Don Griffith

SANTA BARBARA CONVECTIVE BAND SEEDING TEST PROGRAM

FINAL REPORT

Submitted to

UNITED STATES NAVAL WEAPONS CENTER

EARTH AND PLANETARY SCIENCES DIVISION

CHINA LAKE, CALIFORNIA

Contract No. N00123-75-C-0047

By

NORTH AMERICAN WEATHER CONSULTANTS

REPORT NO. 6-135 JUNE 1975

ABSTRACT

Tests to determine the effectiveness of seeding convective portions of winter storm systems passing over Santa Barbara County were conducted from a 1065 meter mountain ridge using a pyrotechnic fusee during four winter seasons from 1967-68 through 1970-71 (Phase I).

After an experimental period in 1970-71, full scale Phase II aerial operations were continued through the 1973-74 seasons. Aerial seeding using an AgI-NH_4I-acetone solution was conducted just west of Santa Barbara County with the nucleant being dispensed by a burner developed by the Naval Weapons Center. A limited amount of seeding was also conducted from the mountain ridge site utilizing a modified version of the Naval Weapons Center acetone burner.

Organized areas of convection (convective bands) were identified and tracked through the project area by means of telemetered raingages and radar. In both phases, the program was randomized with approximately one half of the convection bands being seeded. However, the randomization scheme in Phase II was revised so that all the convection bands which occurred in a given storm period (48 hours duration) were similarly treated (either all seeded or all not-seeded).

The primary mode of evaluation was a comparison of rainfall from bands with a test area of about 27,000 square kilometers containing approximately 100 raingages available for analysis. Single ratio analyses of seeded to not-seeded convection band precipitation, band duration, and storm precipitation are presented. It addition, several analyses based on temperature, wind direction, and pressure distributions were made to investigate mesoscale effects related to seeding.

On the basis of the statistical results, it is concluded that seeding convective bands is an efficient means of augmenting water supplies with increases on the order of 50 to 100% indicated within seeded bands.

TABLE OF CONTENTS

Section (Cont'd)

APPENDICES

Figures Page

Figures		Page

SANTA BARBARA CONVECTIVE BAND SEEDING TEST PROGRAM

FINAL REPORT

1. INTRODUCTION

The Santa Barbara Project was initiated in the fall of 1967 by North American Weather Consultants (NAWC) to test the effectiveness of various seeding devices and seeding modes in west coast cyclonic winter and spring storms. The study area of the program covers Santa Barbara County and portions of adjacent counties as shown in Figure 1-1. All seeding was conducted during the passage of organized convective activity (convection bands) through the project area. The initial phase of the project (Phase I) ran from the 1967-68 season through the 1970-71 season. During this period, the primary seeding mode was ground based seeding from a mountain crest (1065 meters MSL) using high output pyrotechnic fusees, which were ignited at intervals during the passage of convection bands.

The primary seeding mode during Phase II was aerial seeding with a continuously burning acetone-AgI-NH_4I jet seeder developed by the Naval Weapons Center (NWC). Officially, Phase II began in the fall of 1971 and continued through the 1973-74 season. A limited amount of experimental aerial seeding was conducted during the 1970-71 season concurrent with the Phase I ground operations and this experimental seeding has been included in the Phase II operations. The ground based seeding mode was also continued during Phase II as a backup method when aerial seeding was not feasible for any reason. However, the ground seeding was conducted with a ground version of the acetone-AgI burner developed at NWC instead of the pyrotechnic devices used during Phase I.

This report will summarize the results of the Phase I operations and will report in detail on the results of the Phase II operations.

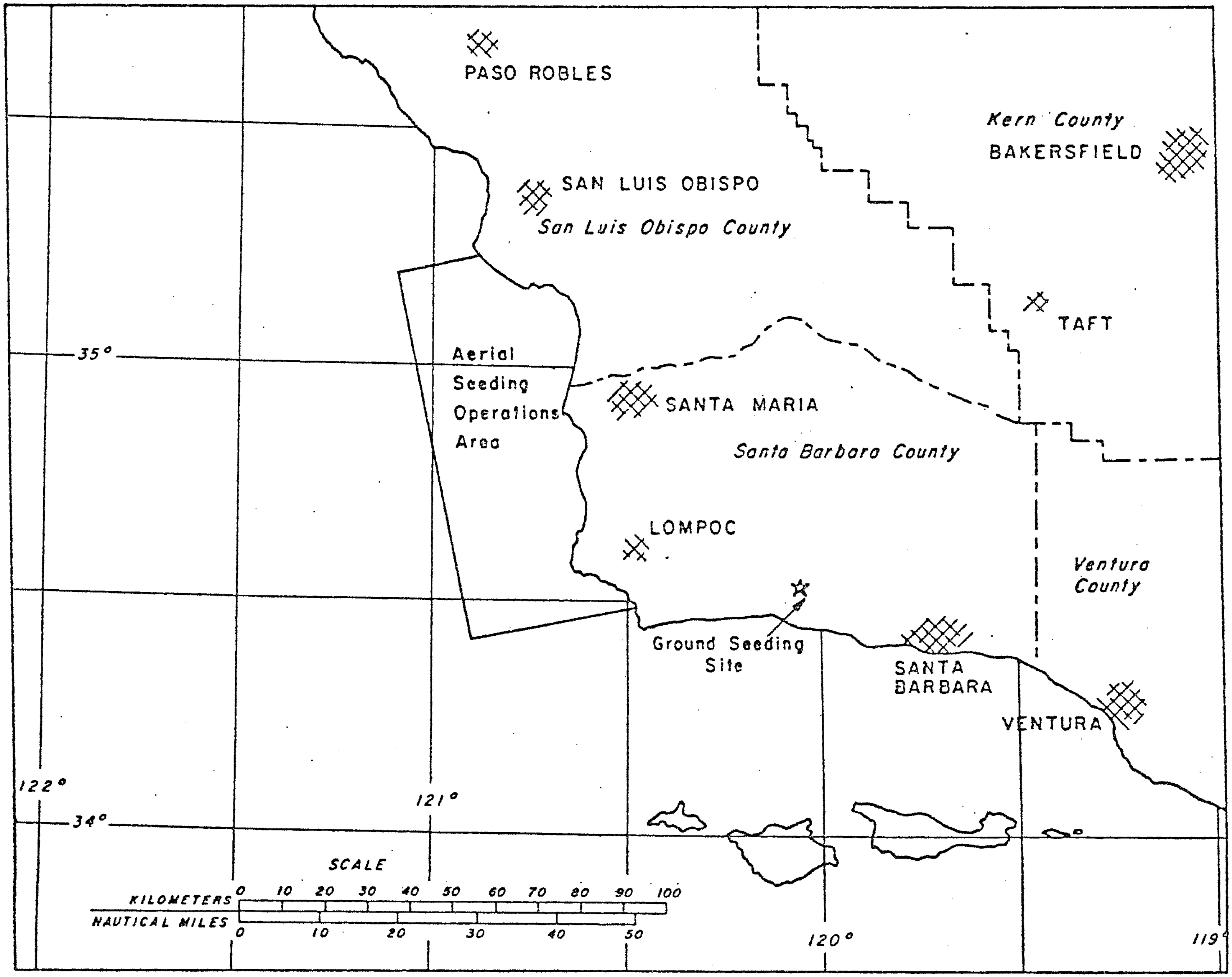


Figure 1-1. Map of Santa Barbara County project area and adjacent counties.

2. PROJECT DESIGN AND HISTORY

2.1 Convective Band as a Unit

Historically, the choice of the observation unit to be used in a research cloud seeding project has been a trade-off between selecting a unit which is of long enough duration to be clearly identifiable and trackable and yet short enough to provide a sufficiently large sample. In some situations, an individual cloud may be an adequate unit, as in a summertime cumulus seeding test. Often, a complete storm period has been used as the observation unit. These units are based on identifiable physical mechanisms, an approach which enables the investigator, for example, to follow the life cycle of the system for treated and non-treated cases. Another type of observational unit is based on a finite time period such as an hour, a day, or a season. This approach tends to force the mixing of different physical mechanisms within a single unit and thus to reduce the sensitivity of the test and to confuse the physical interpretation of results. A clear physical interpretation is the key to transferring knowledge of seeding effects gleaned in one area to another area possessing differing terrain features and storm synoptic climatology.

The use of the convective band as an observation unit in winter storms originated from an investigation of the cloud-water budget of Pacific storms by Aerometric Research, Inc., (an affiliate of NAWC) under contract to the National Science Foundation during the period 1961-64 (Elliott and Hovind, 1964a; 1964b; and 1965). This study showed the presence of organized convective bands within extra-tropical winter cyclones and made it possible to distinguish between the mean storm motion precipitation component, the orographic precipitation component, and the augmentation of precipitation rates caused by the organized convection bands.

A number of other researchers have studied convective bands in various parts of the world. Kuettner (1959), Winston and Tourville (1961), and Malkus (1963) have all reported visible evidence of banded cloud patterns. Harper and Beimers (1958), Boucher and Wexler (1961), Browning and Harrold (1969), Harrold (1973), Kreitzberg and Brown (1970), and Browning, et. al., (1973), have all studied the structure of rain bands using precipitation gages and/or observations and aerological measurements to explain the mechanisms controlling the formation and movement of these bands. Convection bands not only produce most of the storm precipitation in west coast storms, but also contain the strong updrafts and supercooled water most conducive to cloud seeding effectiveness. Bands typically last about one to one and one half hours at a given station (although some last much longer) and are spaced about three to four hours apart. An average of three seedable convection bands per storm is typical, although the number may vary from one to as many as six or more.

The distribution and approximate percentage of precipitation that can be expected to occur in bands is illustrated in Figure 2-1. This figure, which utilized data collected in the period 1971-74, was prepared by dividing the precipitation observed during identified band passage (both seeded and not-seeded) by the total storm precipitation to obtain the percentage of precipitation that fell during band passage at each station. Since operational constraints did not allow that every convection band in every storm be identified, some band precipitation was undoubtedly included in the denominator of the equation with the net effect that the percentages are conservatively low; perhaps as much as 10% lower than if all the band precipitation which occurred was assigned to the numerator. At any rate, Figure 2-1 indicates that better than 50% of the precipitation occurring in storms affecting the main area of interest (Santa Barbara County) does fall during band passage with percentages in excess of 60% along the immediate coastal strip and extending inland some 40-50 kilometers in the western portion of Santa Barbara County. A second area with band precipitation in excess of 60% is located in the southwestern portion of Kern County. This area, which is 100-150 kilometers downwind from the seeding zone, may reflect a higher percentage of band precipitation than the adjacent regions due to the fact that bands which were seeded in Santa Barbara County appear to extend into the "dry" portions of Kern and San Luis Obispo Counties more than do the not-seeded bands.

Those areas of the figure which reflect less than 50% of the precipitation occurring in bands are located in the higher elevation portions of the counties suggesting that much of the precipitation there is due to orographic effects.

2.2 Phase I Design

With the decision made that the observation and seeding unit would be the convective band, it was necessary to select a site suitable for testing the effectiveness of ground-based seeding using the high output pyrotechnic device. It was desirable to locate the seeding site at an elevation high enough to be near the base of convection and above the cool marine layer which affects the area near the coast. Conveniently, the Santa Ynez Mountains, which average over 1000 meters at crest line, are located only a few kilometers north of Santa Barbara. A survey of the area located a suitable spot (known as El Capitan Lodge) at the 1065 meter level within 20 km of the NAWC office and a seeding site (see Figure 1-1), was established utilizing

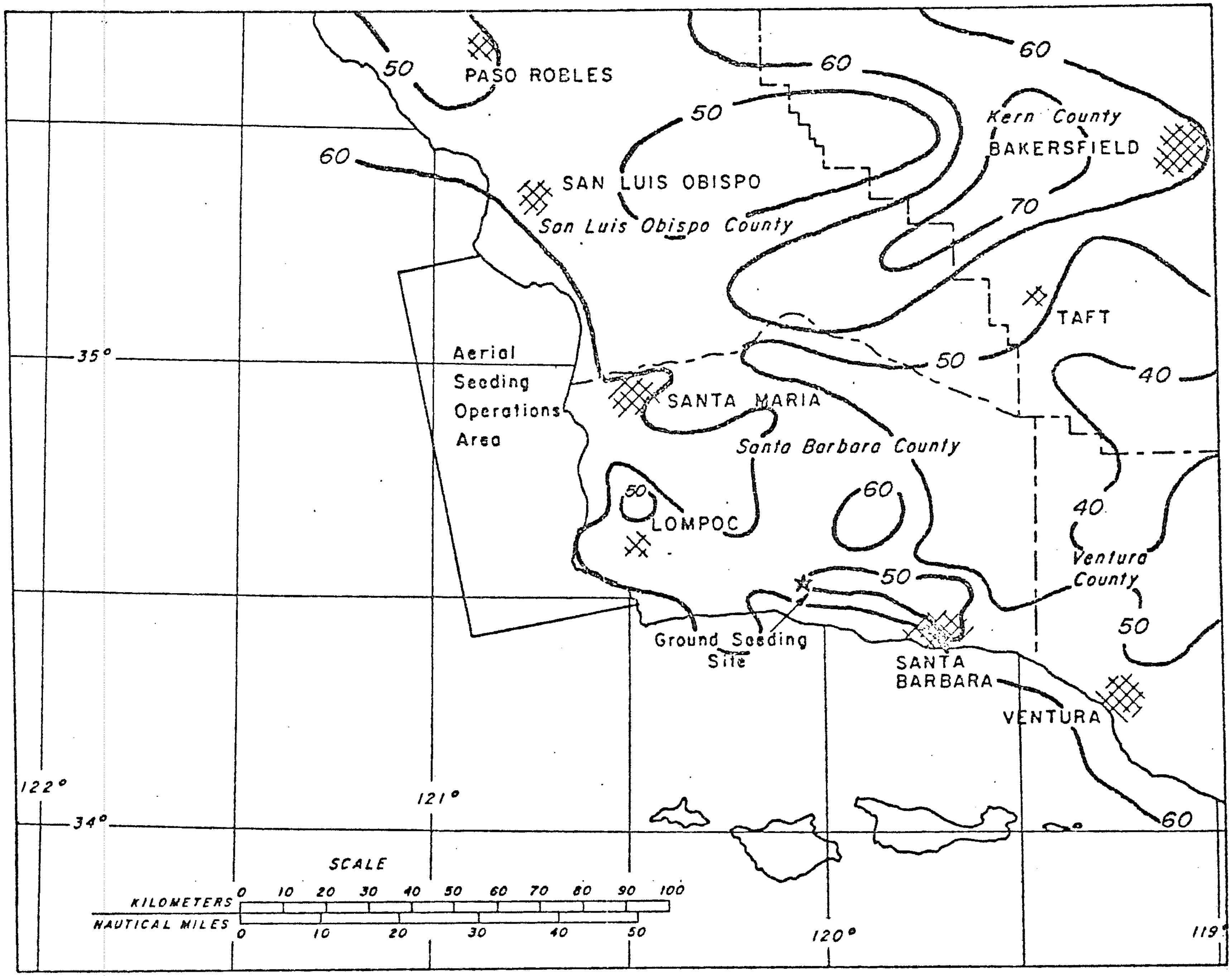


Figure 2-1. Approximate percentage of precipitation occurring in convection bands, 1971-74 seasons.

a mobile trailer for radar and personnel shelter with two-way radio communication to the NAWC operations center at the Santa Barbara Airport.

The principal method of assessing the success or failure of the seeding operations was through a detailed analysis of a dense recording raingage network available in Santa Barbara and adjacent counties.

The raingages in the western portion of the county, approximately from Lompoc northward to Santa Maria, were designated "control area" gages. The rest were designated "test area" gages. Within the control area, six raingages with consistently good record were used in the evaluation methods which are described in a later section.

A detailed discussion of the topographic features of the project area and a map of the test and control areas showing raingage locations is also presented in a later section of this chapter.

The key to a successful operation was in the accurate identification and tracking of the convective band. Therefore, certain guidelines had to be established and rules formulated to insure continuity in the selection of bands.

A purely objective definition of band configuration would have to be based upon:

- Point precipitation intensity changes
- Continuity between stations
- Discrimination between individual cells and the band (group of cells arranged in a line)

The formulation and application of such a rigid procedure to the real time situation where weather radar and other observational data would also be employed, was out of the question. Accordingly, professional judgement, under a set of band detection guideline criteria (see below) was applied by the Project Director. He did not know whether a particular band was to be seeded or not, so his decisions were not biased.

2.2.1 <u>Band Detection Guideline Criteria</u>. Selection of these criteria was based in part on our knowledge of band and cell structure and in part on the equipment network and characteristics of the individual instruments. For ground seeding, a philosophy was adopted that, to qualify as a band, precipitation associated with it should reach a minimum rate of rainfall increase for a minimum period of time at one of the telemetered stations, to be considered eligible. Since a single cell at a single station could meet any such criterion, additional evidence had to be collected to confirm the existence of a band. This could be in terms of precipitation rate at another telemetered station or radar observations if credible. When all the necessary criteria were met, the band was confirmed and then either seeded or not-seeded depending upon the random selection.

2.2.2 General Seedability Guideline Criteria. The general seedability criteria were faily well known from past applications and can be summarized as follows:

a) The wind flow was to be such that with the existing thermal structure, the effects of the seeding would fall mainly in the area to the north and/or east of the seeding site.

b) The air mass structure should be such as to insure mixing from the seeding site to the -4°C level or higher.

In general, strict application of (b) was not made, but rather, those cases that conformed to (a), and to the band detection guideline criteria, were treated. It was not possible to adhere to condition (b) since bands arrived at the radiosonde site and the NAWC office simultaneously or later than at the seeding site. The radiosondes were launched just as the band arrived and this made it impossible to determine the air mass structure of the band until it had passed the seeding site. Therefore, all bands that met condition (a) were considered seedable, regardless of condition (b).

To perform comparisons of seeded and not-seeded cases, it was decided to seed about half of the convection bands passing through the area. This required identification and tracking of the band from the upwind area into the test area. Tracking was done using real-time telemetered information from raingages in the upwind area into the NAWC operation center. Use was also made of weather radar information from a modified 3 cm marine radar, supplied by the Navy, and installed and operated by NAWC personnel from the seeding site which offered an unobstructed view of the upwind areas. This radar had an effective range of 55 kilometers, except when attenuated by precipitation. With its limited range, it was frequently unable to identify accurately a convection band before the band had been identified by telemetry. Because of its proximity to the ocean to the south, the radar was most useful in tracking bands moving from the southwest. When an identified band reached the seeding site, a predetermined random decision was read by the personnel at the site and, if the band was to be seeded, a pyrotechnic fusee was ignited. Additional fusees were ignited every 15 minutes until the band passed the seeding site.

The pyrotechnic device employed was the LW-83 formulation (Table 2-1) in the form of a fusee 1-1/2 inches in diameter by 11-1/2 inches in length.

Table 2-1. LW-83 Formulation.

Component	% by Weight
$AgIO_3$	78 (481 grams/unit)
AI	12
Mg	4
Binder	6
	100

AgI output (calculated): 65% (399 grams/unit)

Number of effective nuclei/gm AgI: 10^{13} (-10°C), 10^{14} (-15°C)

Curves showing the number of nuclei produced per gram of AgI for both the LW-83 pyrotechnic and the aerial jet seeder are shown in Figure 2-2.

When ignited, the unit burned for about three minutes, emitting 399 grams of silver iodide, in smoke form, giving a single source total output of 1596 grams hr^{-1} in the mode employed.

During the course of the storms, soundings were made at frequent intervals with the GMD-1 equipment at the Santa Barbara Airport. These soundings, along with others taken at nearby Government installations, were later used in the analyses in determining the air-mass characteristics of each band.

In the design of the program, it was necessary to develop a preliminary seeding model which would predict, under average conditions, the area of effect, i.e., the area where precipitation enhancement could be expected. This model's prediction is portrayed on the map in Figure 2-3. The predicted area of effect is hatched. Note that the hatching is heavier on the upwind side of the target area, to indicate a stronger seeding effect. The basis for this model is as follows: After release from the seeding site, the nucleating smoke follows a low-level trajectory until it moves near to a convection cell in the advancing band. Entrainment into this cell could occur immediately at the seeding site or as much as fifteen kilometers downwind in the low-level flow. Since the cells are normally spaced at intervals of 10 to 15 kilometers, a drift of 15 kilometers was chosen to be the upper limit.

The figure also shows the characteristic low-level flow for the 1000 meter level under storm conditions. It is known from previous work in this area and from observations made on this project, that with a southwesterly flow at the Santa Barbara Airport, there is a sharp backing of the wind as it approaches the southern crestline

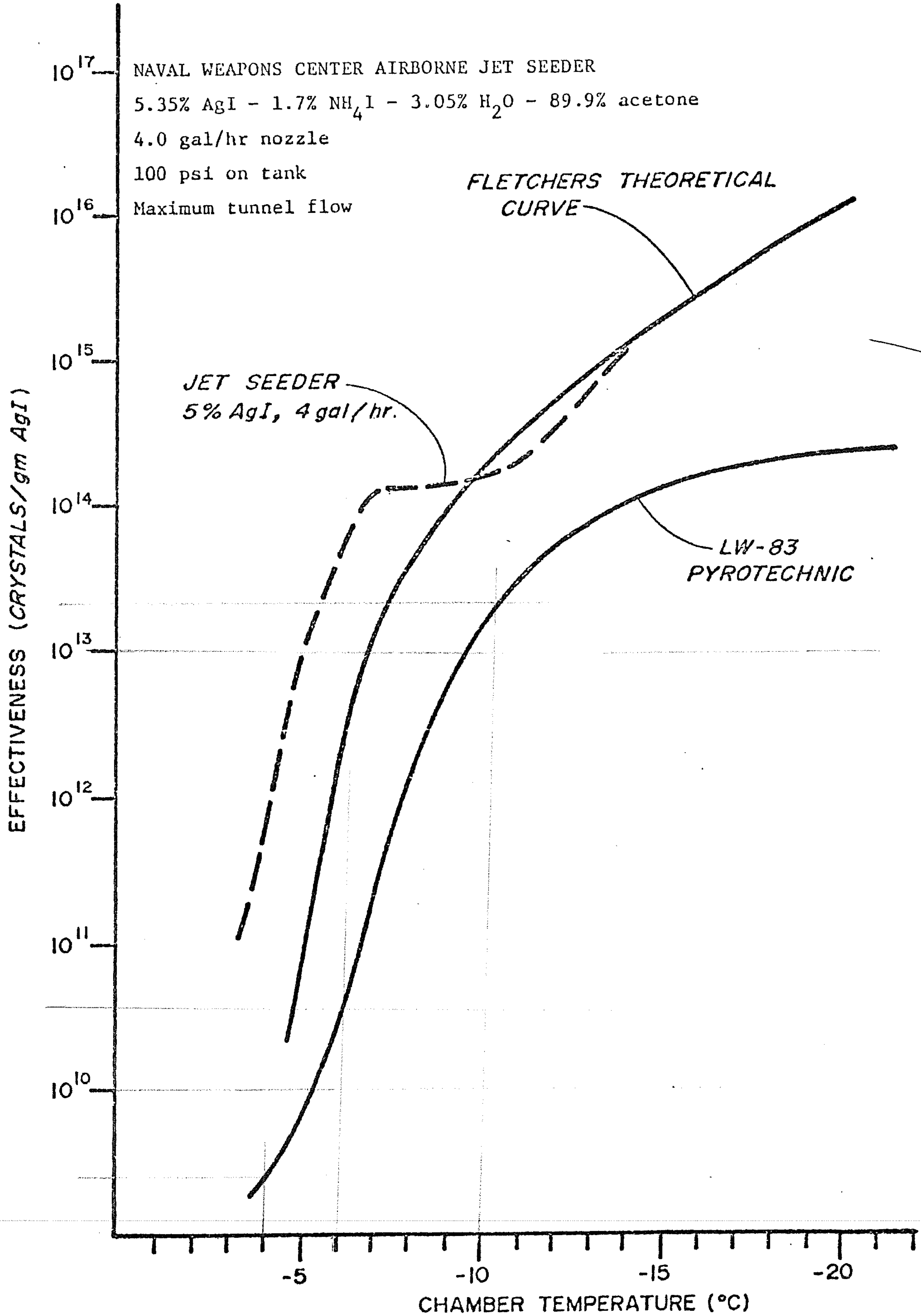


Figure 2-2. Comparative effectiveness of AgI generators. (Tests conducted at the Cloud Simulation and Aerosol Laboratory, Colorado State University, March and May, 1972).

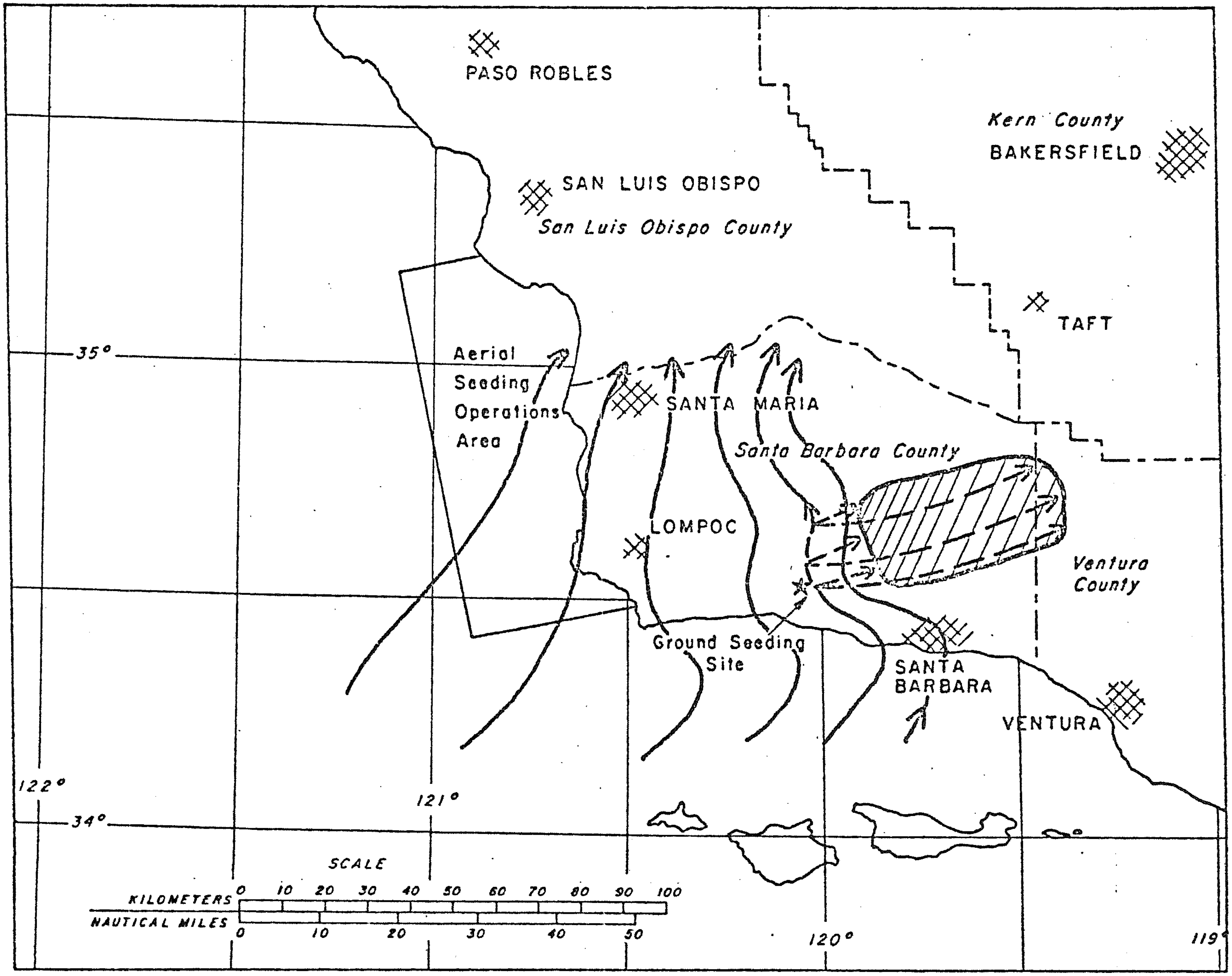


Figure 2-3. Typical storm 1000 m flow and design area of effect for ground seeding.

so that south to southeasterly winds occur there. Due to the constriction of flow over the crest itself, wind speed there exceeds that in the free air. The dashed arrow pointing from the seeding site to the northwest and north represents an effective mean line source of 15 kilometers. The 3 short arrows indicate the trajectory of precipitation particles formed at the -5°C level as they fall to the ground while the 3 longer dashed arrows describe the trajectory of precipitation formed at the -20°C level. At higher levels, glaciation would presumably lead to a very flat trajectory, with no measurable reflection in surface precipitation.

Due to the large number of nuclei produced at relatively warm temperatures by the LW-83, it was anticipated that large numbers of crystals would become effective at the -5°C level and accordingly, rapid growth would occur there, reducing the reservoir of upward moving cloud water available for transformation to precipitation at higher levels. This would lead to the production of heaviest fallout just downwind of the -5°C trajectory end point, as indicated in the figure. The details of the area of effect model employed later in the analysis appear in Appendix G. A more complete treatment is presented in another publication (Elliott, 1969).

2.3 Phase II Design

Consideration of the results achieved with fixed-point ground seeding suggested that more extensive effects might be obtained by seeding from an aircraft flying at or near the freezing level, along a 30 to 60 kilometer track within the band and transverse to its direction of movement. Confining such seeding to an area within 10 to 30 kilometers of the coast, upwind of the centroid of the instrumented area, would allow more effective use of the entire instrument network for assessment. This operational mode was tested, using a commercial nucleant generator burning an AgI-NH_4I-acetone solution (St. Amand, et. al., 1971a; Finnegan, et. al., 1971) aboard a light aircraft under radar control from Vandenberg Air Force Base (see Figure 1-1), on seven bands (three seeded, four unseeded) during the 1970-71 season. Although this sample was inadequate for statistical analysis, the results obtained were sufficiently encouraging to warrant adoption of this operating mode for the next phase of the program, which commenced with the 1971-72 winter season. It was also decided to augment the program data-gathering capabilities to include (1) airborne visual and instrument observations within and between bands, (2) radar measurement of cloud-top altitudes, and (3) radar PPI observations from several locations, to monitor the movement and evolution of the convection bands approaching and transversing the target area.

Several changes in experimental design were dictated by the new operational mode. Use of an aircraft for within-cloud seeding called for (1) a volume of air-space in which instrument (IFR) flight could be carried out without interference with other aerial activity, and without problems of terrain clearance, (2) a means for reliably identifying and locating suitable convection bands upwind of the seeding zone (as noted above, in the previous phase this function had been provided by a set of telemetered raingages in the upwind control area, augmented by a small X-band radar installed at the seeding site), and (3) an aircraft surveillance and control system for directing the seeding aircraft to suitable portions of the band, and insuring operational safety. Conveniently, all of these requirements were met by the facilities of the Air Force Western Test Range, headquartered at Vandenberg AFB, at the western edge of the project area. Virtually all of the airspace off the western and southern coasts of Santa Barbara County is subject to reservation for test purposes by the Air Force, either alone or conjointly with the Navy's Pacific Missile Range at Pt. Mugu, in southwestern Ventura County. Since seeding operations would be conducted during storm conditions, minimal interference with range activities or civil flights would be expected. The 1970-71 tests showed that the 500-kw ARSR L-band (23 cm) air surveillance radar located at South Vandenberg, suitably adjusted, could provide sensitive long range detection and surveillance of convection bands, while the experienced and highly qualified Air Force air traffic control staff could direct the maneuvers of the seeding aircraft. The cooperation of Air Force, Navy, and Federal Aviation Agency authorities was solicited and readily obtained.

One criticism of the band-by-band randomization scheme employed in the preceding phase of the program was that, although it did provide adequately for the possibility of interactive effects between a seeded band and unseeded bands preceding or following it within a given storm, it did not permit the testing for any multiplication effects which might occur if all bands within a given frontal zone were seeded. To meet this objection, a randomization mode, based upon a rigid 48-hour time block, was adopted in which, during the 48-hour period subsequent to the onset of precipitation, each convection band was treated in accordance with the randomized decision for the block as a whole. Since storms in this area have typical durations of between twelve and thirty-six hours, this provided effective randomization on a storm-by-storm basis, while retaining the advantage of large sample size provided by statistical treatment of rainfall data for individual bands.

The LW-83 pyrotechnic flares provided by the Naval Weapons Center for the first phase of the program represented the most efficient ground-based source of freezing nuclei available in 1967 (St. Amand, et. al., 1970); their effectiveness is attested to by the results obtained by their use. An alternative method for generation of AgI nuclei is by the combustion of a solution of AgI and an alkali iodide in acetone. The alkali iodide assists the process by forming a soluble complex with the silver iodide, which by itself is not soluble in acetone (Vonnegut; 1949, 1950). "Acetone burners" have been employed in weather modification programs for over two decades; the results have been highly variable and inconsistent. A recent reconsideration of the nature and properties of acetone burner output products has led to the realization that these inconsistencies resulted chiefly from the almost universal employment of sodium or potassium iodide as the solubilizing agent. The combustion products from such solutions are complexes and mixtures of AgI with NaI or KI, which may be rendered temporarily or permanently ineffective as freezing nuclei by hydration upon contact with atmospheric moisture. When, however, as proposed by Vonnegut in 1949, ammonium iodide (NH_4I) is used as the solubilizer, the only solid product of combustion is AgI. This solution is therefore definitely to be preferred for in-cloud or cloud-base seeding (St. Amand, et. al., 1971b). In view of the cost and safety advantages offered by the acetone burner, especially for aircraft use where horizontal dissemination is desired, this approach was selected for the aerial seeding phase of the program. Initial tests were performed during the 1970-71 season, using a commercial (Lohse) acetone burner originally designed for light aircraft use with NaI and KI-based solutions. Although generally successful, these tests revealed some problems associated with the high concentrations of the AgI-NH_4I acetone solutions employed, and with their corrosive reactions with some of the materials used in constructing the burner. Development of a more sophisticated burner was therefore undertaken at NWC during 1971. This new ramjet generator was first operated during the 1971-72 season, utilizing the AgI-NH_4I-acetone solution. During most of the 1971-72 season a 10% (by weight) solution of AgI was used. This concentration was released at a rate of 9.5 liters hr^{-1} which produced 850 to 900 grams of AgI hr^{-1}. At the normal aircraft operating speed of 55 m sec^{-1} indicated air speed this was equivalent to about 4.4 gm km^{-1}. Some ignition problems did develop with the 10% solution so the concentration was reduced to 5% near the end of the season and that same concentration was successfully used during the 1972-73 and the 1973-74 seasons. To compensate for the lower AgI concentration, the flow rate was increased to 15 liters hr^{-1} which gave an AgI output of 700 gm hr^{-1}. At this slightly reduced rate the aircraft generator was dispensing AgI at about 3.5 gm km^{-1}.

For use on occasions in which range scheduling conflicts or other problems made aerial seeding impractical, a ground-based version of the airborne acetone burner was employed. This burner was designed to produce relatively large-sized AgI nuclei, suited to passage through a warm, moist environment prior to reaching the freezing level. This generator also burned the AgI-NH_4I-acetone solution. The fuel flow rate was about eight liters per hour. Using a solution containing 5% AgI, the output was approximately 350 grams per hour. The composition of the seeding solution used and the output of the seeding material dispersed are summarized in Table 2-2 and 2-3, respectively.

During the 1972-73 season, two of the seeding flights were made utilizing a Navy P-3 Orion aircraft equipped with droppable WMU-1/B pyrotechnic flares. On both of the flights, the random decision was "seed" and the effects of the seeding flights have been incorporated in the four year composite results. These flares, which were dropped when an updraft was sensed in the aircraft, were injected into the convective band at a point near cloud top. During their burn time of 43 seconds, they would drop approximately 1800 meters and be totally consumed while still well above ground level. A total of 24 of these pyrotechnics were utilized in the two seeding flights.

Table 2-2. Composition of AgI-NH_4I-Acetone Solution.

Component	Percentage By Weight		Weight (gm)	
AgI	10.0	5.0	(10%) 1,750	(5%) 875
NH_4I	3.2	1.6	560	280
Water	2.9	1.4	508	254
Acetone	83.9	92.0	14,682	16,091
Totals	100.0	100.0	17,500	17,500

Table 2-3. Output of seeding material for various seeding operations.

Seeding Mode	AgI Concentration (by wt)	Fuel Flow Rate (liters hr^{-1})	AgI Output Rate (gm min^{-1})
Aerial	10%	9.5	14.4
Aerial	5%	9.5	7.2
Aerial	5%	15.0	11.7
Aerial	WMU-1/B Pyro (20%)		29.3
Ground	5%	8.0	5.8
Ground	LW-83 Pyro (65%)		129.0

2.4 Data Network

As stated earlier, the principal mode of assessment was based upon raingage records. These consisted of a dense network of recording raingages operated by various government agencies and supplemented by several raingages installed by NAWC and its affiliate company, Aerometric Research, Inc. (ARI). Complete raingage locations are listed in Appendix A. Initially, four telemetered raingages were installed for upwind band tracking over the northwestern and western portions of Santa Barbara County. The telemetry network was later expanded to include a gage to the southwest of the seeding site, a gage further upwind near the northern limit of the aerial seeding operations area, and two gages within the anticipated area of effect in the central portion of the county. The total raingage network is shown in Figure 2-4. The ground seeding and radar site, the Vandenberg radar site, and the meteorological operations center at the Santa Barbara Municipal Airport are also shown on this figure.

Santa Barbara County consists of a series of west-to-east oriented mountain ridges with valleys between. The terrain is higher in elevation to the east sloping to near sea level in the west and northwest county. The Santa Ynez Mountains run west to east, approximately 10 km north of the southern boundary of Santa Barbara County. Because ground seeding was conducted from a single fixed source under a variety of wind conditions, it created a "floating target" rather than a fixed target area that was being seeded by several sources. This meant that the area of effect varied from band to band or at least from storm to storm. The test area, on the other hand, was fixed and large enough to embrace all anticipated floating target areas of effect. The El Capitan Lodge ground seeding site (Point NA) was located at the 1065 m level in the Santa Ynez Range which marked the southern limit of the test area, while the western limit of the test area was near a break in the Santa Ynez Range at Gaviota Pass. This is about 10 km west of the seeding site along a north-south line between stations S257 and S236. In ground seeding operations, convection bands with winds which would produce a seeding effect south or west of these limits were not considered seedable.

The primary target area for ground seeding operations was that area north of the Santa Ynez Range and east of a line from stations S236, N5, N6, and N20. This included the eastern half of the Santa Ynez Valley (north of the Santa Ynez Range) and all the area eastward into the western portion of Ventura County.

West of the target area and out of the area of effect, a control area was designated which contained the western portion of the Santa Ynez Valley, and to the

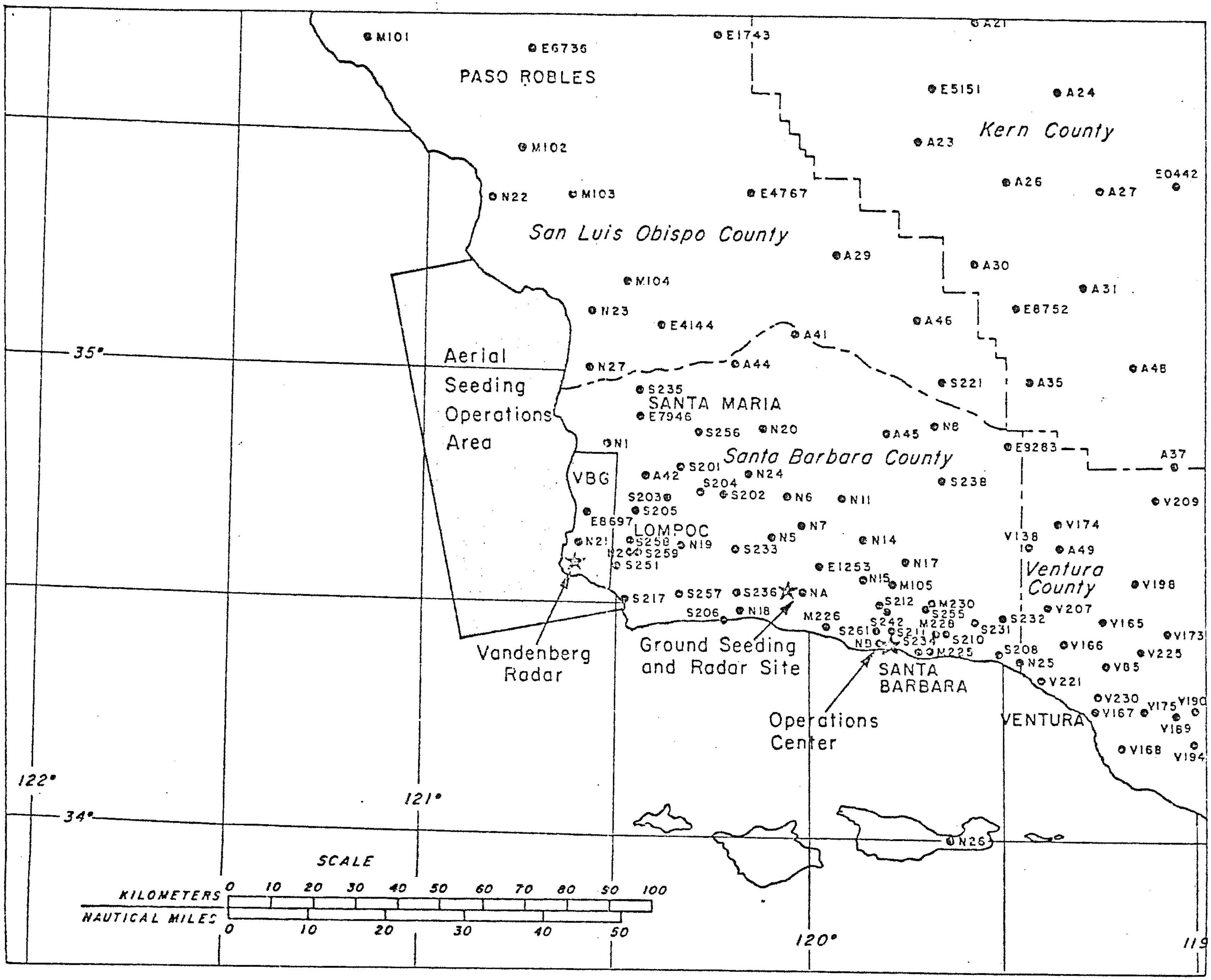


Figure 2-4. Project map showing raingage locations, radar and seeding sites.

north, the Santa Maria area. The six control stations used in a portion of the Phase I evaluation extended from the Santa Maria area in the northern flatlands to south of Lompoc in the southern Santa Ynez Mountains.

Since the effects of aerial seeding were likely to extend from near the coast eastward through most of the county, it was not possible to employ a control area for aerial seeding unless one was selected well to the north of Santa Barbara County. This was not practical from the standpoint of raingage coverage. It was subsequently determined that a control was not required for evaluation anyway. Various analyses that were made on the data pertaining to the four years of ground seeding indicated that normalizing the data by the use of a control area did not materially change the results unless there was a large random selection bias. Although raingage records were the basis for determining band movement, some means of monitoring and recording the band movement over and above the analysis of raingage time-intensity records was desired. Echo returns from a Raytheon Model 2502 X-band radar, formerly used at the pyrotechnic ground seeding site, had been photographed periodically in an attempt to acquire such data. Its limited maximum range (90 kilometers) and the severe attenuation of 3 cm signals in precipitation, however, limited its utility in this respect. Although S-band (10 cm) radar is normally preferred as the best compromise between sensitivity to, and penetration of precipitation for meteorological purposes, experience with the Vandenberg ARSR, and with L-band air surveillance radars employed in other NWC programs, had demonstrated that these 23 cm radars, of adequate power and equipped with MTI (moving target indicator) circuitry to suppress stationary (i.e., ground) returns, could provide an excellent tool for long range weather surveillance. Arrangements were therefore made for photography of each sweep on the ARSR PPI scope. These photographs were found to provide an excellent record of the shape, intensity, and movement of convection bands approaching and entering the target area; a display of the coastline, control areas, and transponder returns from the seeder and other aircraft in the area was also included. The location of the ARSR radar, however, was such that the coastal mountains seriously impeded the detection and display of echoes from bands passing further inland. It was therefore decided to install a transportable 500-kw TPS-1D L-band traffic control radar owned by NWC at the El Capitan Lodge ground seeding site; this radar was also equipped with MTI circuitry and photographic capability. From this vantage point, coverage was provided overlapping that of the ARSR to sea, and extending over most of the target area. The X-band radar, formerly located at this site, was moved to the NAWC operations center, where it provided the project forecasters with direct observation of bands approaching the coast from the south, across the Santa Barbara Channel.

One critical parameter in the interpretation of the results of seeding of convective systems is the actual height, and thus, the temperature of the cloud tops, both naturally and following seeding. Previous attempts to observe and measure cloud tops visually and photographically from a light aircraft, during the 1968-69 and 1969-70 seasons, had met with only limited success (Cooper, et. al., 1969; Cooper and King, 1970). Therefore, stratification of the analyses by cloud top temperature had to be based upon the 500 mb temperatures as derived from meteorological soundings (Elliott and Thompson, 1972). It was determined that a more accurate assessment of cloud top temperatures might be obtained by the use of an X-band radar with height-finding capability. An M-33 tracking radar suitable for this purpose was also available from NWC, and it was installed adjacent to the TPS-1D, from which location cloud top measurements could be made over the entirety of, and somewhat beyond, the seeding and target areas.

During the last year of the project, an Enterprise Electronics Corporation WR100-5 weather radar was installed by NAWC at North Vandenberg AFB at a location about 10 kilometers from the coast. This location, which offered an undisturbed view of the offshore aerial seeding area, allowed us to make observations of cloud tops in the seeding area, both before and after the convection bands were treated and before they were possibly affected by coming over the land area. This 5 cm radar was equipped with an echo processor designed to perform pulse-to-pulse averaging of weather targets and to record the information on 7-track magnetic tape. The unit became operational in January 1974 and was tested on several storms to 1) augment the raingage network, 2) to obtain detailed cloud top observations, and 3) to obtain detailed three-dimensional information about the structure of the bands. A supplementary report on the results of these observations will be made separately.

The characteristics of the radars employed in the present phase of the program are summarized in Table 2-4.

The NAWC forecast office was provided with National Weather Service teletype circuits A, C, and O, and with facsimile maps and satellite photos. Frequent soundings made during storms at the Santa Barbara Airport and special soundings for range operations at Vandenberg ARB and Point Mugu Naval Air Station were also available. These data have been supplemented by the seeding aircraft, which was equipped with a Metrodata "minilab" airborne meteorological data collection package. This package

Table 2-4. Santa Barbara program Phase II radar characteristics.

Radar	ARSR-1	TPS-1D	M-33	Raytheon Mdl. 2502	EEC WR 100-5
Wavelength	23 cm	23 cm	3.3 cm	3.3 cm	5.4 cm
Pulse repetition frequency	360 Hz	400 Hz	1000 Hz	6000, 2000, 1000 Hz	259 Hz
Pulse duration	2 μsec	2 μsec	0.25 μsec	0.05, 0.5, 1.0 μsec	2 μsec
Peak power	5000 kw	500 kw	250 kw	20 kw	250 kw
Beam dimensions	1.2° horiz. 6.2° vert.	2° horiz. 17° vert.	1.1° horiz. and vert.	2° (conical)	2.1° (conical)
Scan mode	Auto PPI	Auto PPI	Manual	Auto PPI	Auto PPI/Manual
Range	370 Km	300 Km	11 Km	90 Km	320 Km
Photography	Yes, 35mm	Yes, 16mm	No	No	Yes
Location	Vandenberg AFB	NWC site	NWC site	NAWC headquarters	Vandenberg

is capable of recording a variety of meteorological parameters on digital incremental magnetic tape for subsequent computer reduction to tabular and graphical form (Table 2-5).

Table 2-5. Minilab characteristics.

Parameter	Sensor System	Range
Time	Digital clock	24 hr (by sec)
Altitude	C.I.C. Mdl. 7000 Altitude Transducer (from aircraft pitot-static system)	0-900 meters
Indicated Airspeed	C.I.C. Mdl. 7000 Airspeed Transducer (from aircraft pitot-static system)	0-175 m/sec
Temperature	W.S.I. TS-22 Temperature System (Thermistor bridge)	-30°C to +30°C
Dew Point	Cambridge Mdl. 137-C3 Dew Pointer (Cooled mirror)	-50°C to +50°C
Liquid Water Content	Johnson-Williams LWC Indicator (Hot-wire bridge)	0-2 g/m^3 (low range) 0-6 g/m^3 (high range)
Vertical Velocity	Ball Mdl. 101-B Variometer (Capillary leak)	-900 to +900 m/min

The data sampling rate, in continuous mode, is 2.4 scans per second.

The meteorologically instrumented WP-3 aircraft was provided to the project for a four week period from Weather Reconnaissance Squadron Four, Jacksonville, Florida. This aircraft added to the project a number of capabilities not otherwise available. Among the more important were, 1) a platform for on-top seeding, 2) flight level wind observations, and 3) a dropsonde capability. The range of this aircraft and the crew comfort add significantly to its contribution to the project. Although the WP-3 was available for only two operations, February 3 and February 10, 1973, it made possible physical measurements indicating the existence of a low level jet along the axis of one of the bands. Without a platform such as the WP-3, it would be almost impossible to investigate the air flow associated with a band in such detail.

3. OPERATIONAL PROCEDURES AND SUMMARY OF OPERATIONS

3.1 Phase I

Weather situations were monitored in the NAWC laboratory at the Santa Barbara Airport, and on the approach of a storm, project personnel were alerted and assumed their posts. The control meteorologist then examined his upwind telemetry and weather radar reports for the approach of the first convection band. When this band appeared, and was confirmed by tracking across the upwind area, the seeding technician was informed when to ignite the first seeding flare.

Typically, the operation would occur in two stages: 1) a band alert stage, and 2) a band confirmation stage. A band alert was called when any one of the telemetered stations reported 0.02 inch in a 15-minute period or when the radar operator reported a banded echo approaching the target area.

If the band was detected by radar, the band was confirmed when any telemetered station recorded 0.02 inch/15 minutes, provided this coincided with the radar position of the band. If the band was detected from raingage data, the band was confirmed either by a radar report of the band or by a subsequent precipitation report of .02 inch/15 minutes from any other telemetered station. For tracking purposes, the bands were required to meet the objective criteria as much as possible, but the most important feature in band tracking was the continuity of similar events at the various upwind telemetered gages. Obviously, at times, the meteorologist's subjective evaluation of the situation had to prevail. Once the existence of the band was confirmed and if the wind direction criterion was met, the decision to seed was made.

The first ignition was timed to occur just prior to onset of band precipitation. Prior to any firing, the seeding technician consulted a book of pre-prepared randomly selected yes or no decisions in order to know whether or not he should seed the selected band. The seeding technician was the only person who knew what bands were actually seeded until after the band analysis was completed at the end of the season. If the band was seeded, then another pyrotechnic device was ignited every 15 minutes until the decision was made that the band had passed the site.

The routine of band recognition, and subsequent seeding or simulated seeding, continued throughout the storm period or until termination of operations. Every attempt was made to work as much of each storm as possible. At times, however, some convective bands were not worked, either because the crew was down for required rest, the wind direction was considered to be wrong for movement across the target area, or rarely, the band was not recognized as such until it had moved past the seeding site.

During the course of the storms, upper air soundings were made at frequent intervals with the GMD-1 equipment at the Santa Barbara Airport. A rough schedule of radiosondes at three to four hour intervals was kept, but an attempt was always made to release into the convection band as it passed over the airport.

The initial set-up of the project was not completed until mid-January 1968 with the first convective bands identified late in the month. Even with the late start, the season produced eight storm periods in which a total of 22 convection bands were identified and treated.

The winter season of 1968-69 was one which yielded above normal seasonal precipitation throughout southern California. Most of the season's precipitation occurred in two periods in the months of January and February, while other months during the season were below monthly normals. During these periods of concentrated precipitation, especially in the last third of January, the threat of flooding caused the temporary termination of all seeding operations until the flood threat had passed. This meant that many bands, and indeed several storms that occurred from late January to mid-February, were not available for operation. A similar period existed from late February until mid-March after which operations were resumed.

In all, 41 bands were identified and tracked during the operational period from November 1, 1968, through April 30, 1969. The first storm occurred November 14-15, 1968, and the last operation occurred April 5, 1969.

The season of 1969-70 in Southern California produced from one half to two thirds of the normal precipitation for the period. In this respect, it was somewhat like the season of 1967-68 which also was characterized by below normal precipitation, and unlike the winter season of 1968-69 which had very heavy and much above normal precipitation over all of Southern California. The middle year also produced much warmer storms from lower latitudes and contained a large number of storms and their associated bands which occurred in relatively stable air masses. Both the first and third years, however, contained a large percentage of colder storms and were associated with more unstable air masses.

Actually, twenty-five convection bands were intially identified and worked during the 1969-70 season. Before the precipitation analysis was completed, however, three of the bands were eliminated from the sample because their movement and/or orientation was such that the area of effect was not within the limits of the project design. These bands were eliminated by the project meteorologist without his knowledge of whether the band was seeded or not.

The winter season of 1970-71 had many good seeding opportunities during November and December. Thereafter, an extended dry period developed with only minor opportunities in January, Feburary, March and April. The storms tended to be relatively cold from the middle of December on.

This season saw the introduction of aerial seeding (Phase II) to the project but only in a limited way as a myriad of technical problems associated with the aircraft operations precluded the consistent use of the aircraft. Because of these technical problems, more bands were ground-seeded in the mode of previous years than were aerially seeded. However, the inability to conduct aerial seeding was not generally due to weather causes so that neither sample was biased by the switch from aerial to ground seeding. There were 13 seeded and 9 not-seeded bands in the ground mode and three seeded and four not-seeded bands in the aerial mode.

3.2 Phase II

In general, the procedures adopted for Phase I were continued for Phase II. However, since the operation of the aircraft within the Western Test Range area of responsibility required close coordination with several support groups on the range, this meant that the entire operation had to be pre-scheduled. This required a continual watch on weather developments and occasional rescheduling of operations at the range when the storm system either slowed down or sped up in its movement toward the California Coast.

In actuality, the Phase II operations varied somewhat, depending upon the availability of personnel to perform the duties, but typically, the NAWC project director always went to the radar control room at Vandenberg AFB, from which point he directed subsequent activities by radio and telephone. (Ground operations were still directed from NAWC headquarters). In addition to the radar information from the ARSR, raingage telemetry and hourly weather reports were fed to the project director via a telephone link with the duty meteorologist at the NAWC office. When a convection band was detected and tracked toward the coast, the NAWC radar crew located at the ground seeding site in the Santa Ynez Mountains set the TPS-1D and M-33 radars into operation, to monitor and record cloud top heights and band structure. At the same time, the aircraft crew, consisting of the pilot, a copilot who doubled as radio and acetone-burner operator, and, on occasion, an observer who operated the Minilab, were briefed on the weather situation and proposed operating schedule, filed their flight plan, and departed on their mission. To provide maximum use of aircraft range and duration (approximately 4-1/2 hours), take-off was timed to allow the aircraft to intercept the band 50 to 75 kilometers off the coast.

After all available information had been considered, if in his opinion the convection band was suitable in character and moving toward the coast, the project director declared a "go" situation. The aircraft crew was then directed to consult a table of 50-50 randomized decisions by cumulative storm number, prepared in advance of the season. If the decision called for seeding, the crew ignited the burner when vectored to the band intercept point and given a "begin seeding" signal. Seeding operations were conducted in the band at an altitude 150 to 300 meters below the freezing level (typically 1800 to 3000 meters MSL). The aircraft was then vectored along a seeding track consisting of a series of parallel legs 30 to 60 kilometers long, parallel to and within the long axis of the band, over the ocean upwind of the instrumented area and within 40 kilometers of the coast. This process was continued until the trailing edge of the band had reached the coast, at which point an "end seeding" signal was passed to the crew. If the decision was not to seed, the same procedure was followed except the burner was not ignited. As in Phase I, the nature of the decision was not communicated to the director or the analysis staff until the post-season data analysis was completed in order not to introduce any analysis bias.

Following the seeding run, if time, fuel, and oxygen supplies were sufficient, the aircraft would either return to its base at the Santa Barbara Airport in Goleta, or stand by to operate on the next band. Turnaround time on the ground for refueling and seeding solution and oxygen replenishment was approximately 60 to 90 minutes, and the crew and aircraft were usually limited to two flights in succession before an eight to twelve hour rest period was required. Two flights would generally suffice for the majority of storms; however, the ground generator was available, if conditions were suitable, to conduct seeding operations until the aircraft was again ready to fly.

Radar operations were continued for as long as the storm was within surveillance range. Rawinsonde observations were again made from the NAWC headquarters at intervals of three to four hours, with a major effort to time them to coincide with passage of the bands over Goleta. These and other available soundings were used in the subsequent analysis to determine the air-mass characteristics of the storm, which were fed into the Elliott area of effect model to forecast the region of precipitation enhancement.

It was hoped that in the Phase II operations the aircraft and the M-33 radar would help document the cloud tops. Unfortunately, in actual practice, the aircraft was only able to climb on-top infrequently. In the few observations made by the aircraft, tops in bands ranged from the 4000 to the 7000 meter level. The M-33 operations were severely limited by the strong winds which frequently were observed at the crest of the mountain range. Most of the time during storm and band passage the wind speeds were such that the radar antenna could not be aimed in any direction except downwind and level (zero elevation). The few cloud top observations that were made with the radar would have to be considered questionable at best.

It was mentioned earlier that a limited amount of aerial seeding was conducted during the latter half of the 1970-71 season on an experimental basis. Consequently, the 1971-72 winter season was the first full season's operation of Phase II. Unfortunately, the winter of 1971-72 was one of the driest on record and seeding opportunities were minimal. Rainfall was abundant during December; however, the major stormy period was centered during Christmas week which made operations difficult. During the season, seven storm periods containing seven bands (3 seeded, 4 not-seeded) fell into the aerial operations category and three bands (all not seeded) fell into the ground seeding category. In one 48-hour storm period, two bands were identified during aerial operations and one ground band was identified when the aircraft was not available. Otherwise, the ground and aerial modes were not mixed during storms with the ground generator being used only once during the season. In this same storm period, which was a "seed" decision, ignition problems with the aerial generator precluded the seeding of the second band. This band was treated as a "not-seed" band, but the storm period was classified as seeded.

It was originally intended to operate the ground-based acetone burner at the site previously used for the pyrotechnic generators. This would have permitted direct comparison of the acetone generator's effectiveness with that of the pyrotechnics. A fire in the mountains above the Carpenteria-Summerland area in October 1971 made this location undesirable during the 1971-72 season, due to the possibility of enhancing the possible flood damage (such flooding did in fact occur in December at Carpenteria). The ground burner was therefore installed at a low elevation site 16 kilometers southwest of Santa Maria in the northwestern corner of the project area. Since the ground burner was used only once during the season, the one band which was treated has been eliminated from the analysis since a sample of one would be of little value in the evaluation. The ground-based burner was returned to the original seeding site for the 1972-73 season so that the aforementioned comparison with pyrotechnic seeding could be made.

Unlike the previous two seasons, rainfall was plentiful during the 1972-1973 season with a total of eighteen storms observed during the period from November through March. No rainfall was observed in the spring months of April or May. Seeding was conducted from either the aircraft or the ground site in nine of the 18 storms. During the season, 39 convection bands were declared operational; a total almost triple the number of bands accumulated during the first two seasons of the Phase II operations. Seventeen of these were worked in the aerial seeding mode with eight of the 17 bands seeded; twenty-two were in the ground seeding mode with 15 of the bands seeded. After three years of aerial seeding, a total of 31 bands had been identified with 14 of them seeded. The Phase II ground seeding from the ridge line using the acetone generator was begun during this season but the three not-seeded bands identified during the ground operations of 1971-72 were included in the evaluations to yield a sample of 15 seeded and 10 not-seeded bands.

The final year of the Phase II operations, the 1973-74 season, was one in which average total rainfall was observed in most areas but the number of storms was below normal. A large portion of the total rainfall occurred during the first week of January 1974, but then the normally wet month of February was almost totally dry. No measurable rainfall was recorded after the first week of April. Nine storm periods were observed from mid-November to early April. Within these nine storms a total of 19 convection bands were identified. Fourteen of those bands were worked in the aerial mode but only four of the fourteen were destined to be seeded by the random choice decision process. The remaining five bands were worked in the ground seeded mode and as fate would have it, all five were seeded within two seeded storms.

The total number of seeded and not-seeded bands for each Phase is listed in Table 3-1. A complete listing of the Phase I ground seeding operations and the Phase II ground and aerial seeding operations are included in Appendix C, Band and Storm Chronology.

Table 3-1. Number of seeded and not-seeded bands in each operating phase.

Phase	Seeding Mode	Seeded	Not-Seeded
Phase I -	Ground Seeded	56	51
Phase II -	Ground Seeded	20	10
Phase II -	Aerial Seeded	18	27

4. ANALYSIS PROCEDURES

4.1 Band Precipitation Analysis

The statistical analysis procedures that were employed were generally the same for both Phase I and Phase II.

The first step in the analysis involved the tracking of the precipitation band pattern across the gage network on the basis of plots of all available precipitation and radar information. In order to insure lack of subconscious bias, the meteorological analyst was uninformed as to which bands were seeded, and which were not. Once a realistic pattern for the band movement was obtained, each station was assigned a total precipitation value for that band. The total time (band duration) required for each band to pass the station was also determined from each gage record, to permit determination of the effects of seeding upon band width or rate of movement.

In addition, since in Phase II each band in a given storm was subjected to the same treatment within the 48 hour randomization block, the total storm (or block) precipitation was also tabulated for each gage to determine the effects of band seeding on the total water produced by the storm. Seeded/unseeded precipitation and duration ratios for bands were then subjected to statistical tests for significant differences attributable to seeding. The total band precipitation and band duration for both Phase I and Phase II are listed for each station in Appendices D and E, respectively. The storm total (48 hour) for Phase II operations is listed for each station in Appendix E. In Appendices D and F the precipitation totals have been listed as they were recorded, i.e., in inches and hundredths of inches. These values may be converted to millimeters by multiplying the listed precipitation totals by the factor 25.4. The band duration totals in Appendix E are listed in minutes.

4.2 Air Mass Analysis

4.2.1 Stability. In Phase I an evaluation of the air mass characteristics of each band was made from the radiosonde data available. A critical examination of the soundings taken during the passage of the Phase I bands revealed four different air mass structures which, when considered from the standpoint of seeding from the 1065 meter ridge line (about 900 mb level), led to four categories of air mass stability and seedability.

In the following categories of stability (Table 4-1), the lapse rates have been compared to the moist adiabatic lapse rate since it was assumed that the air mass in the band was at or near saturation. The Convective Instability Base (CIB) is that level at which the air mass lapse rate first reaches or exceeds the moist adiabatic lapse rate. The Convective Instability Top (CIT) is the level at which the air parcel lifted from the CIB along the moist adiabatic lapse rate curve again intersects the air mass lapse rate curve.

Table 4-1. Aerological Stability Categories.

	Category	CIB (Ht.)
1.	Unstable, Low CIB	Below 1065 meters
2.	Unstable, High CIB	Between 1065 and 1830 meters
3.	Stable (A)	Above 1830 meters
4.	Stable (B)	No CIB

The most seedable cases fall in Category 1. In these cases the ground level smoke plume has a high assurance of being entrained into convection, a virtual necessity if seeding is to occur.

Bands with Category 2 stability characteristics were considered as marginally seedable. If local heating was present near the seeding site or there was strong mechanical turbulence over the ridge, then the nuclei may have been entrained.

Bands that occurred in partially or totally stable air masses (Categories 3 and 4) were the least likely to entrain nuclei from the ground pyrotechnic source and probably should be considered essentially unseedable by this method, although they were seeded in this research program. However, bands occurring in either Categories 2 or 3, both exhibiting instability above the seeding site, most assuredly could be seeded from a higher ground source or by aircraft.

Bands classified in Categories 3 and 4, while not seedable by convective mixing, might be seeded by frontal lifting, provided the front is a sharp cold front type which fits the precipitation intensity criterion. This lifting could raise the nucleant to the CIB in a Category 3 type air mass and to the -4°C level in a Category 4 type air mass. The effect should be further downwind in Category 3 than with Categories 1 or 2 and the effect should be very far downwind with Category 4.

Based on the above air mass statility categories, the bands were stratified into one of the four categories. For analysis purposes, Categories 2, 3, and 4 were lumped into one group, with Category 1 constituting the other group.

The radiosonde data available in Phase II were not similarly classified as the aerial operations were generally near the freezing level and above stable layers or inversions which often were located in the lower atmosphere. The sounding data associated with Phase II ground seeding were not similarly classified as the sample size was not considered large enough to partition.

4.2.2 Temperature. There has been a great deal of interest in the dependence of seeding effectiveness on cloud top temperature. In the Climax experiments this was well documented by Mielke and Grant (1967), using the 500 mb temperature as an indication of cloud top temperatures. We had very little reliable cloud top temperature information, especially in Phase I, but from our knowledge of the local area, it was felt that the cloud tops during storms were close to 5500 meters (about the 500 mb level). Therefore, each convection band was assigned a 500 mb temperature measured from the sounding data. These bands were subsequently stratified on the 500 mb temperature and various seeded to not-seeded ratios computed. A complete 500 mb temperature listing for each band is also included in Appendix C.

As mentioned in Chapter 3, it was hoped that these cloud top heights could be documented by aircraft and radar observations. But for the reasons given in that discussion, we were not able to successfully measure the cloud tops very often. Therefore, in spite of its shortcomings, for lack of better information it was decided to continue listing the 500 mb temperature for each band in Phase II as well.

4.2.3 Convective Band Cross-Section. The large number of soundings available from Santa Barbara and Vandenberg associated with the storm periods under study have made possible the construction of a composite cross-section of the atmospheric associated with non-frontal convection bands. This cross-section, shown in Figure 4-1, was constructed from sounding data associated with 79 non-frontal bands and presents the average temperature, moisture, vertical velocity, and wind flow during the four hours before band passage to four hours after band passage. Those bands associated with the surface frontal position were eliminated from this composite since frontal bands typically have one or more convective bands within the four hour period preceding them and, therefore, present a distorted view of the relationship between in-band and between-band air mass characteristics.

Figure 4-1 was constructed with time, in hours before (-) passage and hours after (+) passage, along the abscissa and elevation, in millibars, along the ordinate. Average wind directions and velocities have been plotted at 100 mb levels for each hour on the graph and are represented in the conventional way with a wind

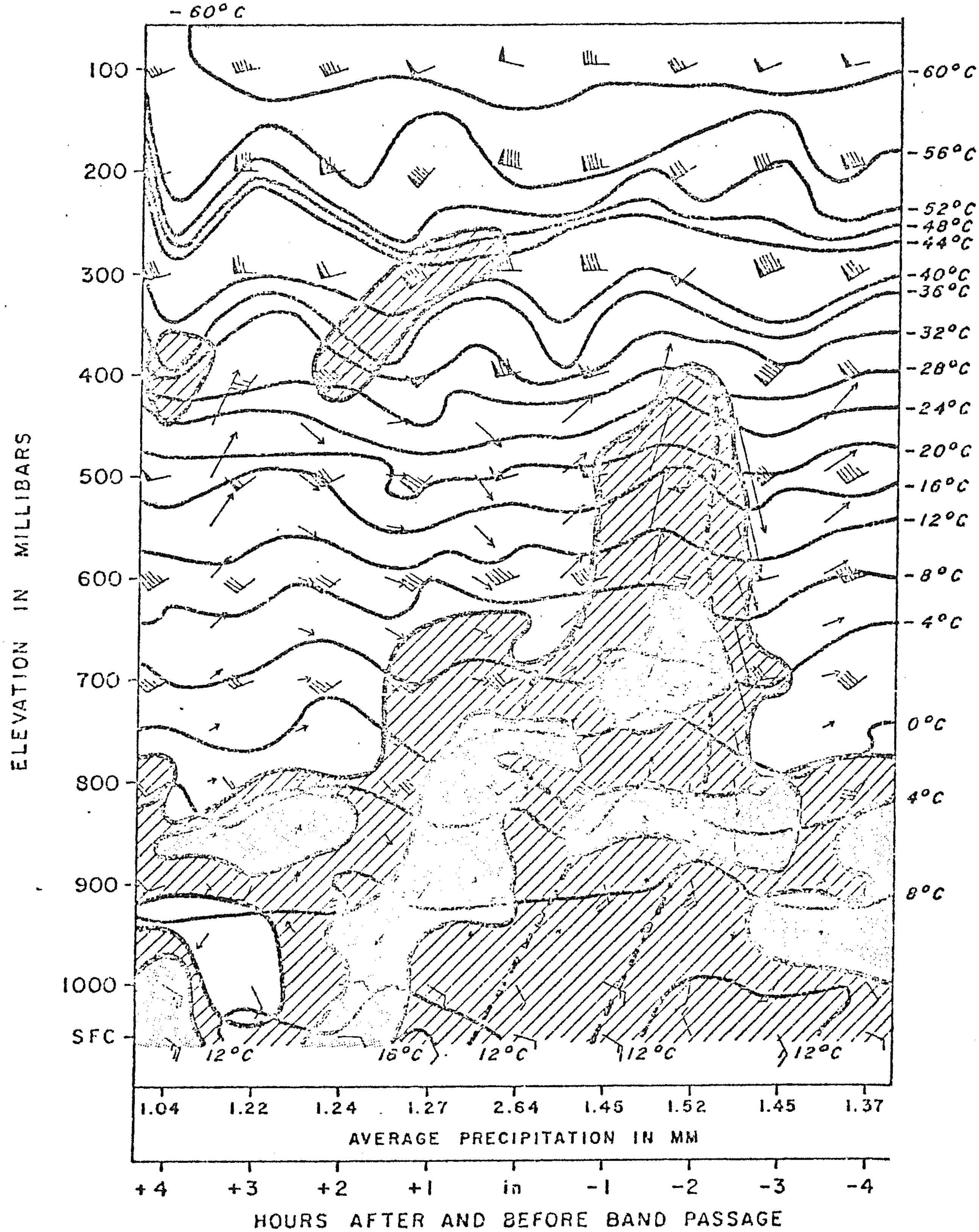


Figure 4-1. Composite time section of the atmosphere for non-frontal convection bands at Santa Barbara.

arrow and barbs (or flags) representing each five knots of wind (2.5 m sec^{-1}). In addition, computations of vertical and horizontal convergence have been made for 50 mb increments starting at 975 mb. These computations were based upon the assumption that the bands extended, and had a uniform flow field, to the north and south. Thus, the wind convergence and divergence would occur due to motions in the XZ plane (east and up) only. An average band speed of 32 km hr^{-1} toward the east was used to convert time to space. The resultant wind vectors for these layers have been plotted at each 50 mb level starting at 950 mb and are shown by the arrow vectors. Regions of rising and sinking motion are clearly delineated. Isotherms have been drawn for each 4° interval to depict the vertical temperature structure and, finally, the moisture deficit has been analyzed for those areas in which the temperature-dewpoint spread was 2.0°C or less (shown as the stippled area) and those areas where the spread was 2.1°C to 5.0°C (shown as hatched). If we arbitrarily define the band as that area containing high moisture values (less than 5° spread) and significant vertical motion, then the band appears to be as shown by the heavy dashed line. The band dimensions are about 50 km wide (1.5 hours duration at an average speed of about 35 km hr^{-1}) and 6000 meters deep - extending from a cloud base near 870 mb to cloud top at 400 mb. There is a suggestion that the band leans forward with height and the heavy precipitation falls from the trailing portion of the band. The highest cloud moisture concentrations are at cloud base and in the core of the updraft. A strong downdraft area precedes the band. The precipitation rates for the Santa Barbara Airport, shown at the bottom of Figure 4-1, indicate quite steady hourly values before and after the band with the rates within the band being about twice the rate between bands.

4.3 Band Pressure Analysis

Basically, the barometric network used consisted of National Weather Service and Federal Aviation Administration operated recorders primarily located at airports, but was supplemented by project operated recorders at key locations within the network to increase the density. A total of seven supplemental microbarographs were installed during the Phase II portion of the project. Five of these, however, were installed only during the last season of operation and because of their very limited records have not been included in the data bank. Complete identification, location, and years of record of the recorders used can be found in Appendix B. A mean barometric station pressure was assigned to each band at each of the several stations for which recorded barometric pressure was available. The mean station pressure difference between the not-seeded and the seeded bands was then calculated and plotted for each of the recording stations and the results analyzed to determine if seeding had a noticeable effect on surface pressure.

4.4 Evaluation Methods

The heart of the evaluation program was protecting the objectivity of the analysis. Great care was taken that only the operator at the seeding site was aware of the random seeding instructions for each band. This secrecy was maintained until each band's seedability had been determined and a decision made as to whether it should be included in the total storm sample. The meteorologist who analyzed the precipitation records and assigned a quantitative value to each band at each station was quite unaware as to whether a band was seeded or not-seeded.

Initially, the basic test statistic used in Phase I for the ground seeding evaluation was the double ratio:

$$D.R. = \frac{\overline{T}_s / \overline{C}_s}{\overline{T}_{ns} / \overline{C}_{ns}} \qquad (1)$$

where:

$\overline{T}_s$ = Test station seeded band average precipitation

$\overline{C}_s$ = Control area seeded band average precipitation

$\overline{T}_{ns}$ = Test station not-seeded band average precipitation, and

$\overline{C}_{ns}$ = Control area not-seeded band average precipitation.

This provided a simple way of comparing seeded and not-seeded precipitation ratios, corrected for the natural intensity of a given seeded band as measured by the control area average precipitation.

Because of the method of seeding from the same point source with varying winds (creating the floating target), double ratios for individual bands vary considerably across the target area. Consequently, while an individual band analysis was made for all bands, double ratios for individual bands were not prepared in all cases. More meaningful were the analyses of the ratios composited for the four years and particularly in relation to the effects of seeding compared to the computed area of effect (in this case the envelope of all the individual band area of effects) from the area of effect model.

In order to determine whether normalizing the data by using the upwind control had a pronounced effect on the ratio results, a second evaluation was conducted using a single ratio:

$$S.R. = \frac{\overline{T}_s}{\overline{T}_{ns}} \qquad (2)$$

where:

$\overline{T}_s$ = Test station seeded band average precipitation, and

$\overline{T}_{ns}$ = Test station not-seeded band average precipitation.

When the two results were compared, it was found that no significant difference was apparent between the two evaluations. On that basis, therefore, it was decided that the single ratio technique would suffice for both phases, since there did not appear to be any reasonable solution to selecting a control area for the aerial seeding that was to come in Phase II operations. A number of composite ratios, both double and single, however, were made at the end of the Phase I operations for various temperature classes and air mass stabilities and these are presented in detail in the final report submitted by NAWC at that time (Elliott and Thompson, 1972). Where relevant, some of these have been included in this report for comparison with Phase II results.

A similar evaluation was made on the duration of bands by computing the single ratio (also the double ratio for Phase I data) of the test station seeded band average duration to the test station not-seeded band average duration. In Phase II, the ratio of precipitation total for seeded to not-seeded storms was computed from (2) where $\overline{T}_s$ and $\overline{T}_{ns}$ represented all the precipitation which fell in the designated 48-hour period.

To test for the significance of the results, the data at each station associated with the seeded and the not-seeded bands were ranked from highest to lowest value. The Wilcoxon, Mann-Whitney U Test (Siegel, 1956) was then applied to the data used in the various ratio evaluations to determine if the seeded sample showed significantly different ranking than the not-seeded sample.

5. RESULTS

While this report deals primarily with the results of the Phase II operations, several comparisons are made between the Phase II and Phase I results. For convenience in making these comparisons, some figures from the Phase I operations have been included where appropriate. For a more complete treatment of the Phase I operations, the reader is referred to NWC TP 5308, Santa Barbara Convective Seeding Test Program, 1970-71 Season, and 1967-71 Summary.

5.1 Precipitation Analyses

5.1.1 Phase II Aerial Band Precipitation Analysis.

Ratios of mean seeded band precipitation to mean not-seeded band precipitation were computed for some 104 recording raingages in Santa Barbara and adjacent counties. As much of the data as possible has been used in making the analyses, but at times the data sample was reduced because of missing data. In general, only those stations which had more than half the sample available were considered in making the final analyses and evaluations.

The results of the analysis of aerial seeding conducted from 1970-74, using a continuous seeding mode is shown in Figure 5-1. (Data used to construct Figure 5-1 and other figures in this section are summarized in Appendix H). The total sample size consisted of 18 seeded bands and 27 not-seeded bands. For ease of identification in this and subsequent figures, ratio areas of 1.5 or larger have been shaded while the corresponding decrease areas of 0.75 or less have been hatched. The area of primary effect as determined by the area of effect model composited for all the seeded bands is shown by the heavy solid line. Within the area of effect ratios range from greater than 1.0 to about 2.0, although it should be stressed that the overall pattern is more significant than the absolute value of the ratio number. The highest ratios are along the coastal strip immediately east of the seeding area and in the eastern portion of the target, an additional 60-80 kilometers eastward from the seeding zone. These high ratio areas tend to be elongated north to south. This orientation is parallel to the track of the seeding aircraft which generally flew on a north to south track within the aerial seeding operations area. A third high ratio area, also elongated north to south, is apparent at a distance of 70 kilometers east of the second area (a total of 140 km east of the seeding zone), suggesting that a sort of sinusoidal effect may have been induced by the aerial seeding of convection bands. Two low ratio areas are centered in southwestern Kern County about 135-150 kilometers downwind from the seeding zone.

Within the primary area of effect there are 33 precipitation stations with good record. The average ratio for these stations was 1.43 while the average ratio outside

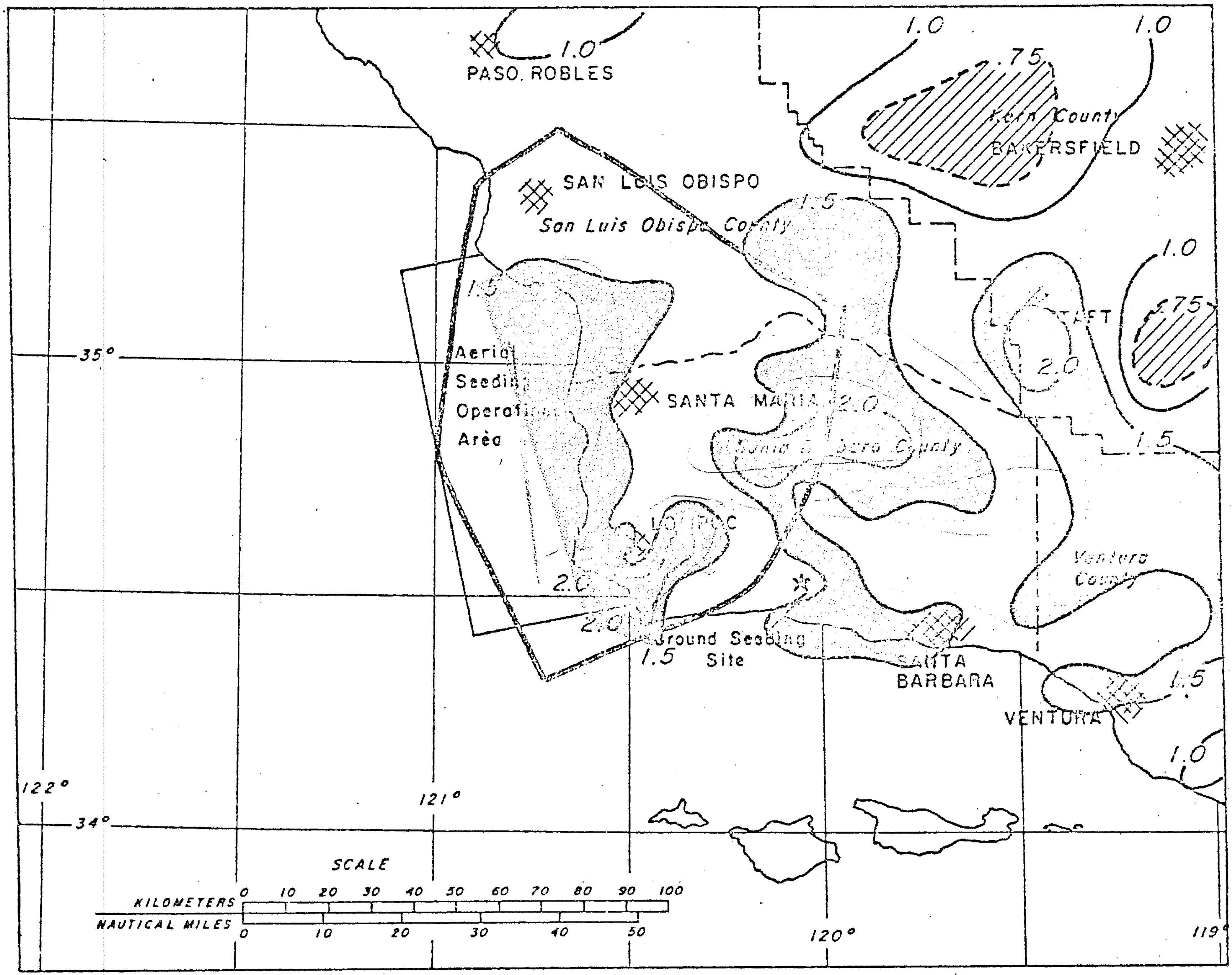
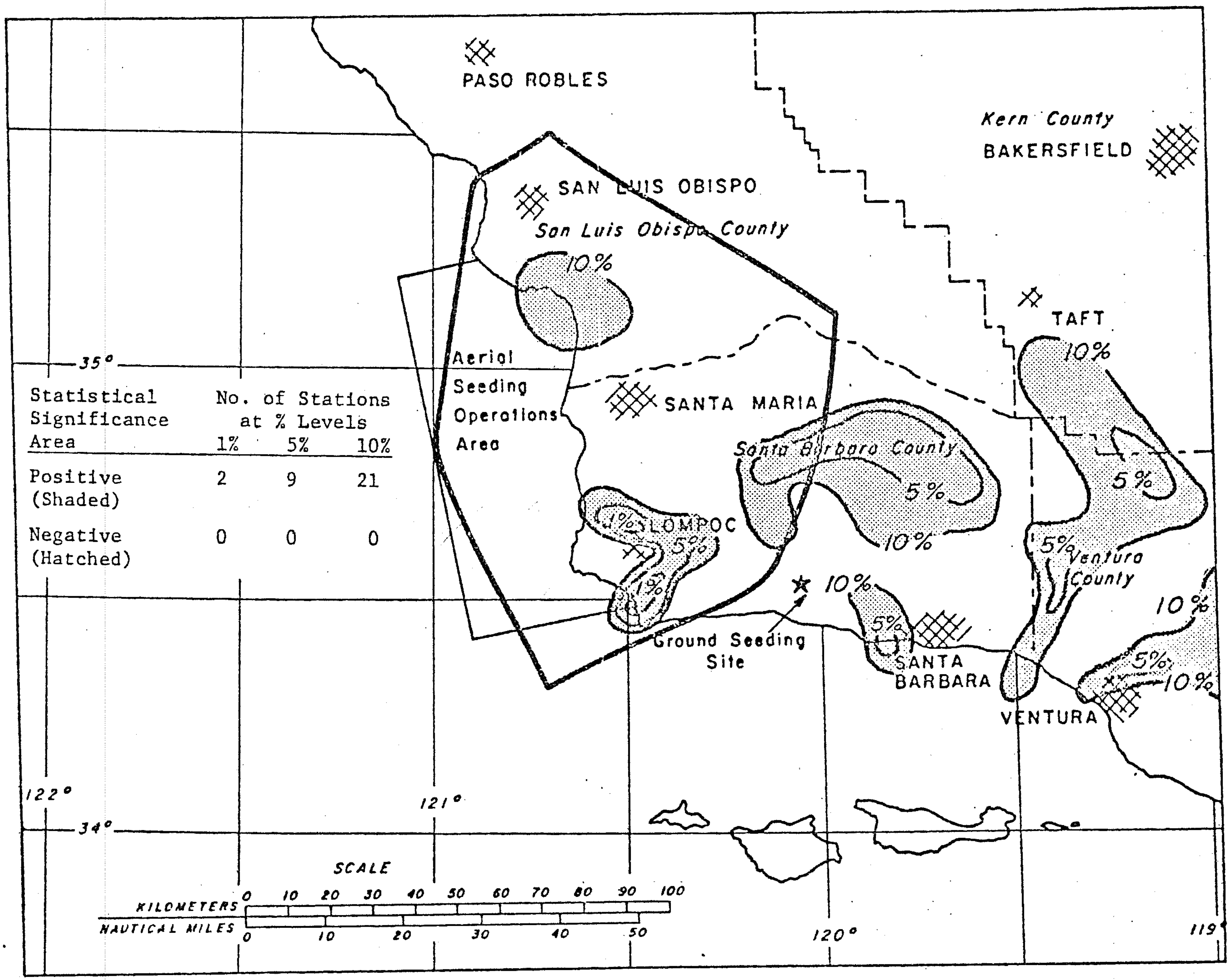


Figure 5-1. Seeded/not-seeded ratios of band precipitation for Phase II aerial operations 1970-74 seasons: 18 seeded and 27 not-seeded bands.

the predicted area of effect was 1.36. It should be noted that most of the stations outside of the area of effect envelope are in the region of apparent "downwind" effect. Several investigators including Adderley (1968), Brier, et. al., (1973), and Brown and Elliott (1971), have found that these "downwind" areas frequently indicate increases greater than those in the target area.

Figure 5-2 is a companion figure to 5-1 in which those areas which contained stations that exhibited statistical significance at the 10% or better level have been delineated. The number of stations that were significant at either the 10, 5, or 1 percent level are indicated in the table at the left of the coastline. Of interest is the fact that of the 104 stations available for analysis, 21 exhibited significance at the 10% or better level; a figure somewhat larger than might be expected to occur by random chance. Seven of these stations are within the primary target area, including both of the stations that were significant at the 1 percent level. These areas also agree well with the area of high ratios shown on Figure 5-1. It is also important to note that there were no significant decreases produced by the four years of aerial band seeding, even in the area of southwestern Kern County, where the ratio analysis showed ratios less than 1.0.

To compare the effects of aerial seeding with the ground band seeding accomplished in Phase I, Figures 5-3 and 5-4 are presented. These figures show the seeded to not-seeded ratios from ground seeding and the areas of statistical significance, respectively. It is to be noted that in the Phase I ground seeding, a high ratio area began near the ground seeding site and extended eastward within the area of effect, with the long axis parallel to the west to east Santa Ynez Mountain Range. Forty raingages were located within the area of effect envelope with an average ratio of 1.39. Outside the envelope the ratio for the remaining stations in the Phase I analysis averaged 1.21. A second high ratio area was centered well north of the predicted area of effect in the San Joaquin Valley near the city of Bakersfield, some 120 kilometers downwind (northeast) from the seeding site. Both of these areas exhibited high statistical significance but otherwise, the patterns of Phase I ground and Phase II aerial seeding are markedly different, with the Phase I ground seeding results showing none of the north to south "banded" orientation that is visible in Figure 5-1. Conversely, unless it is the northern portion of the middle high ratio area in Figure 5-1, there does not appear to be a separate well defined high ratio center downwind (northeast) from the aerial seeding area as there is in Figure 5-3. It has been suggested by Brown and Elliott (1971) that the high ratio area evident



Statistical Significance Area	No. of Stations at % Levels 1%	5%	10%
Positive (Shaded)	2	9	21
Negative (Hatched)	0	0	0

Figure 5-2. Areas of statistical significance associated with band precipitation [illegible]

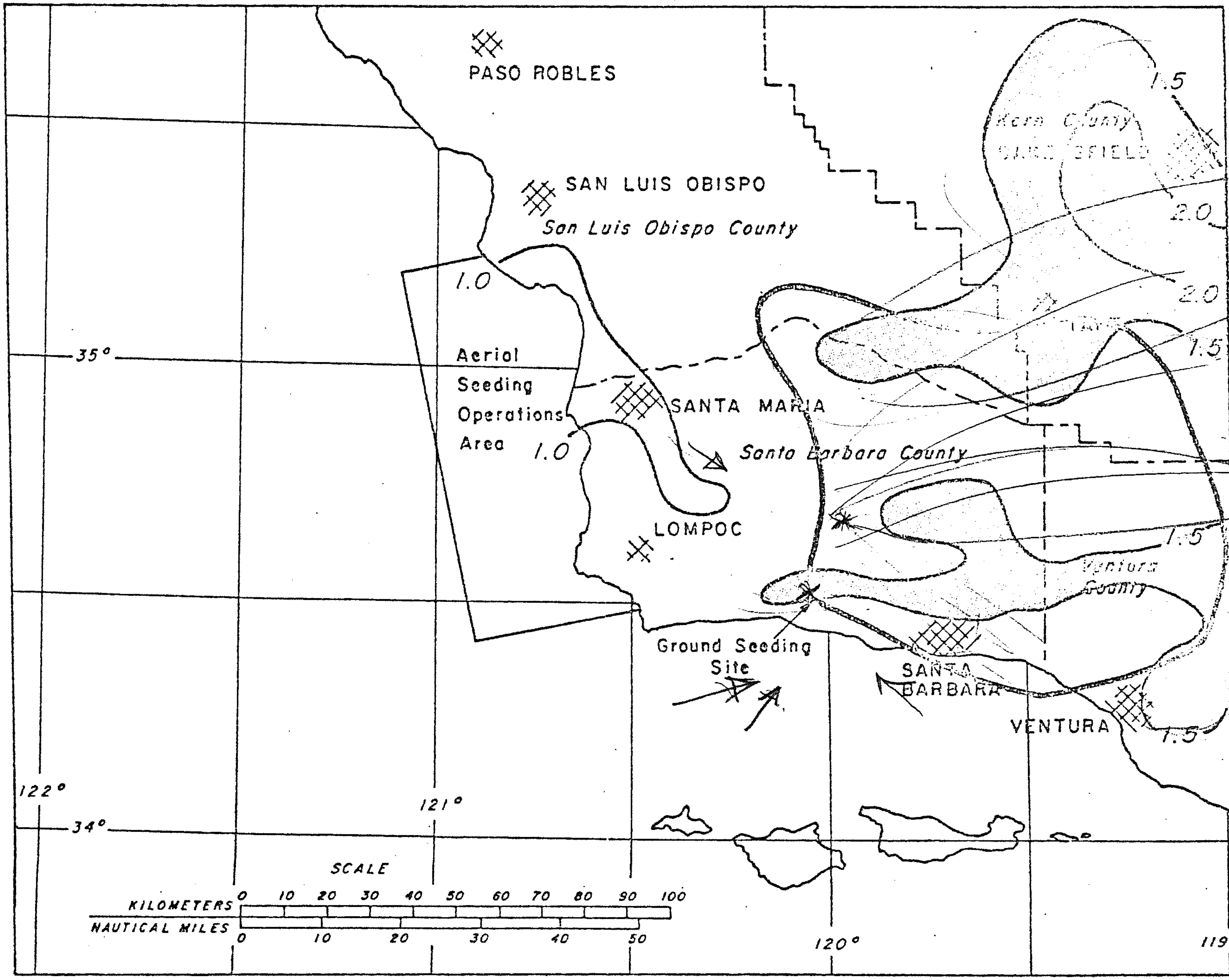
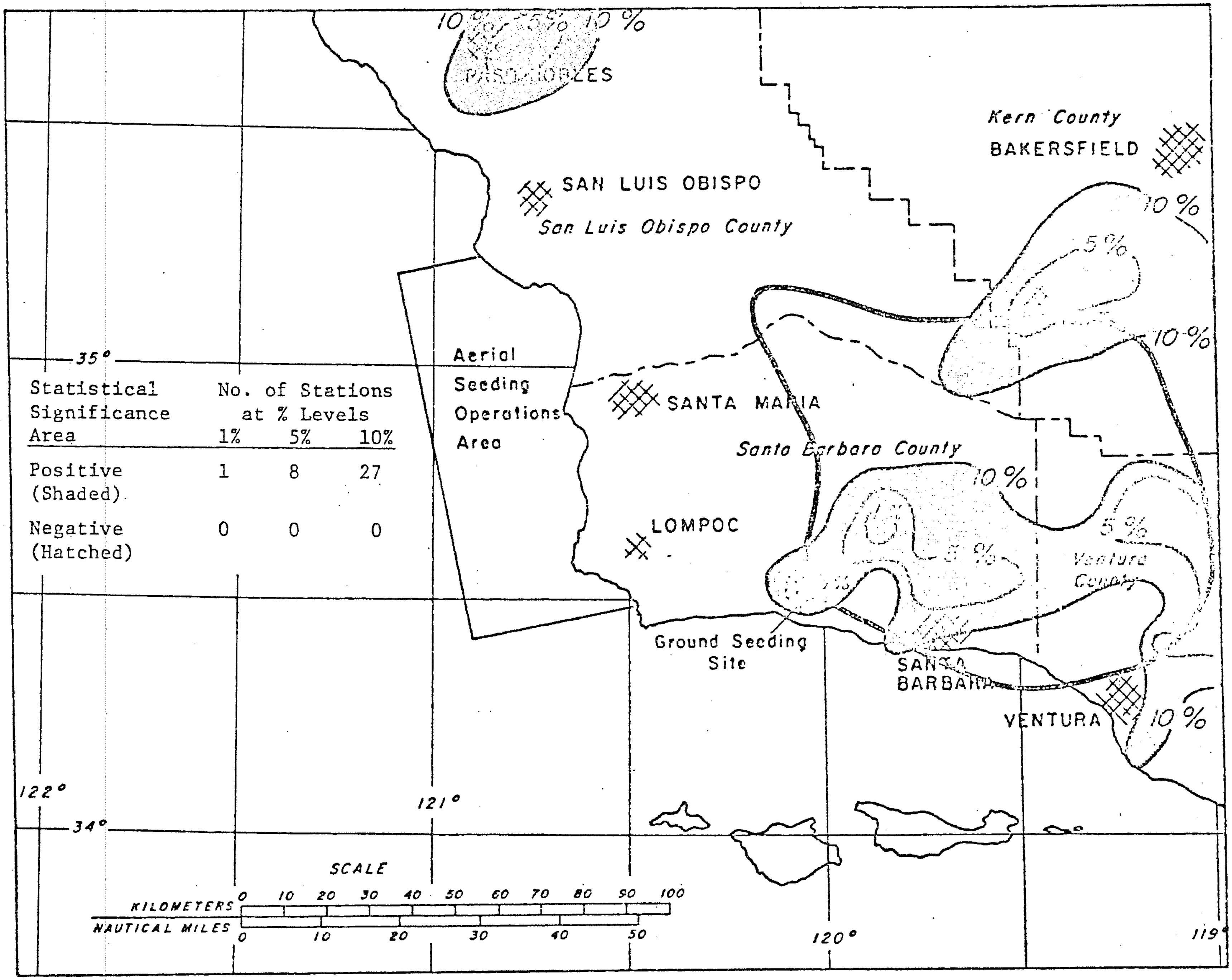


Figure 5-3. Seeded/not-seeded ratios of band precipitation for Phase I ground operations, 1967-71 seasons; 56 seeded and 51 not-seeded bands.



Statistical Significance Area	No. of Stations at % Levels 1%	5%	10%
Positive (Shaded)	1	8	27
Negative (Hatched)	0	0	0

Figure 5-4. Areas of statistical significance associated with band precipitation ratios, Phase I ground operations, 1967-71 seasons.

in the San Joaquin Valley in Phase I seeding was along the 700 mb wind vector and might be due to a microphysical "downwind" effect that extends that far northward from the seeding site. If such an effect also occurred with aerial seeding, it is not apparent.

It has been hypothesized (Brown, Elliott and Thompson, 1973) that the area of precipitation increase in the San Joaquin Valley is due to direct microphysical effects while the increase to the east of the seeding site is due to a dynamic intensification of the convective band. The comparison of the two seeding modes (Phase I - Ground and Phase II - Aerial) suggests that both methods produce a dynamic response with the attendant increase in precipitation to the east but only the ground seeding mode produced an effect in the "downwind" area of the San Joaquin Valley. This would be consistent with the mechanics of the two seeding modes. Aerial releases were made continuously along a 30 to 60 km line at a rate of about 700 gm hr^{-1} or 11.7 gm min^{-1} either within the cloud or at cloud base. The Phase I ground seeding used high output pyrotechnics in short bursts, releasing about 1600 gm hr^{-1} or 133 gm min^{-1} from a single point several hundred meters below the cloud base. The latter method would certainly be more likely to produce excess nuclei which could be carried by the cloud level winds into a downwind area, either as unused nuclei or in ice particles from portions of the cloud which were glaciated from the high concentrations of AgI.

The areas of significance for Phase I ground seeding are shown in Figure 5-4, where it appears that a large area of the primary target contained stations significantly at the 10% or better level. All told, 21 of the 27 stations that exhibited statistical significance at these levels were located within the target. The high ratio area in southern Kern County, north of the predicted area of effect, was also statistically significant, and a small area far to the northwest near Paso Robles showed significance. The latter area could not have been effected directly by the seeding operation since the bands were almost always beyond that area when seeding commenced. The statistical significance indicated at this station must therefore be considered as a chance variation.

5.1.2 <u>Phase II - Ground Band Precipitation Analysis</u>. The results of the Phase II ground seeding operations have generally been disappointing, primarily due to the relatively small number of cases and to the uneven random draw that saw several bands with large totals fall into the not-seeded category. These large amounts of precipitation occurred both in and out of the study area with the net effect that the results are strongly biased toward low ratios over all of the analysis area.

This can be seen in Figure 5-5, which is a plot of the ratio of ground seeded to not-seeded band precipitation for the 1971-74 Phase II ground operations. The total sample size consisted of 20 seeded and 10 not-seeded bands. It is apparent

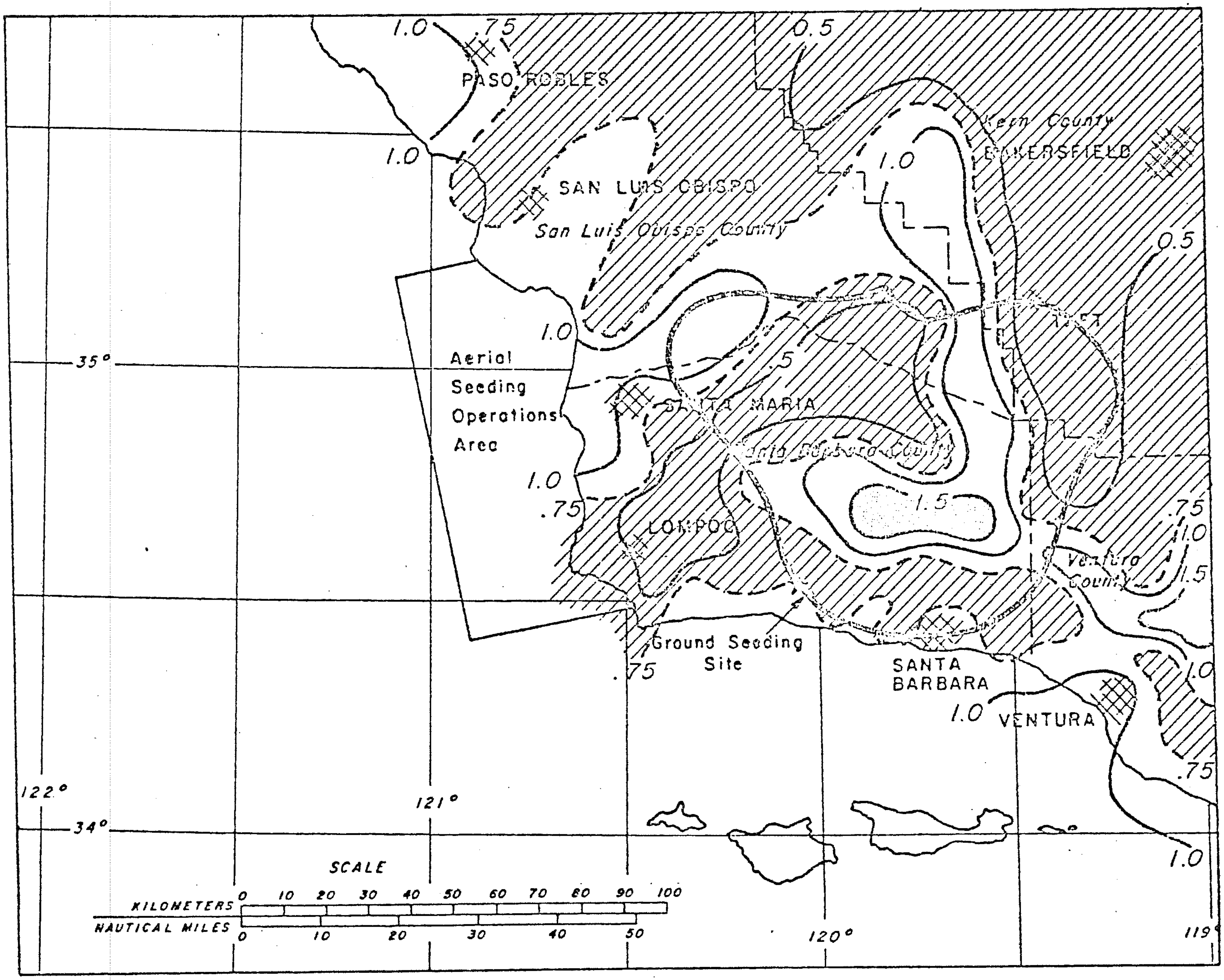
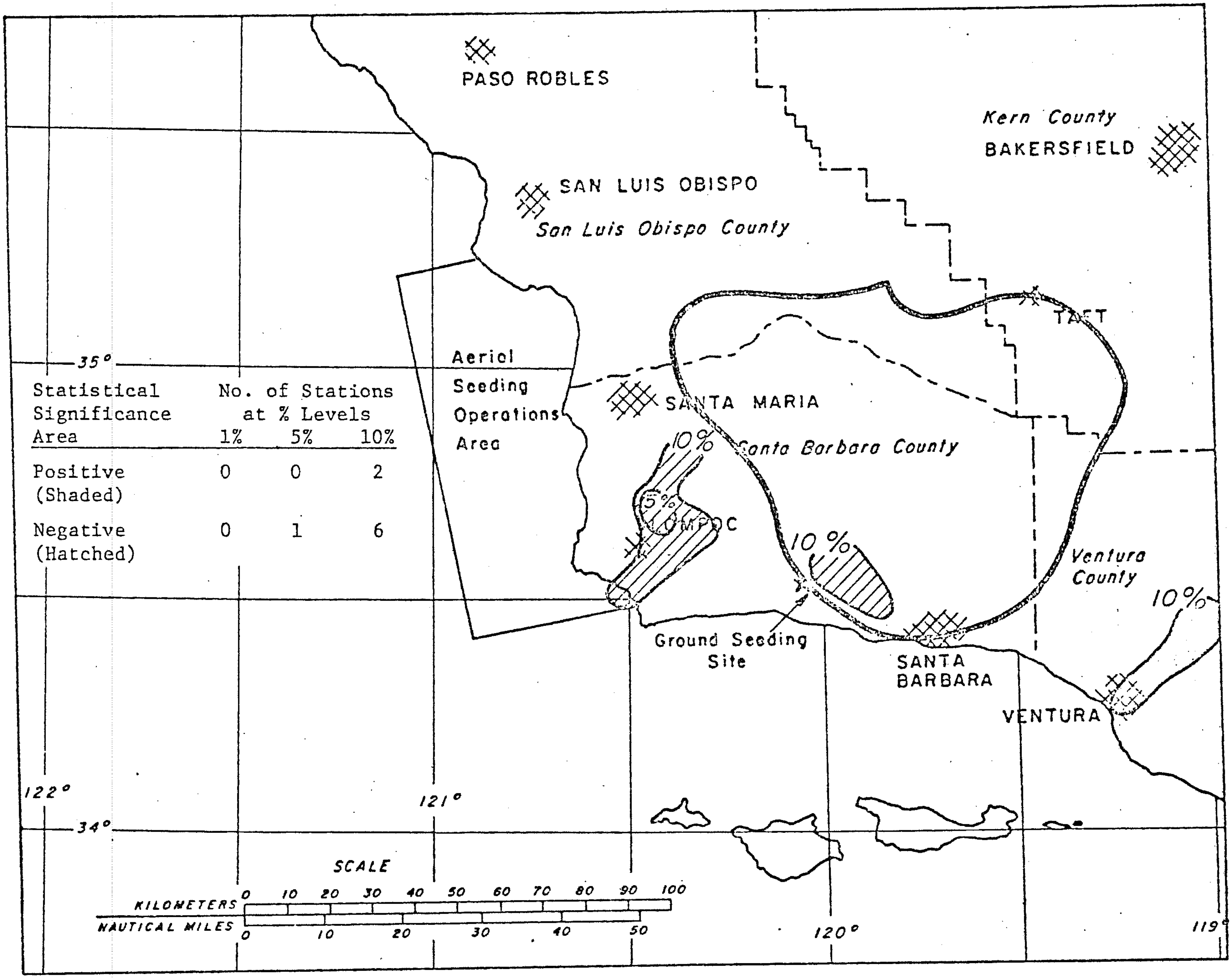


Figure 5-5. Seeded/not-seeded ratios of band precipitation for Phase II ground operations, 1971-74 seasons; 20 seeded and 10 not-seeded bands.

from the analysis that generally low ratios exist throughout the entire analysis area. The average ratio for the 37 stations in the predicted area of effect is only 0.73 with the remaining stations outside the target averaging 0.76. It is of some interest that the two highest ratios on the map are located within the target and to the east of the target in Ventura County. However, as Figure 5-6 shows, only two stations showed positive significance and neither of these were within the primary target. Of more interest is the fact that six stations showed negative significance. One of these is within the target, while the remaining five are located upwind (westward) of the seeding site at an average distance of 40 kilometers.

In an attempt to reduce the possible bias which could be caused by a bad random draw with a few very large bands in the unseeded sample, a second analysis was made, comparing the Phase II ground seeded bands with all the unseeded bands from both Phase I and Phase II. This gave a maximum of 20 seeded and 61 not-seeded bands for those stations which had a complete sample. The ratio analysis pattern revealed by this grouping (see Figure 5-7) does not appear to have been changed markedly from the results shown in Figure 5-5. The numerical value of the ratios has generally become more positive throughout the map, but otherwise, the overall pattern is similar to the results of Figure 5-5 with the highest ratios along the south coast (just south and southwest of the target), in Ventura County (east of the target), and far upwind in northern San Luis Obispo County. Low ratios continued over all of southern Kern and eastern San Luis Obispo Counties and through much of northern and western Santa Barbara County in the northern portion of the target. Thirty one stations in the target had an average ratio of 1.03 while those stations outside the target averaged 1.08.

Looking at the area of significance map for this grouping, in Figure 5-8 we can see a major change from Figure 5-6. Firstly, the number of positively significant stations has increased to 34, while the number of negatively significant stations has remained at six. These positively significant stations form a solid area covering the southern portion of the area of effect and extend eastward into Ventura County. Secondly, the large area of negative significance visible on Figure 5-6, west of the target, is still apparent on Figure 5-8 but has decreased markedly in size with only one station showing significance at the 10% level. Thirdly, a large area of negative significance has appeared in the northeast portion of the target and beyond into Kern County. Five of the six stations which showed negative significance are within this area with two of these significant at the 5% level. This



Statistical Significance Area	No. of Stations at % Levels 1%	5%	10%
Positive (Shaded)	0	0	2
Negative (Hatched)	0	1	6

Figure 5-6. Areas of statistical significance associated with band precipitation ratios. Phase II ground operations, 1971-74 seasons.

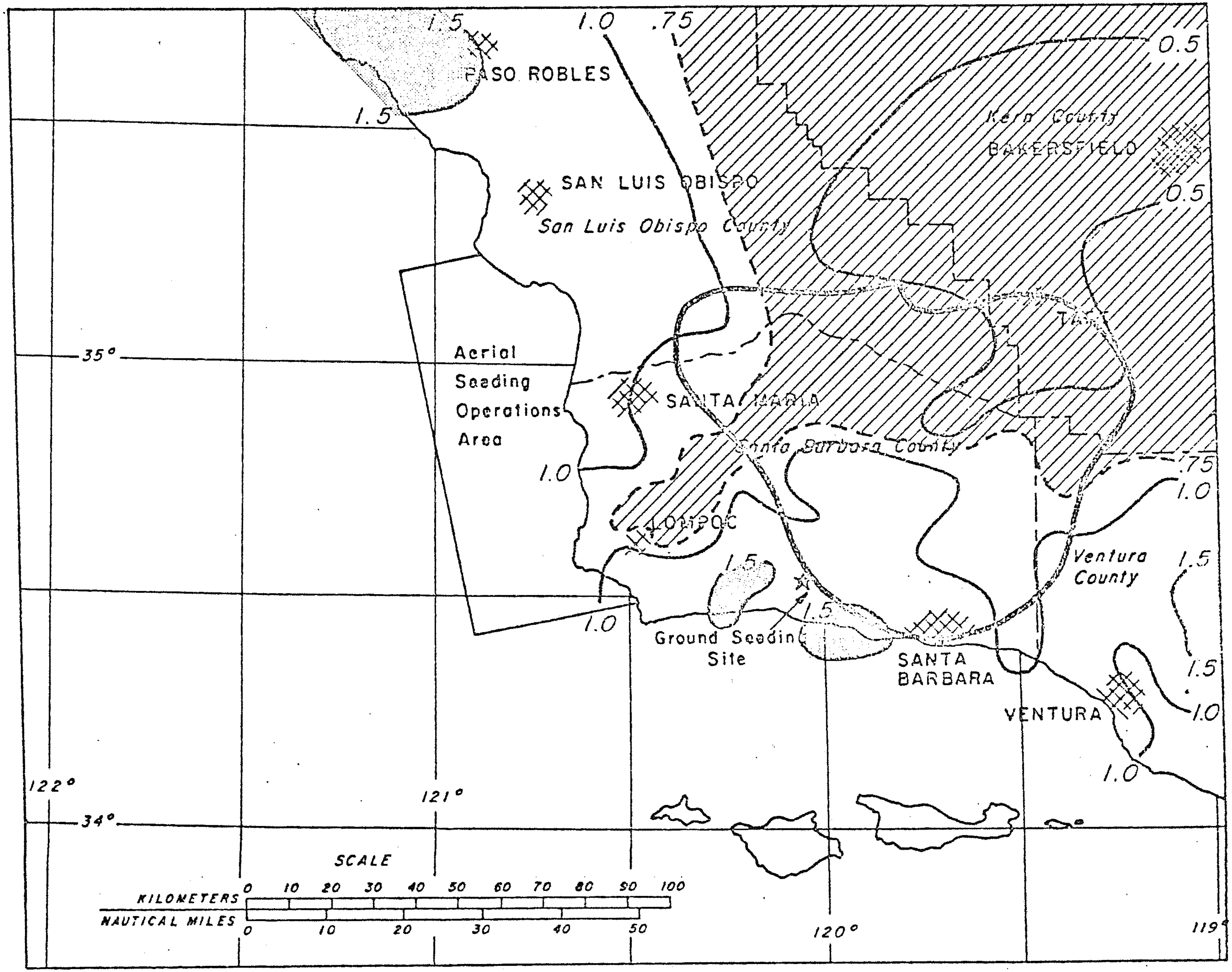
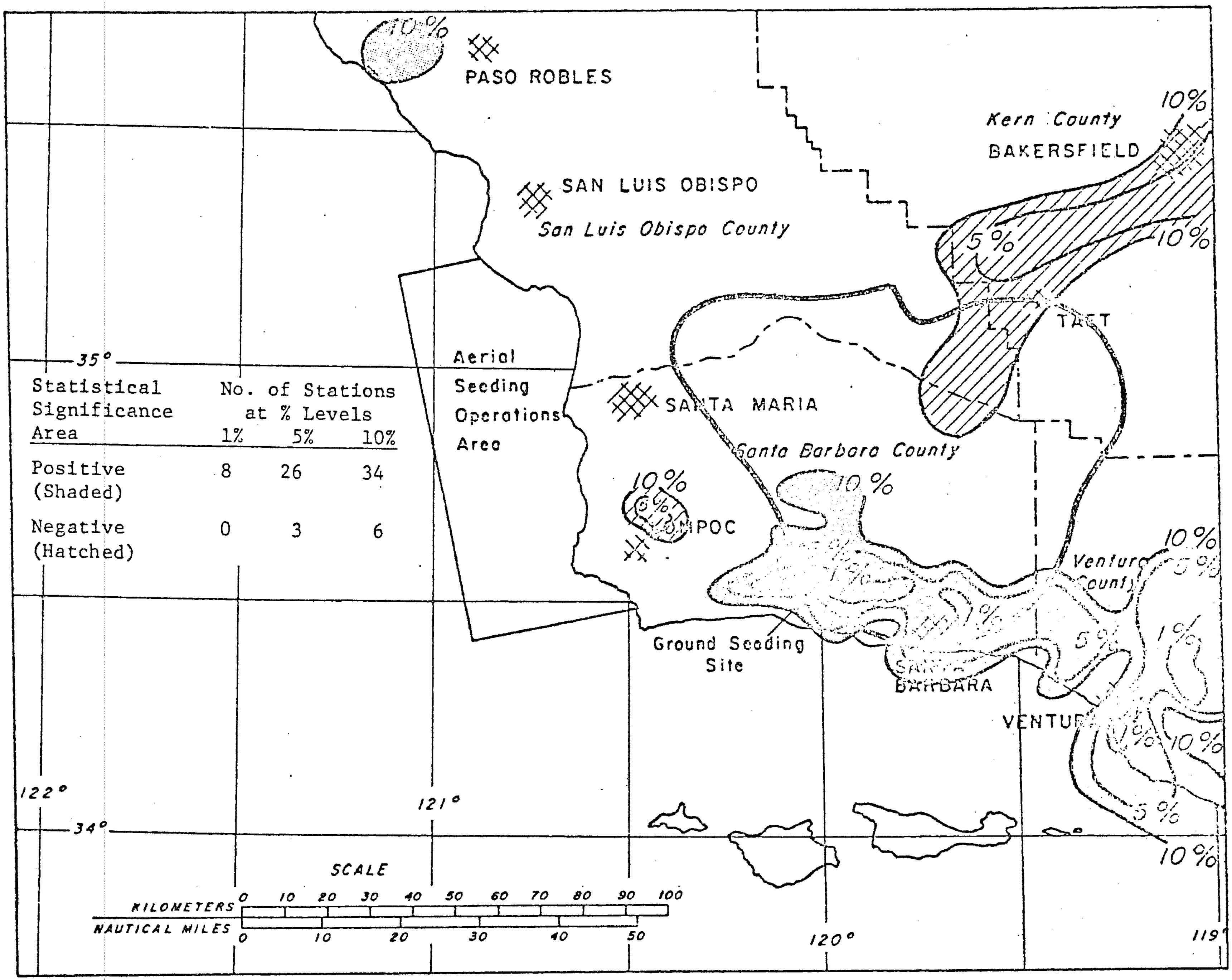


Figure 5-7. Seeded/not-seeded ratios of band precipitation for Phase II ground operations; 20 seeded bands from 1971-74 seasons and 61 not-seeded bands from 1967-74 seasons.



Statistical Significance Area	No. of Stations at % Levels 1%	5%	10%
Positive (Shaded)	8	26	34
Negative (Hatched)	0	3	6

Figure 5-8. Areas of statistical significance associated with band precipitation ratios, Phase II ground operations, including large not-seeded data [illegible]

is also a low ratio area with ratios of about 0.5 evident on Figure 5-7, suggesting that some significant decreases in band precipitation may have occurred in this region with the Phase II ground seeding techniques.

The ratio-pattern revealed in Figure 5-7 is somewhat different than either of the patterns revealed in Figure 5-1 (aerial seeding) or Figure 5-3 (Phase I, ground seeding). Overall, however, it is more like the latter in that the high ratio areas produced tend to elongate west to east in the southern half of the target and eastward. A major difference in the pattern is the existence of a low ratio area in Kern County where a high ratio area appeared in Phase I.

5.1.3 Comparison of High Ratio Centers. One of the objectives of changing the seeding mode and location from a single site at the ground to an aerial line source was to determine if the high ratio areas detected during the first phase of the program would shift locations in a logical manner. Since the seeding site was moved about 60 kilometers to the west, we might expect these ratio centers to move a comparable distance unless the mechanism producing these centers is closely related to topography.

In order to compare the two modes of seeding, the ratio centers shown in Figure 5-1 (Aerial Seeding-Precipitation) and those produced by the Phase I ground seeding (Figure 5-3) were superimposed in Figure 5-9. There is a rather remarkable similarity in the patterns produced by the two seeding modes. It appears that the centers did shift westward when the seeding site was moved to the west indicating that the seeding effect is not topographically-produced.

5.1.4 Temperature Dependence of Precipitation. As stated earlier, direct measurements of the cloud-top height in bands were infrequent. It was therefore decided to use the 500 mb temperatures as an approximation to the band cloud-top temperature with each convective band being assigned a 500 mb temperature representation of cloud-top. Five stations, namely, E1253, M105, N14, N15, and N17, located within the calculated area of effect were then selected and a band precipitation average was computed for each band. These band averages were then compared for the seeded and not-seeded bands stratified by 500 mb band temperature. To reduce the scatter, the 500 mb temperatures were averaged over seven degrees (three and five degree averages were also calculated, but these showed considerable fluctuation from point to point). The same five stations were used with the Phase I and Phase II ground seeding bands since the area of effect for these two seeding modes was almost in the same place. The aerial area of effect, on the other hand, was much

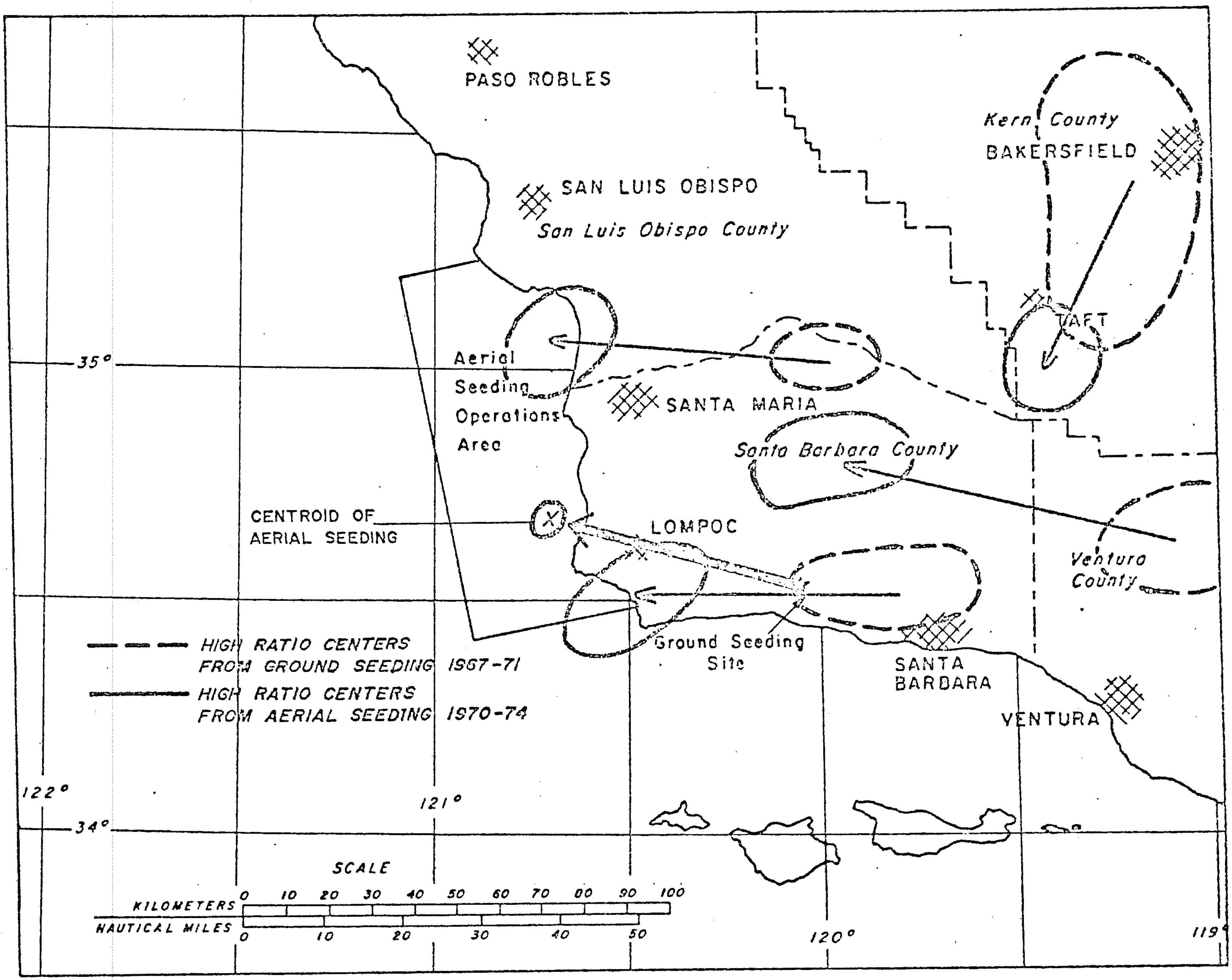


Figure 5-9. Comparison of high ratio precipitation centers observed during Phase I ground and Phase II aerial operations.

further west and five different stations within that target were selected. These stations consisted of E7946, E8697, N1, N2, and S217.

Figure 5-10 shows the result of this stratification for the Phase I pyrotechnic ground seeding method. The 500 mb temperature has been plotted along the abscissa with the seeded to not-seeded ratio and the five station precipitation average plotted along the ordinate. The Wilcoxon, Mann-Whitney U Test was used to determine whether there was any significant difference between the seeded and not-seeded precipitation samples for each temperature value. These probabilities have been plotted near the top of the figure for each temperature level. It is apparent from examination of Figure 5-10 that there was a difference between the seeded and not-seeded sample in the warm end of the temperature spectrum with the seeded bands averaging about .10 inch (2.54 mm) more precipitation than the not-seeded bands. The temperature curves begin to merge at about the -22°C level and cross over between -25°C and -26°C, suggesting that the LW-83 pyrotechnic seeding would not be effective with 500 mb temperatures colder than about -25°C. The seed to not-seed ratio plotted in the lower portion of the figure indicates a ratio near 1.5 in the warm end, decreasing to slightly below 1.0 in the cold end. The curves are statistically significant at the 10% or better level from T = -15°C to T = -24°C, with the significance increasing to the 1% level between -17°C and -20°C.

A similar pattern is evident in the results of the Phase II acetone ground seeding operations as well. Figure 5-11 indicates that the warmest temperatures yielded the greatest difference between seeded and not-seeded precipitation averages with a steady decrease in these differences as the 500 mb temperature got colder. The cross-over point indicated in this figure occurs between -21°C and -22°C, which is about 4 degrees warmer than with the pyrotechnic seeding. However, the non-parametric statistical test indicated that there was a significant difference between the seeded and unseeded populations at the -23°C level with the seeded population having higher ranks even though the seeded band average precipitation was lower than the unseeded. This is due to some large precipitation values in the unseeded category and a relatively small sample in the seeded category with uniformly moderate amounts of precipitation. This suggests that there is still a positive seeding effect at -24°C and we are unable to determine a true cross-over point since there were insufficient cold bands in the seeded sample. The highest statistical significance in both the Phase I and Phase II ground based seeding operations occurs with a 500 mb temperature of -19°C.

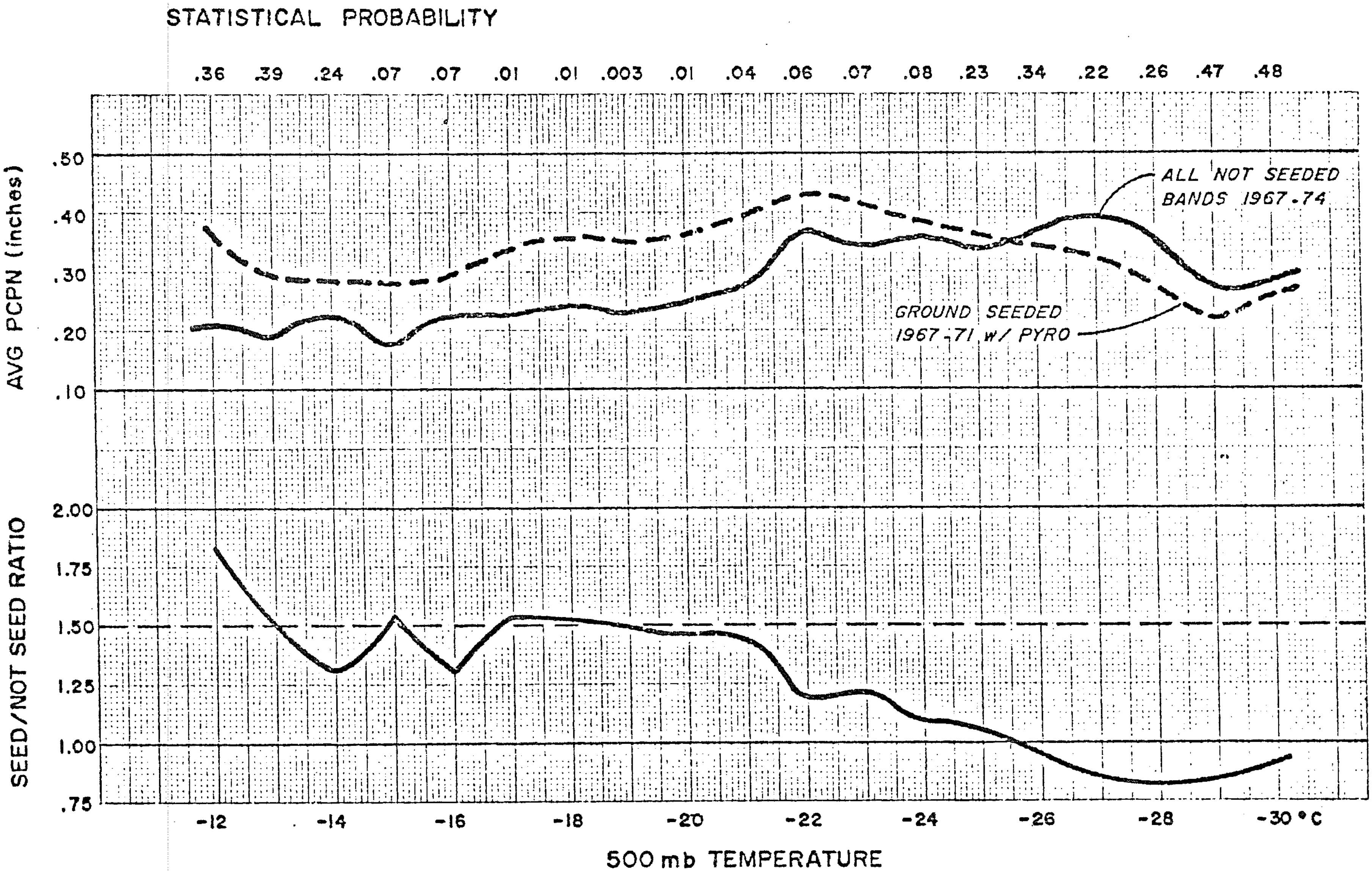


Figure 5-10. Seeded/not-seeded precipitation ratios, band averages and probabilities for five target stations stratified by 500 mb temperatures (seven degree averages), Phase I 1967-71 ground seeding with LW-83 pyrotechnic.

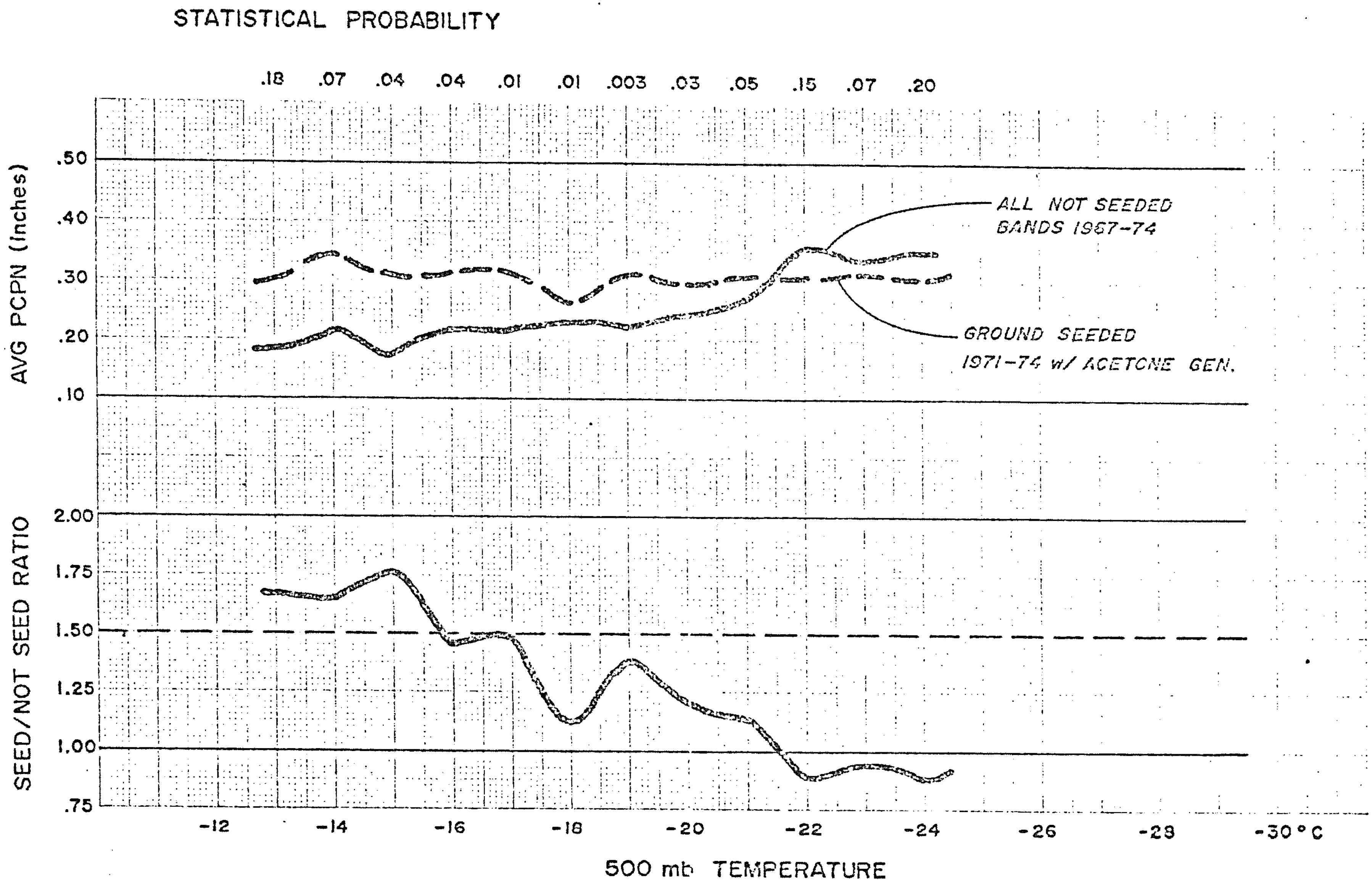


Figure 5-11. Seeded/not-seeded precipitation ratios, band averages and probabilities for five target stations stratified by 500 mb temperatures (seven degree averages), Phase II 1971-74 ground seeding with acetone generator.

A somewhat different set of curves was revealed when the aerial cases from Phase II were examined. These are shown in Figure 5-12. The difference between the seeded band average precipitation and the not-seeded band precipitation for the five stations within the aerial area of effect is much greater in the warmer temperatures than either of the ground seeded results were. It averaged about .18 inches (4.57 mm) more from -15°C to -20°C which is almost twice the average of the ground seeded differences. Unlike the Phase I ground seeded results, the seeded and not-seeded curves do not cross, mainly because the precipitation with the not-seeded curve does not increase as much in the cold end of the spectrum as it did with the Phase I and II ground operations. The two curves do converge, however, and become parallel at about the -23°C level. Less statistical significance is achieved with the aerial seeded cases; however, those values in the warm end between -16°C and -19°C are significant at the 10% level.

In order to determine whether these warm temperature/high ratio relationships applied outside of the target area as well, seed to not-seed ratio maps for Phase I, ground seeded and Phase II, ground and aerial seeded, were prepared statifying the data into warm and cold temperature categories. The data was split at -22°C with all bands warmer than -22°C being considered as warm and -22°C and colder considered as cold. The smaller number of Phase II cases did not allow a very large number of cases in the cold temperature category, but nevertheless, the results in all cases were quite similar. The warm temperatures generally had the highest ratios and the most significant number of stations both in and eastward from the target area. The cold temperature stratifications had less consistent patterns and a fewer number of significant stations. Of particular interest, however, is the fact that no significant decreases were indicated with the cold cases.

A cautionary note should be made that the use of the 500 mb temperature to indicate cloud top temperature can introduce significant errors under certain storm types and in some geographical areas. The fact that the Santa Barbara data indicates a fairly strong relationship between 500 mb temperature and seeding effectiveness suggests that cloud tops in convective bands in Southern California may be fairly consistently at about 6000 m MSL. It is likely, however, that a measured or calculated cloud top temperature would provide a more accurate picture of the relationship between seeding effectiveness and temperature. Time constraints have precluded this approach for this report but it is planned to use a calculated cloud top temperature on these data from the Santa Barbara Project in the preparation of

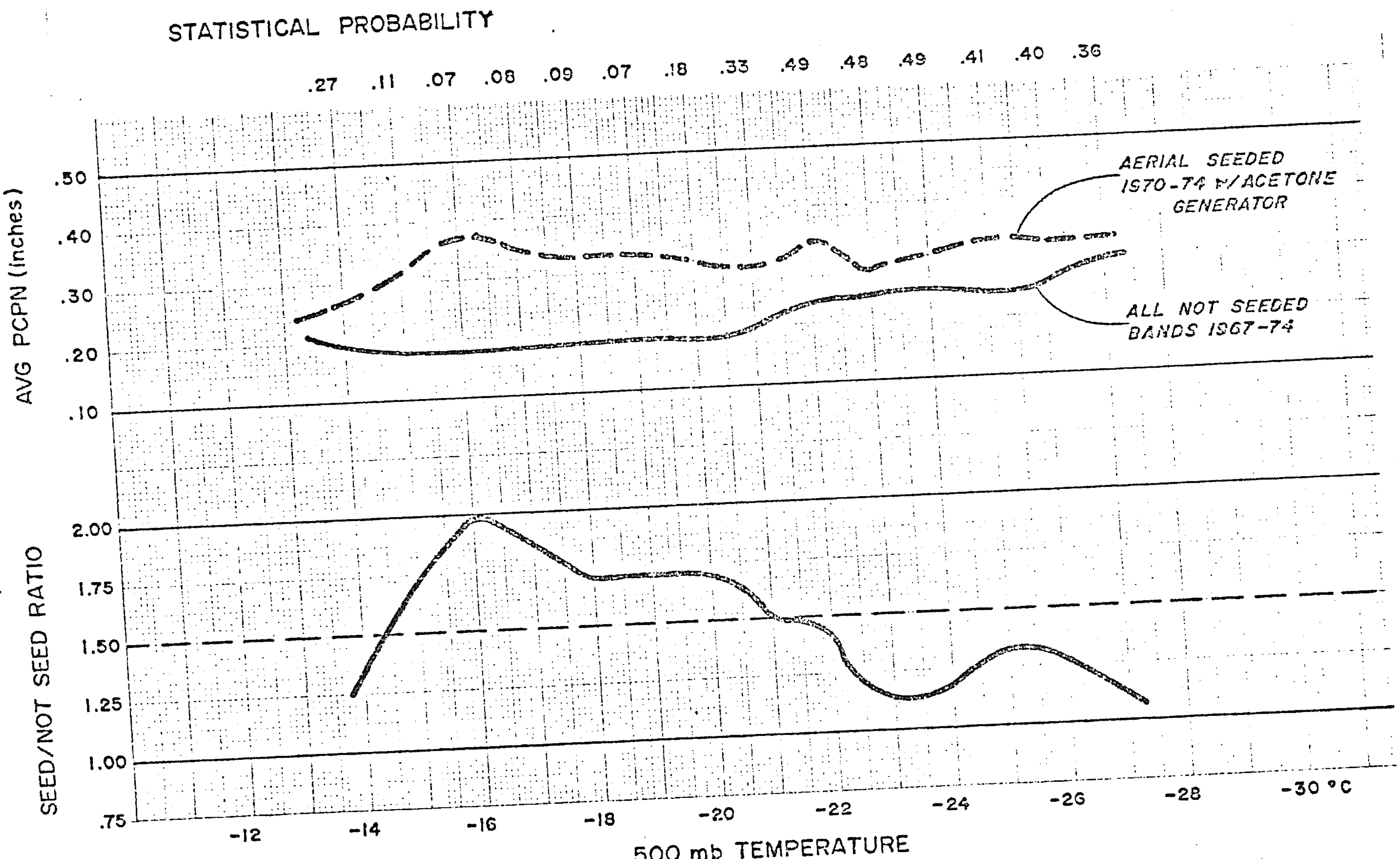
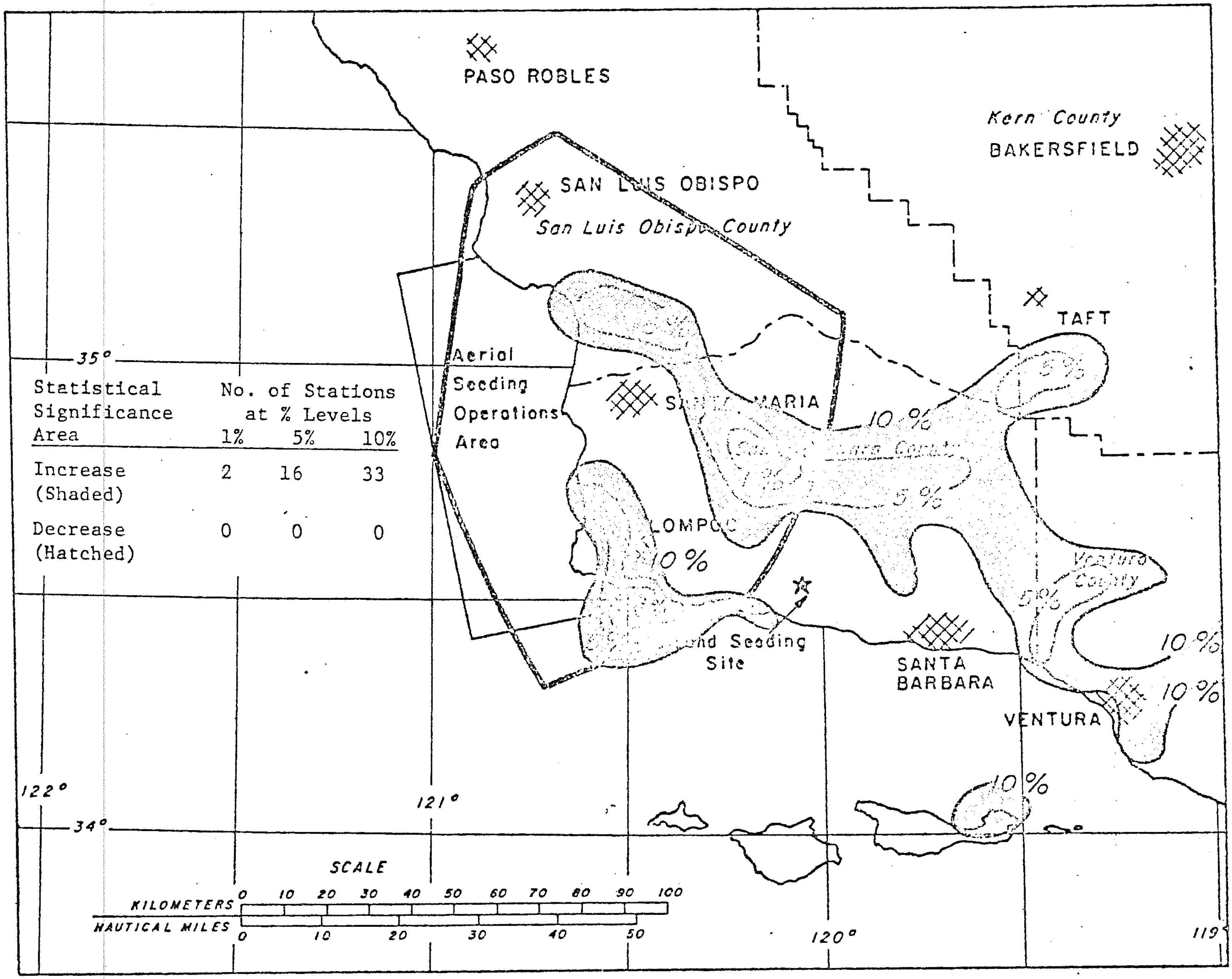


Figure 5-12. Seeded/not-seeded precipitation ratios, band averages and probabilities for five target stations stratified by 500 mb temperatures (seven degree averages), Phase II 1970-74 aerial seeding with acetone generator.



Statistical Significance Area	No. of Stations at % Levels 1%	5%	10%
Increase (Shaded)	2	16	33
Decrease (Hatched)	0	0	0

Figure 5-14. Areas of statistical significance associated with band duration ratios, Phase II aerial operations, 1970-74 seasons.

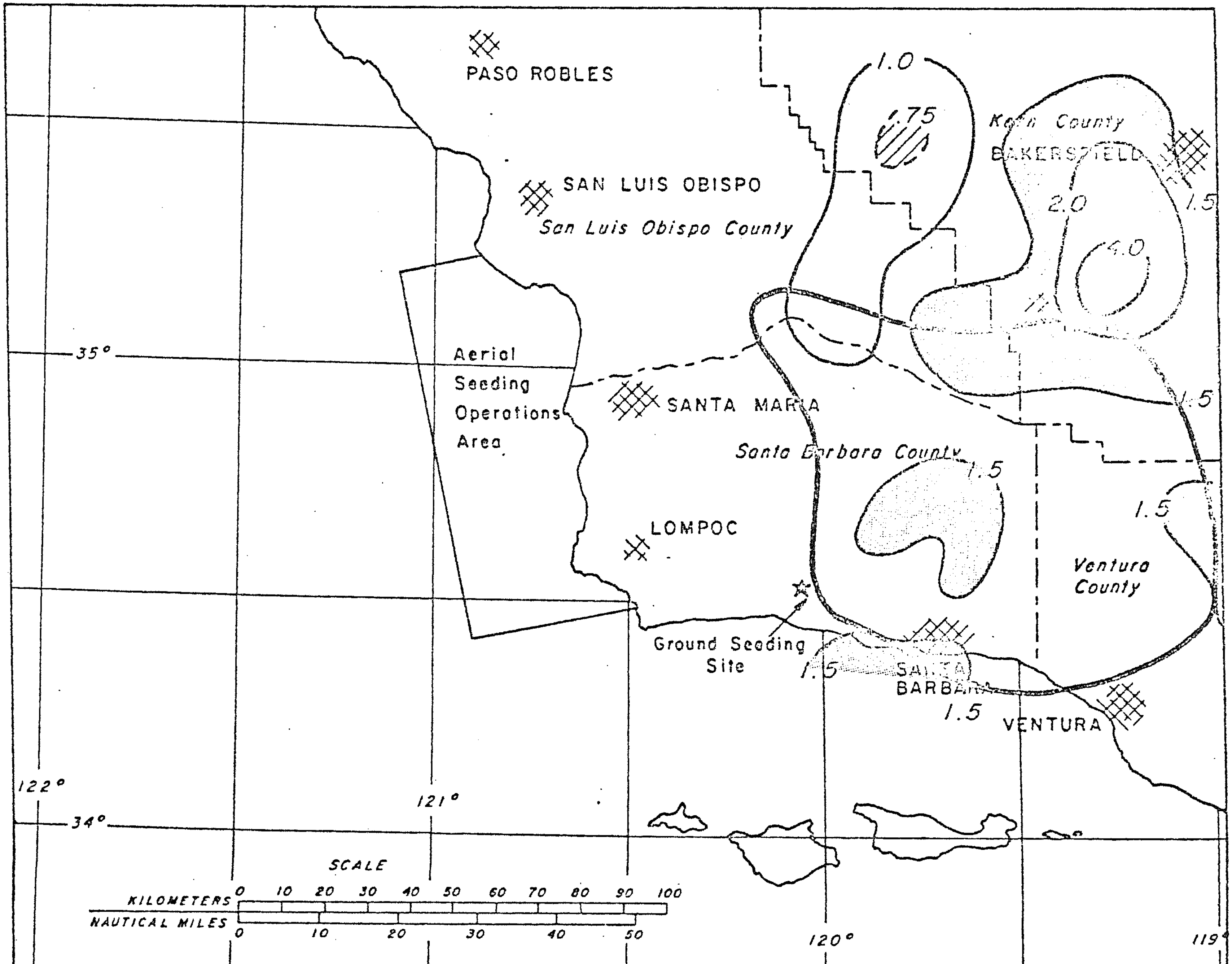
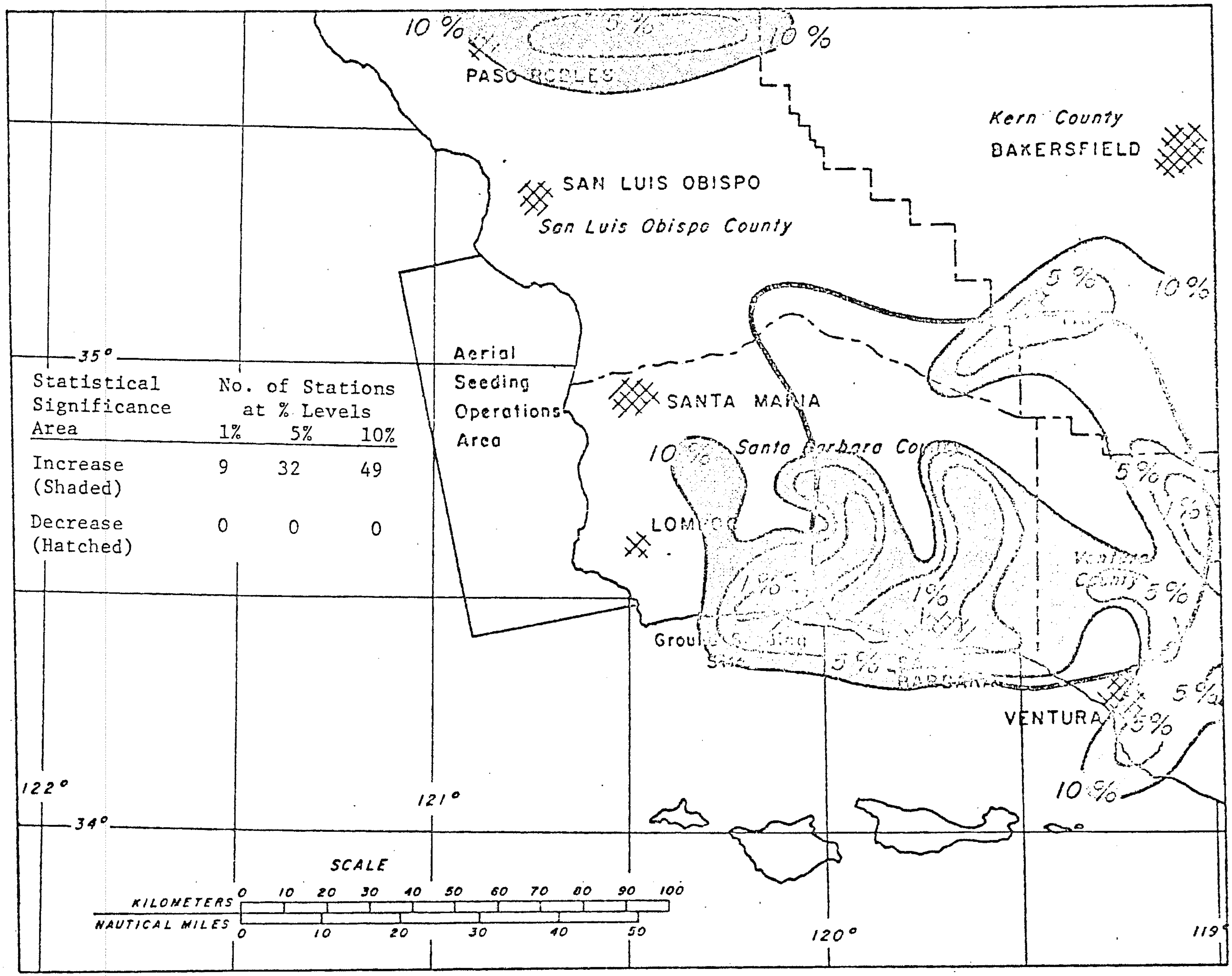


Figure 5-15. Seeded/not-seeded ratios of band duration for Phase I ground operations, 1967-71 seasons; 56 seeded and 51 not-seeded bands.



Statistical Significance Area	No. of Stations at % Levels 1%	5%	10%
Increase (Shaded)	9	32	49
Decrease (Hatched)	0	0	0

Figure 5-16. Areas of statistical significance associated with band duration ratios, Phase I ground operations, 1967-71 seasons.

32 at the 5% or better, and nine at the 1% level. With the exception of the small apparently random area far to the north, these make up the major portion of the primary target and immediately adjacent areas.

5.2.2 Phase II Ground Band Duration Analysis. Since a high correlation exists between band precipitation total and band duration, the Phase II ground seeding analyses suffer from the same problems; namely, a small number of cases, and the bias toward longer-stronger bands in the not-seeded category.

For completeness, the analysis of the 1971-74 data containing the 20 seeded and the 10 not-seeded bands is presented in Figure 5-17. The analysis results are much like those for the band precipitation (Figure 5-5) wherein most of the chart is covered by ratios less than 1.0. A small portion of the target area near the seeding site has positive ratios as does the extreme northwest part of the target. The target average was .80 while those stations outside the target averaged .85.

Figure 5-18 contains the areas of significance for the ratios in Figure 5-17. A total of 12 stations were significant, all negatively. Most of these were either in or adjacent to the target area.

When the not-seeded bias is reduced, however, by including the not-seeded bands from Phase I, a completely different pattern for the Phase II ground seeded band duration emerges. This relatively flat pattern is evident in Figure 5-19, where it now appears that all of the map has positive ratios except for the northern half of the target and the area immediately northward therefrom. Small high ratio centers are centered just west of the northwestern portion of the target, within the target just downwind from the seeding site, and to the southeast of the target in southwestern Ventura County. Target station ratios average 1.29 even with the northern half of the target indicating ratios below 1.0. The remainder of the area outside the target averages 1.47.

A high degree of statistical significance is evident from the analysis in Figure 5-20. Forty-nine stations show statistical significance at the 10% or better level with 44 of these at the 5% or better level, and an amazing 17 at the 1% level. Only two stations show negative significance in the area just north of the target.

5.3 Total Storm Precipitation Analysis

One criticism of the Phase I randomization scheme, which had both seeded and not-seeded bands within the same storm, was that it did not allow testing the efficacy of the band seeding mode of operation in increasing the total water produced by a storm system. During Phase II, therefore, the randomization scheme was changed

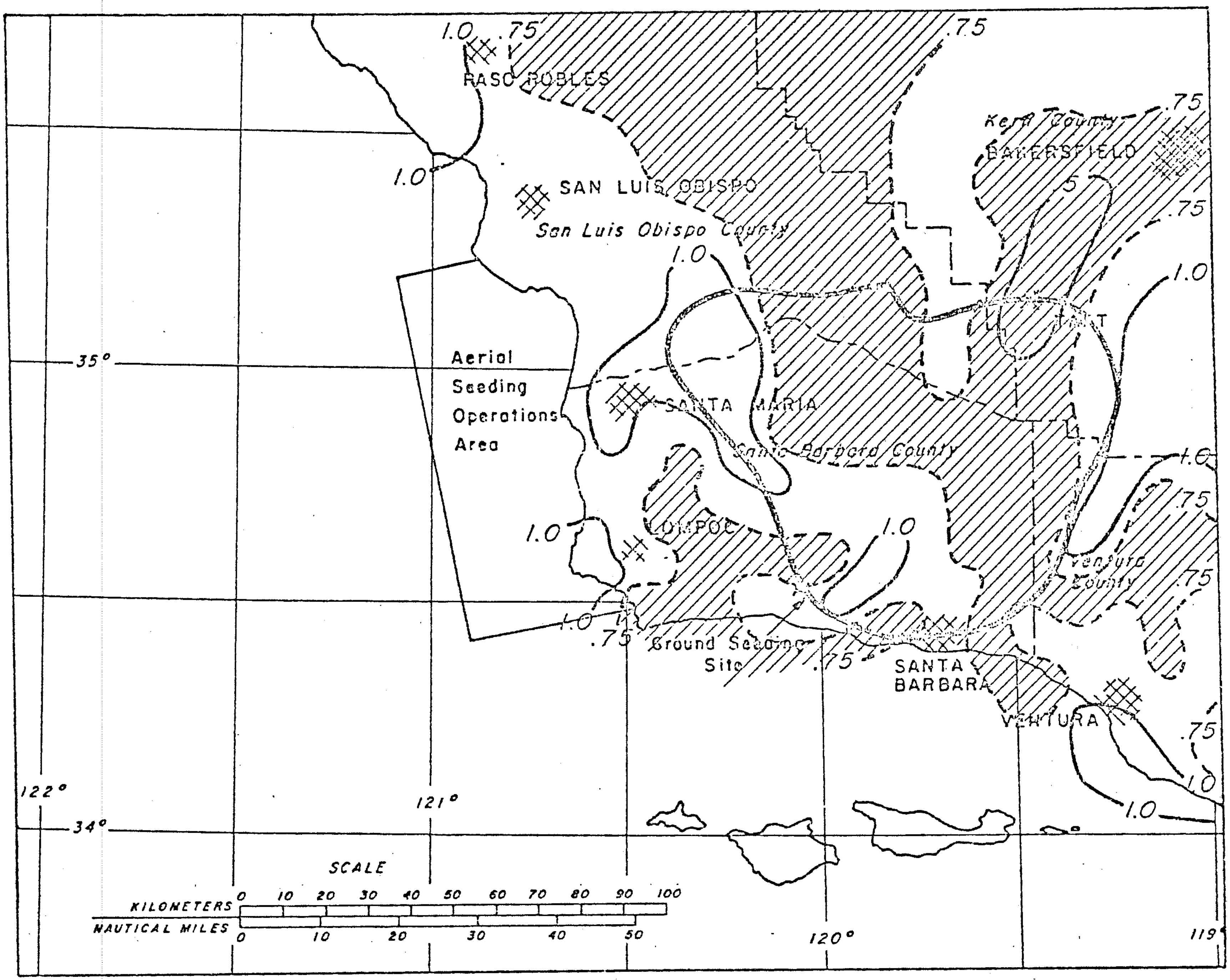
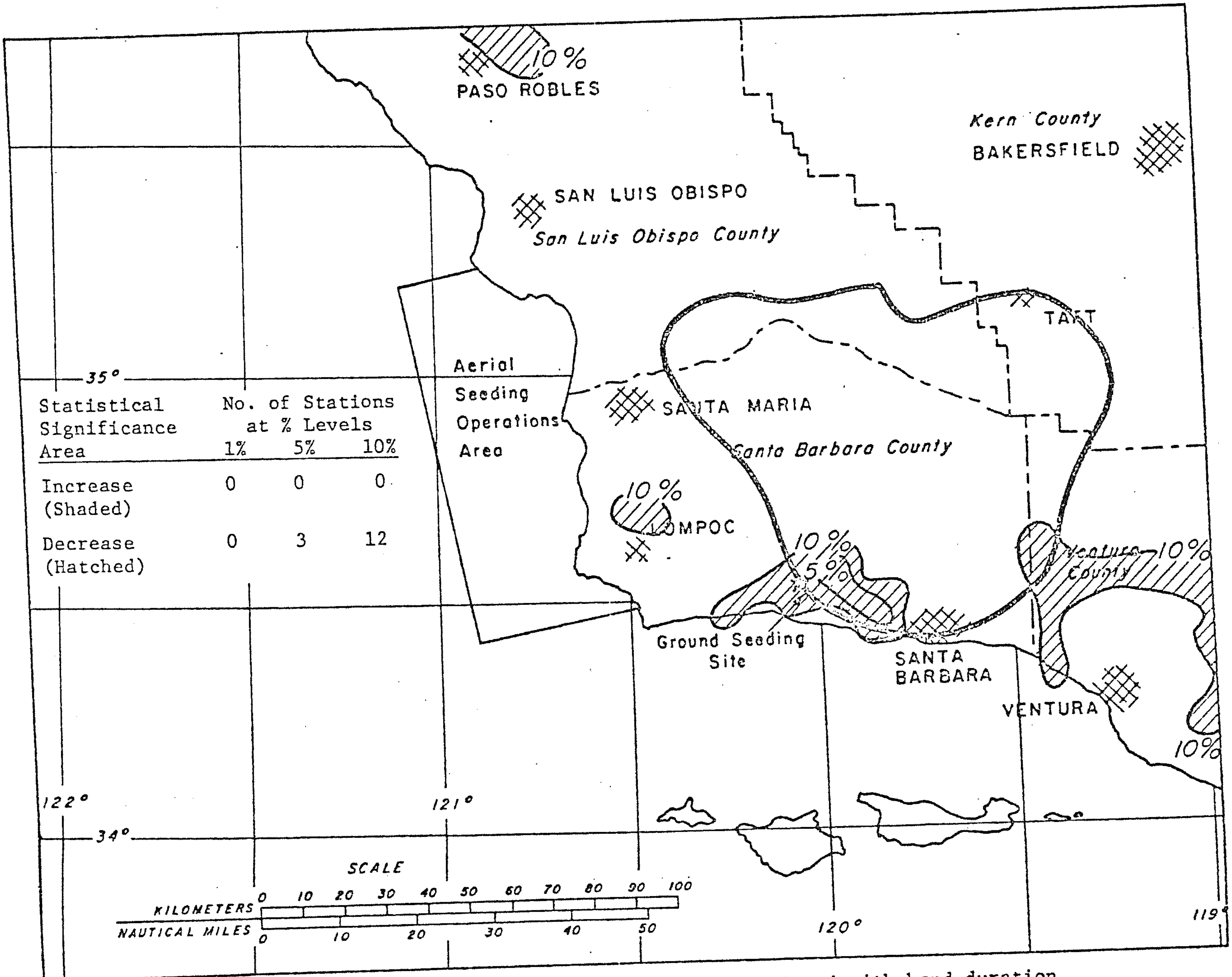


Figure 5-17. Seeded/not-seeded ratios of band duration for Phase II ground operations, 1971-74 seasons, 20 seeded and 10 not-seeded bands.



Statistical Significance Area	No. of Stations at % Levels 1%	5%	10%
Increase (Shaded)	0	0	0
Decrease (Hatched)	0	3	12

Figure 5-18. Areas of statistical significance associated with band duration ratios, Phase II ground operations, 1971-74 seasons.

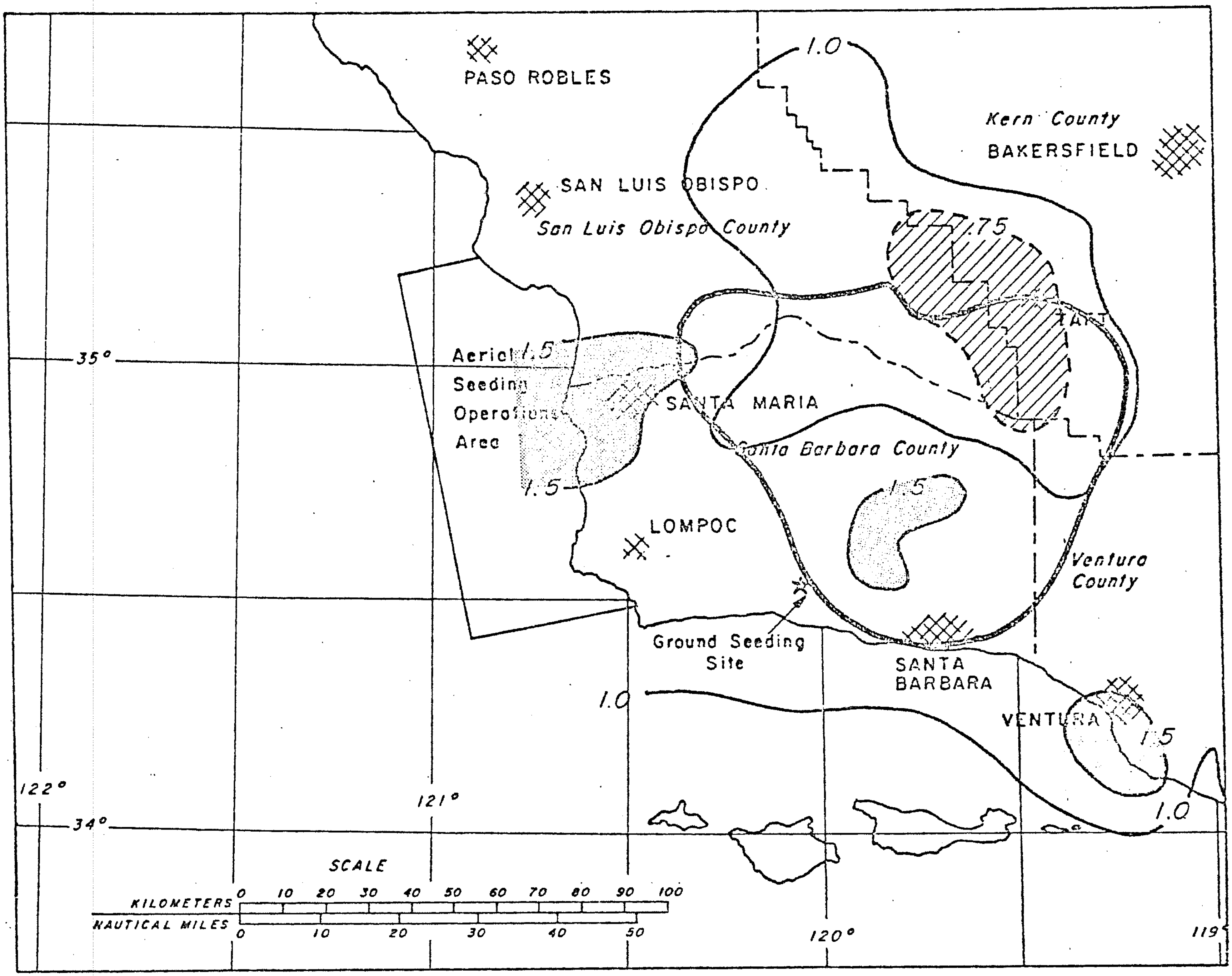
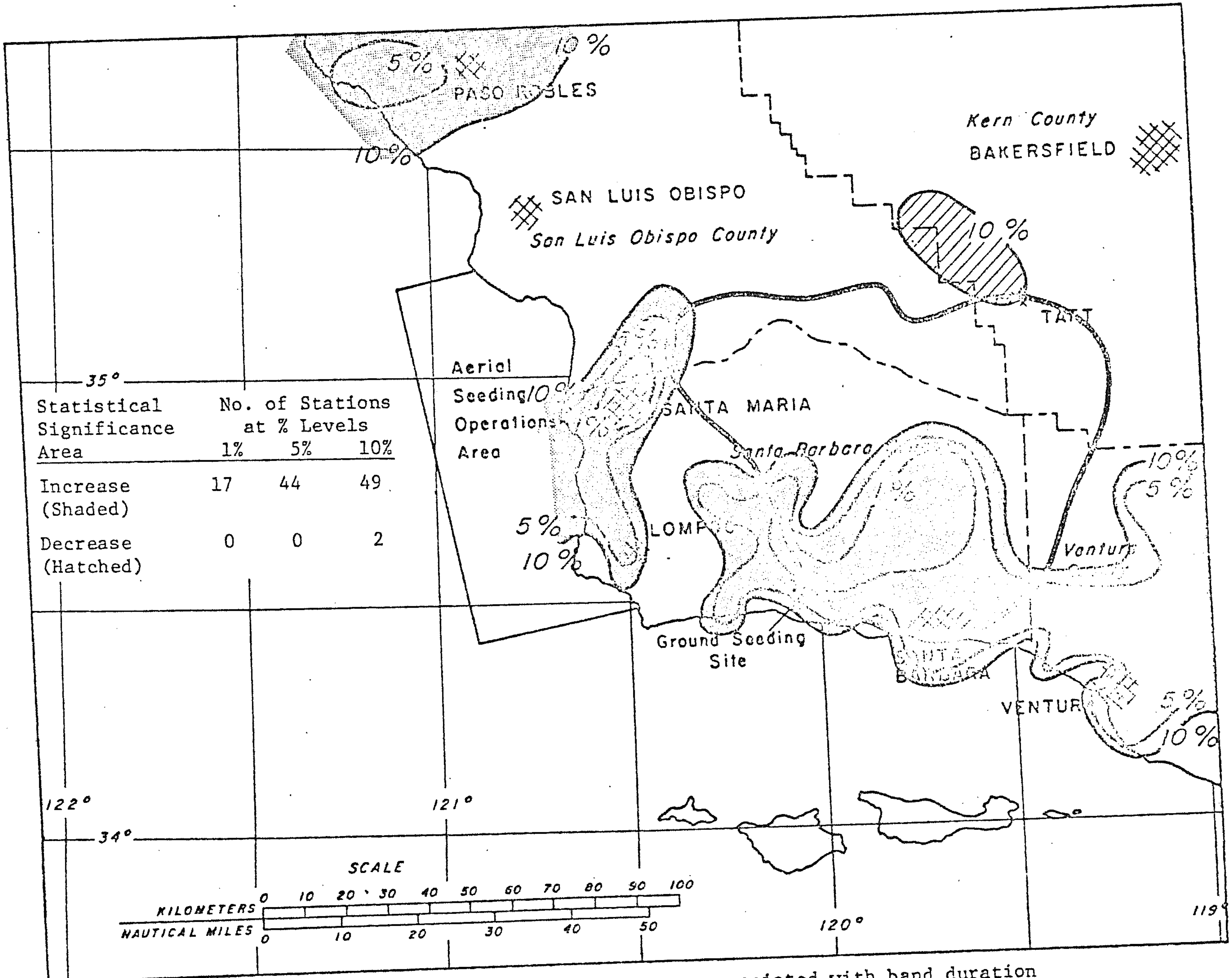


Figure 5-19. Seeded/not-seeded ratios of band duration for Phase II ground operations; 20 seeded bands from 1971-74 seasons and 61 not-seeded bands from 1967-74 seasons



Statistical Significance Area	No. of Stations at % Levels 1%	5%	10%
Increase (Shaded)	17	44	49
Decrease (Hatched)	0	0	2

Figure 5-20. Areas of statistical significance associated with band duration ratios, Phase II ground operations including large not-seeded data ... Phase I

to one wherein all identified bands were treated alike for the duration of the storm. A total of 34 storms constitute the sample collected in the 1971-74 period with 16 (47 percent) of these being seeded either by air or ground generators. Of the 16 seeded storms, eight were exclusively aerially seeded, six were seeded from the ground, and the remaining two were seeded by both air and ground sources. The seeded to not-seeded ratio pattern revealed in Figure 5-21 would suggest that seeding has increased the storm total. The combined targets (indicated by the heavy solid and dashed lines) cover the southern portion of San Luis Obispo County and almost all of Santa Barbara County. Within this envelope the average ratio of seed to not-seed precipitation is 1.34 with high ratios extending east of the envelope into western Ventura County. Ratios outside the target average 1.26 with a slight deficit in seeded storm totals (not significant) centered downwind in Kern County.

The area of significance map, Figure 5-22, shows only positive significance with a large portion of the combined targets covered by those stations significant at the 10% or better level. The large number of significant stations (59 at the 10% level or better, including 27 at the 5% level and 7 at the 1% level) certainly suggests that a difference does exist between the seeded and not-seeded populations. The potential increase is probably larger than indicated since some of the precipitation recorded in seeded storms actually occurred in seedable bands which were not seeded because of operating limitations. Had all of these seedable bands been seeded, the ratio analysis quite likely would indicate even higher ratios and more significance than it does.

5.4 Estimate of Total Precipitation Produced by Band Seeding

Precipitation ratios are highly dependent on the relative amounts of precipitation, i.e., large ratios are more likely to occur in arid regions than in areas of high rainfall and therefore do not always give a true picture in terms of water yield. To calculate the total amount of additional water that was apparently produced during Phase I by ground seeding with pyrotechnics, and in Phase II by the aerial seeding method, the following calculations were made. For Phase I, the difference between the average of the 56 seeded bands precipitation and the average of the 51 not-seeded bands precipitation was determined for each station. This difference was then multiplied by the number of seeded bands (56) during the four years of operation. The resulting value was considered to be the estimate of the total precipitation produced by band seeding. This procedure was repeated for the 18 seeded and the 27 not-seeded bands that make up the Phase II aerial seeded operations package but was not attempted for the ground seeded mode because of the strong

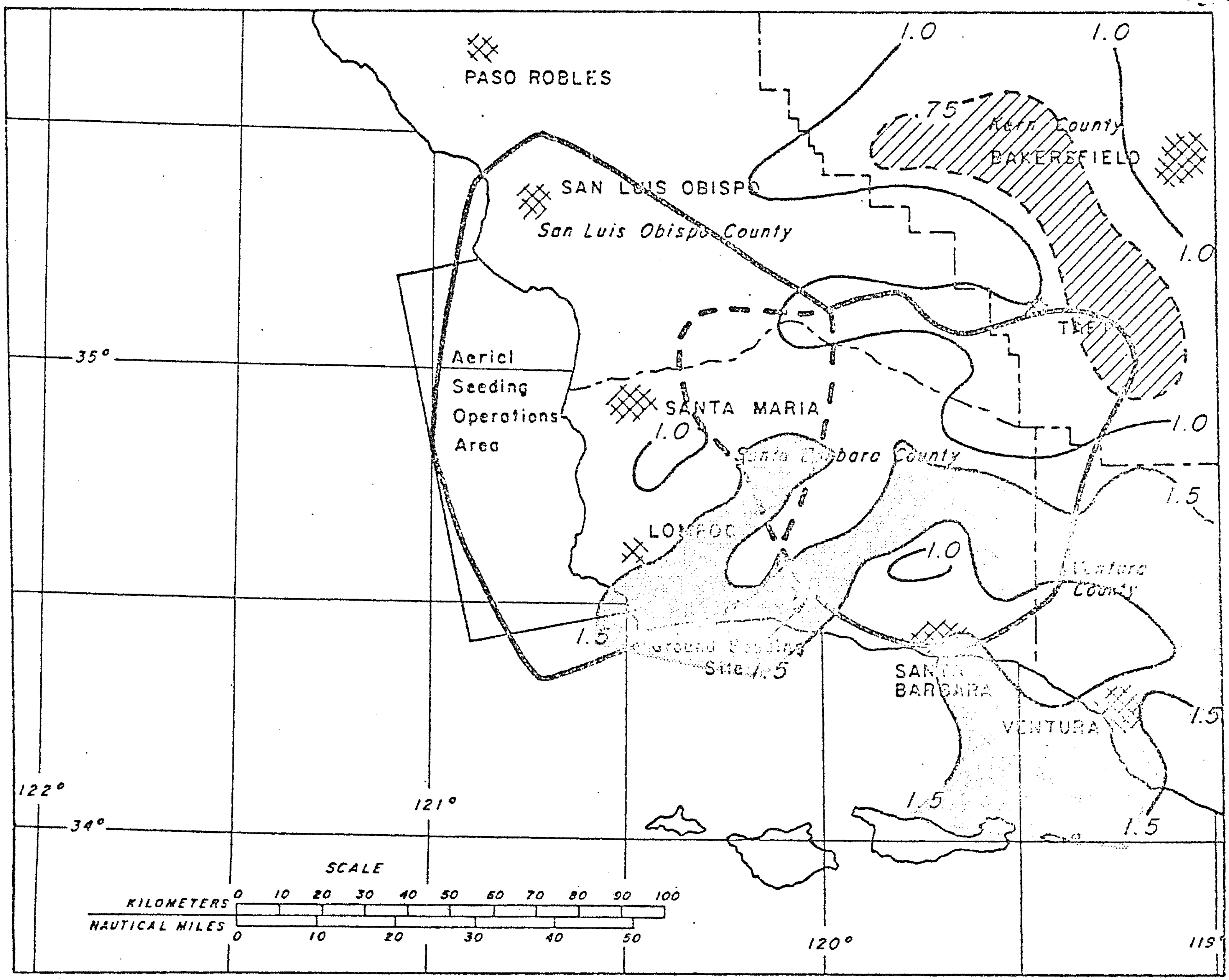
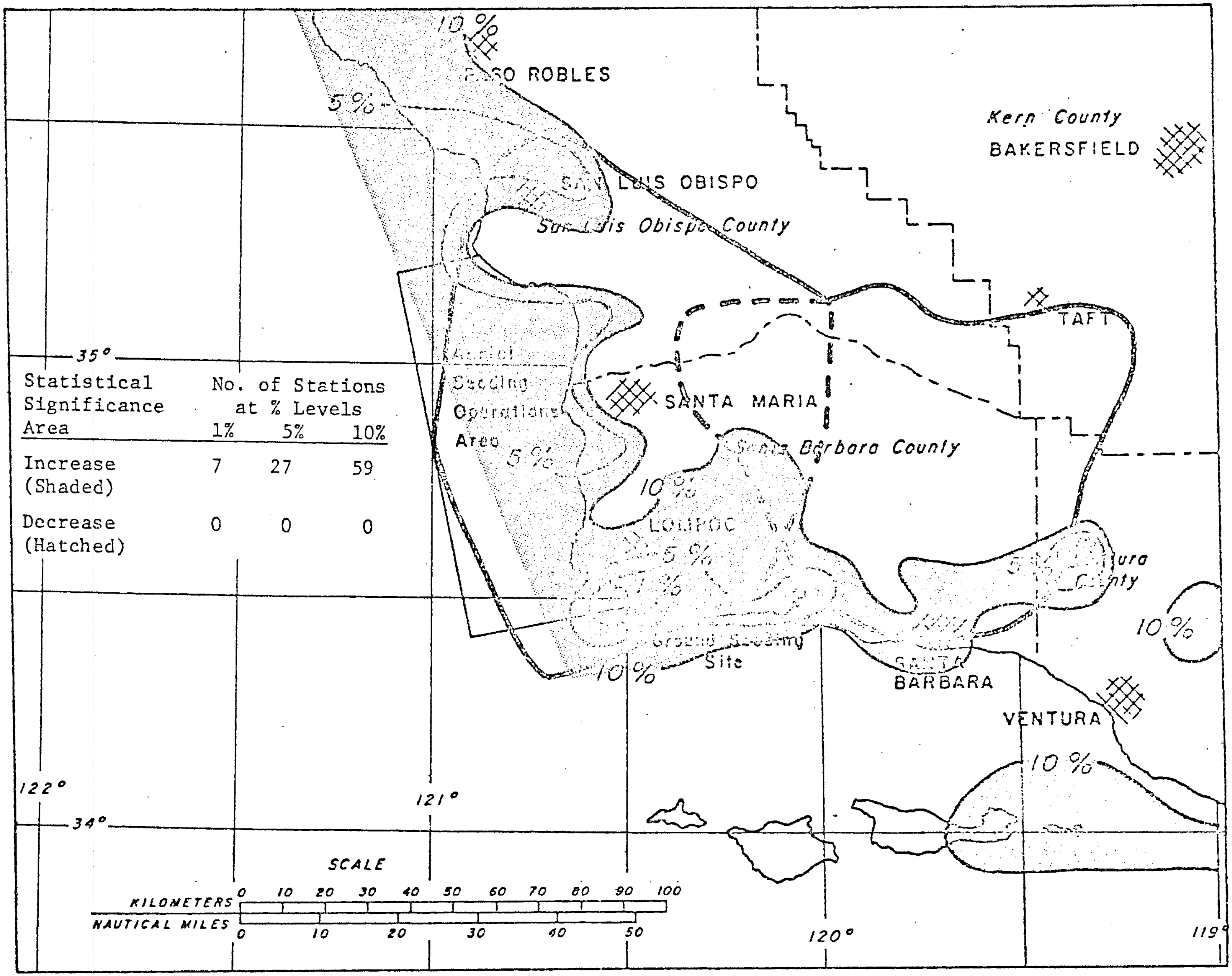


Figure 5-21. Seeded/not-seeded ratios of storm precipitation for Phase II, aerial and ground operations, 1971-74 seasons; 16 seeded and 18 not-seeded storms.



Statistical Significance Area	No. of Stations at % Levels 1%	5%	10%
Increase (Shaded)	7	27	59
Decrease (Hatched)	0	0	0

Figure 5-22. Areas of statistical significance associated with storm precipitation ratios, Phase II aerial and ground operations, 1971-74 seasons.

not-seeded band bias of the data sample. The results of these calculations are produced for Phase I ground operations and for Phase II aerial operations in Figures 5-23 and 5-24, respectively. (The values are shown in inches where 1 in = 25.4 mm).

From Figure 5-23 it would appear that with ground seeding from the mountain crest, increases of six to 10 inches of rainfall occurred over the mountainous regions of Santa Barbara and Ventura Counties during the four years of seeding. In the southern portion of Kern County, where high ratios of over 2:1 were observed, increases of about 2 inches are indicated. Since these values were produced by seeding approximately one-half of the available bands, the potential increase should be nearly twice as much as shown in the figure.

The results of aerial seeding, shown in Figure 5-24, indicate that increases of two to four inches of additional water were produced in the southwest corner of Santa Barbara County and in the higher mountain sections of eastern Santa Barbara and western Ventura Counties. In the high ratio areas of north-central Santa Barbara and southeastern San Luis Obispo Counties, increases of one to three inches are indicated. The low ratio areas of Kern County generally indicate values near zero. On the basis that 40% of the aerial bands were actually seeded, these values represent less than half the additional water that might be expected if all the available bands had been treated.

5.5 Mesoscale Effects Related to Seeding

In order to gain more insight into whether seeding might have been instrumental in producing mesoscale changes in the wind or temperature parameters, Table 5-1 was prepared. This table gives a summary of the 700 mb and 500 mb median wind direction and speed for the seeded, the not-seeded, and the all bands combined categories. The 500 mb temperature median is also included in the table.

Except for the smaller Phase II ground seeded group, the median wind directions at the 700 mb and the 500 mb levels are more southerly than are the corresponding not-seeded winds. The reverse is true for the Phase II ground seeded group. No other apparent differences are to be noted in the table except that the 500 mb wind speeds for Phase I ground seeding are about 5-8 m sec^{-1} lower than for the Phase II ground or aerial seeded groups.

In order to determine whether the observed differences in the 700 mb wind direction were due to chance variation, a χ^2 Median Test was applied to these values and they are shown in Tables 5-2 and 5-3. (Winds which were exactly at the Median value were dropped from the analysis). With significance near the 10% level it appears

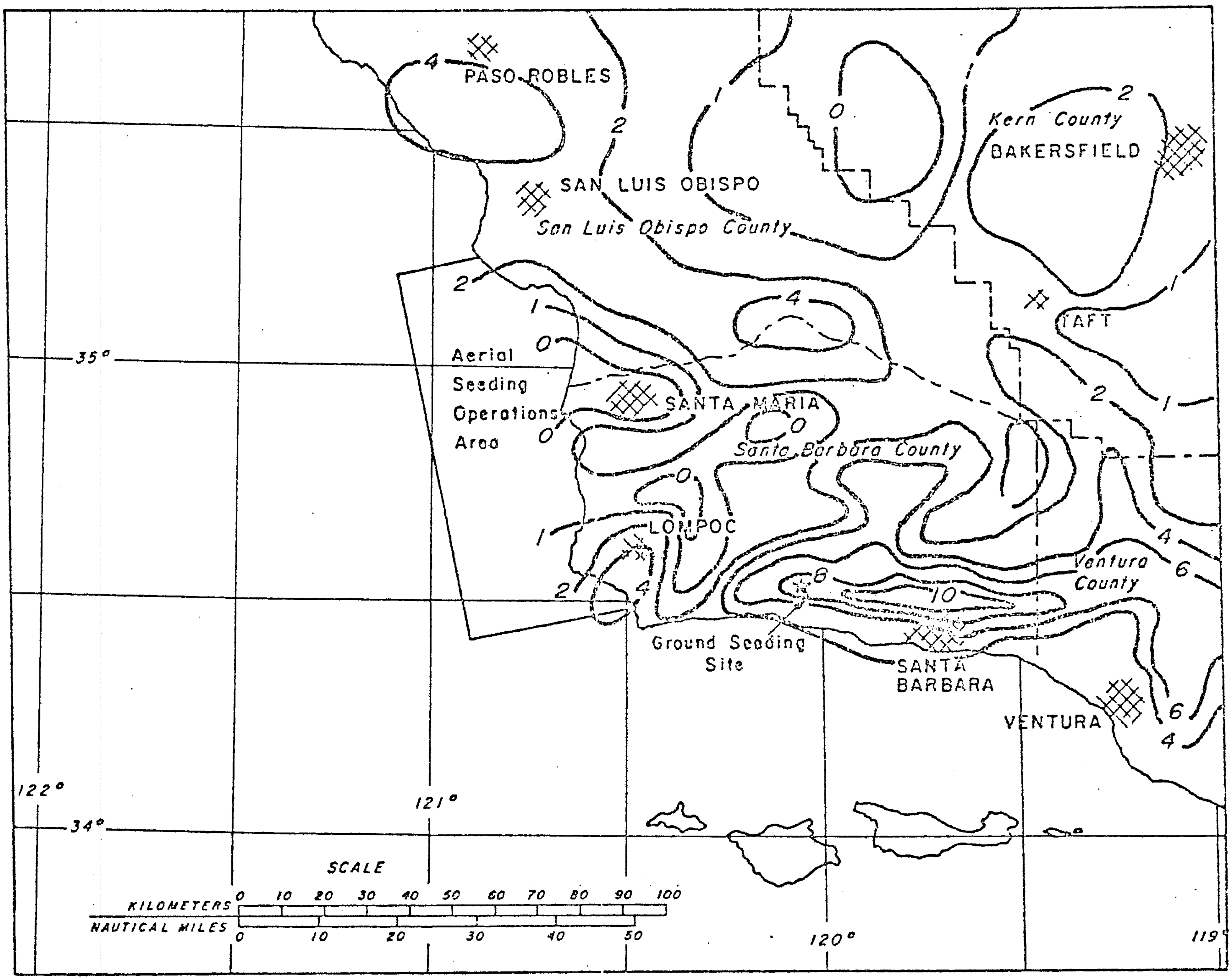


Figure 5-23. Estimated total precipitation increase (inches) produced during Phase I ground seeded bands, 1967-71 seasons.

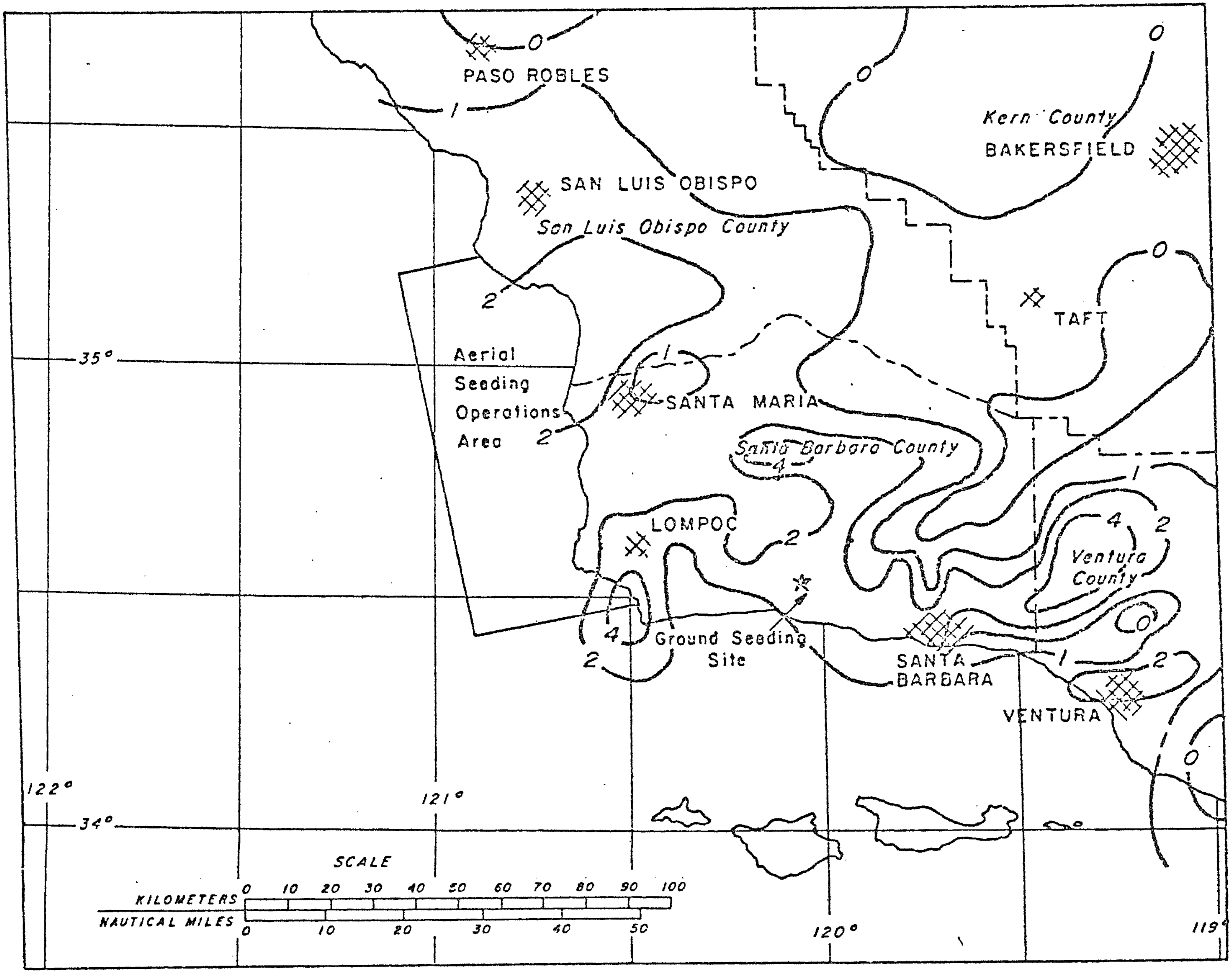


Figure 5-24. Estimated total precipitation increase (inches) produced during Phase II aerial seeded bands, 1970-74 seasons.

Table 5-1. Median values of winds and temperatures associated with seeded and not-seeded bands.

	PHASE I GROUND			PHASE II GROUND			PHASE II AERIAL		
	S	NS	COMB	S	NS	COMB	S	NS	COMB
Number of Bands	56	51	107	20	10	30	18	27	45
700 mb Direction	229.0	235.0	230.0	232.5	225.5	230.0	227.0	243.0	239.0
700 mb Speed (m sec^{-1})	17.5	17.5	17.5	16.8	15.8	16.5	17.0	20.0	19.0
500 mb Direction	240.0	249.0	240.0	246.0	230.0	245.0	234.0	250.0	250.0
500 mb Speed (m sec^{-1})	25.0	23.5	24.0	30.0	28.2	29.8	33.0	34.0	33.5
500 mb Temperature °C	-20.4	-19.5	-20.1	-20.5	-21.4	-20.5	-19.1	-19.5	-19.7

Table 5-2. SBA-II Phase I - 700 mb wind direction - ground based seeding.

	Seeded Bands	Unseeded Bands	Total
> Median	23	28	51
< Median	29	18	47
TOTAL	52	46	98

$\chi^2 = 2.14$, probability $\simeq .14$

Table 5-3. SBA-II Phase II - 700 mb wind direction - aerial seeding.

	Seeded Bands	Unseeded Bands	Total
> Median	6	16	22
< Median	12	10	22
TOTAL	18	26	44

$\chi^2 = 2.35$, probability $\simeq .12$

that seeding may have caused the 700 mb wind direction to have a more southerly component at least in the area to the south of the primary seeding effect. In order to postulate a cause for this apparent backing of the cloud level wind direction, it should be observed that the rawinsondes taken at the Santa Barbara Airport would usually be sampling a seeded environment. The airport is located 20 km east-southeast of the ground seeding site and about 70 km east-southeast from the aerial seeding zone. Since seeding has been shown to produce a dynamic intensification and broadening of the convective band, it is logical to assume that the vertical motion within the band was increased. Greater vertical velocity would cause increased inflow into the activated portion of the band. Since the Santa Barbara rawinsonde was located on the southern edge of the area of seeding effect, this inflow would result in a backing of the wind. This apparent change in 700 mb wind direction could account for the slower movement of the seeded bands since it was found by Boucher and Wexler (1961) that band speed correlates best with the 700 mb wind component normal to the line. Similar analyses of the 700 mb wind speed and of the 500 mb temperatures showed no significant changes between the seeded and not-seeded bands at statistical levels near 10%.

Bands that were seeded in Phase I, on the average, moved from the west (267°) with (from Table 5-1) a 700 mb wind direction from the southwest (median value 229°). If we superimpose these directions on the areas of high statistical significance associated with the band precipitation seeded/not-seeded ratios of Figure 5-4, we can see, in Figure 5-25, that the major features of the statistical significance patterns correlate well with these two movements. The Phase II aerial seeded bands on the average, moved from 281°. The 700 mb wind direction for these same bands had a median at 227°. Superimposing these directions on the statistically significant areas from Figure 5-2, we see in Figure 5-26, a high correlation between the high significance areas and the direction of band movement, but the agreement between the 700 mb wind direction and the areas of statistical significance near the western coastline is not as good as with the Phase I seeding.

The analyses made earlier of band duration have shown that seeded bands have a longer duration than unseeded bands. This appears to be due, in part, to a slowing of the seeded bands. The seeded bands moved 3% slower than the unseeded bands during the Phase I program and 12% slower in the Phase II sample. A more important factor in the increased duration of seeded bands appears to be a widening of the band after seeding. Analyses indicate that while the leading edge of the band slows slightly, the trailing edge slows significantly, thus producing a wider band. This

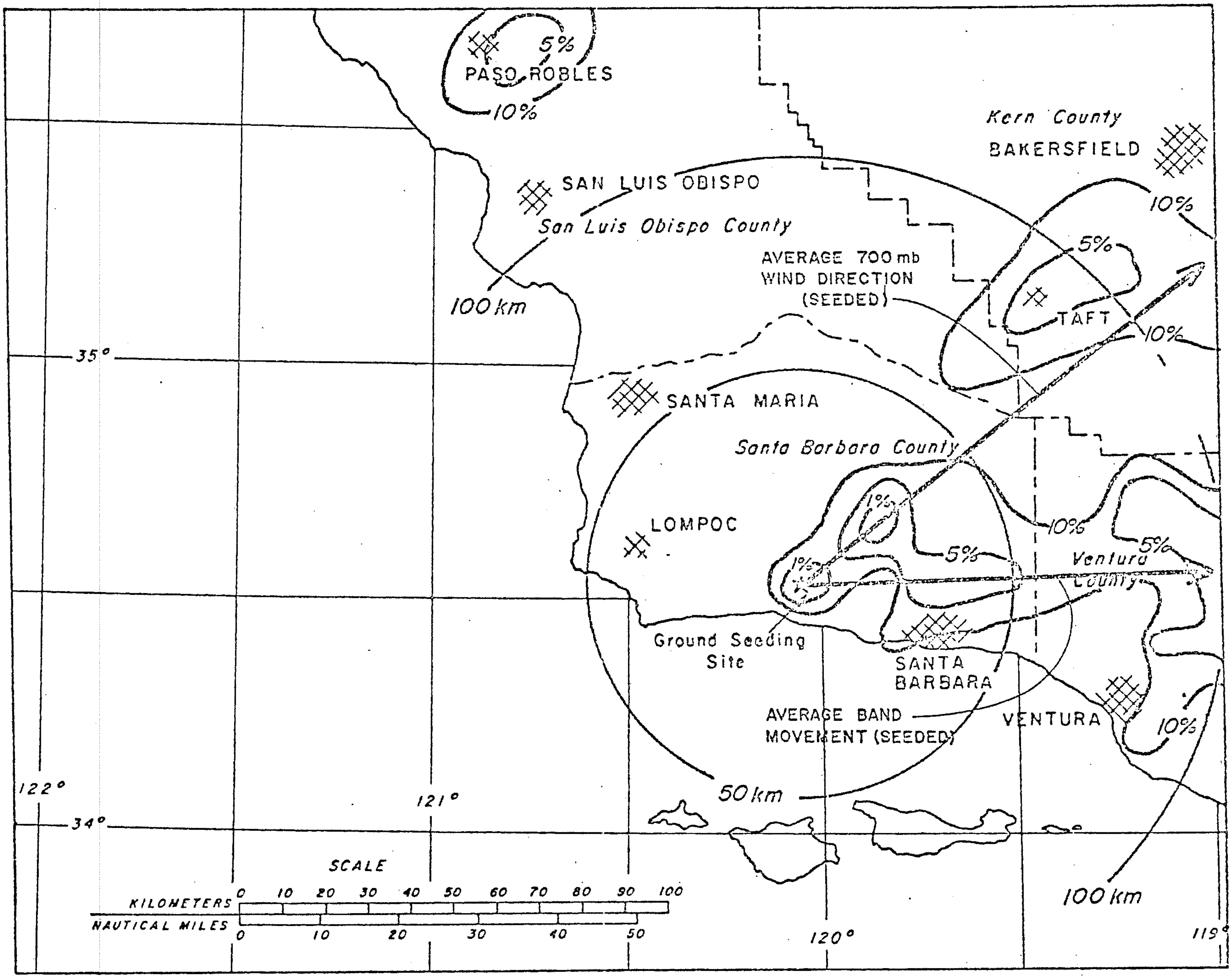


Figure 5-25. Comparison of 700 mb wind direction and convective band movement with areas of high statistical significance associated with band [illegible]

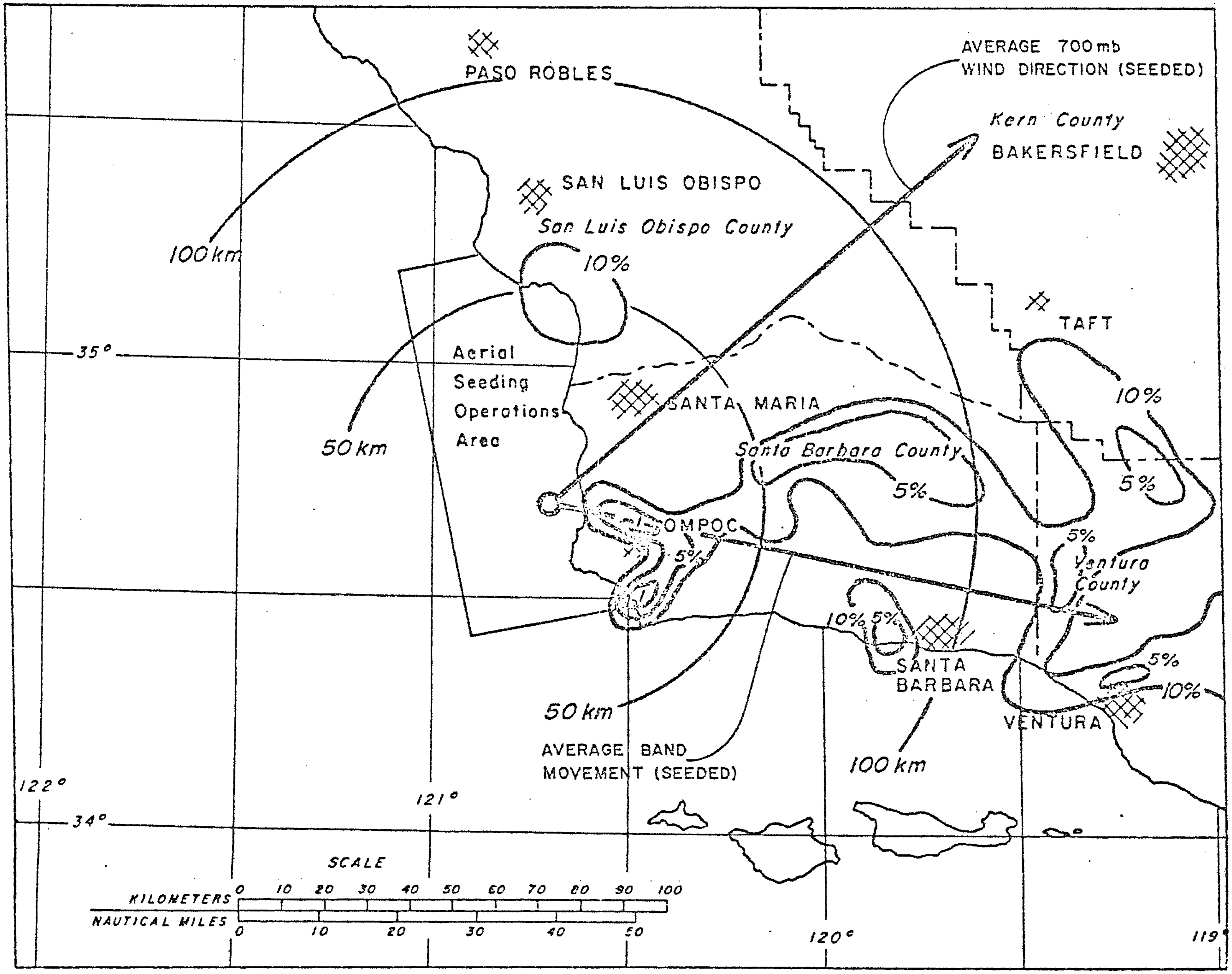


Figure 5-26. Comparison of 700 mb wind direction and convective band movement with areas of high statistical significance associated with band precipitation ratios from Phase II aerial operations.

slowing and widening of the convective band due to seeding indicates that a large part of the observed increase in precipitation is due to an increase in duration of the heavier rainfall rather than an increase in precipitation intensity.

During the course of this research program, increasing attention was paid to possible effects of cloud seeding on surface pressure measurements beneath the convective bands. This interest was prompted by theoretical calculations which showed that the pressure could be reduced by a measurable increment due to a combination of seeding effects. A small reduction in surface pressure would be caused by the dynamically produced dispersion of air warmed by the release of the latent heat of fusion within the nucleating zone and spread by mixing through a greater depth and laterally over the entire band segment. The increased updrafts would also cause increased condensation as more low-level moist air is processed by the cloud system. The extra heat of condensation released is sizeable. If we assume this heat was distributed in the lowest 500 mb of the convection band, then the condensation required to produce an additional millimeter (.04 inches) of precipitation would result in a 0.5°C heating effect. If this heat were distributed across the band only, it would be reflected hydrostatically in a 1.8 mb drop in surface pressure. In addition to this heat produced reduction in pressure, there would also be an incremental reduction due to the removal of liquid water from the band by the increased precipitation efficiency caused by seeding. Compensatory mesoscale redistribution of the air mass would probably preclude the appearance of the full effect at ground level; however, even a fraction of this value would result in an increase in the low level horizontal convergence of air and of water, into the convection band.

The mean station pressure difference between the 27 not-seeded and the 18 seeded aerial bands at 17 stations is shwon in Figure 5-27. The network of stations extend from Salinas (SNS) and Fresno (FAT)(well north of the predicted area of effect) in the north, to Long Beach (LGB) and San Nicholas Island (NSI) in the south. The data sample is complete for the four seasons, 1970-74, except for the project operated recorders at Taft (TFT) and Cuyama (CUY) which were installed in the 1972-73 season. The data from the five additional recorders installed during the 1973-74 season were not included in this analysis because of their limited sample size. The pattern shows a lowering of pressure of about one millibar in the "downwind" area about 100 km east-northeast of the seeding zone, strongly suggesting that band seeding effects in the downwind area are dynamically produced. However, none of the storms showed high statistical significance in this analysis.

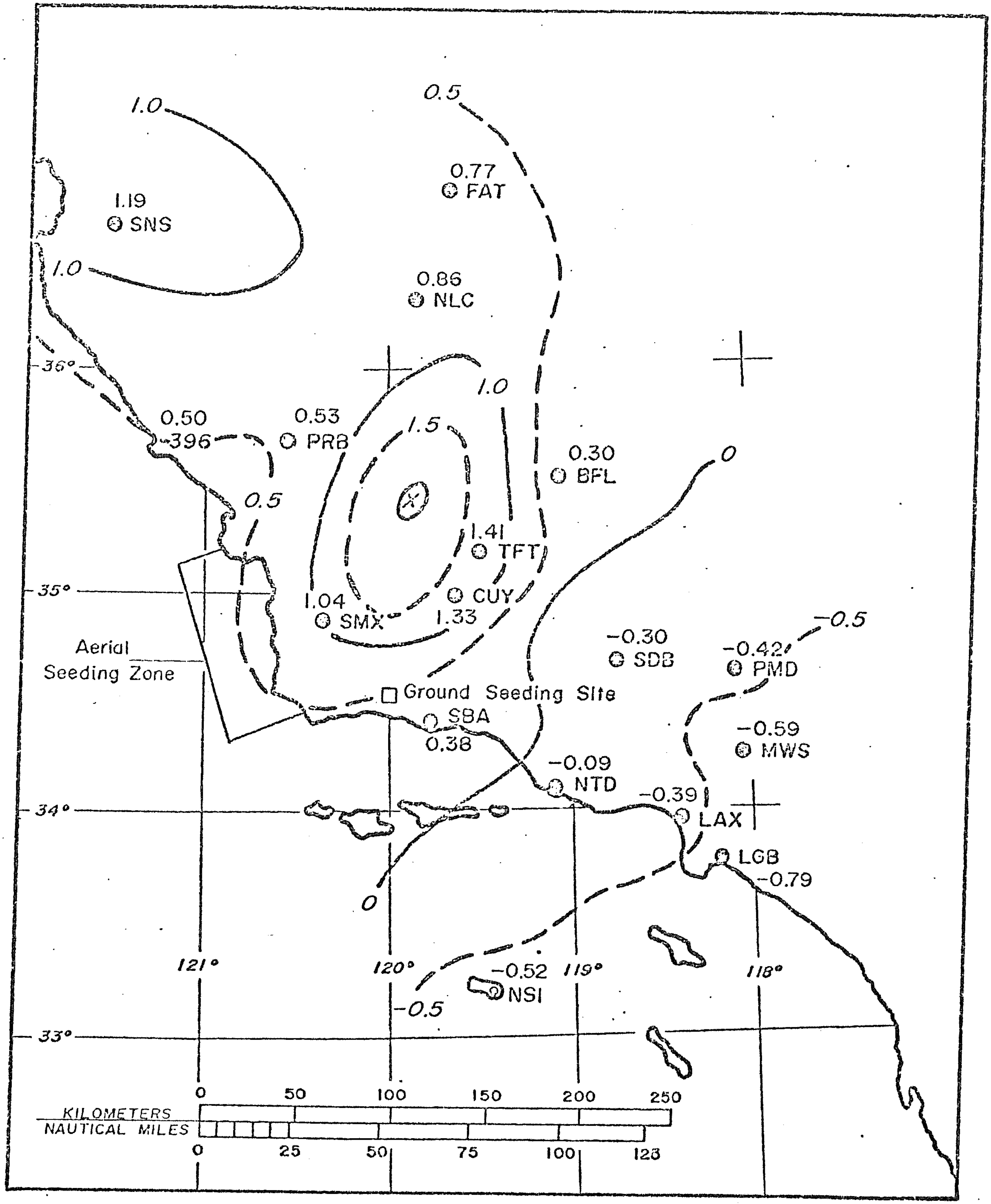


Figure 5-27. Mean station pressure (mbs): not-seeded aerial bands (27) minus seeded aerial bands (18), Phase II 1970-74 seasons.

The same analysis (Figure 5-28) was made for the ground seeding operations of Phases I and II, combined. The sample size consisted of 61 not-seeded bands and 76 seeded bands. The pattern produced is very similar to that of Figure 5-27 with a "downwind" decrease of about one millibar centered at a distance of about 90 km from the seeding site. Stations that exhibited a high level of statistical significance (10% or better) are indicated on the figure by a square, circle or triangle around the station dot. It can be seen that a large number (10) of the stations show statistical significance at the 10% or better level. The shift in the center of the maximum pressure drop from Phase I to Phase II compares favorably with the shift in seeding sites; in both cases, a movement of about 60 km to the northwest.

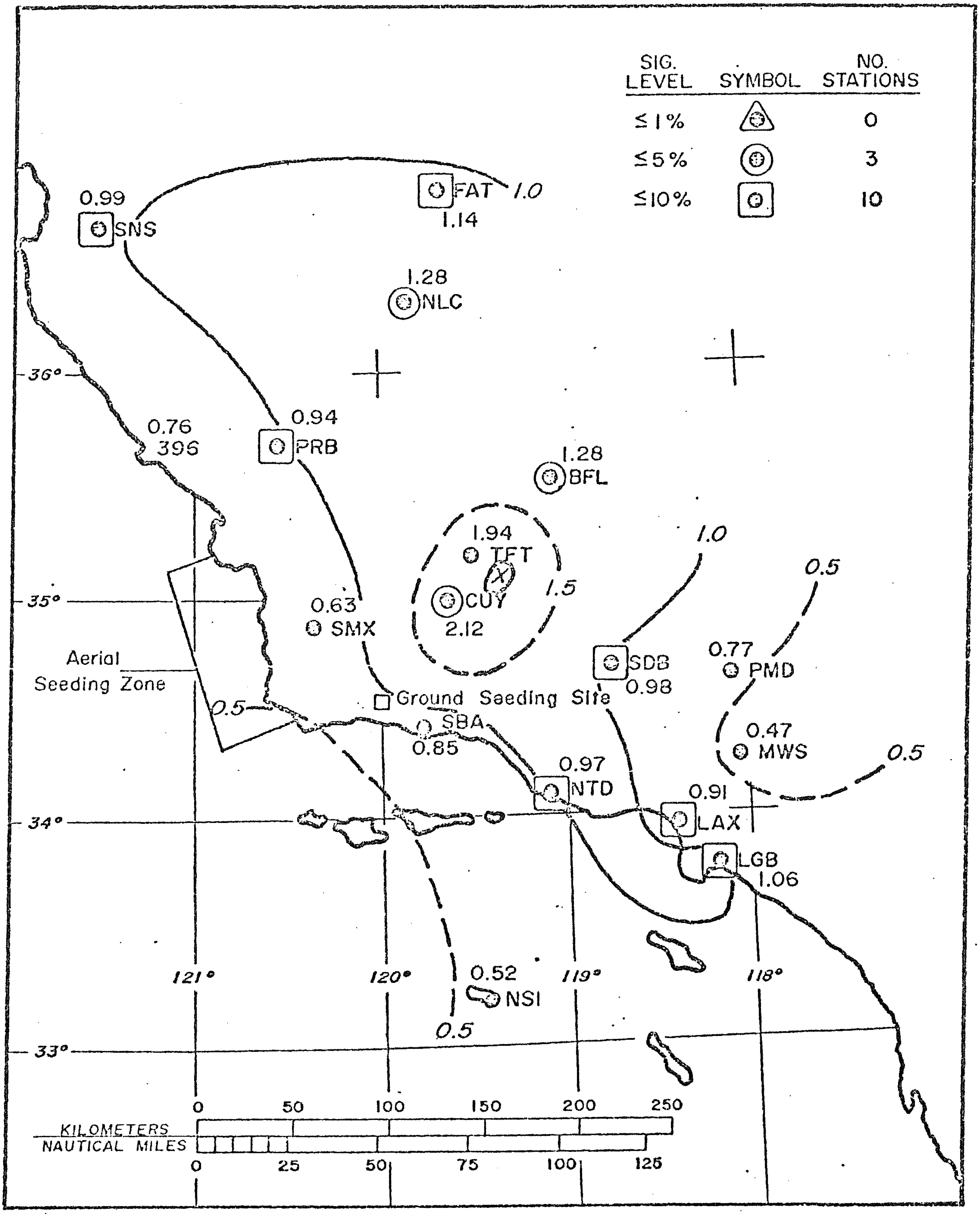


Figure 5-28. Mean station pressure (mbs): not-seeded ground bands (61) minus seeded ground bands (76), Phase I and II 1967-74 seasons.

6. SUMMARY

The Santa Barbara project extended over seven winter seasons from 1967-68 through 1973-74 and was divided into 2 phases; Phase I covering the period 1967-68 through 1970-71, and Phase II covering the 1970-71 through the 1973-74 seasons with a one year overlap. The object of both phases was to test the effectiveness of seeding clouds within convection bands. These convection bands, which are a mesoscale feature of west coast storms, are essentially north to south oriented bands or lines of convection moving eastward through the area. They last about 1.5 hours at one site and are spaced 3-4 hours apart. They contain 50-70% of storm precipitation.

A pyrotechnic device (LW-83) located on a 1000 meter mountain ridge was employed as a nuclei source during the first 4 years, and an aircraft equipped with a high output $AgI-NH_4I$-Acetone type burner was used during the second phase. In addition, some seeding was also done by use of a ground based high output generator on some bands during Phase II.

The design of the project called for a randomized decision to be made to seed or not to seed (50% chance of calling for seeding) following identification of a seedable band. The advance of the band eastward to the western boundary of the test area was monitored by telemetered raingages and weather radar. After the randomization decision, the further advance through the test area (central and eastern part of Santa Barbara County and adjacent areas) was recorded by a dense raingage network of over 100 recording gages. A statistical evaluation of results was made by comparing the seeded and not-seeded band precipitation values at the various test stations.

The air mass structure and wind flow were monitored and recorded by means of a rawinsonde taken during every band passage.

The aerial seeding in Phase II was conducted just off the coast with the aircraft directed by means of the ARSR L-band radar at Vandenberg AFB. The main track ran north to south over a 30-60 km line.

The evaluation of results showed that, except for those cases with cloud top temperatures (as represented by the 500 mb temperature) lower than about -24°C to -25°C, there were substantial excesses of band precipitation for seeded bands over not-seeded bands with large areas of over 50% excess and some smaller areas with greater than doubling indicated for the seeded cases. A much larger than expected number of gages showed statistically significant differences in the ranking of seeded over not-seeded precipitation.

On the basis of area of effect model runs and of winds aloft data, it was concluded that the direct microphysical effects of seeding spread on the average to the northeastward of the seeding source beyond the northern boundary of Santa Barbara County and into the San Joaquin Valley. However, a more extensive area of positive effect spread eastward from the source across Santa Barbara County and into Ventura County. This latter area is postulated to be due to the dynamic intensification of the circulation within the seeded bands and the persistence of this enhancement for several hours during the eastward movement of the band.

The seeded bands definitely experienced a (significant) increase in duration at a given gage in the test area, indicating a physical broadening of the band through seeding. There was marginal evidence that the surface pressure was reduced by up to 1.5 mb beneath seeded bands.

Both ground seeding and aerial seeding produced similar amounts of increased precipitation, although the patterns of augmentation areas differed somewhat due to the change from point seeding to line seeding. The centers of maximum increases in precipitation shifted westward by an amount comparable to the westward shift in the nucleant source between Phase I and Phase II operations.

7. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been made as a result of seven years of research in seeding convective bands. The conclusions are listed in a descending order of certainty.

1. Seeding convective bands is an efficient means of augmenting water supplies from west coast winter storms.
2. Two seeding modes tested (ground-based seeding with high output pyrotechnics and aerial seeding with acetone burners) produced comparable results.
3. The magnitude of the precipitation increase is on the order of 50 to 100% within the bands seeded and 25 to 50% for the storm total.
4. The primary location of the enhanced precipitation is predicted fairly well by the area of effect model, but increases also extend well beyond the predicted cutoff point.
5. The convective bands tend to widen and possibly slow down after seeding, indicating that much of the increase in precipitation is due to a change in duration of band precipitation rather than an increase in intensity.
6. Seeding effectiveness is related to the temperature structure of the band airmass. Seeding is most effective when the 500 mb temperature (presumed to be an indicator of cloud top temperature) is between about -17 and -20°C and appears to become ineffective at a temperature of about -24 or -25°C.
7. There is some evidence that the dynamics of convective bands are altered by seeding to produce a reduction of surface pressure beneath the band and an increase in convergence into the band as reflected by a backing of the 700 mb wind in the area on the south side of the seeding effect zone.

The major area where further research is needed is in improving our understanding of the dynamic effect of seeding convective bands. The entire interrelationship between cells, mesoscale convective bands and synoptic scale storms must be investigated. The evidence cited in conclusion number 7 above suggests a potential for major modifications in storm dynamics and possibly storm steering or control which could expand weather modification applications into a new area. There is clearly a need for physical measurements to expand on the statistical evidence shown in this report leading to a conceptual model of convective band and storm dynamics.

ACKNOWLEDGEMENTS

This investigation was accomplished through the support of the Earth and Planetary Sciences Division, Naval Weapons Center, China Lake, California. Particular thanks are due to its director, Dr. Pierre St. Amand, and to the Project Officer, Dr. S. D. Elliott, Jr., for their help and timely suggestions. Over a period of seven years, a lot of people have contributed much help and a good many helpful suggestions, and it is not possible to personally acknowledge all of them, but we are indeed grateful. We would like to express our appreciation to the U. S. Forest Service for their cooperation in raingage and radar operations and to the many persons at Vandenberg Air Force Base who were most necessary and helpful during the aerial operations. A special thanks is also due to the many organizations which contributed to the precipitation records so vital to the project.

The authors also wish to express their thanks to Mr. Wally McDonald and Mr. James Enlow who spent many long hours in the cockpit of the seeding aircraft. Invaluable assistance has also come from many members of North American Weather Consultants' staff. In particular, the authors wish to acknowledge the tireless work of Mr. Martin Thorp, Mr. William LaPolla, and Mr. Chet Wisner, who served as field personnel during the data collection phase. Finally, valuable assistance was also contributed by Mrs. Leona Shaffer, Mrs. Deborah Dal Zuffo, Mrs. Joan Adams, and Mrs. Constance Derek in the preparation of this report.

REFERENCES

Adderley, E. C., 1968: Rainfall increases downwind from cloud seeding projects in Australia. Proc. First Wea. Mod. Conf., Albany, Amer. Meteor. Soc., Boston, pp 42-46.

Boucher, R. L., and R. Wexler, 1961: The motion and predictability of precipitation lines. J. Meteor., 18, 160-171.

Brier, G. W., L. O. Grant, and P. W. Mielke, Jr., 1973: An evaluation of extended area effects from attempts to modify local clouds and cloud systems. Proc. International Conf. on Wea. Mod., Tashkent, USSR.

Brown, K. J., and R. D. Elliott, 1971: Large scale effects of cloud seeding. Final Report, ARI-71-1. Contract Number 14-06-D-6841, Bureau of Reclamation, October, 1971.

______, R. D. Elliott, and J. R. Thompson, 1973: Large scale effects of cloud seeding Final Report, ARI-73-2. Contract Number 14-06-D-6841, Bureau of Reclamation, October, 1973.

Browning, K. A., and T. W. Harrold, 1969: Air motion and precipitation growth in a wave depression. Quart. J. Roy. Meteor. Soc., 95, 288-309.

______, M. E. Hardman, T. W. Harrold, and C. W. Pardoe, 1973: The structure of rain-bands within a mid-latitude depression. Quart. J. R. Met. Soc., 99, 215-231.

Cooper, L. W., et. al., 1969: Santa Barbara Project: Cloud-top photographic and nucleus count experiments, Part I (Weather Science Inc. Report WR901 to U. S. Naval Weapons Center), April 1969.

______, and W. J. King, 1970: Santa Barbara Project 1969-70: Aircraft support operations to a pyrotechnic seeding experiment, Part I (Weather Science Inc. Report WR003 to U. S. Naval Weapons Center), June, 1970.

Elliott, R. D., 1969: Cloud seeding area of effect numerical model. Aerometric Research, Inc., Goleta, California (CFSTI, Springfield, Va).

______, and E. L. Hovind, 1964a: On convection bands within Pacific Coast storms and their relation to storm structure. J. Appl. Meteor., 3, 143-154.

______, and E. L. Hovind, 1964b: The water balance of orographic clouds. J. Appl. Meteor., 3, 235-239.

______, and E. L. Hovind, 1965: Heat, water and vorticity balance in frontal zones. J. Appl. Meteor., 4, 196-211.

______, and J. R. Thompson, 1972: Santa Barbara convective seeding test program, 1970-71 season and 1967-71 summary. Final Report, Naval Weapons Center Technical Publication 5308, February 1972.

Finnegan, W. G., et. al., 1971: Evaluation of ice nuclei generator systems. Nature, 232, 113-114.

Harper, W. G., and J. G. D. Biemers, 1958: Movement of precipitation belts. Quart. J. R. Meteor. Soc., 84, 242-249.

Harrold, T. W., 1973: Mechanisms influencing the distribution of precipitation within baroclinic disturbances. Quart. J. R. Met. Soc., 99, 232-251.

Kreitzberg, C. W., and H. A. Brown, 1970: Mesoscale weather systems within an occlusion. J. Appl. Meteor., 9, 417-432.

Kuettner, J., 1959: The band structure of the atmosphere. Tellus, 11, 267-294.

Malkus, J. S., 1963: Cloud patterns over tropical oceans. Science, 141, 767-778.

Mielke, P. W. Jr., and L. O. Grant, 1967: A randomized cloud seeding experiment at Climax, Colorado, 1960-65. Proceedings of the 5th Berkeley Symposium on Mathematical Statistics and Probability. Volume 5, Weather Modification, University of California Press, Berkeley, California, pp. 115-131, 1967.

Siegel, S., 1956: Nonparametric statistics for the behavioral sciences. New York, McGraw Hill, 116-127.

St. Amand, P., et. al., 1970: Pyrotechnic production of nucleants for cloud modification, Part II. Pyrotechnic compounds and delivery systems for freezing nucleants. J. Weather Mod., 2, 33-52.

______, et. al., 1971a: Understanding of the use of simple and complex ice nuclei generated from pyrotechnics and acetone burners. J. Weather Mod., 3, 31-48.

______, et. al., 1971b: Effects of solubility on AgI nucleation effectiveness. J. Weather Mod., 3, 106-110.

Vonnegut, B., 1949: Nucleation of supercooled water clouds by silver iodide smokes. Chem. Rev., 44, 227.

______, 1950: Techniques for generating silver iodide smoke. J. Colloid. Sci., 5, 37.

Winston, J. S., and L. Tourville, 1961: Cloud structure of an occluded cyclone over the Gulf of Alaska as viewed by TIROS I. Bull. Amer. Meteor. Soc., 42, 151-165.