Weather Modification from Cooling Towers: A Test Based on the Distributional Properties of Rainfall[1]

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ABSTRACT

A statistical technique for the treatment of data from weather modification experiments is presented. This work, a part of the Meteorological Effects of Thermal Energy Releases (METER) Program, is aimed at determining the potential precipitation modification effects of the Bowen Electric Generating Plant near Cartersville, Georgia. For that purpose a network of 49 recording raingages and four recording windsets situated on a square (42 km side) grid was installed in early 1978.

The statistical technique utilizes a design which resembles the crossover statistical design used in cloud seeding studies and employs the distributional properties of the sample skewness and kurtosis. Based on the storm data from the above network for the period February 1978–August 1978 the technique demonstrates an anomaly in the target area rainfall with a 90% confidence level. This anomaly is interpreted as a plant-induced modification of the spatial variability of rainfall volume.

1. Introduction

The potential effects of the natural draft cooling towers of a large power plant on local rainfall is investigated with a comparison of the characteristics of the distribution of storm rainfall amounts. The statistical design of this study resembles the crossover control-target statistical design used in cloud seeding experiments (Moran, 1959). The results are based on data acquired with a network of recording raingages and windsets[2] installed around the plant.

This work is a part of a Department of Energy (DOE) sponsored program called METER (Meteorological Effects of Thermal Energy Releases) aimed at determining the extent to which the heat and moisture discharged by the cooling towers and cooling ponds of large power generating facilities affect local weather (Patrinos and Hoffman, 1978, 1979).[3,4] Among the considered potential atmospheric effects is that of precipitation modification. The Oak Ridge National Laboratory (ORNL) is addressing this potential effect with extensive climatological studies around the Bowen Electric Generating Plant (Plant Bowen) in northwestern Georgia.

Earlier work by ORNL (Patrinos *et al.*, 1979) utilized monthly rainfall totals from the NWS Cooperative Network in the vicinity of the plant. A method using the spatial correlation as an indicator of effects revealed positive evidence of rainfall modification in the target areas as determined by the prevailing surface and upper air winds. This modification manifested itself as an increase in the rainfall pattern variability rather than a rainfall volume enhancement or reduction. The obvious limitations in the quality and quantity of the NWS data discouraged any strong conclusions regarding this effect and necessitated the extensive field study initiated by ORNL in the spring of 1978.[5] Furthermore, the suspected nature of the effect set the tone of the statistical investigations with the data of the installed precipitation network. Specifically, it was hypothesized that the potential effect would appear

[1] Research sponsored by the Advanced Nuclear Systems and Projects Division, U.S. Department of Energy, under Contract W-7405-Eng-26 with the Union Carbide Corporation.

[2] Wind speed and wind direction recording instruments.

[3] Patrinos, A. A. N., and H. W. Hoffman, 1978: Meteorological Effects of Thermal Energy Releases (METER) program annual technical progress report for period October 1976–September 1977. Oak Ridge National Laboratory Tech. Memo. ORNL/TM-6248, 312 pp. TM-6248, 312 pp. [NTIS].

[4] Patrinos, A. A. N., and H. W. Hoffman, 1979: Meteorological Effects of Thermal Energy Releases (METER) program annual technical progress report for period October 1977–September 1978. Oak Ridge National Laboratory Tech. Memo. ORNL/TM-6867, 126 pp. TM-6867, 126 pp. [NTIS].

[5] Miller, R. L., R. E. Saylor and A. A. N. Patrinos, 1978: The METER-ORNL Precipitation Network: From design to data analysis. Oak Ridge National Laboratory Tech. Memo. ORNL/TM-6523, 52 pp. TM-6523, 52 pp. [NTIS].

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as a significant anomaly in the skewness ($\sqrt{b_1}$) and kurtosis (b_2) of the distribution of the storm rainfall data in the target areas. This hypothesis was indeed confirmed by a statistical test based on the joint distribution of skewness and kurtosis. The anomaly between control and target area rainfall was observed at the 90% confidence level.

2. Meteorological background

Plant Bowen is located in the southern part of a broad valley, approximately 64 km northwest of Atlanta, Georgia. It is a coal-fired, 3160 MW (electric) power plant utilizing four natural draft cooling towers and two smokestacks. Details on the topography and climatology of the region can be found in the earlier paper (Patrinos *et al.*, 1979). Of interest to this study is the possible mechanism by which the cooling tower and smokestack plumes can affect local precipitation. With regard to the cooling tower plumes several theories have been advanced. Huff (1972) theorized that the plumes could serve as a triggering mechanism upsetting latent instabilities in the atmosphere and disrupting storm patterns. Overcamp and Hoult (1971) examined the role of the wind forces to determine the conditions under which precipitation can occur from a natural draft cooling tower. Current studies consider the rapid growth by coalescence of the drift droplets ingested by convective clouds as a cause of early and anomalous precipitation. The role of the condensation nuclei introduced by the smokestack plumes is generally not well understood. Their potential effect on rainfall, however, is not expected to appear on a local scale (within ~25 km from the plant) and thus, with some reservation, condensation nuclei are ignored in this study. It is believed that further numerical and experimental work is required to identify and describe precisely the underlying mechanism, e.g., airborne studies exploring the microphysics of power plant effluent ingestion by clouds. The pioneering work performed in the cloud seeding field (Simpson and Dennis, 1974) is a case in point. The study described in this paper does not deal with the microphysical aspects of the problem except, of course, in a corollary sense since the results could serve as the testing grounds for various working hypotheses.

It should be emphasized that the primary goal of this study is the delineation of the potential plant-induced effects on rainfall in the vicinity of the plant. This is reflected in the size of the precipitation network employed and is dictated by the natural decision of exploring the close-in before venturing outward. It is plausible to assume that the potential anomaly could occur at larger distances, for example, because of a delayed-action response to the triggering mechanism, and could be of a scale larger than the one accommodated by the presently employed network. Under those circumstances alternative studies will be considered during the various evaluation stages of this project.

3. The METER-ORNL Precipitation Network

Work with the spatial correlation as an indicator of effects (Patrinos *et al.*, 1979) dealt with monthly precipitation totals recognizing the limitations of the employed NWS data. Any serious precipitation modification study, however, dictates the examination of rainfall patterns on a storm-event basis (Thom, 1957; Huff, 1971). This allows greater versatility in the stratification of events with respect to the responsible large-scale weather disturbance (frontal, convective, etc.) and permits the determination of the control and target areas on the basis of the actual winds rather than overall wind statistics which often impair the validity of the postulated statistical design (Patrinos *et al.*, 1979). An additional weakness of the earlier study was the low NWS raingage network density when compared with the state-of-the-art of weather modification experiments (Huff, 1971). The METER-ORNL Precipitation Network was designed to meet the required specifications. Fig. 1 displays this network superimposed on the topographical map of the area. The network was installed in February 1978 and is composed of 49 recording raingages and four recording windsets for the tracking of surface (6 m above ground) winds. The raingages are situated on a 7×7 square (42 km side) grid centered at Plant Bowen. Upper air (850 and 500 mb) winds are obtained from the Athens airport situated ~145 km east of Plant Bowen. The network is expected to operate for a total of five years. The results presented in this paper are based on the data of the first 6-month period (22 February–31 August 1978). This data set appears in complete detail in the report by Miller *et al.*[6] The data base employed contains 98 precipitation events (storms). A storm is defined as a period of rainfall separated from another rainfall period by at least 2 h of no rainfall over the entire 49-station network. The information analyzed here includes the precipitation amounts at the 49 stations and the prevailing surface and upper air winds during each one of the 98 storms. These winds were determined by suitable spatial and temporal averaging of the available wind data during the storms. No attempt was made here to differentiate between storms of various individual types or to discriminate between events with different levels of power plant output.

[6] Miller, R. L., A. A. N. Patrinos, and R. E. Saylor, 1979: Storms over the METER-ORNL Precipitation Network: The first six months. Oak Ridge National Laboratory Tech. Memo. ORNL/TM-6883, ORNL/TM-6883, 547 pp. [NTIS].

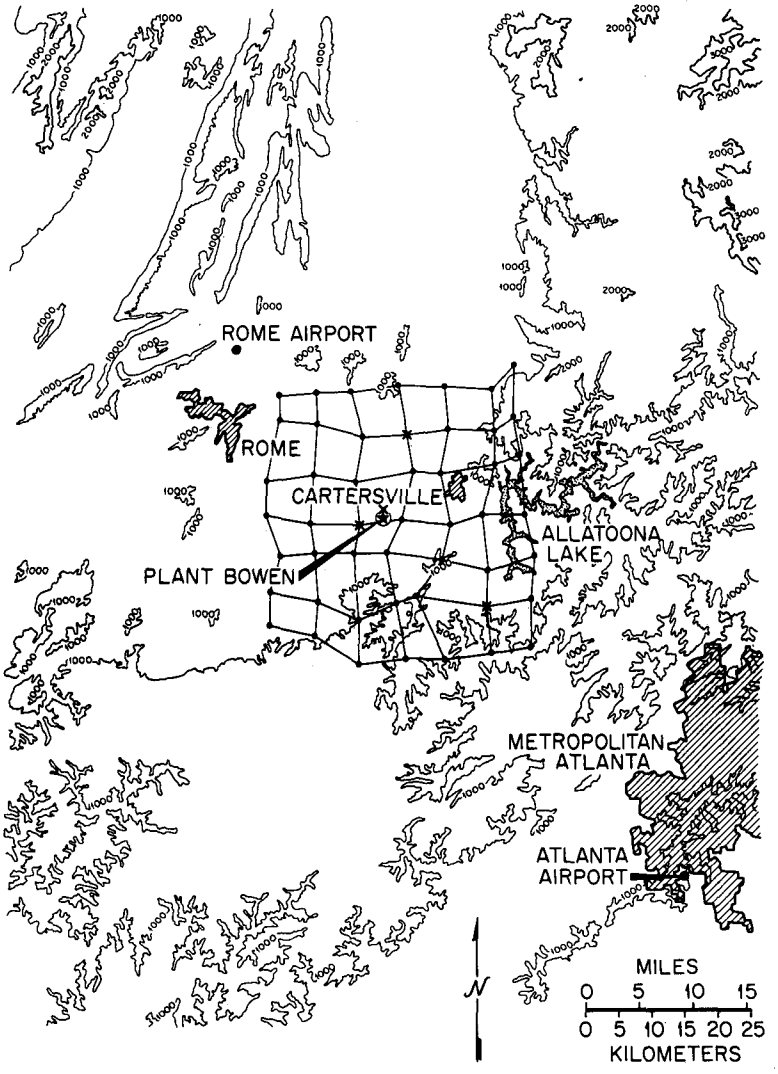

FIG. 1. The METER-ORNL Precipitation Network superimposed on the topographical map of the area. Dots denote the positions of the raingage stations and crosses represent the windset sites. The minimum elevation in the valley is ~600 ft MSL.

4. The statistical design

The analysis employs a design which is akin to the crossover statistical design employed in some cloud seeding operations (Mielke, 1974; Moran, 1959; Wu *et al.*, 1972). The target area for each storm is defined as the smallest area sector confined between the surface and upper air wind vectors positioned at the plant. The diametrically opposite area is defined as the primary control area while the remaining two area sectors comprise the secondary control areas. Fig. 2 exemplifies the above. When the two wind vectors coincide (or when the angle between them is less than 30°) an artificial area sector is created by adding and subtracting an angle ϕ to the common direction (the average direction). The underlying hypothesis of the statistical design is that the cooling tower plumes initially move in the direction of the surface winds. As they rise and mix with the upper air, they shift to the direction of the upper air winds. Consequently, somewhere in the area defined by the two wind vectors the effect is expected to maximize. The target and control area data sets are created by including all the nonzero precipitation amounts at the target and control stations during the 98 storms. The zero amounts are not considered in this analysis since it is recognized that they severely limit the range of applicable statistical distributions. The distributions are investigated both for the data in their original form and following a square-root transformation which reduces somewhat the large skewness of the raw data.

5. Statistical tests

There are two basic approaches to the treatment of data from weather modification experiments: nonparametric and parametric (Brier, 1974). In the first approach, no attempt is made to determine the distributional properties of the data sets under study. Such tests as the Wilcoxon (Mann-Whitney) test, the squared rank test (Mielke, 1974), the root-double-ratio test (Gabriel and Feder, 1969), etc., have had considerable application in cloud seeding operations. The second approach attempts to approximate the data sets under study with known distributions. This often permits the transformation of the original data sets to normality thus facilitating the application of the numerous statistical tests which have been developed for normal distributions (t-test, F-test, analysis of variances, etc.). Frequently employed distributions include the gamma distribution (Thom, 1957; Simpson *et al.*, 1975) and the log-normal distribution (Biondini, 1976; Mielke *et al.*, 1977).

Despite several attempts the first approach (nonparametric) has had limited success in this weather modification experiment. As mentioned earlier the potential effect is expected to appear as an anomaly in the higher moments of the distribution. A nonparametric approach which tests significant differences in the first two moments (mean and variance) was not expected to succeed in this case.

Initial efforts during the second approach (parametric) attempted to determine the distribution which best described the data base. The gamma and log-normal distribution hypotheses failed convincingly the goodness-of-fit test. Temporary success was achieved with the Johnson's S_B distribution, but the ultimate transformation failed the omnibus test of departure from normality (Bowman and Shenton, 1975). In addition, the observed data distribution was inverted J-shaped, a form not included in the Johnson system. The Pearson system of curves was used because the higher moment ratios ($m_5/m_2^{5/2}$,m_6/m_2^3) of the data were less discrepant. It should be mentioned that although higher moments of data may have large sampling errors, the sample sizes involved in the present study (500 or more) are large enough to alleviate this problem.

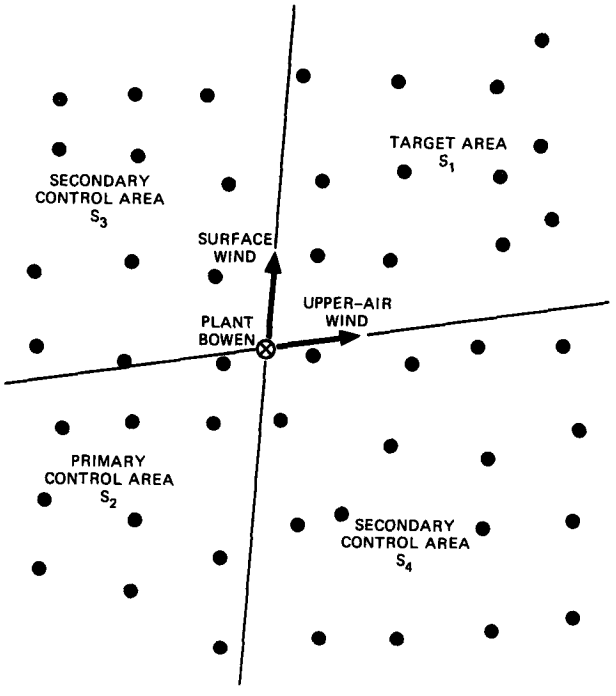

FIG. 2. Determination of control and target areas on the basis of surface and upper air winds.

TABLE 1. Related moments of four sets of data (square-root transformed).

	Target		Control	
	S_1	S_2	S_3	S_4
m_1'	0.5541	0.6011	0.5949	0.5784
m_2	0.1551	0.1495	0.1615	0.1511
$\sqrt{b_1}$	1.164	0.887	0.970	0.882
b_2	3.881	3.295	3.375	3.171
$m_5/m_2^{5/2}$	9.045	6.816	7.152	6.368
m_6/m_2^3	25.792	20.150	20.901	17.955
n	672	610	651	585
$\sqrt{\beta_1}$	1.17	0.89	0.97	0.89
β_2	3.90	3.31	3.38	3.18
$\mu_5/\mu_2^{5/2}$	9.76	7.01	7.41	6.51
μ_6/μ_2^3	29.83	21.05	21.65	18.67
$E(\sqrt{b_1})$	1.165	0.886	0.966	0.886
$E(b_2)$	3.887	3.299	3.371	3.173

For a random sample $(x_1, x_2, \ldots, x_n)$ with mean $\bar{x}$, moment ratios are defined as $\bar{x} = m_1' = \Sigma x_i/n$, $m_s = \Sigma(x_i - \bar{x})^s/n$, $\sqrt{b_1} = m_3/m_2^{3/2}$, $b_2 = m_4/m_2^2$, $\sqrt{\beta_1} = \mu_3/\mu_2^{3/2}$, $\beta_2 = \mu_4/\mu_2^2$.

Greek symbols in the table represent population moment parameters, and $E(x)$ refers to the mathematical expectation of the random variable x.

Table 1 presents the sample-moments of the distribution for the target and the three control areas. The data are in their square-root transformed form (with the zeros removed) and the angle $\phi = 45°$. These distributions were initially compared by considering the differences in the mean and the variance. The non-normal sampling of the t-statistic (test of two means) has been approximated by Geary (1947) and this approximation was used to test the means of the target and control areas. The results indicated that the approximation formula was not accurate enough for the available data. At present there is no other available method of testing the differences between means from the same non-normal population. Skewness and kurtosis statistics, however, are independent of scale and location parameters and their distributional properties, when sampling from non-normal distributions, have been studied extensively.

TABLE 2. Coefficients (in powers of n^{-1}) in the Taylor expansions of the moments of the skewness and kurtosis in Pearsonian sampling. Population sampled: Pearson type I, $\sqrt{\beta_1} = 1.17$, $\beta_2 = 3.90$.

	n^0	n^{-1}	n^{-2}	n^{-3}	n^{-4}	n^{-6}	n^{-8}
$E(\sqrt{b_1})$	1.17	−3.042	−15.648	40.071	1406.38	−294430	59841710
$\mathrm{Var}(\sqrt{b_1})$	0	5.1614	4.183	−412.85	−7138.7	4251205	−2079932481
$E(b_2)$	3.90	−8.7816	−92.253	291.03	13309.1	−3378575	657806604
$\mathrm{Var}(b_2)$	0	72.5796	94.628	−16308	−351023	295721212	−161852454712
$E(b_2\sqrt{b_1})$	4.563	−3.9352	−132.564	−1753.70	−28707.5	30517375	*

* Entry omitted because of round-off error.

a. *Errors in the sample skewness ($\sqrt{b_1}$) and kurtosis (b_2)*

The following null hypothesis is postulated: The distribution of the rainfall data of the target area (S_1) and the control area (S_2,S_3,S_4) have the same parent distribution. To investigate the properties of the distribution, we use the statistics sample skewness and kurtosis ($\sqrt{b_1}$ and b_2) and define the population sampled. With a moderate sized set of data, we take the estimates of $\sqrt{b_1}$ of $\sqrt{\beta_1}$, b_2 of β_2 as acceptable guides; in any event there are few alternatives.

Moments of $\sqrt{b_1}$ and b_2 in sampling from various distributions (Pearson, normal mixtures, etc.) and developed in Taylor series in powers of n^{-1} (n the sample size) are given[7] for various sets of grid points $(\sqrt{\beta_1},\beta_2)$. Since the procedures involved require considerable computer facilities, interpolation for $(\sqrt{\beta_1},\beta_2)$ should be sufficient for most practical purposes. For example, for the data associated with target area S_1 (Table 1), $\sqrt{b_1} = 1.164$, $b_2 = 3.881$, in the neighborhood of this point, the bias of $\sqrt{b_1}$ is $4.3/n$ and that of b_2 is $-9/n$. With $n = 672$, the population parameters corrected for biases are $\sqrt{\beta_1} = 1.17, \beta_2 = 3.90$. Examples of the coefficients in the moment series are shown in Table 2. Iterative methods would yield $E(\sqrt{b_1})$ and $E(b_2)$ identical to the empirical data, but for all practical purposes, the estimated distributions are acceptable for our example.

b. *Confidence regions*

From the moments of $\sqrt{b_1}$ and b_2 we can set up confidence regions at a given level α of acceptance. These regions are based on a bivariate model for the joint distribution of the skewness and kurtosis in general sampling (Shenton and Bowman, 1977).

The joint distribution of $\sqrt{b_1}$ and b_2 in sampling from a Pearson type I distribution has been approximated by a bivariate product density (Shenton and Bowman, 1977)

$$f(\sqrt{b_1},b_2) = w(\sqrt{b_1})g(b_2|\sqrt{b_1}),$$

where $w(\cdot)$ refers to the Johnson S_U approximation to the marginal probability density function of $\sqrt{b_1}$, and $g(\cdot\,|\,\cdot)$ to a conditional gamma distribution. Specifically,

$$w(\sqrt{b_1}) = [\delta(2\pi)^{-1/2}][\lambda^2 + (\sqrt{b_1} - \xi)^2]^{-1/2} \exp(-Z^2/2),$$

where

$$Z = \lambda + \delta \sinh^{-1}[(\sqrt{b_1} - \xi)/\lambda],$$

$$Z \in N(0,1),$$

$$g(b_2|\sqrt{b_1}) = k[k(b_2 - 1 - b_1)]^{[\theta(\sqrt{b_1})-1]} \times \{1/\Gamma[\theta(\sqrt{b_1})]\} \exp[-k(b_2 - 1 - b_1)],$$

where $k > 0$, $\theta(\sqrt{b_1}) = a + b\sqrt{b_1} + cb_1 > 0$ for all real $\sqrt{b_1}$, and ξ, λ, γ, δ are found in Johnson's (1965) tables. The values a, b, c and k are evaluated from $E(b_2)$, $\mathrm{Var}(b_2)$, $E(\sqrt{b_1}b_2)$ and $E(b_1b_2)$.

For example, for target area data S_1 (Table 1), we assume sampling from a Pearson type I distribution with parameters $\sqrt{\beta_1} = 1.17$, $\beta_2 = 3.90$ and sample size $n = 672$. Then $\gamma = -12.7105$, $\delta = 17.8218$, $\lambda = 1.2327$, $\xi = 0.2083$, $a = 94.4377$, $b = 0.5478$, $c = 55.7848$ and $k = 112.6327$.

An acceptance region with probability content α is found by determining the contours of equal probability in the $(\sqrt{b_1},b_2)$ plane and adjusting these to the point where the total content is the desired α. Fig. 3 shows these contours at the level $\alpha = 90\%$ for the four sets of data (target S_1, and controls S_2, S_3, S_4). First, we construct regions for each of the controls to test for consistency. This being satisfactory, we plot the $(\sqrt{b_1},b_2)$ for the target set (S_1) and find that it lies outside the acceptance region at the 90% level. We thus reject the null hypothesis at that probability level.

For reference purposes we have also constructed the 90% region for the target data, and this could be studied in case there is an interest in the power of the test (Kendal and Stuart, 1961).

c. *Effect of the square-root transformation*

In case there is doubt about the efficacy of the root transformation, Table 3 provides the sample

[7] Bowman, K. O., and L. R. Shenton, 1975: Tables of moments of the skewness and kurtosis statistics in non-normal sampling. Union Carbide Corporation Nuclear Division—Computer Sciences Division, Rep. UCCND-CSD-8.

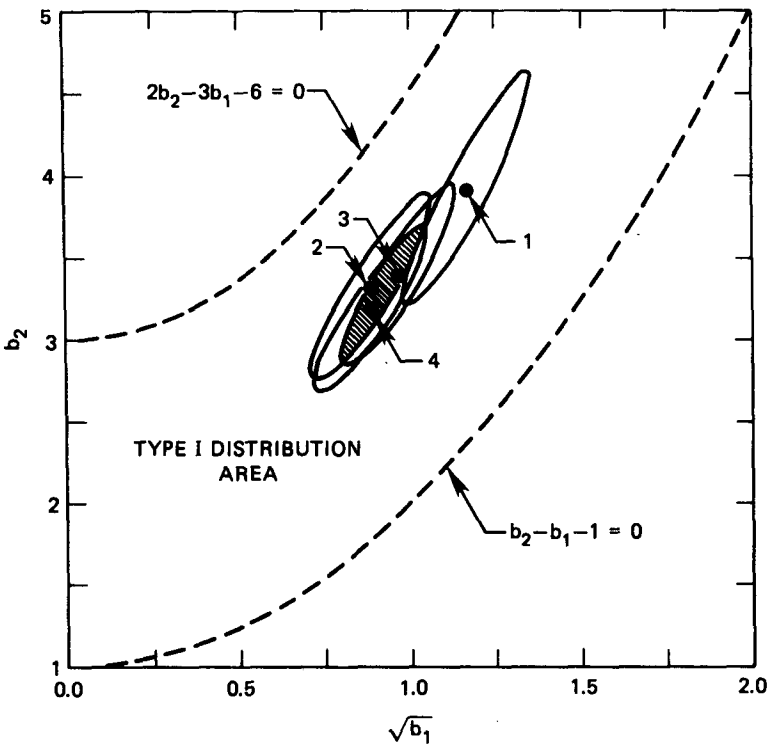

FIG. 3. Contours of equal probability (α = 90%) for the target (1) and the control (2,3,4) data sets in the ($\sqrt{b_1}$,b_2) plane. The shaded area represents the common acceptance region based on the control area results. The precipitation data are squared-root transformed.

moments of the original data. Whereas the means are only slightly affected, the reduction in the skewness and kurtosis of the square-root transformed data is dramatic. This regression toward the normal point alleviates the problem of finding a good approximating distribution to the data, and the related problem of the acceptability of the bivariate model for the joint distribution of ($\sqrt{b_1}$,b_2). It may be noted that the power of a root transformation in precipitation studies was studied by Stidd (1953).

It turns out that constructing confidence regions following the procedure described in previous paragraphs, leads to the same conclusion: i.e., we reject the null-hypothesis (see Fig. 4). It is apparent from Fig. 4 that the areas of the confidence regions of the original data are much larger than the corresponding ones of the square-root transformed data.

6. Summary and future plans

The investigation of potential plant-induced precipitation modification has focused on comparisons of control-target area precipitation distributions; emphasis was placed on the skewness and kurtosis of these distributions. Utilizing the joint distributions of these statistics and assuming a 90% confidence level, we concluded that the distribution of target area precipitation data is significantly different from the distribution of the control areas. This result lends some support to the claims of the earlier paper (Patrinos *et al.*, 1979) regarding the suspected nature of the effect. It was argued that the effect would manifest itself as an increase in the frequency of scattered rainstorms in the target area thus increasing the general spatial and temporal variability of rainfall volume. It is possible that the increased values of the higher moments of the target precipitation distributions represent a positive indication of this hypothesis. Moreover, since the data cover the spring and summer seasons with their larger potential for scattered rainfall events (Table 4), the hypothesis is further strengthened. It is recognized, however, that these results are based on a short sam-

TABLE 3. Moments of the four sets of data (in original form).

	Target		Control	
	S_1	S_2	S_3	S_4
m_1'	0.4622	0.5108	0.5154	0.4872
m_2	0.4174	0.3905	0.4403	0.3728
$\sqrt{b_1}$	2.314	2.087	2.108	2.015
b_2	8.379	7.971	7.779	7.283
n	672	610	651	585

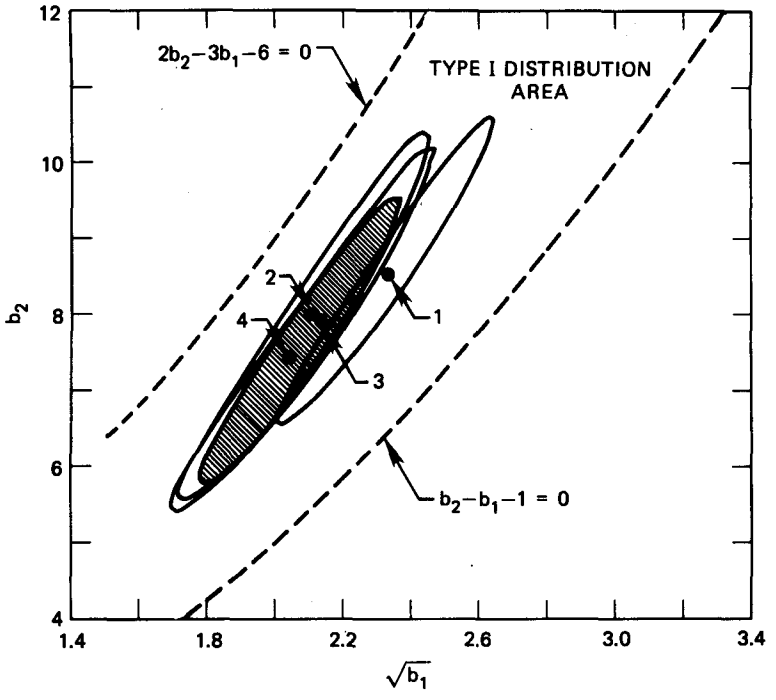

FIG. 4. Contours of equal probability (α = 90%) for the target (1) and the control (2,3,4) data sets in the $(\sqrt{b_1}, b_2)$ plane. The shaded area represent the common acceptance region based on the control area results. The precipitation data are in their original form.

ple and firm conclusions cannot as yet be reached. The presumed effect contrasts with the suspected effect in cloud seeding operations where considerable evidence suggests rainfall volume increases in a multiplicative sense (Brier, 1974). Even in cloud seeding operations however, there is some speculation that seeding might at some times increase precipitation while decreasing it at others without a significant increase or decrease in total rainfall volume. The resultant situation might, under those circumstances, resemble the situation hypothesized for the cooling tower plume effect.

TABLE 4. Frequency distribution of precipitation events (storms) for period 22 February–31 August, 1978 by storm type.

Storm type	Number of storms	Average rainfall (mm)	Average number of stations with rainfall
Stationary front	19	4.3	24
Occluded front	3	15.8	41
Cold front	7	6.9	33
Warm front	1	16.3	49
Pre- and post-frontal	9	5.1	27
Squall line	18	14.0	35
Squall zone	8	9.7	38
Low pressure center	2	8.6	49
Air mass	26	1.3	12
Cold air mass	5	1.8	33
Total	98		

It should be emphasized that in this analysis no attempt was made to stratify the precipitation events by storm type or by power plant output. These options are reserved for future analyses with the larger data sets. The decision to use only positive precipitation data was made to increase the manageability of the storm amount distributions but does raise some questions regarding its validity. Finally, the inclusion of all target and control data sets was prompted by the desire to introduce all available information into the analysis especially since the effect was expected to appear as an anomaly in the higher moments.

As mentioned earlier nonparametric tests had limited success with the data. Nevertheless, with the increase of the size of the data sets these tests could potentially prove valuable in the determination of any effects especially if these effects appear as disturbances in the mean or variance. With regard to a parametric distribution, adequately representing the available samples, efforts are continuing. Likely candidates such as the gamma, log-normal and Johnson's system of distributions were discarded after several attempts. This is not to say that these distributions could not potentially succeed with the larger data sets especially if some

stratification such as by storm type is implemented on the data.

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