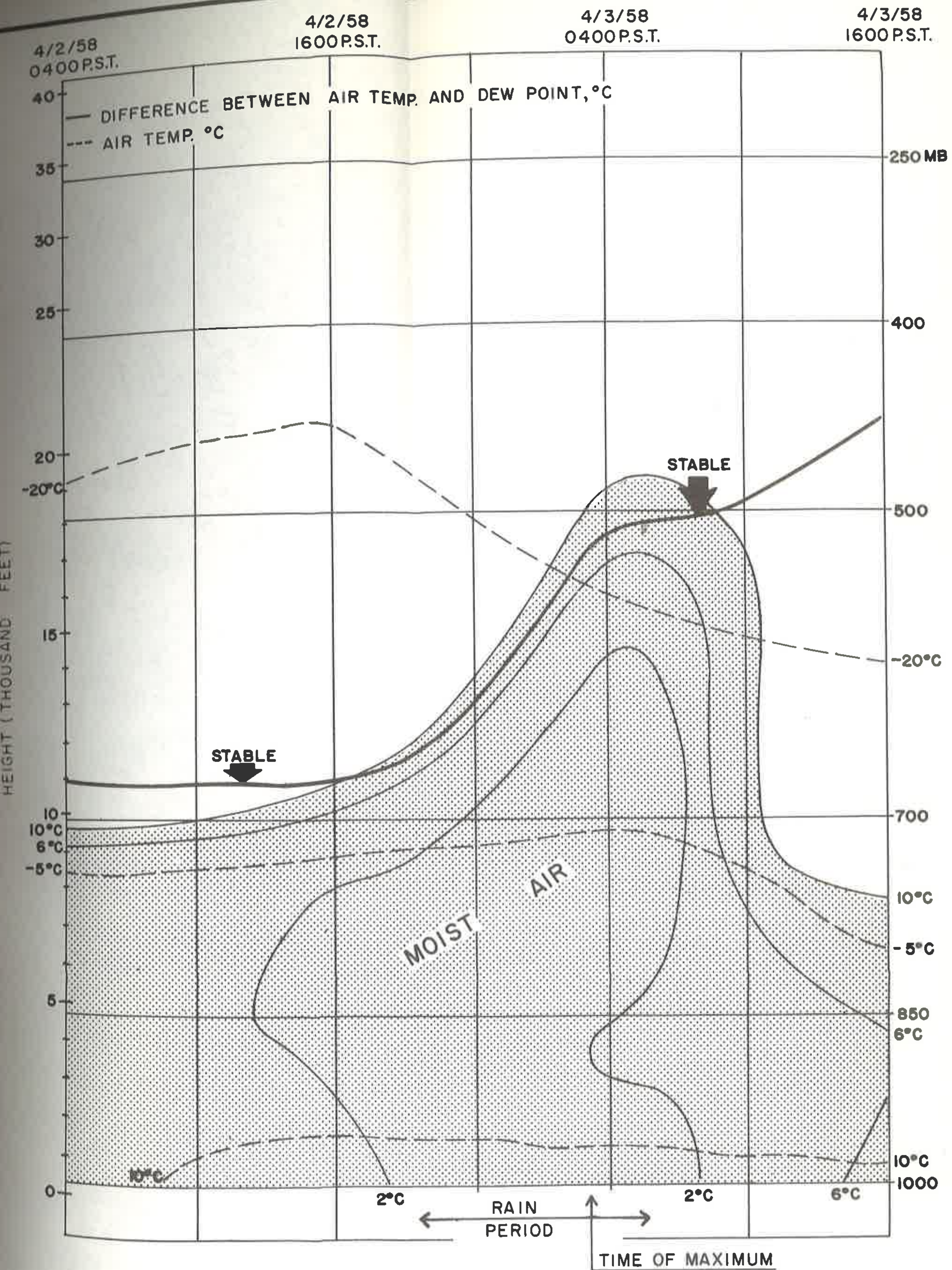

Fig. VI-4 TIME-HEIGHT STORM STRUCTURE

METEOROLOGY RESEARCH, INCORPORATED

SANTA BARBARA WEATHER MODIFICATION PROJECT

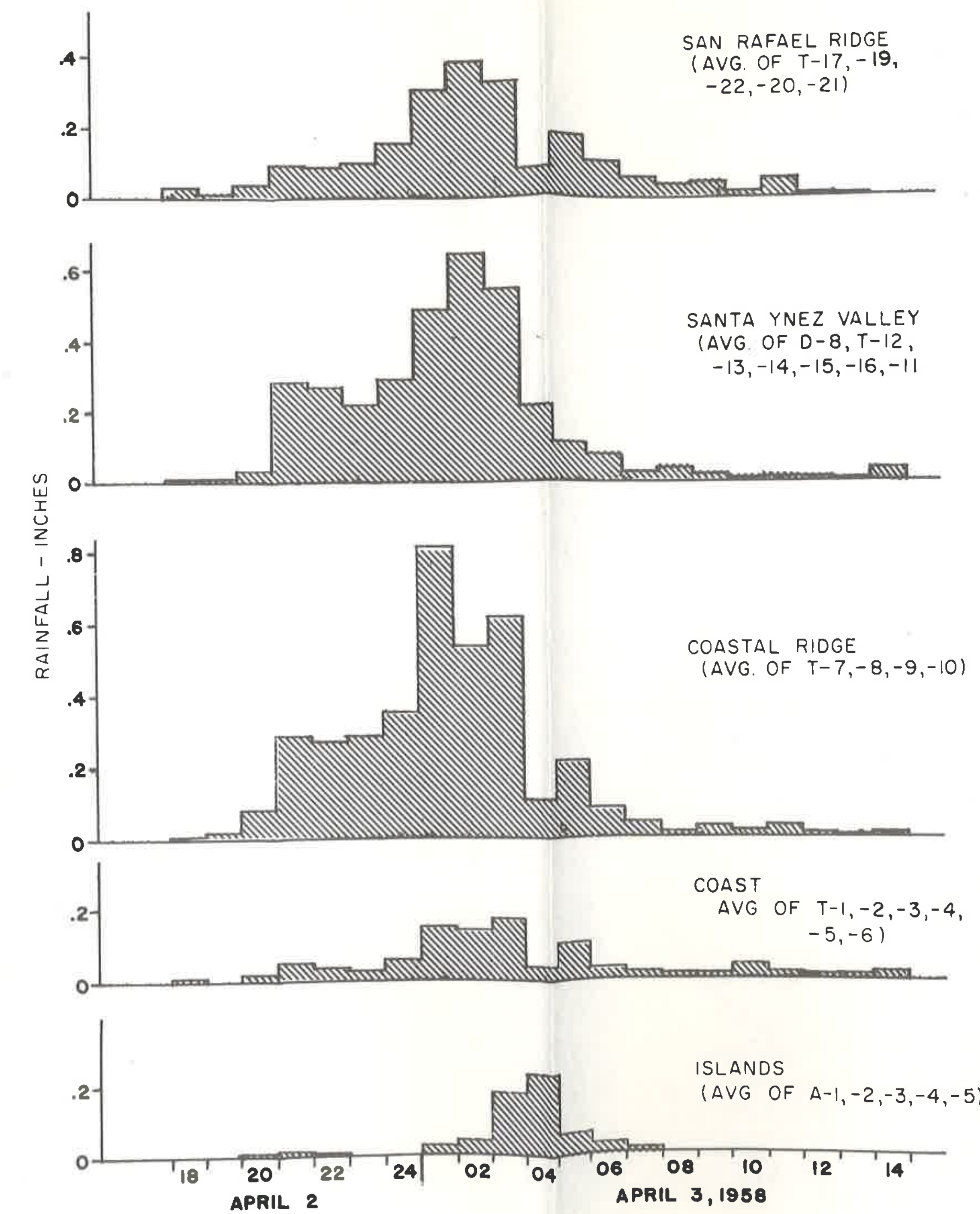

Fig. VI-8 HOURLY RAINFALL AMOUNTS

STORM OF APRIL 2-3, 1958

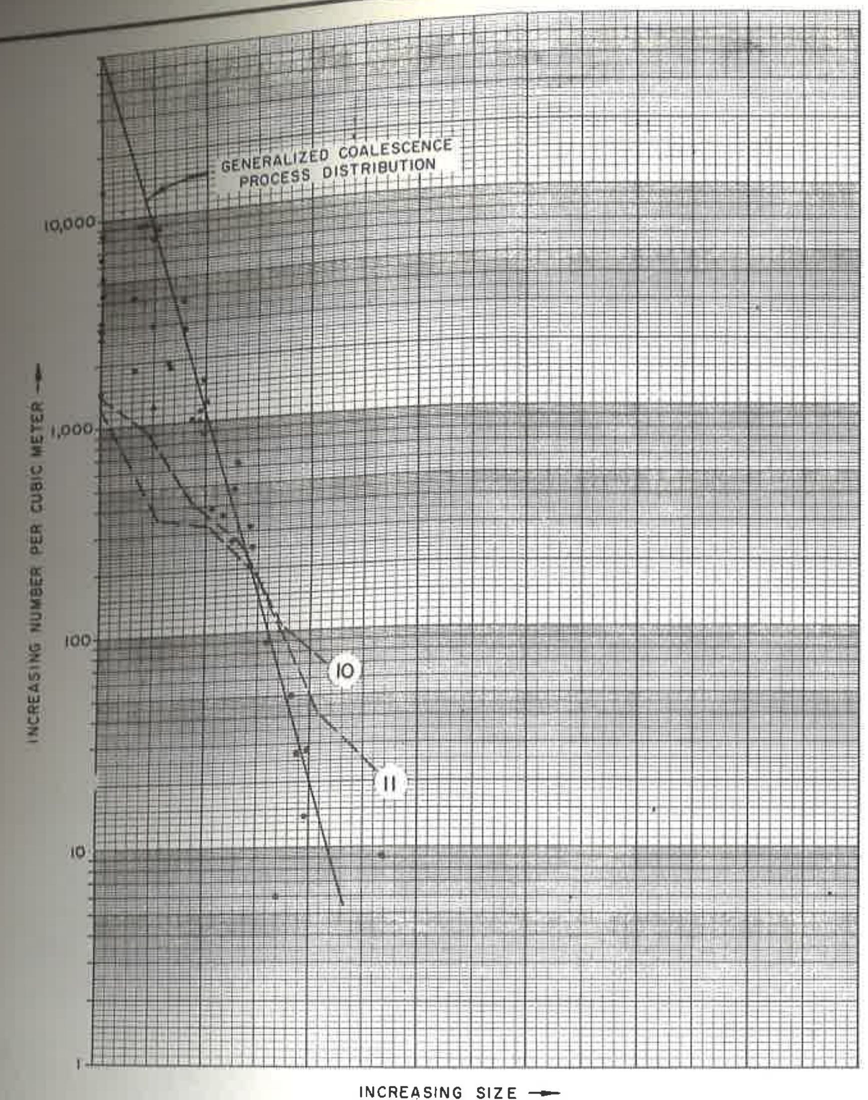

Fig. VI-5 WATER RAINDROP SIZE DISTRIBUTION
APRIL 2, 1958
SAMPLES 10 & 11

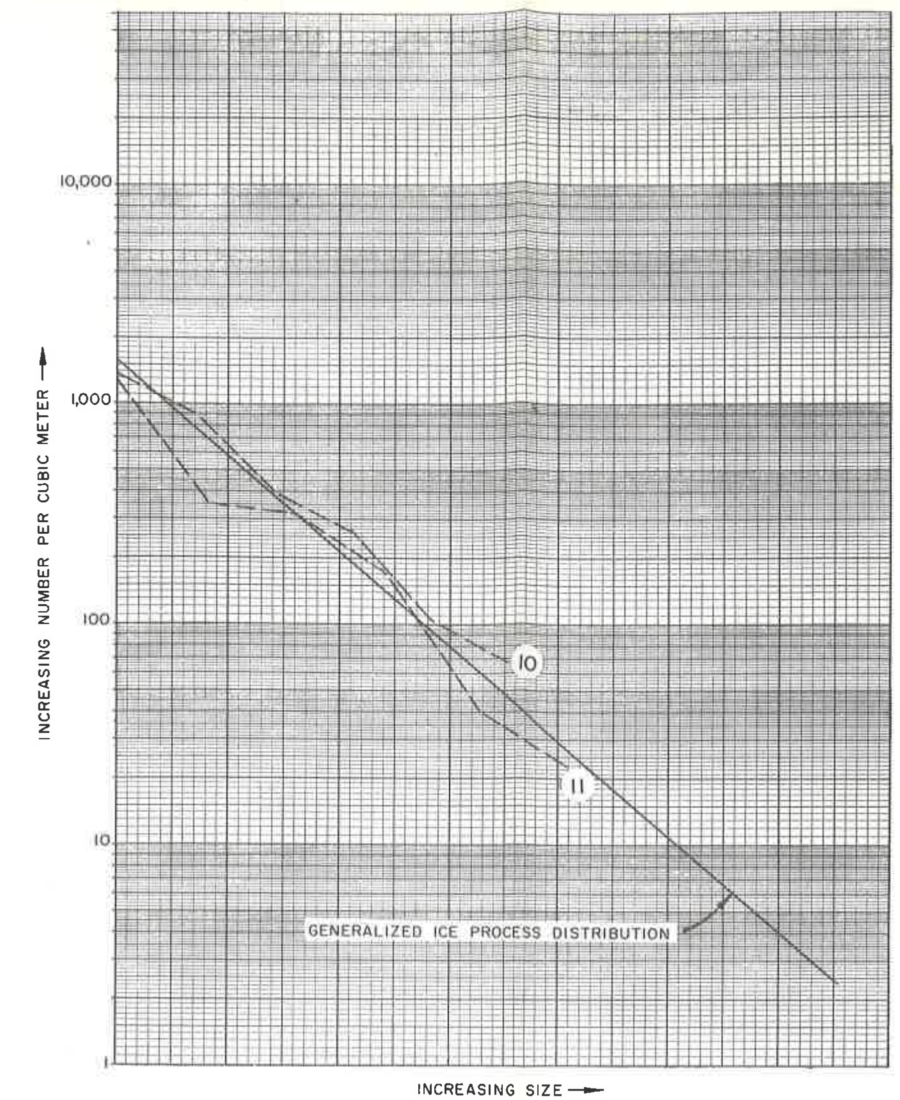

Fig. VI-6 ICE RAINDROP SIZE DISTRIBUTION
APRIL 2, 1958
SAMPLES 10 & 11

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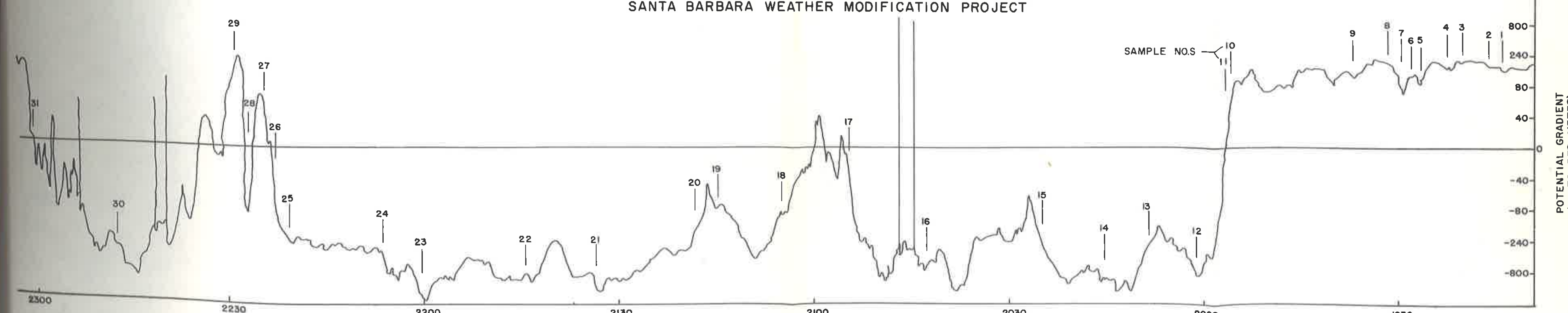

Fig. VI - 7 TIME IN HOURS
APRIL 2, 1958

RAINDROP SIZE STUDIES

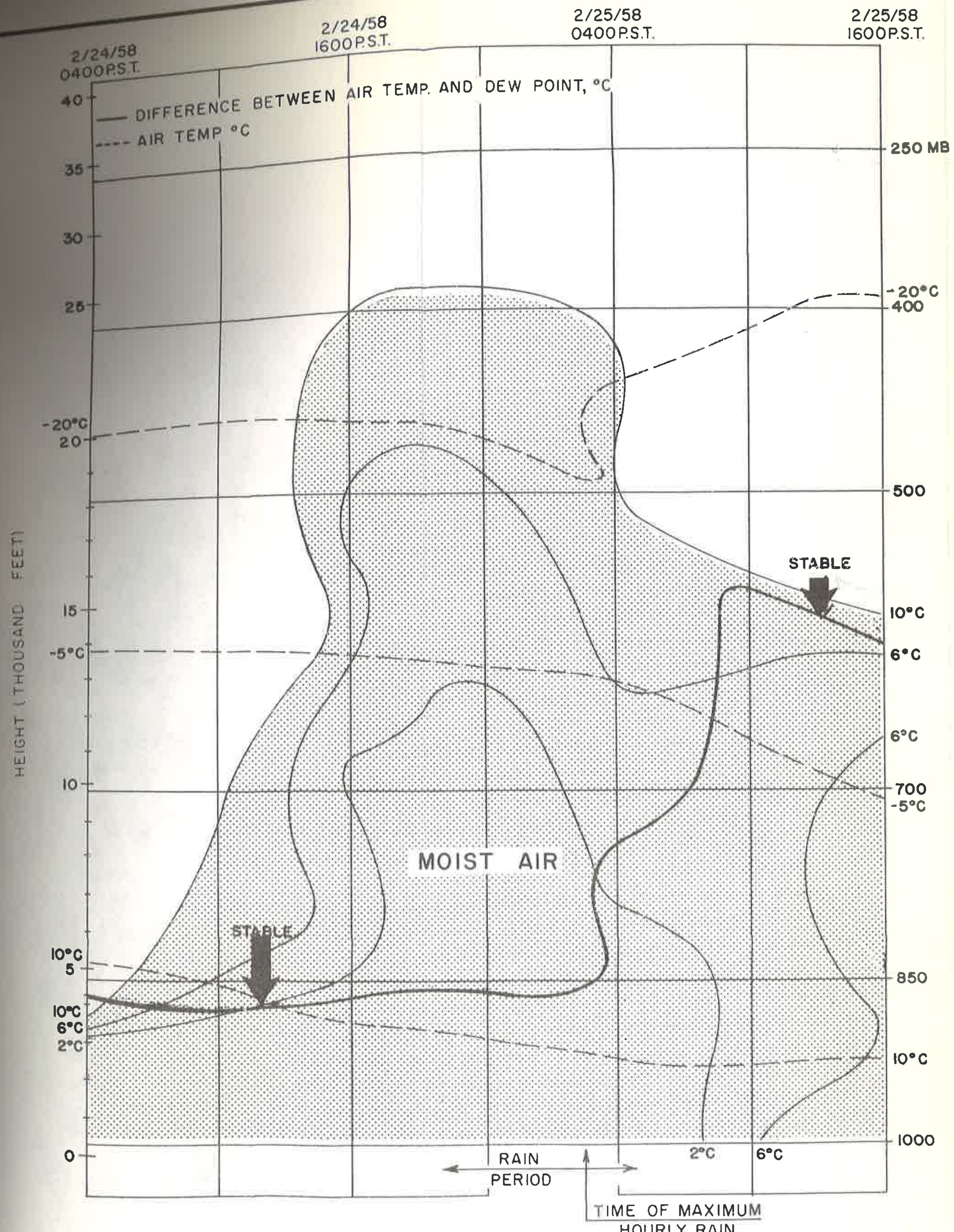

Fig. VI-9 TIME - HEIGHT STORM STRUCTURE

METEOROLOGY RESEARCH, INCORPORATED

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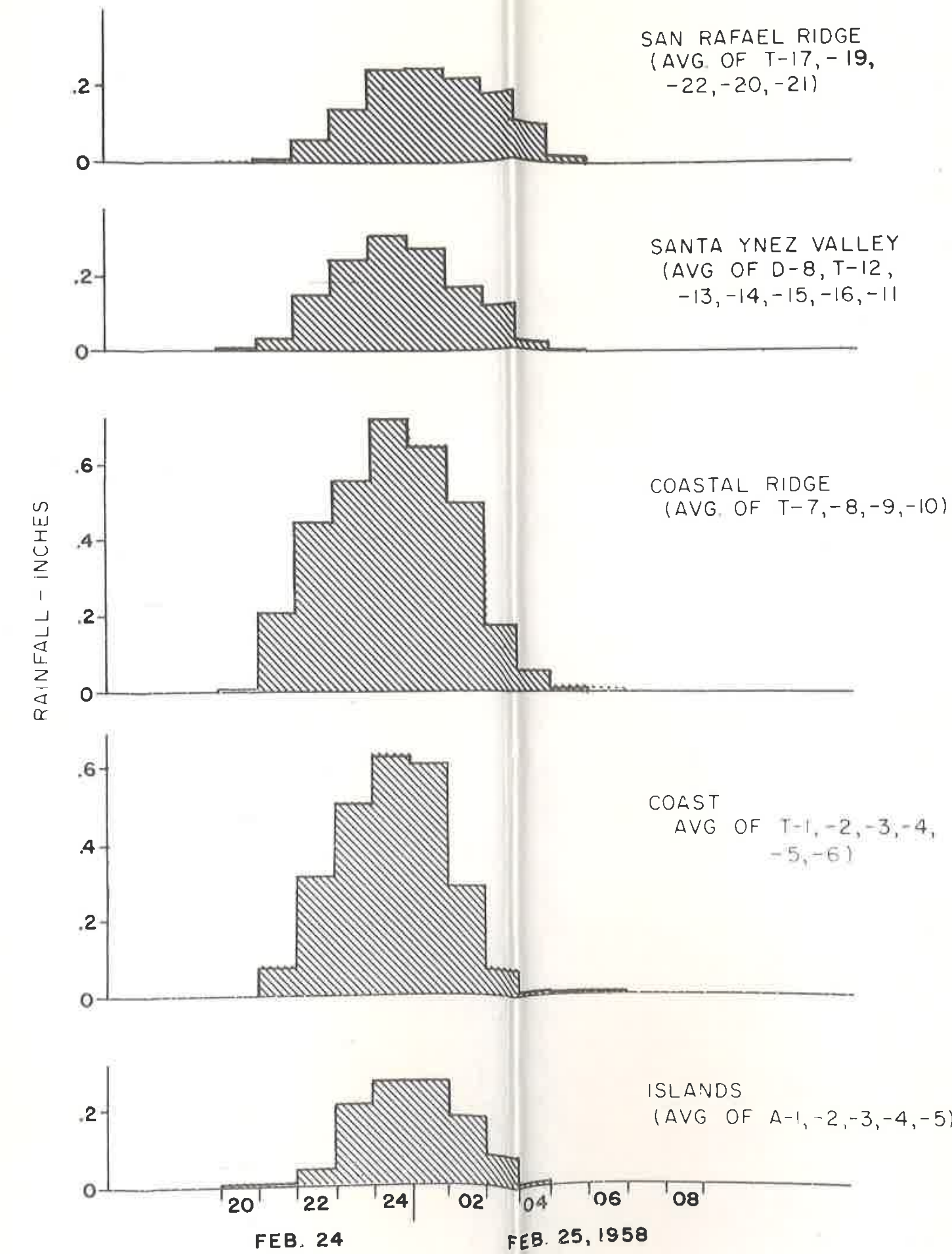

Fig. VI-10 HOURLY RAINFALL AMOUNTS

STORM OF FEBRUARY 24-25, 1958

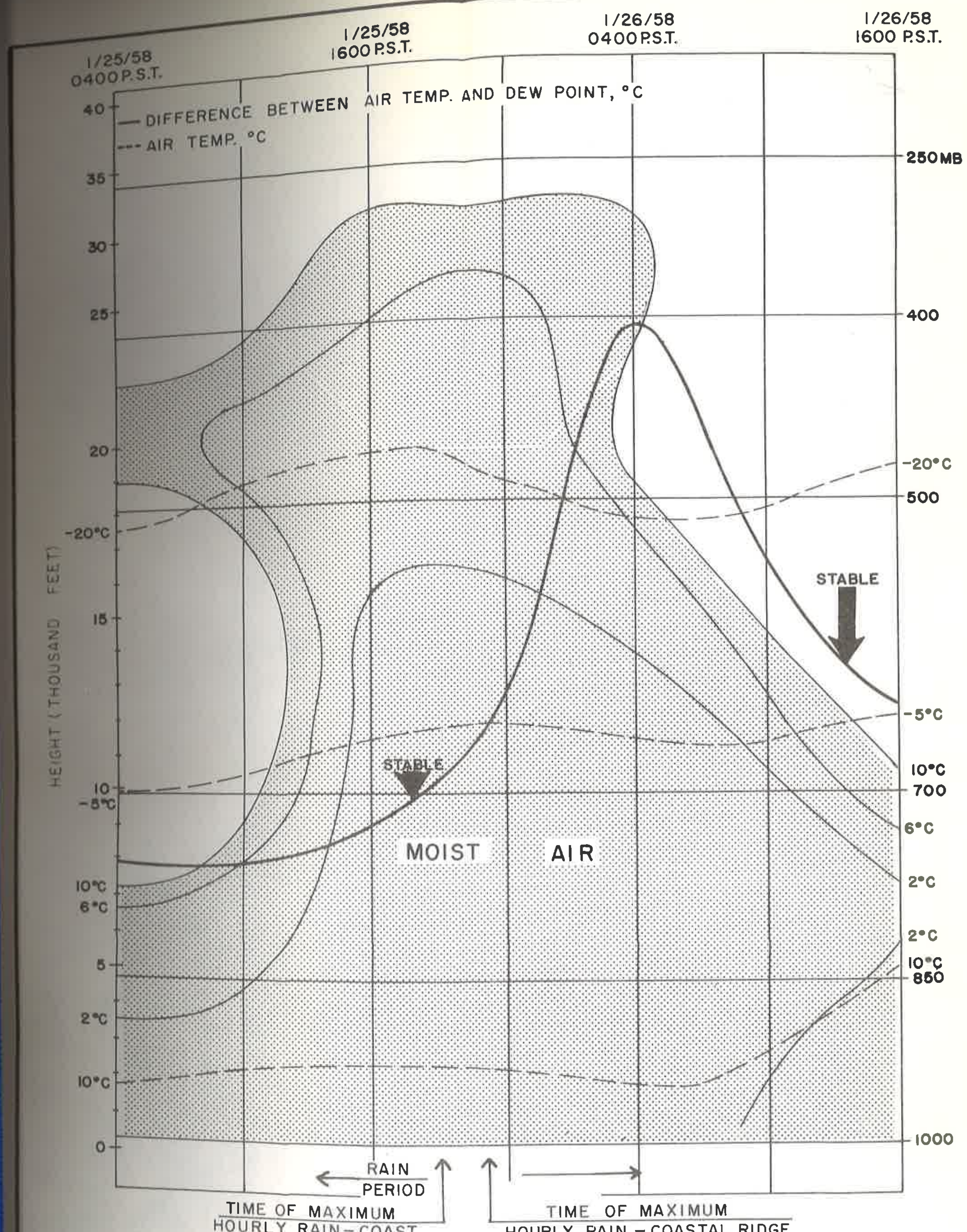

Fig. VI-11 TIME-HEIGHT STORM STRUCTURE

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SANTA BARBARA WEATHER MODIFICATION PROJECT

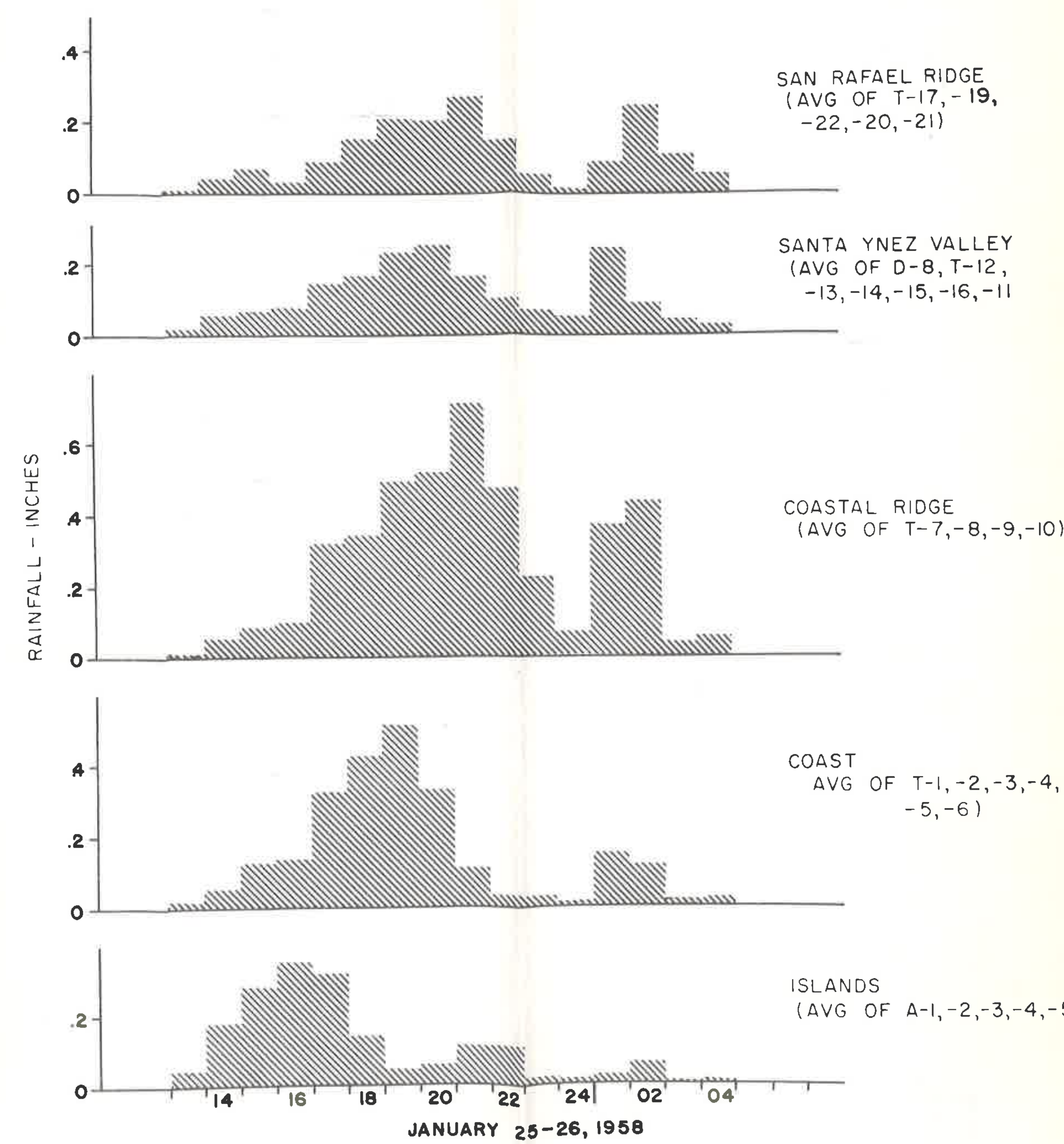

Fig. VI-12 HOURLY RAINFALL AMOUNTS

STORM OF JANUARY 25-26, 1958