Cloud Seeding in Southern Puerto Rico, April–July 1965

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ABSTRACT

With the most severe drought on record in its eighteenth month, causing severe damage and hardship in Puerto Rico, several large private concerns and government agencies interested in water decided that the immediate need for water greatly outweighed the uncertainties involved in cloud seeding, and collaborated to sponsor a program of rainfall stimulation. Operations of an emergency nature began 26 April and continued until 18 July 1965.

The result is evaluated by estimating the amount of rain that would have fallen if no seeding had been done, from the average rainfall per rainy day during a 19-year (unseeded) period. This analysis indicated an increase of 2.69 inches, equivalent to a 14 per cent increase nominally significant at the 10 per cent level.

No formal evaluation of the economic outcome is offered, but crop reports suggest that the cloud-seeding program returned value many times its cost, hence justifying the undertaking in the face of the uncertainties involved.

1. Introduction

The 1964 average rainfall of Puerto Rico and the Virgin Islands was the lowest on record, and the severe drought that began in the final months of 1963 was continuing unabated into April 1965. Rainfall in many areas was less than 70 per cent of normal, and on the south coast of Puerto Rico it was as little as 30 per cent of normal. Ground water tables were appreciable lowered, and salinity was becoming a problem in many wells. Impelled by these conditions, several large private concerns and government agencies interested in water, weighing the near certainty of a prolonged need for additional water against the uncertainties of cloud seeding, decided that the likelihood of gain outweighed the risk of loss and undertook to sponsor a program of rain stimulation through the agency of Lluvia Artificial Incorporada, a non-profit corporation established expressly for this purpose. The target area was the whole south coast of Puerto Rico, south of a line from Yabucoa through Cerro La Santa, Cayey, Aibonito, Matrullas Reservoir, Adjuntas and Maricao to Hormigueros and Mayagüez.

Alleviation of the drought was the primary objective, and the randomized alternation of seeded with unseeded periods that would have been desirable in designing a scientific evaluation was forgone for the sake of maximizing the rainfall increase that might be achieved during the limited period of operation. Evaluation was not expected to furnish proof of reality of an increase, but to derive as much information as possible that might be useful in assessing the socio-economic value of the program and deciding what future trials should be made, or what further study should be undertaken of the potential long-range utility of cloud seeding as a factor in water resources planning and management.

2. Physiography and climate

Puerto Rico lies within the zone of northeast trade winds, and the local distribution of rainfall is greatly influenced by interaction between the mountains and the trade wind marine layer as the latter changes depth and direction of motion. Showers are relatively frequent on slopes facing northeastward even when the marine layer is not deep; the deepening and shift to easterly or southeasterly winds that usually accompany disturbed weather bring less frequent but sometimes heavy rain to southeast-facing slopes.

The most pronounced terrain features are the Central Range, which coincides closely with the northern limit of the rain-stimulation target in most of its length, and the Luquillo massif which occupies the northeastern corner of the island. The Central Range, lying ten or fifteen miles inland from the south coast, is mostly 800–900 m high, reaching a maximum elevation of about 1300 m near its center; the highest peak of the Luquillo range reaches 1060 m elevation.

Along the northeast slopes, the mean annual rainfall increases almost linearly with altitude, from about 60 inches at the shore to a local maximum of about 200 inches near the crest of the Luquillo massif. The south coastal plain is much drier, since it lies in the rain-shadow of the Central Range and receives significant rain only when the normal trade wind is interrupted by intervals when it has a southerly component.

The undisturbed tradewind regime is marked by a shallow marine layer of moist air capped by an inversion and overlain by dry air subsiding out of the Azores high. Clouds are restricted to diurnal cumulus humilis, often with dense haze below the inversion, and showers occur only where orographic lift and terrain heating are strong. This regime in interrupted from time to time by incursions of cooler air aloft, by local convergence and deepening of the marine layer accompanying the passage of either easterly or westerly troughs, by combinations of these, or by the infrequent visits of tropical depressions and hurricanes. During these interruptions, diurnal clouds reach a higher stage of development and showers become heavier and more general, reaching greatest intensity where the terrain favors local convection.

Several distinct centers of convection can be clearly identified. One is the aforementioned Luquillo massif, which not only produces local showers but also generates a cloud street that affects the pattern of cloud developments far downwind. A series of major convection centers is found along the Central Range, of which the easternmost, near Carite, appears to be influenced frequently by the cloud street generated by the offshore islands of Culebra and Vieques. The strongest of these centers is associated with the highest peaks of the Central Range, from which showers drifting westward with the prevailing wind drop rain as far away as the western coast.

3. Cloud seeding operations

Cloud seeding was carried out both with silver iodide for stimulation of rain in clouds containing supercooled water and with salt for stimulation of coalescence in "warm" clouds. The rationale of the silver-iodide seeding is that, in clouds that rise above the freezing level, the presence of additional ice-forming nuclei increases the number of particles large enough to initiate the coalescence that leads to precipitation, and hence increases the probability that a given cloud will rain. The additional nuclei also lead to strengthening of convection by release of latent heat of fusion. The rationale of the salt seeding is that the presence near the cloud base of additional particles large enough to initiate coalescence will likewise increase the probability of precipitation. These concepts are more fully presented in a previous publication by one of the authors (Howell, 1960).

Silver-iodide seeding was done from a network of 23 smoke-generator stations situated in the sector from north through east to south of the principal convective centers and equipped with string-burning generators capable of producing about 3×10^{11} nuclei sec^{-1} active at -10C. These stations were supplemented by three mobile units equipped with pyrotechnic flares having a nuclei output about double that of the fixed generators. During the period of operation, silver-iodide seeding was performed on 47 days for a total of 2559 generator-hours.

Salt seeding was done from aircraft flying a short distance beneath the cloud base in regions of cloud development to which they were directed by the field meteorologist. Part of the seeding was done by dispersing brine in the form of a spray having a volume-median drop size of about 30 μ, and part with an airborne grinder dispersing ground block salt at a particle size of about 30 μ directly into the slipstream. Dispersal rate was about 0.5 kg of salt per km of flight. Salt seeding was carried out on 35 different days for a total of 90 hours.

The seeding program ran from 26 April until 18 July. Seeding was done on all days when cloud development, in the judgement of the field meteorologist, indicated that seeding had even a remote likelihood of being effective.

4. Evaluation

The method most usually employed for obtaining an estimate of the rain that would have fallen on the target if cloud seeding had not been done is that of regression, comparing target rainfall with the rainfall on some nearby control area during periods when no seeding was done by a covariance analysis and using the relationship thus obtained to estimate the natural target rainfall on occasions of seeding. This method was attempted in the present instance, characterizing the target by the rain measured at regular gauging stations within the target area and using various groupings of gages in the northern two-thirds of the island as controls. However, it was soon apparent that the degree of association between the rainfall on the target and that on other parts of the island is very poor, apparently because rain on the target is associated with one sort of weather regime and rain on the rest of the island with another.

Previous investigations had shown that the rainfall in the tropical localities studied was strongly related to the number of days when rain exceeded some rather small lower limit, making it possible to estimate the natural rainfall during an experimental period on the basis of the number of rainy days (López and Howell, 1965). This procedure becomes a test of the suggestion by Thom (1957) that seeding, if it has an effect, increases the scale parameter of the rainfall frequency distribution more than it increases the shape parameter.

With the assistance of the San Juan office of the U. S. Weather Bureau, Puerto Rican data were examined to determine whether rainfall in the target area was strongly related to the number of rainy days. Such a relationship was found, and was used to test for an effect of seeding on the average rainfall per rainy day, here called the specific raininess.

The data used were the daily rainfall observations on file in the San Juan office of the Weather Bureau, which include some data not published in "Climatic Data, U. S. by Sections." Observing the restriction that only stations having substantially complete data for the historical period be used, the maximum amount of usable data was found to be that corresponding to the 19-year period 1946–1964, for the 25 stations

TABLE 1. Target rain gage stations.

1. Adjuntas
2. Aguirre
3. Cabo Rojo
4. Carite Camp
5. Cayey 4 NW
6. Central San Francisco
7. Coamo Dam
8. Ensenada
9. Garzas Dam
10. Guayabal
11. Guayama
12. Guineo
13. Jájome Alto
14. Juana Díaz Camp
15. Maricao
16. Matrullas Dam
17. Mayagüez
18. Patillas
19. Ponce
20. Potala
21. San Germán
22. Toro Negro
23. Villalba
24. Yabucoa
25. Yauco

listed in Table 1 and shown by corresponding number on the map, Fig. 1.

For this evaluation, the specific raininess of a particular month was defined as the total rainfall summed over all 25 target-area gages, divided by the number of daily gage readings in the month that equalled or exceeded some specified lower limit. After some trial and error, it was found that a lower limit of 0.10 inch yielded the best degree of association between specific raininess and total rainfall. All the work up to this point was done before data from the seeded period became available, and hence the details of the procedure were settled upon prior to any possible influence from the project results.

Since the seeded period included only the last five days of April, which as a matter of fact were more similar meteorologically to the following month of May, and since the seeded portion of July was very similar to June, data for the historical analysis were limited for the months of May and June. A test made showed that the specific raininess characteristics for this period are quite homogeneous so that the historical data for these two months can be treated together. The main reason for including the seeded first part of July with the May and June data is that the first two weeks of July were more representative of the rainy season weather that usually prevails in May and June. One would be just as statistically biased by comparing this first half of July with all of the historical July months.

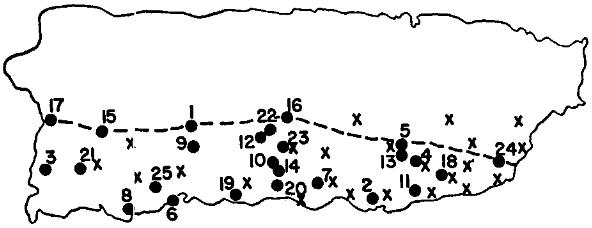

FIG. 1. Map of Puerto Rico showing target area of cloud seeding operations and locations of rain gages used in evaluation (circles) and fixed generator stations (crosses).

The average monthly rainfall, the specific raininess, and the number of rainy days k (rainfall occasions divided by the number of gages) were tabulated for the target for each of the 38 historical months.

It was desirable to transform the rainfall so that the best-fit regression estimate in the case of zero rainfall occasions corresponds to our intuitive estimate of zero target rainfall. The regression model would then be of the form

$$R^q = bk,$$

in which R is the best estimate for the rainfall for the month for k rainy occasions. The exponent q was to be chosen to make the y-intercept of the best-fit line zero. This would require that

$$\text{Intercept} = 1/n \sum R^q - 1/n \sum k r_{R^q,k} \sigma_{R^q}/\sigma_k = 0,$$

which simplifies to the condition that q be the root of the equation

$$\sum k^2 \left(\sum R^q / \sum k\right) - \sum k R^q = 0,$$

in which the summations extend over all the historical months analyzed.

After transformation of variables, the data were first subjected to the usual covariance analysis. Estimates of the statistics of the population from which the test data were drawn were then obtained, using the relationships

$$\sigma_x' = \sigma_x n^{\frac{1}{2}} (n-1)^{-\frac{1}{2}},$$

$$r'^2 = r^2 - (1-r^2)^{\frac{1}{2}} (n-2)^{-1},$$

$$S_x' = \sigma_x (1-r'^2)^{\frac{1}{2}},$$

where n is the number of historical data (months), and σ_x, r and S_x are the standard deviation, the correlation coefficient and the standard error of estimate, respectively. Unprimed values pertain to the test data and primed values to the population from which the test data were drawn.

With respect to the fractions of April and July that were seeded, the target rainfalls and the numbers of rainy days were first divided by the fractions of these months that were seeded, and then a point was found which is the weighted mean of the resulting fictitious whole month and an average month, thus, in effect, making the conservative assumption that the entire variance was accumulated during the real fraction of the month.

The significance of the difference between the actual rain x and the natural rain $\hat{x}$ estimated from the regression was tested by the statistic

$$t = \frac{x - \hat{x}}{S_x'} \left[\frac{n}{n + 1 + (k - \bar{k})^2 / \sigma_k^2} \right]^{\frac{1}{2}},$$

where k and $\bar{k}$ are respectively the observed (or adjusted) and the mean numbers of rainy days and σ_k^2 is the variance of k. The statistic t has a Student's

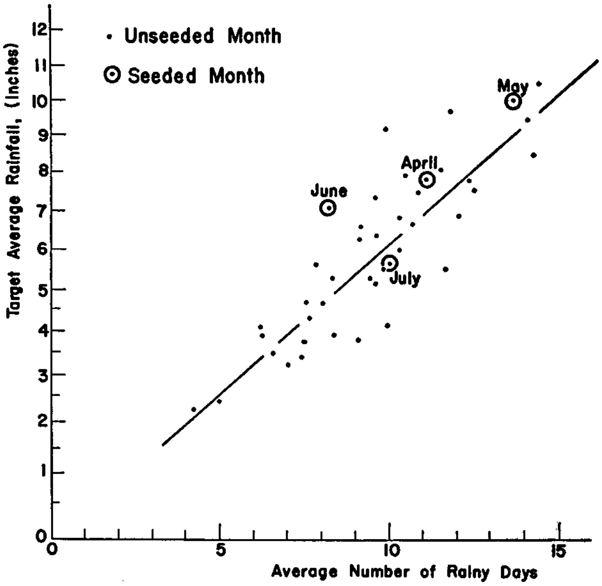

FIG. 2. Regression of average monthly rainfall (transformed) on average number of rainy days for 19 years, 1946–1964, during months of June and July, with seeded months, April–July 1965.

distribution with $(n-1)$ degrees of freedom. The data are shown in Table 2 for the historical period, in Table 3 for the seeded period and graphically in Fig. 2. Computation yielded a value of 0.819 for the transforming parameter q. A covariance analysis of the transformed data was performed by the usual method of least-squares with the following results:

Average number of rainy days in historical period = 9.490;

Average of (transformed) rainfall in historical period = 4.230;

Coefficient of correlation between number of rainy days and (transformed) rainfall = 0.869;

Regression of (transformed) rainfall in number of rainy days $= R^{0.819} = 0.444k$;

Standard deviation of number of rainy days = 2.409;

Standard deviation of monthly (transformed) rainfall = 1.246;

Standard error of estimate of (transformed) rainfall = 0.616.

TABLE 2. Historical rainfall data from 25 target stations.

	May		June	
Year	Average number of rainy days	Average rainfall	Average number of rainy days	Average rainfall
1946	11.54	8.04	7.48	3.77
1947	10.72	6.67	7.00	3.23
1948	10.28	6.00	11.64	5.48
1949	9.60	5.20	9.68	7.34
1950	7.52	4.68	6.21	4.10
1951	14.38	10.46	8.04	4.67
1952	10.46	7.95	9.42	5.31
1953	9.16	6.27	12.04	6.87
1954	8.28	3.91	9.13	6.55
1955	9.91	4.13	9.68	6.37
1956	12.36	7.84	9.92	9.16
1957	9.09	3.82	8.32	5.28*
1958	14.08	9.41	14.26	8.50
1959	10.88	7.48	5.00	2.43
1960	9.92	5.55	12.56	7.50
1961	6.52	3.57	7.40	3.43
1962	7.83	5.66	10.33	6.85
1963	11.84	9.70	6.26	3.87
1964	4.22	2.24	7.65	4.31

* Stations 2, 7, 10, 11, 14, 19, and 20 were within a seeded target during the second half of June 1957.

The above results together with the number of rainy days were used to obtain estimated rainfall amounts if seeding had not been done. The data for these periods, derived from official U. S. Weather Bureau data, are also shown in Table 3.

If the four separate months of the trial period are regarded as four separate tests, the probability of the departure accumulated during the entire period can be estimated by the method of Fisher (see Birnbaum, 1964) according to the formula

$$P=Q\sum_{1}^{m-1}(-\ln Q)^m/m!,$$

where Q is the product of the four individual probabilities and m is the number of separate trials. The statistic P has a chi-square distribution with $2m$ degrees of freedom.

Computation from the values in Table 3 indicates that the rainfall during the seeded period was 2.69

TABLE 3. Actual and estimated natural rainfalls for seeded period.

Month (days)	Number of rainy days	Target rainfall	Estimated natural rainfall	Indicated increase (decrease)	Student's statistic
Apr. (5)	2.292	1.814	1.522	0.292	0.63
May (31)	13.792	9.896	9.164	0.732	0.60
Jun. (30)	8.280	7.080	4.916	2.164	2.08
Jul. (18)	5.920	3.182	3.680	(0.498)	−0.63
Totals	30.284	21.972	19.282	2.690	2.68

inches or 14 per cent greater than that estimated from the number of rainy days, and that the probability of occurrence of this indication is 0.09. Thus, the increase is nominally significant at the 10 per cent level.

5. Discussion and conclusions

The evaluation presented above offers a partial answer to the meteorological part of the question about the value of the cloud-seeding program: if the seeding influenced the rainfall but did not influence the number of rainy days, then the most probable amount of rainfall increase is 14 per cent and such an indication should be expected by chance less than once in ten trials.

If the seeding decreased the number of rainy days, then the evaluation procedure has overestimated the the increase of rainfall. However, physical reasoning leads to the probability that the number of rainy days was somewhat increased, and that our procedure has underestimated the actual rainfall increase effected by the seeding.

There remain other possible sources of bias that are difficult to identify and evaluate. For instance, it may be asked whether the effectiveness of the stimulation increases with increasing elevation of the terrain, i.e., with increasingly favorable conditions for cloud formation. Since most of the rain gauging stations are in valleys, they yield a sample biased toward the lower elevations. If the answer to the question above is yes, then our procedure has underestimated the increase; if the reverse is true, the increase has been overestimated: we have no adequate physical basis for passing judgement. If the data involved in the test are not a representative sample of the weather to be expected, then the ground is cut away beneath the basic assumptions involved in the regression analysis. In this respect there are grounds for doubting that weather is a "stationary" process in the sense that we could count on drawing two successive samples of data from the same parent population.

The value of the program and the soundness of conclusions to be drawn from it can be judged only by weighing these uncertainties against the importance of the increase in rainfall that appears to have been achieved, not only for relief of the drought prevailing at the time of the experiment, but also as a technique for the future planning and management of water resources for Puerto Rico. Agricultural reports published in the "Weekly Weather and Crop Bulletin" of the Department of Agriculture covering the seeded period specifically mentioned the beneficial effects on agriculture of the rainfall being received (there were two reporting periods when rain was slightly deficient), and the only reference of adverse effects on agriculture related to temporary interference with sugar-cane harvesting and some reduction in the percentage of sucrose, coupled, however, with mention of great improvement in the state of young cane. Substantially all the rainfall, therefore, including any increment attributable to seeding, was of value to agriculture, and represented probable realization of economic benefits amounting to many times the cost of the weather modification program.

The great economic importance of water for Puerto Rico and the promising indications so far achieved by cloud-seeding experiments point to the advisability of an energetic program aimed at determining the role that weather modification is capable of playing in water resources development and management. Furthermore, the experiences of this brief period of operation lend considerable encouragement to the outlook for scientifically sound results from a program of moderate duration.

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