Twelve Years of Cloud Seeding in the Andes of Northern Peru

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ABSTRACT

A program of cloud seeding for rain stimulation has been carried on since September 1951, interrupted only by flood periods and the winter dry seasons, on the headwaters of the Rios Moche, Chicama and Jequetepeque and adjacent parts of the continental divide between about 7S and 8S, using mainly silver iodide seeding from the ground. The climate is one of winter drought and summer convective rain resulting from complex interactions between the Pacific marine layer and the overlying easterlies. Compared with seasonal averages for twelve seasons before seeding began, twelve seeded seasons indicate a rainfall increase estimated at from 8 to 15 per cent. Conventional tests show significance at about the 2 per cent level but are rendered inconclusive by lack of prescribed experimental design and the fact that practical application is the primary mission of the program with experimental design having been subordinated. Criteria establishing the economic break-even point for continuance of the program are, however, amply exceeded.

1. Introduction

Sugar is one of the principal export crops of Peru. Its production on the Pacific coastal plain is entirely dependent upon irrigation which is supplied from rivers rising near the continental divide. A prolonged drought in the 1949–50 and 1950–51 seasons, combined with high economic value for any additional water, led one of the principal sugar producers to undertake a program of cloud seeding for rain stimulation that began operation in September 1951, and has been in continuous operation since that date with the exception of suspensions during the winter dry months of July and August and occasional suspensions during periods of flood danger. Since the program was begun at a time when very little was known regarding the results that might be expected from cloud seeding in a tropical climate, no definite expectations of performance were established in advance. Recognizing that evaluation, in view of the paucity of historical data, would be difficult and inexact, the operational plan was directed mainly at applying principles of rain stimulation developed in the United States so as to achieve the maximum effectiveness from a moderate amount of seeding effort; and considerations of experimental design for the purpose of evaluation were definitely made secondary. Nevertheless, through the intervening years, a sufficient body of meteorological experience has been gained with this program to make a report worthwhile.

2. Physiography and meteorology of the target

The target of this seeding operation, shown on the map of Fig. 1, is the headwaters area of three adjacent rivers, the Rios Moche, Chicama and Jequetepeque. The target also includes adjacent pasture lands on both sides of the continental divide. It extends for a distance of approximately 200 km along the continental divide, with the area of significant rainfall extending about 50 km west of the divide toward the Pacific ocean. The physiography and meteorology of the region were described elsewhere (Howell, 1953) in considerable detail. Briefly, the terrain descends from a line of more or less rounded summits at a mean altitude of about 4.2 km into valleys separated by westward-running ridges that extend 40 km or so toward the Pacific at nearly the same altitude as the divide. The valleys open out toward the coast onto alluvial plains that slope toward the shore. Eastward from the divide, there is a series of valleys and mountain ranges roughly parallel to the coast before the Amazon basin is reached.

Between 7S and 8S, this area is under the influence of the prevailing easterly circulation that brings tropical air across the Andes from the Amazon basin. The area is never visited by cyclonic storms or by middle-latitude fronts, weather changes being associated primarily with the movements of the intertropical convergence zone, which in this area is often fragmented, and by easterly waves and occasional polar troughs. The diurnal period of tropical convective cloudiness and rain is modulated by these disturbances of the easterly current and by the usual seasonal influences, as well as by the orography. Infrequently, the easterlies are interrupted by northwest monsoons, which bring clear, dry weather.

The local meteorology of the target reflects contrasting influences from east and west. On the Pacific side, an inversion is maintained throughout the year over the adjacent ocean by the cold water of the Humboldt current, which, in combination with the

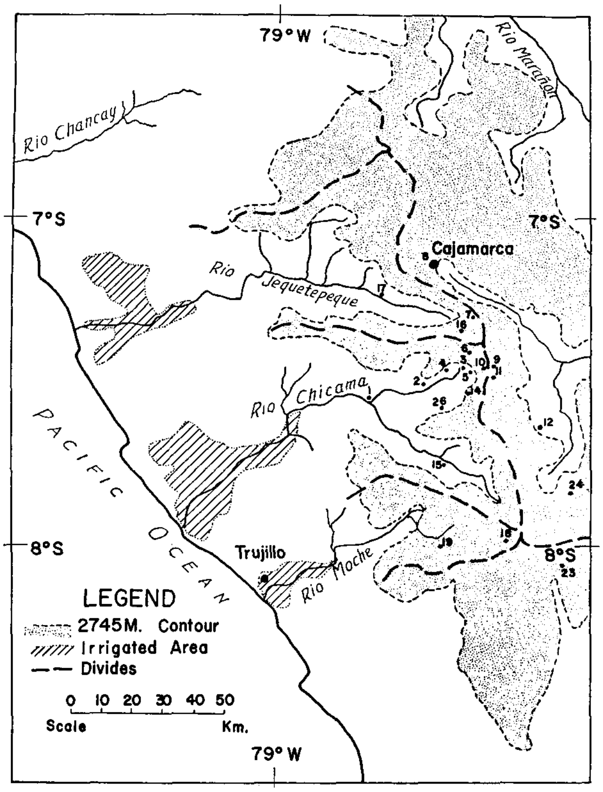

FIG. 1. Map of operating area. Numbered sites are raingauges (see Table 1).

downslope motion of the prevailing easterlies, maintains desert conditions over the entire Peruvian coastline. The moist air of the Pacific marine layer beneath this inversion is carried inland, however, in a diurnal tide under the influence of the strong daytime heating of the interior of the continent. Except during the winter, this tide produces condensation and cloudiness over the higher slopes west of the divide, and, flowing across the divide and down into the valley to the east, produces hydraulic jump phenomena that influence convective cloudiness in the overlying tropical air. The rainfall of the area is therefore conditioned by complex interactions between the air from the Amazon basin and that from the Pacific marine layers.

3. Cloud seeding operations

The cloud seeding operations are conducted by the Companía Peruana de Servicios Meteorologicos, S. A. (CPSM), which has an office in Lima and operating headquarters at Sunchubamba, an hacienda near the continental divide, where headquarters for the ranching operations of the sponsor company is also situated. Direction of the cloud seeding operations is exercised by the project meteorologist at Sunchubamba who receives radio weather synopses and forecasts from Lima prepared by the meteorological staff of Corporacion Peruana de Aeropuertos y Aviacion Comercial (CORPAC), through liaison with the manager of CPSM. In addition, he receives fragmentary meteorological information intercepted by radio listening watches on various frequencies used by airlines and other companies operating in eastern Peru. However, since the daily synoptic weather map of South America at Lima shows enormous blank spaces in the Amazon basin, maximum use must be made of local observations and radio intercepts.

Local observations are supplied principally by a meteorological observatory constructed in 1952 on a low summit of the continental divide called El Kanzel, overlooking Sunchubamba and the Chicama valley to the westward and overlooking the Condebamba valley to the eastward. The site of this observatory, at an elevation of 3970 m, is shown in Fig. 2. This observatory is equipped as a first-order weather station and is manned continually except during the dry winter season. In addition to a full routine of synoptic observations, hourly observations and spherics direction-finding on local thunderstorm centers, these meteorological observations are supplemented during certain periods at the direction of the project meteorologist, by observations of electric-field strength and space charge. This is the only weather station in the whole Andean chain situated on the continental divide with free exposure to both east and west.

Generator operations within the Chicama valley and adjacent sites to the east of the divide are under the immediate supervision and control of the field meteorologist, with a high degree of reliability having been achieved. The operations in and to the east of the Moche valley, including Araqueda, are subject to direct supervision by the field meteorologist only by means of occasional field inspection and maintenance trips, the road conditions being such that ten days to two weeks are required for visiting all these sites. Cooperation given by operators and local supervisory personnel in this area have, however, been excellent, and reliability of operations has been good. Supervision in the Jequetepeque valley likewise is by occasional field inspection trips, but here the conditions have been less satisfactory. Repeated difficulty has been experienced in obtaining compliance with generator operating orders, and maintenance by local personnel has been so unsatisfactory that the generators near Huacraruco have been out of service for unrecorded but considerable lengths of time.

During the first three years of the program, silver iodide smoke generators of the acetone-propane type were used, but in 1954 these were replaced with a string-burning type, generating approximately $2\text{–}5\times10^{11}$ ice-forming nuclei per second active at -10C. The location of these generators in and around the target area, shown in Fig. 1, is determined partly on the basis of wind directions, up-slopes, convective centers, etc., but is also greatly influenced by availability of access

FIG. 2. Meteorological Observatory, El Kanzel.

and communications to acceptable sites and by the presence of personnel qualified to operate them. Because of the extremely rugged terrain and the primitive nature of the road and communication systems, there are many parts of the target that are inadequately served by cloud-seeding generators. Only in the region immediately around Sunchubamba, which is also the region where most of the raingauge stations are situated, does the distribution of generator sites approach the density usual in most programs of applied cloud seeding. At the south end of the target area, in the headwaters of the Rio Moche, the distribution of generators approaches the same density.

The program was usually suspended or operated only intermittently during the winter months from about mid-June to about mid-September, when conditions suitable for seeding are infrequent. Suspensions at other times, as shown in Table 1, were ordered by the sponsoring company at times of flood danger.[1] From Sep-

[1] The longest continuous suspension in both areas was 98 days in 1953; there were no suspensions in 1961 or 1964. When suspension was ordered in both areas, the median duration of such suspension was 9 days.

TABLE 1. Days lost from seeding on account of flood risk.

	Chicama—Jequetepeque					Moche					
Year	Jan.	Feb.	Mar.	Apr.	May	Jan.	Feb.	Mar.	Apr.	May	Average total
1952	4	15	20	4		4	15	20	4		43
1953		28	31	30	8		28	31	30	8	97
1954	4					13					8
1955		9	6				9	6			15
1956			29	5				29	5		34
1957			24	29				24	29		53
1958			22	1				18	8		24
1959			19					12			16
1960			6				12	18			18
1962			29	30	3			29	30	3	62
1963				5					5		5
1965			23	5				30	23		40
Totals	8	52	209	109	11	17	64	217	134	11	415
Per year	1	4	15	8	1	1	5	15	10	1	30

tember 1959 through May 1962, a schedule of randomized suspensions of seeding was begun for evaluation purposes in certain parts of the watershed, but it was not carried to completion because of the pressure of the practical demand for all possible stimulation effect.

From time to time the silver iodide seeding has been supplemented by other seeding techniques for relatively brief periods and in relatively small parts of the target area. In 1955, following successful experiments in Cuba with salt seeding techniques in warm clouds, a series of measurements was made of the concentration of giant salt nuclei of the sort regarded as capable of initiating coalescence in warm clouds, which extended from the beach near Trujillo to the divide at the Kanzel. The measurements showed these nuclei to be present in the Pacific marine layer in diminishing numbers as it progressed inland, and to be below measurable concentration in the easterlies above the marine layer. Experiments with salt spray were carried out in the Chicama valley watershed, but were discontinued because of the difficulties and expense of placing the spray where it could be effective. Since early 1961, experiments have been in progress with the release of positive space charge from a fine steel wire extended for a distance of about 30 km over a portion of the watershed and charged to a potential of 20,000 volts.

4. Evaluation

The mission of the evaluation program has been to provide the best possible basis for assessing the economic consequences of two alternative management decisions; whether to continue or to discontinue the program. Continuance would be recommended if discontinuance would involve an economic penalty in the loss of the value of water indicated as being supplied by stimulation that is large in comparison to the cost of carrying on the program, and if proof of ineffectiveness on other grounds, such as cloud physics, is lacking. Discontinuance would be recommended if the economic cost of continuing the program is unacceptable in comparison with the best estimate of the economic value of water added by the stimulation, or if cloud physics or some other basis affords reliable proof that cloud seeding is ineffective. Obviously, one decision or the other must be taken, and the criterion for a management decision of this sort is therefore very different from the criterion by which one would test the validity of the hypothesis that cloud seeding increases the rainfall. Because of the high economic value of water, an indication of increase quite insufficient to validate the hypothesis of a seeding effect may, nevertheless, be quite sufficient to justify the modest economic risk of continuing the program, especially when continuation holds out the hope that accumulation of data may eventually provide the basis for an adequate test of the seeding hypothesis. In the present program, it has been estimated that an increase of 2 per cent in the rainfall adequately repays the cost of the operation of the program. Any indication of increase, therefore, larger than this represents a margin of profit that would be forgone if the program were discontinued.

The data available for evaluation are twice-daily rainfall observations at 0700 and 1700 local time from the network of stations belonging to the sponsoring company. Table 2 shows the usual index data for each of the raingauge locations indicated on the map (Fig. 1). Unfortunately, the raingauge at Cajamarca has been moved several times during this period as it was shifted from one observer to another, and the supervision exercised over it has been of a lower quality than that prevailing in the target.

Since rainfall in July and August is extremely light compared to that during the summer season, annual rainfall amounts have been summarized for the water year beginning 1 August. These amounts are shown in Table 2, together with summary data on the cloud-seeding operations.

As noted in previous studies of the local climate, the wind systems of the three valleys composing the target are distinct and to some degree independent one from another. Since the raingauges occupy for the most part sites much nearer to the streams than to the divides between the valleys, and since from an operating viewpoint the conditions in the three valleys were different, the evaluation is considered at first on a valley-by-valley basis.

Considering first the Chicama valley, where operations were most extensive and the rainfall observations are most plentiful, Table 3 shows that the Chicama

TABLE 2. Raingauge stations.

No. Station	S. Lat.	W. Long.	Elev., m	Year established
1. Tambo	7°32′	78°42′	800	1939
2. Campoden	7°31′	78°32′	1700	1939
3. Chicden	7°28′	78°27′	2200	1939
4. Salagual	7°29′	78°28′	2700	1939
5. Sunchubamba	7°28′	78°22′	2400	1930
6. Huaycot	7°22′	78°23′	3000	1935
7. Huacraruco	7°18′	78°26′	2800	1934
8. Cajamarca	7°9′	78°32′	2700	before 1939
9. Huayllabamba	7°28′	78°19′	2700	1941
10. El Kanzel	7°28′	78°20′	3970	1952
11. La Talla	7°28′	78°17′	3200	1953
12. Araqueda	7°40′	78°11′	2670	1951
13. Corralpampa	7°39′	78°12′	3160	1951
14. Casais	7°32′	78°25′	2500	1957
15. Coina	7°46′	78°29′	1800	1958
16. Chontayoc	7°21′	78°26′	3800	1953
17. Magdalena	7°15′	78°39′	1500	1953
18. Quiruvilca	8°00′	78°18′	3800	1941
19. Motil	7°59′	78°32′	3000	1951
20. Cochabamba	7°49′	77°51′	2600	1950
21. Moyan	7°54′	77°55′	2600	1944
22. Munmalca	7°58′	77°53′	3300	1947
23. San Jose	8°03′	78°07′	3000	1950
24. Tres Rios	7°51′	78°06′	3400	1950
25. Arenillas	7°53′	77°55′	3750	1954
26. Sayapullo	7°33′	78°29′	3000	1960

TABLE 3. Seasonal rainfall amounts for water years ending 31 July, in mm.

	Jequetepeque Valley	Chicama Valley							Moche Valley	Condebamba Valley
Year	Huacraruco	Tambo	Campo-den	Chicden	Salagual	Sunchu-bamba	Huaycot	Chicama Average	Quiruvilca*	Cajamarca
1940	1362	130	615	774	1441	896	1576	902		680
1941	1279	148	615	657	1178	776	1416	798		785
1942	1011	98	390	477	680	574	1155	562	(1298)	722
1943	1237	176	636	749	1018	889	1303	795	1387	735
1944	1340	139	549	736	1173	850	1609	843	1242	722
1945	1294	64	473	610	1048	691	1538	737	1176	614
1946	1329	114	493	527	1235	848	1854	845	(1448)	630
1947	1208	84	398	601	831	686	1488	681	(1273)	654
1948	1320	116	583	516	1064	783	1421	747	1267	828
1949	1177	112	542	729	1127	803	1431	791	1295	879
Mean to '49	1255	118	529	606	1082	780	1479	770	(1298)	725
1950	1091	69	332	482	849	587	1247	594	1153	757
1951	1133	60	341	419	992	582	1741	689	1064	691
Mean to '51	1231	109	497	638	1053	747	1482	749	(1260)	725
1952	1867	187	670	806	1413	1037	1496	935	1502	956
1953	1502	167	864	896	1622	1144	2011	1117	1697	789
1954	895	92	470	678	1024	732	1558	759	1496	674
1955	964	124	707	787	1386	876	1644	921	1541	791
1956	1250	103	677	759	1450	829	2166	989	1793	799
1957	1175	133	719	788	1382	827	1650	916	1289	650
1958	1060	108	447	656	1250	757	1588	801	1134	789
1959	893	142	592	657	1176	735	1653	826	1260	681
1960	1089	135	577	683	1401	839	1502	856	1315	655
1961	1040	72	341	589	1052	614	1361	672	1276	537
1962	1240	132	585	796	1372	898	1612	899	1488	842
1963	917	94	410	607	1069	708	1008	649	1212	416
Mean '52–'63	1170	149	588	725	1300	833	1600	862	1417	715

* The available record is ambiguous as to whether the rainfalls for August 1942, August 1945, and September 1946 are zero or missing. In this table they are treated as zero (since July and August in particular are normally dry months) and the affected figures are enclosed in parentheses.

valley rainfall averaged over the seeded years was 15 per cent greater than that averaged over the preceding years. What confidence can be placed in the assumption that this increase is not due to chance factors? Let us test the null hypothesis, the assumptions being that there has been no special influence affecting the seeded years, and that the annual mean rainfalls for the unseeded and for the seeded years were actually two samples drawn sequentially from a single population, starting at random.

It should be noted at this point that the cloud seeding program was not begun at random since the droughts of 1949–50 and 1950–51 were a factor in the decision to begin the cloud seeding program in 1951. Even if cloud seeding had been completely ineffective, there is a positive probability that the seasons immediately following 1949–50 and 1950–51 would have shown a higher mean rainfall than that for those two seasons, thus producing a fictitious indication of artificial increase. However, if we start rejecting unseeded seasons from 1950–51 backward, where should we stop? The following reasoning was used. A decision to terminate the series of unseeded seasons (by beginning seeding), if taken at the end of a season rainier than the average up to that time, would not have been based on immanence of drought. When the area mean rainfall for each season of the unseeded period is compared with the accumulated mean of the seasons up to that time, it is seen that 1948–49 was the last season before the seeding began that had rainfall higher than the average up to that time, and so it is the last season to fulfill the condition established. Therefore, abbreviation of the unseeded series by rejection of the 1949–50 and 1950–51 seasons eliminates the bias introduced by drought as a factor in establishing the starting date of the experiment. On the other hand, it introduces an opposite bias, since these seasons are rejected specifically because they were dry. The increase for the seeded years compared with the abbreviated historical series is 12 per cent. An objective test of the probability that the increase is real, that is, a test of the null hypothesis alone, would properly use only the abbreviated sample. A recommendation of the most advantageous choice, however, between the two alternatives must take into account both biases. For this reason, in the ensuing evaluations, the probabilities corresponding to comparison with each of the unseeded periods, complete and abbreviated, will be noted.

Returning now to the test of the null hypothesis, a parametric form of the test affords the greatest power. The best estimate of the population mean is given by the mean of the unseeded sample. If we accept the assumption that seeding, if it has an effect, will affect the scale parameter of the precipitation distribution

(Thom, 1957), then the best estimate of the population variance is given by

$$\hat{\sigma}^2 = \frac{N_s\sigma_s^2 + (N-N_s)\sigma_h^2}{N-2}, \tag{1}$$

where N_s is the number of seeded seasons, N is the total number of seasons, both seeded and unseeded, σ_s^2 is the variance of the seeded seasons, and σ_h^2 is the variance of the historical seasons.

Next it is necessary to determine whether the rainfall distribution departs significantly from the normal probability distribution. Fig. 3 shows the distribution of annual mean rainfalls of the abbreviated historical period plotted cumulatively on a normal probability scale, along with the Kolmogoroff-Smirnoff 20 per cent confidence bands. At least a 90 per cent probability is indicated that the sample of 10 unseeded points comes from a distribution not distinguishably different from normal. On the assumption that the rainfall distribution is normal, the hypothesis that the seeded and the unseeded samples come from the same population is tested by forming the statistic

$$Z = \frac{m_s - m_h}{\hat{\sigma}_m}, \tag{2}$$

where m_s and m_h are the means of the seeded and the unseeded seasons respectively, and the standard deviation of the samples is

$$\hat{\sigma}_m = \sigma\sqrt{1/N_s + 1/(N-N_s)}. \tag{3}$$

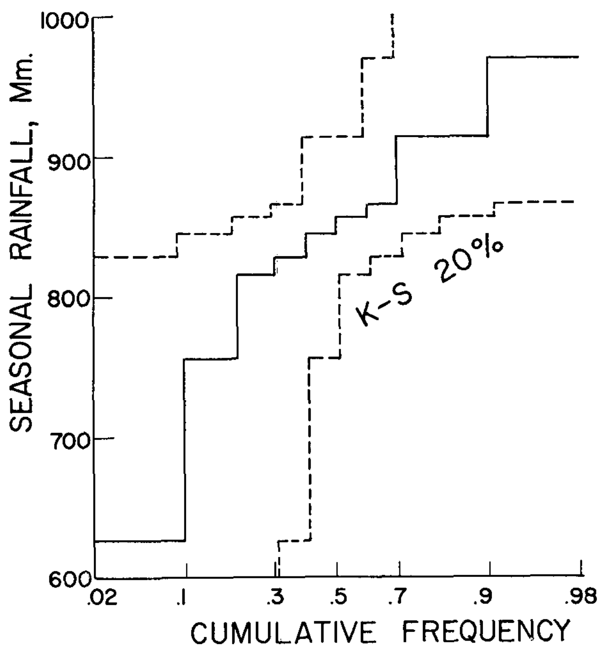

FIG. 3. Distribution of unseeded rainfall, with Kolmogoroff-Smirnoff confidence bands.

This statistic has a t distribution with $N-2$ degrees of freedom. The values of σ_h for the complete and abbreviated unseeded periods are 107 and 91, respectively, with σ_s for the seeded period being 138.

Evaluation of (2) gives the result that the probability is 0.016 of obtaining so large a difference in the means by chance alone, when compared with the complete historical period, and 0.042 when compared with the abbreviated period. It is interesting to note that the variance of the annual rainfall for seeded years was nearly double that of the unseeded years, recalling the question raised by Smith *et al.* (1965) and the appearance of enhanced variance in the course of a number of other cloud-seeding programs as to whether this may be a result of cloud seeding.

Despite the outcome of the Kolmogoroff-Smirnoff test, there remains a possibility that the population from which the samples were drawn is not normally distributed, and that this has influenced the outcome of the test just performed. There is available an alternative test, which has the disadvantage of being less powerful, but the advantage of being non-parametric and thereby avoiding any assumption regarding the normality of the rainfall distribution. This test is based upon the rank standings of each season's rainfall in an ordered list of all seasonal rainfalls. The corresponding statistic is

$$\tau = \frac{T_s - N_s(N+1)}{\sqrt{\frac{N_s(N-N_s)(N+1)}{3}}}, \tag{4}$$

where T_s, the sum of ranks of seeded seasons, is normally distributed and may be used directly to test the null hypothesis. The probability that the increase in the seeded seasons is due entirely to chance, as indicated by this statistic, is 0.014 with respect to the complete sample, and 0.032 with respect to the abbreviated sample. The latter likelihood that the rainfall increase is a happenstance not related to the cloud seeding is approximately comparable to the likelihood of winning a bet on a single number with a spin of a roulette wheel.

Turning now to the evaluation of the results in the Rio Moche watershed, we find that there is only one precipitation gauging station with a record long enough to be of any significance in estimating the effect of seeding, namely the station at Quiruvilca operated since 1940 by the Northern Peru Mining Company. This station, however, is centrally located in the belt of maximum rainfall near the divide, and has been well maintained and supervised. As seen from the data of Table 4, the indicated increase for the seeded years at Quiruvilca is 12 per cent with respect to the entire historical series and 9 per cent with respect to the abbreviated series. The probabilities of chance occurrence of this increase, as indicated by the non-para-

Table 4. Results of probability tests.

	Per cent increase		Probability by chance	
	Complete	Abbreviated	Complete	Abbreviated
Chicama Valley (6 station, 12 historical seasons)	+15	+12		
Parametric test			0.016	0.042
Non-parametric test			0.014	0.032
Chicama Valley (2 stations, 16 historical seasons)	+12	+12		
Parametric test			0.037	0.053
Non-parametric test			0.014	0.021
Moche Valley (1 station, 11 historical seasons)	+12	+ 9		
Parametric test			0.008	0.042
Non-parametric test			0.026	0.055
Jequetepeque Valley (1 station, 12 historical seasons)	−. 4	− 6		
Parametric test			0.288	0.212
Non-parametric test			0.075	0.057

metric test, are 0.008 and 0.026, respectively, or 0.042 and 0.055 for the abbreviated period. Thus the result indicated for the Moche valley is comparable and only slightly less favorable than that for the Chicama valley.

The question may be asked, how closely are the Quiruvilca and Chicama annual precipitations related? Using the non-parametric expression for the correlation coefficient (Spearman, 1908),

$$R^2 = 1 - \frac{6\Sigma D^2}{N(N^2-1)}, \tag{5}$$

where D is the difference in rank between the two data for the same year, the correlation coefficient for the entire series of years is 0.80 (see Table 4). It is curious to note that the correlation coefficient for the seeded period is 0.90, an unexpectedly large difference that leads to the speculation that the seeding may conceivably have led to a greater similarity of rainfall in these two areas than would naturally have been the case. Does the seeding perhaps eliminate one of the chance factors say, presence of ice-forming nuclei, that contributes to the variations of rainfall from place to place? The variance of the seeded years again is noticeably larger than the variance of the unseeded years and the extraordinary increase in variance that showed up in the Chicama area during the seeded years is apparent also in the Moche area.

With regard to the Jequetepeque watershed, Huacraruco alone of all the target stations has less average rainfall in the seeded seasons than in the unseeded, with decreases of 6 per cent with respect to the complete historical period and 4 per cent with respect to the abbreviated period. In this respect it more or less resembles Cajamarca, where a decrease of 2 per cent with respect to both historical periods is indicated. Neither the parametric nor non-parametric tests indicate significance at the 5 per cent level for these apparent decreases. The larger variance for the seeded years is again notable with the variance of the seeded years being more than five times that of the unseeded years.

Without further evidence it is not possible to decide whether the difference between Huacraruco and the Chicama stations during the seeded seasons is accidental or is due at least in part either to the silver iodide taking effect in parts of the valley other than the raingauge location, or to the unsatisfactory operational status of the seeding stations in the Huacraruco area. Chicama and Huacraruco seasonal rainfalls correlate well, with a non-parametric correlation coefficient of 0.88.

In most circumstances, a comparison of the target rainfall with the rainfall in a nearby control area affords a better estimate of the expected natural rainfall than is given by the mean. In the present evaluation, Cajamarca is the only station available for use as a control. Unfortunately, the coefficient of correlation between Cajamarca rainfall and that of the target is so poor that it adds no information; in fact, for the sample of 12 unseeded years, the correlation between Cajamarca and target rainfalls is actually negative, although for the sample of 24 years as a whole it is positive. Thus, despite the geographical propinquity of Cajamarca to the target, it is clear that the valley location of Cajamarca, sheltered behind the principal range of the continental divide, gives it a climate entirely different from that of the highlands above it.

Up to this point, the evaluation procedure has taken no account of the dilution of the seeding effect by suspension of operations during certain periods of high water in the rivers, and by the fact that certain areas of the watershed were less effectively seeded than other areas. There is little that can be done to allow for suspensions during portions of the year, since the effect of the suspensions on the annual mean obviously depends upon the time of year during which the suspension took place, and there is no simple relationship for correcting the annual mean to what it might have been without the suspension.

In an evaluation of this sort, the question always arises as to the advisability of trading off a larger number of stations against a longer period of record. Of the six stations in the Chicama watershed, two, Sunchubamba and Huaycot, have a longer period of record, going back four years before the rest of the stations were established. Using as the unseeded sample the record of these two stations for 16 years, 1936 through 1951, against the means of the 12 seeded years at these two stations, an increase of 13 per cent is indicated with respect to the complete historical period and an increase of 12 per cent with respect to the abbreviated historical period. The non-parametric test of probability is 0.014 for the entire sample and 0.021 for the abbreviated sample. From these data, it does not appear that the indication of increase is significantly changed by narrowing the number of stations and increasing the length of the period of record.

A curious reversal of an historic rainfall relationship has been observed lately in connection with the decommissioning of one of the seeding stations. The station at Huaycot had, until March 1963, been operated by a man interested in and enthusiastic about the cloud seeding program. At that time, he was transferred to a different location, and no suitable operator remained at Huaycot, with the result that operation of the station became very irregular and, after scarcely operating at all during the 1963–64 period, was entirely suspended in the 1964–65 period. Until the virtual cessation of seeding at Huaycot, the annual rainfall for the water year at this station had exceeded that at Salagual in every year of record, seeded and unseeded. Since that time, however, the Salagual rainfall has exceeded the Huaycot rainfall each season. It is perhaps worth noting that the Huaycot generator is situated in the upper part of a narrow valley which acts as a convection chimney, and clouds stemming from it are not unlikely to return overhead in the upper-level easterly flow.

5. Discussion

Although the theatre of operations in Peru does not lend itself readily to carrying out prescribed programs of experimentation designed for testing a hypothesis basic to the assumptions of cloud physics and cloud seeding, it is nevertheless impossible to conduct operations there without raising questions that must be decided in the field regarding the meaning of observed phenomena that are perhaps associated with the seeding, and the interpretation of their significance as guides to the cloud seeding techniques used.

Although it does not appear likely that the site of this operation will ever be ideal for conducting controlled experiments in weather modification, nor that the extension of the experiment in time will greatly increase the confidence with which the outcome can be evaluated (because of the retreat into the past of the comparison period) the indications of increase are more than sufficient to justify continuation of the program on an economic basis, since the likelihood that the program is economically profitable is much greater than the likelihood that it is unprofitable, and the margin of profit attainable is very large in comparison with the economic risks of continuing it. When the program was initiated in 1951, one of the sponsoring companies had under irrigation an area of 14,000 hectares served by its water rights in the Chicama river. In 1963, the area under irrigation from the same water rights was 18,500 hectares. Although this increase in area is not entirely attributable to the cloud seeding program, there is little doubt that it has been a major factor.

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