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WEATHER MODIFICATION IN ARIZONA, 1971

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INTRODUCTION

In recent years there have been many efforts to modify thunderstorms through cloud seeding. Most of these programs and experiments were designed to increase rainfall, although a significant number were efforts to suppress hail or reduce lightning. Thunderstorm (convective cloud) seeding programs and experiments in Arizona all have been efforts to increase rainfall, since much of Arizona, and particularly southern Arizona, is dependent directly or indirectly on thunderstorm rainfall for water supply and forage production. For example, in southeastern Arizona increasing thunderstorm rainfall by 25% would almost double annual runoff, while decreasing it by 25% would about halve annual runoff (Osborn, 1972). This paper includes a review and discussion of convective cloud seeding efforts in Arizona before 1971, and a hydrologic analysis of the operational convective cloud seeding program carried out in Arizona in the summer of 1971. The results of the study further emphasize need for more controlled experiments on a large areal scale.

SANTA CATALINA EXPERIMENT

One of the most comprehensive randomized cloud seeding experiments in this country was conducted by the Institute of Atmospheric Physics, University of Arizona over the Santa Catalina Mountains from 1957 through 1964 (Battan and

Kassander, 1960). Since there were significant changes in operational procedures between 1960 and 1961, the experiment was officially described by Battan (1966) as two experiments, from 1957 through 1960, and in 1961, 1962, and 1964 (there was no seeding in 1963). Silver iodide was seeded upwind from the Santa Catalinas at about 20,000 feet above MSL during the first experiment, and at about 12,000 feet above MSL (the cloud base) in the second. Also, different silver iodide generators were used and experimental days were determined somewhat differently after 1960. The experiments were randomized with seeding days determined as those with more than a predetermined minimum level of moisture aloft. Seeding began at 12:30 pm and continued for over 2 hours and up to 4 hours. In the first experiment, rainfall was estimated from a network of 26 recording rain gages unevenly scattered over and near the Santa Catalinas. In the second experiment, several gages were added in the Santa Catalinas, but gages near the mountains were removed. Therefore, estimates of rainfall were more accurate for the second experiment because of the greater gage density, but applied to a considerably smaller area.

Battan (1966) analyzed the experiments in considerable detail. His analyses of seeding effects on rainfall, which is most pertinent to hydrologists and others interested in water use and supply in Arizona, was restricted to a 5-hour period, 1:00 p.m. to 6:00 p.m., which seemed reasonable at the time. Battan reported that there was no evidence from these experiments to support the hypothesis that seeding with silver iodide increased rainfall amounts or areal extent. He added that there was 30% less rainfall on seeded days, but that this decrease was not significant. Finally, he concluded that additional research was needed on convective cloud seeding "to resolve the conflicting views on the physics of convective precipitation and on the efficacy of various cloud seeding techniques."

The possibilities of more widespread effects of seeding were not analyzed at that time, because there were few recording rain gages within a 20-to 30-mile radius of the Santa Catalinas, and because more widespread effects were not anticipated. However, subsequent indication of possible widespread effects of cloud seeding over longer periods in the Whitetop Experiment (1961-1965) in Missouri, reported by Lovasich and others (1969), led to analyses of recording and standard rain gage records throughout south-central and southeastern Arizona for 1957-1964 in an effort to identify any possible changes in rainfall amounts or patterns from seeding in the Santa Catalinas.

Included in the analyses were recording rain gage records from a dense network of gages located on the USDA, ARS Walnut Gulch Experimental Watershed 65 miles southeast of the Santa Catalinas. Neyman and Osborn (1971) reported apparent effects of seeding on Walnut Gulch rainfall based on records from 26 recording gages that were in continuous operation from 1957 through 1964. They found that when Walnut Gulch was roughly "downwind" from the Santa Catalinas, there was 70% less rainfall for the 24-hour period after seeding as opposed to not-seeded days, which was statistically highly significant ($P = .008$). When Walnut Gulch was roughly "upwind" there also was less rainfall on seeded as opposed to not seeded experimental days, but the differences were not significant. For all experimental days, there was 40% less rainfall on seeded days, which was statistically significant ($P = .03$). The categories of "upwind" and "downwind" are based on dividing the data into 2 sets with wind directions across 180° in each set. Although admittedly crude, the subdivisions seemed reasonable, particularly since any seeding effects at 65 miles probably would be postulated to be indirect rather than from direct contamination of silver iodide nuclei.

Average hourly rainfall amounts for 14 hours from noon to 2:00 a.m. are plotted for two situations--downwind and all experimental days (Figure 1). On seeded days when Walnut Gulch was downwind from the Santa Catalinas, the characteristic double peak of rainfall was missing and rainfall was less than on nonseeded days until about midnight. On upwind days (not plotted) both peaks were evident for both seeded and nonseeded days, although both peaks were lower on seeded days. On all experimental days, seeded rainfall was less than nonseeded from about 3:00 p.m. to about 2:00 a.m. If the seeding did indeed affect rainfall on Walnut Gulch, the timing indicated in the two plots in Figure 1 seems reasonable.

Further analyses of the Santa Catalina data for 24 hours following seeding, indicated a greater difference in rainfall amounts on seeded as opposed to nonseeded days for the second experiment (Figure 2). This suggests that changes in experimental procedures between 1960 and 1961 did make a difference and that, as Battan (1966) suggested, analyses of the 1957-1964 data should be on two sets of data. However, the differences between the two experiments were not statistically significant.

Comparison of Santa Catalina and Walnut Gulch data suggest that seeding may have affected rainfall less on the target than 65 miles from the target. There are two obvious explanations of the contradictions in Walnut Gulch and Santa Catalina analyses. First, the differences may have been entirely by chance and have had nothing to do with seeding; second, the overall effects of convective cloud seeding may have been indirectly greater in some areas surrounding the target than on the target. Also, the Walnut Gulch rain gages represented a denser network and therefore provided a more accurate estimate of rainfall over a limited area than the Santa Catalina gages, particularly in the first experiment; so direct comparison of differences may be incorrect. However, enough questions

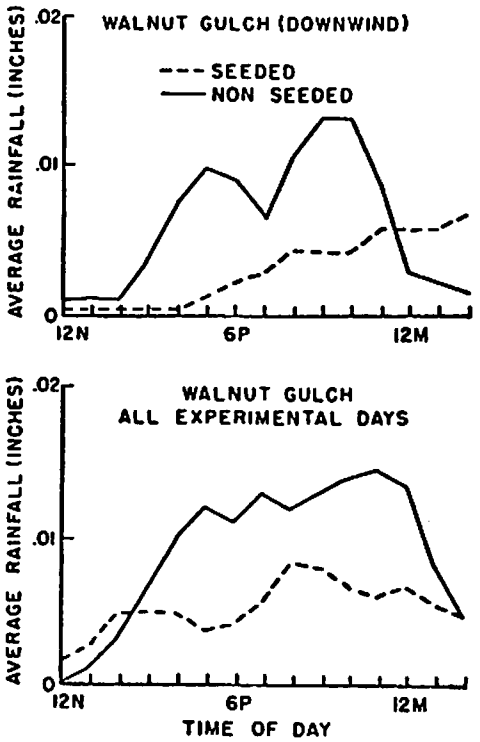

Figure 1. Hourly average rainfall on selected days, Walnut Gulch watershed, 1957-1964.

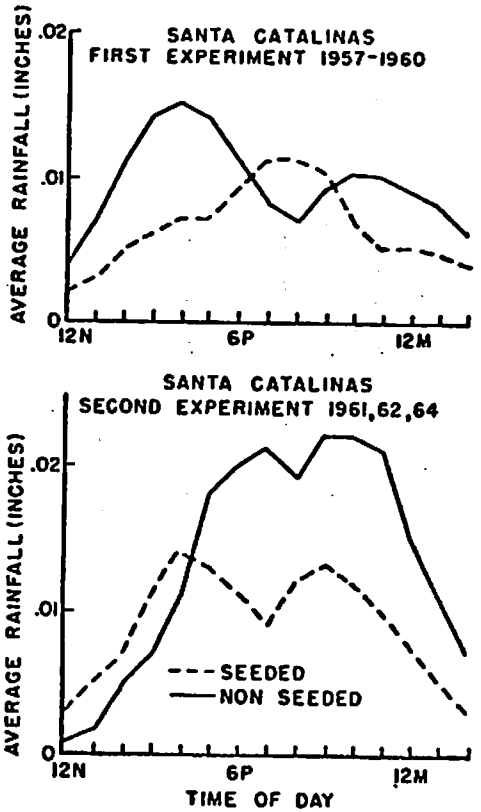

Figure 2. Hourly average rainfall for first and and second experiments, Santa Catalinas.

have been raised by analyses of Santa Catalina and Walnut Gulch data to justify further analyses of other rainfall records in Arizona, and to warrant further experimentation.

OTHER ARIZONA CLOUD SEEDING (before 1971)

From 1966 through 1970, individual convective clouds were seeded under the supervision of the U. S. Bureau of Reclamation near Flagstaff, Arizona. The program was based on the belief that under certain conditions adding silver iodide nuclei to a convective cloud would promote more rapid freezing, thus releasing added heat that would cause the cloud to grow more rapidly and release greater amounts of precipitation. Weinstein and McCready (1969) reported on early results of these experiments based on their one-dimensional model of a cumulus cloud. In their paper, and in later papers by Weinstein (1970, 1971, and 1972) in which model results were extrapolated over large areas, conclusions were based on changes in reflectivity after seeding as estimated by 3-cm radar, with these changes related to predicted but unmeasured changes in rainfall amounts during the experiments. The validity of the model and the claims of success for the experiment have been challenged by several investigators. Warner (1970) challenged the reality of the model and Dennis and Schock (1971) stated "results of seeding experiments aimed at individual clouds or small target areas can not be extrapolated to predict accurately the effects of seeding over large areas."

The experiment failed to answer several questions. Among these are (1) what might have happened to a specific cloud if it hadn't been seeded; (2) if there were significant changes in the seeded cloud, did these changes mean an appreciable increase in rainfall at the ground; and, (3) if there were

significant changes in the seeded cloud, did these changes affect the potential for cloud growth and resulting rainfall in surrounding clouds. To date, these questions have not been answered satisfactorily.

1971 ARIZONA CLOUD SEEDING

An intensive program of seeding individual cumulus clouds with silver iodide from airplanes was carried out in the summer of 1971 in central and eastern Arizona under the supervision of the U. S. Bureau of Reclamation. The program was patterned after the earlier Arizona experiments (cited previously) and similar experiments in Florida reported by Woodley (1970) and Simpson and Woodley (1971). Three planes were stationed in Safford, one in Flagstaff, and one in Show Low with seeding concentrated along the Mogollon Rim on the Salt River Watershed (Figure 3). U. S. Weather Bureau climatological divisions are also indicated in Figure 3. Clouds were seeded daily from July 20 through August 15. In August, it was reported that by the end of the period the seeding would have produced 400,000 acre-feet of additional summer rain over 20,000 square miles (Tucson Daily Citizen, August 14, 1971). This would amount to about 3/8 inch or 15% of the estimated summer rainfall of 2.5 inches for that period. An increase of 15% is well within any reasonable statistical confidence limits for prediction based on the highly variable thunderstorm rainfall. The method used to estimate 400,000 acre-feet of additional rain (most recently reported in the Tucson Daily Citizen, March 19, 1972, as 200,000 acre-feet, or less than 1/4 inch) has not been reported officially, but it was reported that the estimate was based on greater than average natural occurrence of rainfall during the period.

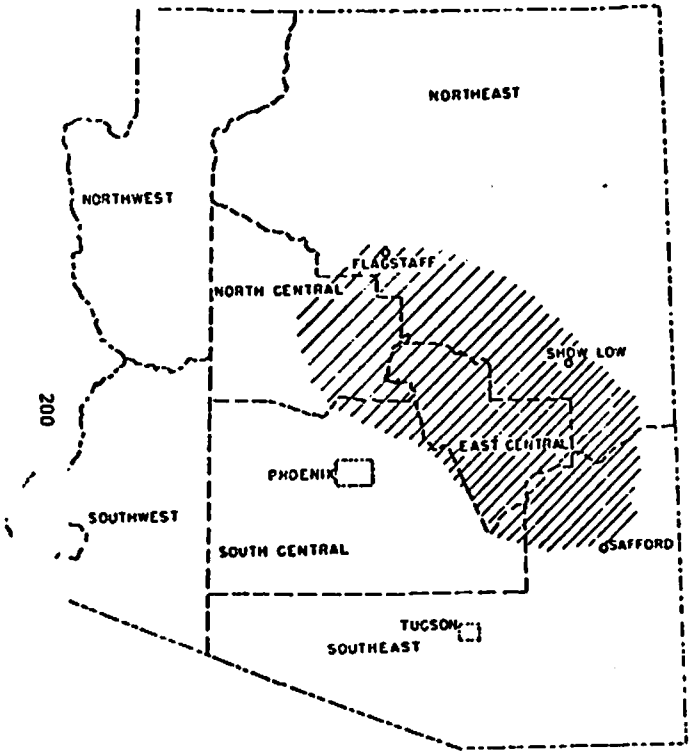

Figure 3. Principal seeded region in Arizona, 1971.

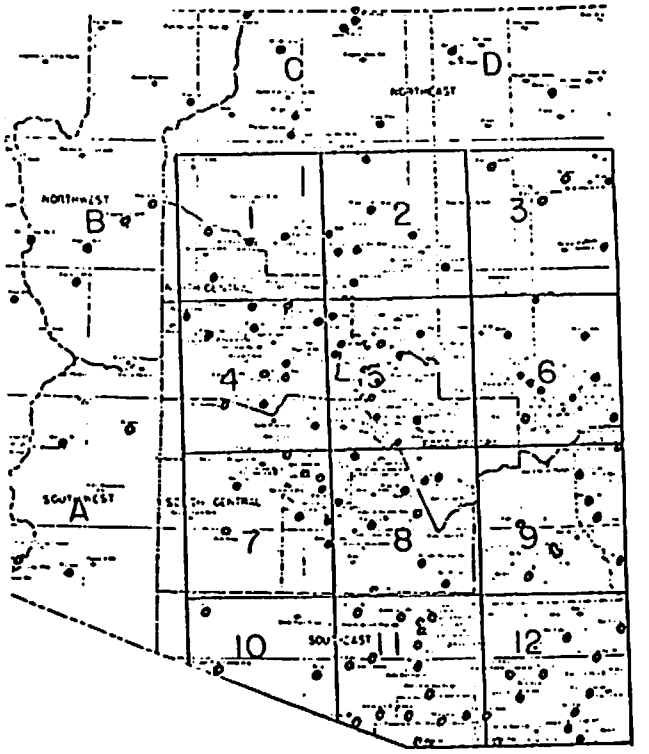

Figure 4. Stations used in analyses of rainfall in Arizona, July 20-August 15, 1971.

Data from 133 U. S. Weather Bureau stations with at least 10 years of continuous record prior to 1971 were used in an attempt to analyze the rainfall pattern throughout Arizona for the seeded period in 1971 (Figure 4). Twelve equal quads were drawn to better illustrate the irregular rain gage network and to facilitate possible statistical analysis. Average annual amounts of rainfall for July 20-August 15 were determined for 10 years of record, 1961-70 (Figure 5). Rainfall in 1971 (July 20-August 15) was compared with the 10-year average rainfall for that period. In general, rainfall appeared above average in southern and western Arizona, about average through central Arizona, and below average in northern and eastern Arizona (Figure 6). In Arizona, summer winds are usually from the south, so north-central and northeastern Arizona normally would have been "downwind" from the seeding. Because of the extreme variability of thunderstorm rainfall and the uncertainty of point averages based on only 10 years of record, any stations within ± 20% of average arbitrarily were assumed average in designating regions that were above average, average, and below average during the period of seeding (Figure 7). Although obviously approximate, the figure again illustrates the large differences in expected versus actual rainfall in Arizona.

Finally, some feeling for the magnitude of the differences and the reliability of the analysis was attempted by first averaging the differences in each of the 12 quads and second by using a simple statistical sign test (Lindgren, 1968) for above or below average rainfall for each of the 12 quads. Assuming that the stations in each quad are representative of that quad, rainfall was above average in quads 1, 7, 11, and 12; below average in quads 2, 3, and 9; and uncertain in quads 4, 5, 6, and 8 (there were only three stations in quad 10, so it was not included in the analysis) (Figure 8). Statistically, rainfall was highly significantly above average in quads 7 and 11 (using zero as average), significantly

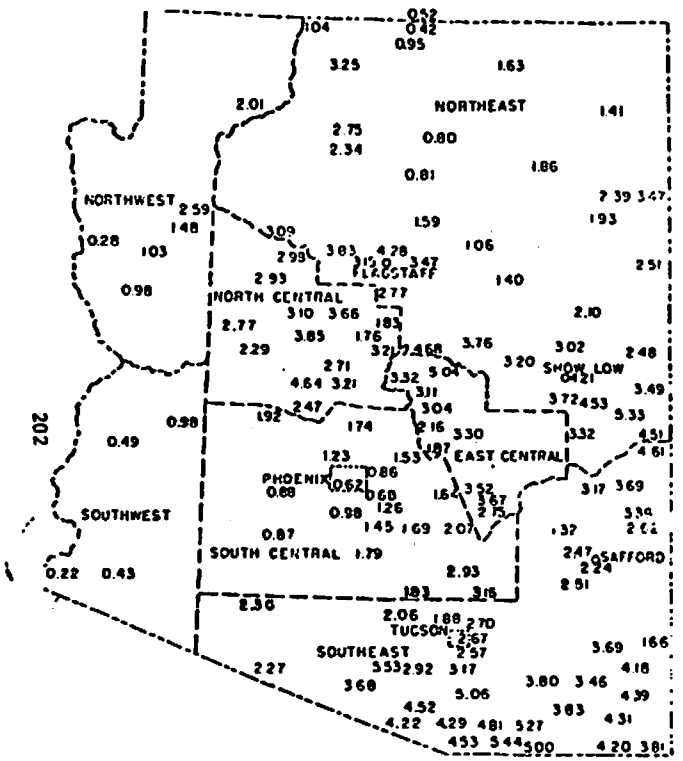

Figure 5. Average rainfall at selected Arizona stations, July 20-August 15, 1961-1970.

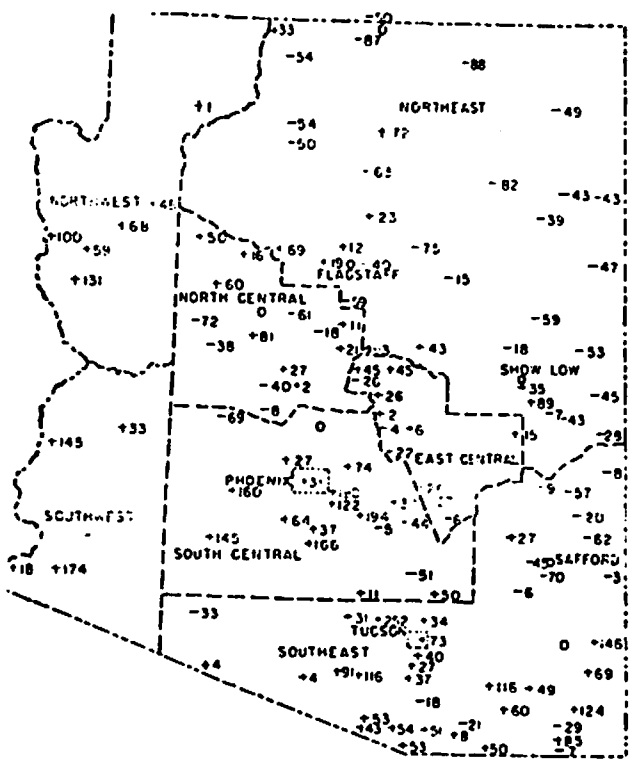

Figure 6. Percentage comparison of average and 1971 rainfall, July 20-August 15.

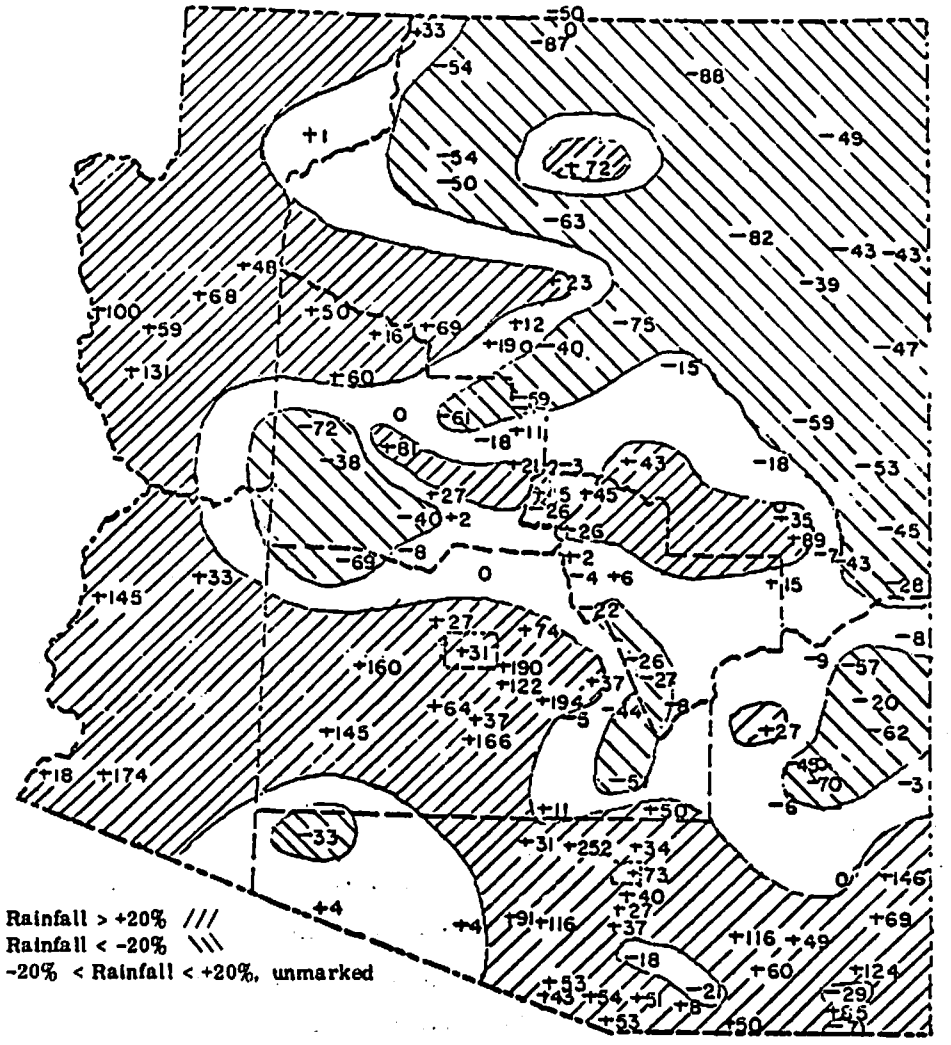

Figure 7. Comparison of average and 1971 Arizona rainfall, July 20–August 15, based on 133 VSWB standard rain gage records.

above average in the far west, and significantly below average in quads 3 and 9 (Figure 9). There was no statistical evidence that rainfall was other than average in quads 2, 4, 5, 6, and 10. Because of the scarcity of gages in most areas, a more rigorous analysis may be impossible.

SUMMARY AND CONCLUSION

There have been two experimental and one operational convective cloud seeding programs in Arizona. The Santa Catalina experiment carried out by the Institute of Atmospheric Physics, University of Arizona, from 1957 through 1964 was by far the most comprehensive and only randomized experiment in Arizona. Early results from this experiment were inconclusive, but there was a suggestion that seeding with silver iodide decreased rainfall on the target. More recent analyses of Santa Catalina and other rain gage records suggested strongly that seeding decreased rainfall on and downwind from the target. Some of these results were statistically significant, whereas earlier results had not been.

Analyses of experimental seeding of individual convective clouds from 1967 through 1970 in the vicinity of Flagstaff were inconclusive because of inadequate experimental control and limited rainfall measurements at ground level. Analyses of a widespread program of seeding individual convective clouds in central Arizona in 1971 were also inconclusive because of insufficient experimental control and scarcity of rainfall data. However, rough analyses of available rainfall data did not support the hypothesis that widespread seeding of individual convective clouds increased rainfall over the seeded region. Furthermore, these analyses raised several questions concerning possible negative effects which can only be answered through more comprehensive randomized convective cloud seeding experiments, with ground measurements of actual rainfall.

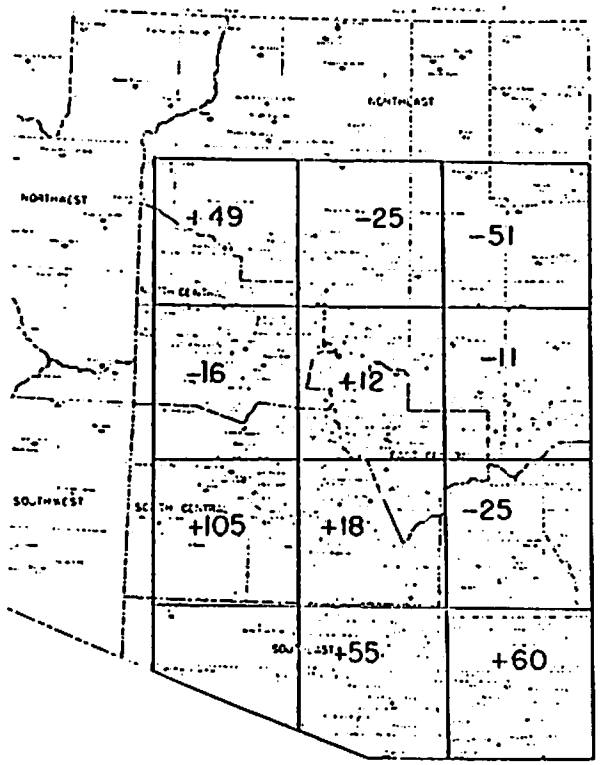

Figure 8. Comparison of average and 1971 rainfall by equal zones, July 20-August 15.

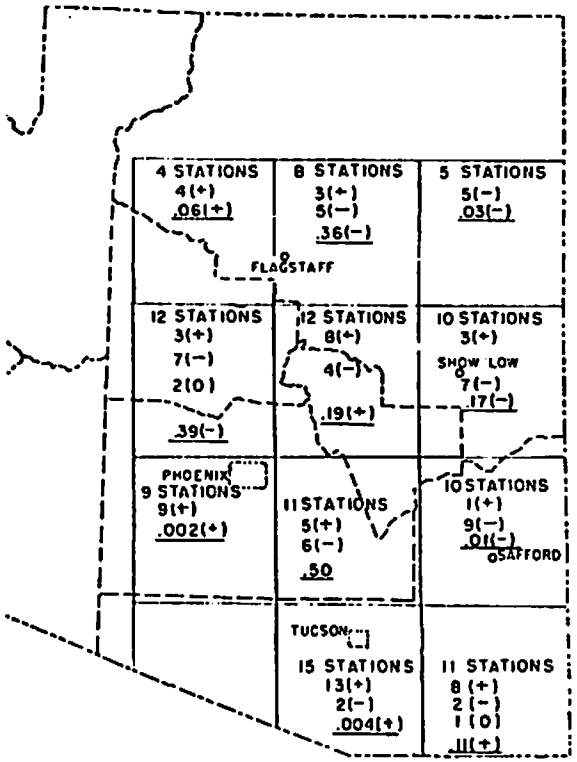

Figure 9. Probability of chance occurrence of rainfall, July 20-August 15, 1971.

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