CONF-781106--1

CONF-780520--6

METEOROLOGICAL EFFECTS OF HEAT AND MOISTURE RELEASES FROM LARGE POWER STATIONS (PRECIPITATION MODIFICATION)*

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*Research sponsored by the U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

1. INTRODUCTION

Among the various atmospheric effects attributed to the operation of the cooling towers and ponds of large power stations is that of precipitation modification.[1] The important characteristics of such cooling systems vis-a-vis the conventional once-through cooling system is that the waste heat is discharged directly into the atmosphere in both sensible and latent forms. This discharge represents a persistent perturbation in the lower atmosphere, which under certain conditions could upset latent instabilities and trigger rainfall storms or enhance the intensity of naturally occurring precipitation events. It should be emphasized that we feel that it is the persistent nature of the perturbation, rather than its magnitude, that is the possible origin of precipitation enhancement.[1] For a modern, four-unit power plant with an electrical capacity of about 3,000 MWe, the estimated atmospheric discharge is about 5,000 MWt and 50,000 gals per min of water; these amounts are small compared with the energy and moisture associated with even a moderately sized thunderstorm. The magnitude of the perturbation could potentially become important, however, if the concept of "energy centers" with electrical capacities exceeding 10,000 MWe, becomes a reality in the future.[2] Such a concept is currently being considered, especially for future nuclear plants to insure nuclear nonproliferation.

The U.S. Department of Energy (DOE) has established a program called METER (Meteorological Effects of Thermal Energy Releases) to investigate the atmospheric effects of cooling towers and ponds.[2,3] Effects being investigated include drift deposition, fog and icing, shadowing, and precipitation modification.[4] As part of this nationwide program, the Oak Ridge National Laboratory (ORNL) is studying precipitation modification from large cooling towers.[5,6,7] For that purpose, the Bowen Electric Generating Plant (Plant Bowen) in Northwest Georgia has been chosen as a test site. This 3,200-MWe coal-fired power plant of the Georgia Power Company uses four natural-draft cooling towers and is the largest of U.S. power plants having cooling towers as the sole cooling method. Completed in the early 1970's, it is situated about 40 mi NW of the city of Atlanta in a broad valley amidst gently rolling hills.

The ORNL activities presently include both climatological and field studies. Extensive use has been made of the U.S. National Weather Service (NWS) data accumulated over several decades in Northwest Georgia. Apart from providing preliminary indications of precipitation modification effects, these data have aided in the general understanding of the climatology in the vicinity of Plant Bowen and have paved the way for the field studies currently underway. These field studies, employing a dense network of rain gauges and windsets, are expected to provide the statistical data base necessary to estimate the plant's effect (if any) on precipitation.

2. CLIMATOLOGICAL STUDIES WITH NWS DATA

The National Weather Service (NWS) collects meteorological data at a number of key stations across the country. Most of these stations are located on major airports. This network of NWS stations is augmented by the Cooperative Network which is operated by volunteer observers who record one or more meteorological variables and report them to the NWS. The meteorological variables, monitored at the above NWS stations, include temperature and humidity, wind speed and direction, precipitation amount, etc. Those of the Cooperative Network generally record precipitation. Figure 1 displays the NWS and Cooperative Networks in Northwest Georgia. Fifty-nine of these stations within a 60-mi radius from Plant Bowen were selected for climatological studies. These stations, operating continuously or intermittently, have provided daily rainfall amounts since 1949. Surface wind data from the two NWS stations (Atlanta and Rome Airports) have also been included in the analysis as well as upper-air wind data from the Athens Airport about 90 mi E of Plant Bowen.

2.1 Data Quality Evaluations

In dealing with precipitation data from the Volunteer Network, it is important to recognize that these data are collected by a great number of individuals over a long period of time and with different instruments. Because of the wide variety of possible errors associated with such data acquisition, we carried out a careful preliminary evaluation of the quality of the obtained data. This consisted of two parts: field visits and analytical tests. The field visits were undertaken primarily to assess the exposure and quality of the instruments themselves. As a result of these field visits, several of the original 59 stations were dropped because of poor exposure.

The analytical method known as "double mass"[8,9] was then used to determine whether extraneous occurrences (e.g., a change of rain gauge location exposure) caused a consistent departure of the recorded data from the long-term mean. Data from another nearby station with dependable records were used as a basis for comparison. Thus, we designate the recorded rainfall

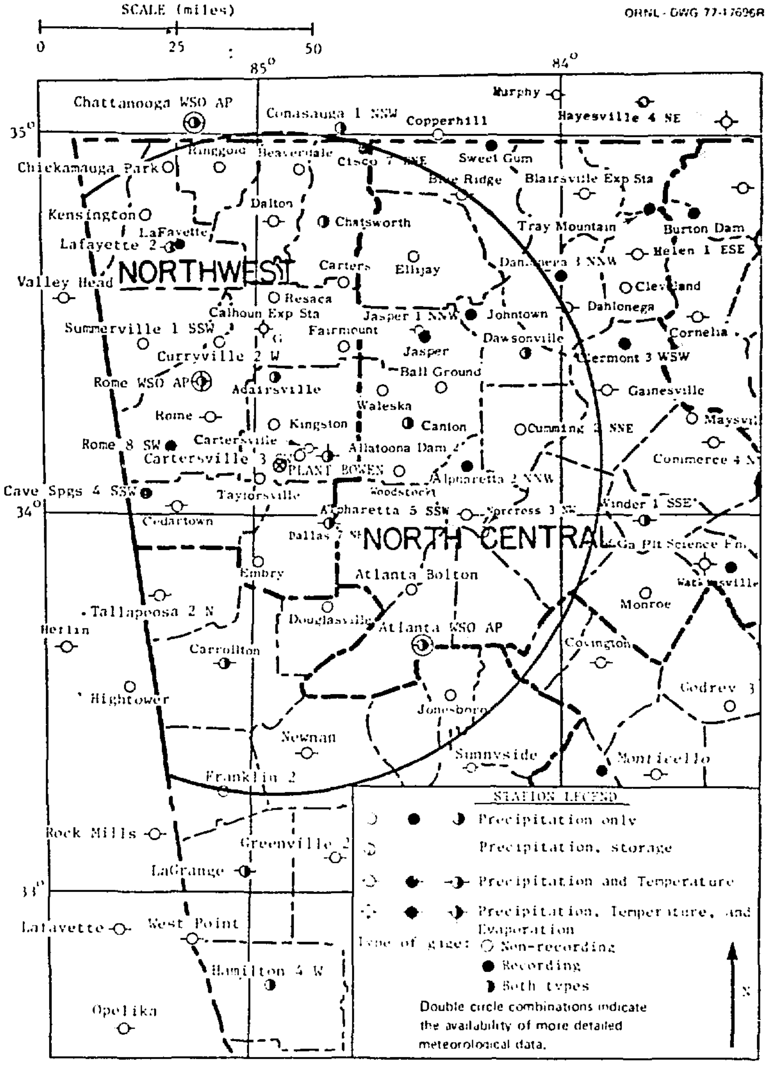

Fig. 1. Map of Northwest Georgia depicting the National Weather Service (NWS) and Cooperative Network stations. The stations within the circle are used for the climatological study.

amount from a given rain gauge station X as X_i where $i = 1,2,\ldots,N$ and i is the constant time interval over which the data are recorded (e.g., daily, monthly, etc.). From a collection of the above data, we created the following cumulative record

$$X_{j+1} = \sum_{i=1}^{j} X_i$$

where $j = 1,2,\ldots,N$ ($X_1 = 0$).

Similarly, for a station Y we have

$$Y_{j+1} = \sum_{i=1}^{j} Y_i \quad (Y_1 = 0) \ .$$

Now assume that station X is the dependable one and Y is the questionable one. By eliminating j from X_j and Y_j, we plot the relationship $Y = f(X)$ on a cartesian coordinate frame. The result will be a series of data points in the first quadrant. If the straight line segments that best approximate consecutive groups of points (i.e., the least squares fits) have approximately equal slopes, then we can conclude that station Y has acceptable data. If an obvious change in the slope is evident after some point, we can conclude that after the time corresponding to that point the continuity of the record was severed. In that case, we either consider the record as being composed of two different records from two different stations prior and subsequent to that point (e.g., in the case of an instrument relocation); or in the case of multiple significant slope changes with no apparent reason, we disqualify the station. Figure 2 displays the double-mass graph of winter precipitation totals (December through February) for the "Atlanta Bolton" station vs the "Atlanta Airport" station. This graph, as well as initial contour maps containing the "Atlanta Bolton" station, led to the discarding of this station's data from further analyses. Figure 3 presents the double-mass graphs for the "Dallas" station's winter record vs the respective ones for the "Embry" and "Douglasville" stations. Despite the fact that the "Dallas" station was relocated six times during the period 1948 to present, the double-mass graphs show no appreciable changes in the slope. As a result, the records from all

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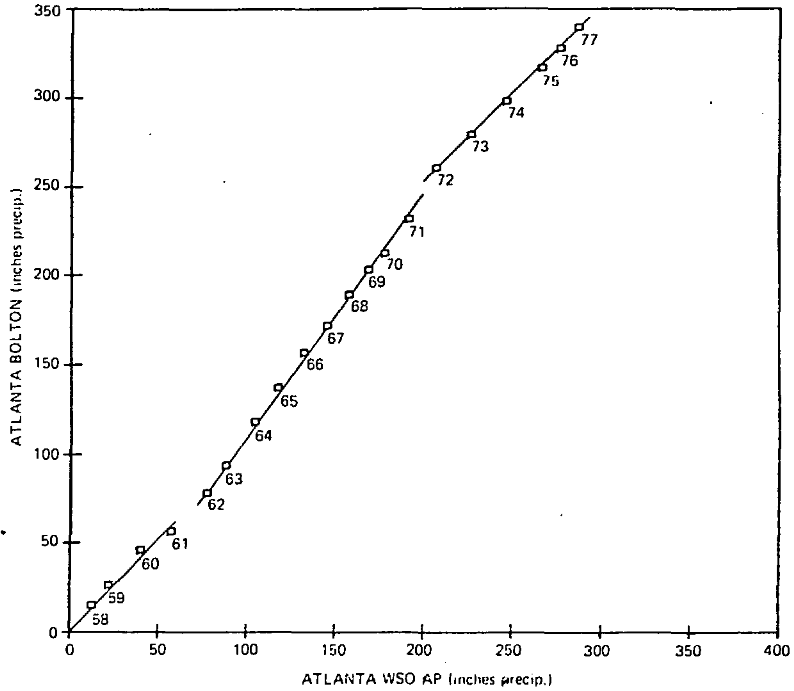

Fig. 2. The "double-mass" graph of winter precipitation totals for the Atlanta Bolton station vs the Atlanta Airport station.

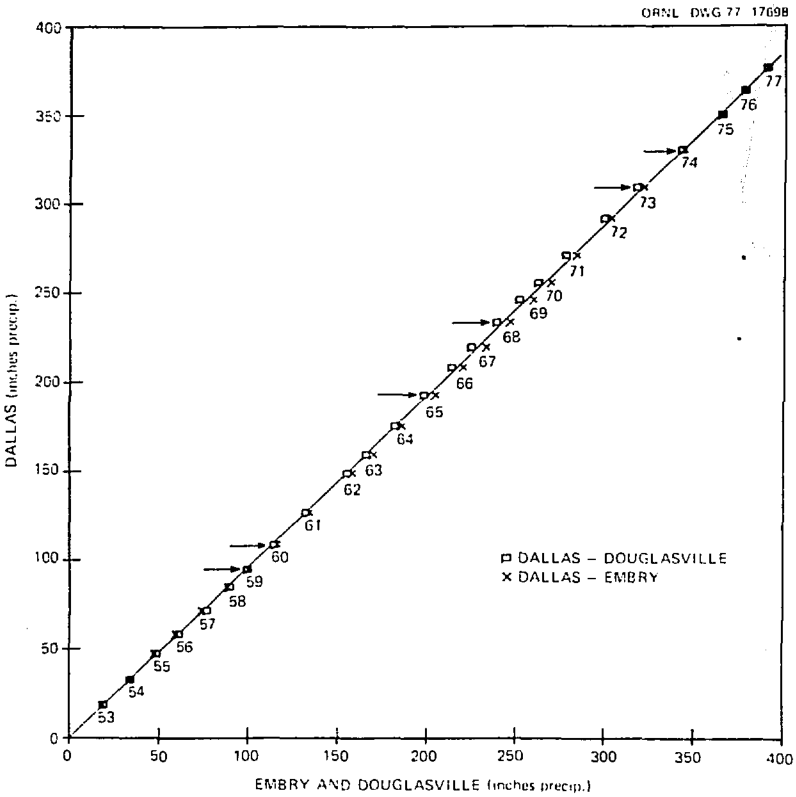

Fig. 3. The "double-mass" graphs of winter precipitation totals for the Dallas station **vs** the Embry and Douglasville stations. Arrows indicate the years during which the Dallas station was relocated.

"Dallas" stations were joined together into one continuous record representing the general area over which the "Dallas" station has been located.

2.2 Data Stratification and Inference

As mentioned in the Introduction, Plant Bowen's effect on rainfall could manifest itself in several ways. The most obvious one is a general increase of rainfall in the downwind area. This additional rainfall can be detected as either an increase with respect to the upwind area or with respect to the areal long-term mean. The natural spatial and temporal rainfall variability complicates the investigations in the choice of the time period for study (storm duration, day, month, etc.); and the determination of the magnitude of the effect since, depending on the time stratification, the potential effect could be buried in the natural "random noise."[10] Another manifestation of the effect could be an increase in storm frequency in the vicinity of the plant with or without a substantial increase in rainfall amounts. In all cases, the monitoring of the power plant's thermal output is important since the effect would be expected to increase with increasing output.

It was apparent at the start that the NWS data would be insufficient by themselves to study the power plant's effect in all the aspects described above, because of limitations of data density and quality.[11] Nevertheless, analyses were carried out utilizing the NWS data. To our surprise, they yield several significant results. It is important to note at this point that in all the analyses using NWS rainfall data the smallest data increment (in the time sense) was one month. Most analyses dealt with seasonal rainfall totals. The seasons were chosen as follows: December through February (winter), March through May (spring), June through August (summer), and September through November (fall). Some work was also done with wet and dry season stratifications, primarily to distinguish between the two main types of rainfall situations (frontal and convective). The wet season included the months of December through April, and the dry season the remaining ones.

The framework for these analysis of rainfall modification based on the NWS data was a combination of target-control and preoperational-postoperational techniques.[10] Some sample results are presented: Figure 4 depicts the surface wind rose constructed from the recorded surface winds at Atlanta

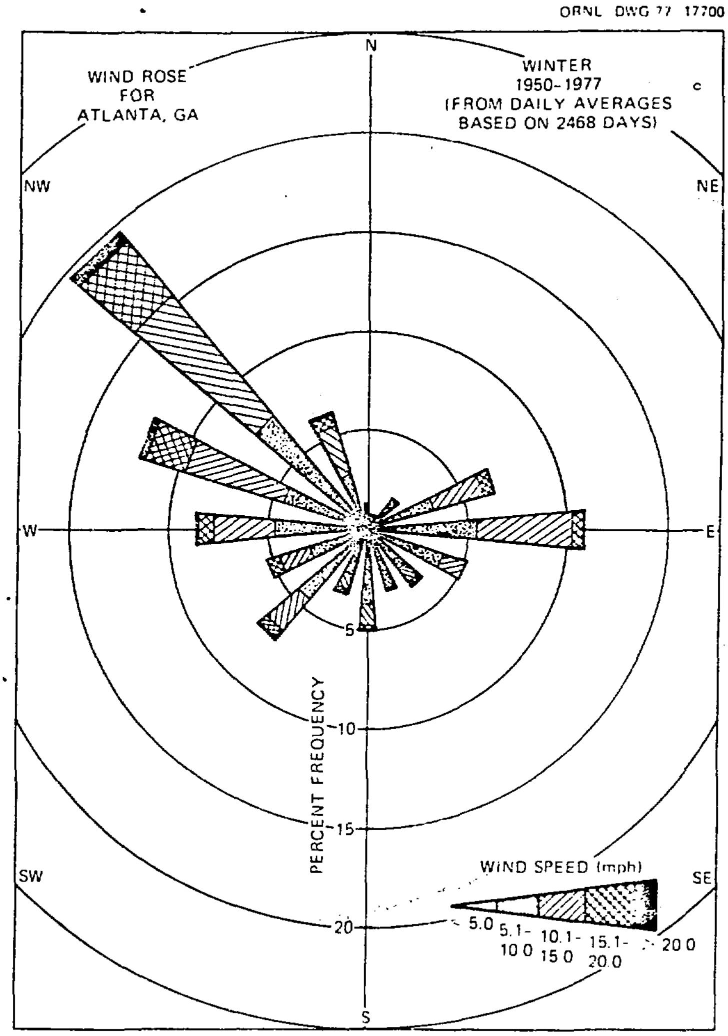

Fig. 4. Surface wind-rose for the Atlanta Airport station for the winters of 1950 through 1977.

Airport for the winters of 1950 through 1977. The resulting distribution displays predominant northwesterly winds. This is a very encouraging fact for the climatological study, since it shows that the city of Atlanta with its potential urban effect lies downwind of the plant. An examination of surface wind data at Rome Airport also indicated a predominant northwesterly direction for the winter months. Figure 5 depicts the wind roses for the upper-air winds at the Athens Airport, about 90 mi east of Plant Bowen, for the period 1956-1976. Wind roses were developed for two pressure levels, 850 and 500 mb, from the data obtained at 12-hr intervals. The prevailing wind direction is clearly from the west at both levels. Based on the prevailing surface and upper-air winds, we postulate the general southeastern area from Plant Bowen as the target area. Figure 6 displays the contour map for the ratios of postoperational (PO) to preoperational (PREOP) normalized winter precipitation means for the 30 stations within a 40-mi radius of Plant Bowen. The normalized precipitation means were generated as follows. The total precipitation amounts for each winter season at each station was divided by the arithmetic areal mean for each winter season. This guarantees that the areal variations of precipitation for each winter season will contribute equally to the subsequent averaging (wet and dry seasons have equal weights). The preoperational means are the arithmetic means of the normalized precipitation values for the period 1950-1971; and the postoperational ones, for the period 1972-1976 (Plant Bowen's first unit became operational in October 1971). The ratios of the latter (PO) to the former (PREOP) are displayed in Fig. 6. It is noted that precipitation high appears in the general downwind area of the plant. As discussed earlier, it is premature to attribute this result to a plant-induced effect. In fact, following the application of a rank (Wilcoxon T) test,[12] it was found that the statistical significance of the result was rather small. Nevertheless, this result serves as a starting hypothesis to be confirmed or discredited by the results of the field study. Figures 7-10 display the contour plots for the ratios of the five-year postoperational normalized means to four different five-year preoperational means (51-55, 56-60, 61-65, 66-70). Taking into account natural variations, we observe that the precipitation high persistently appears to the south and east of the plant (the downwind region). Similar five-year running mean ratio plots were generated with other preoperational five-year

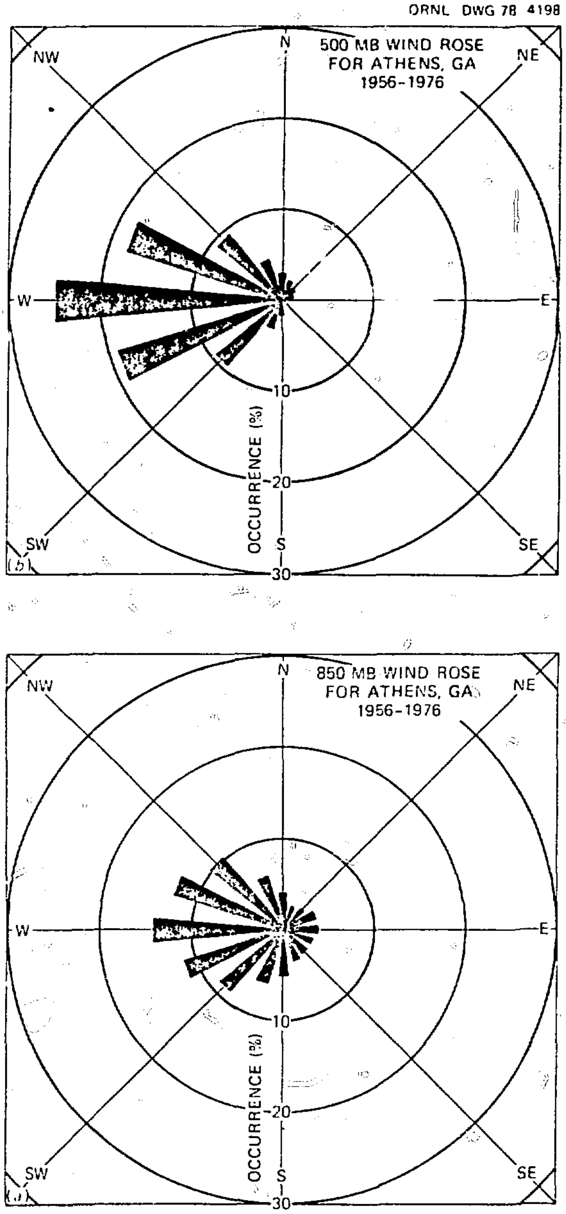

Fig. 5. Wind direction distributions of winds at the 850- and 500-mb pressure levels at the Athens Airport for the period 1956-1976.

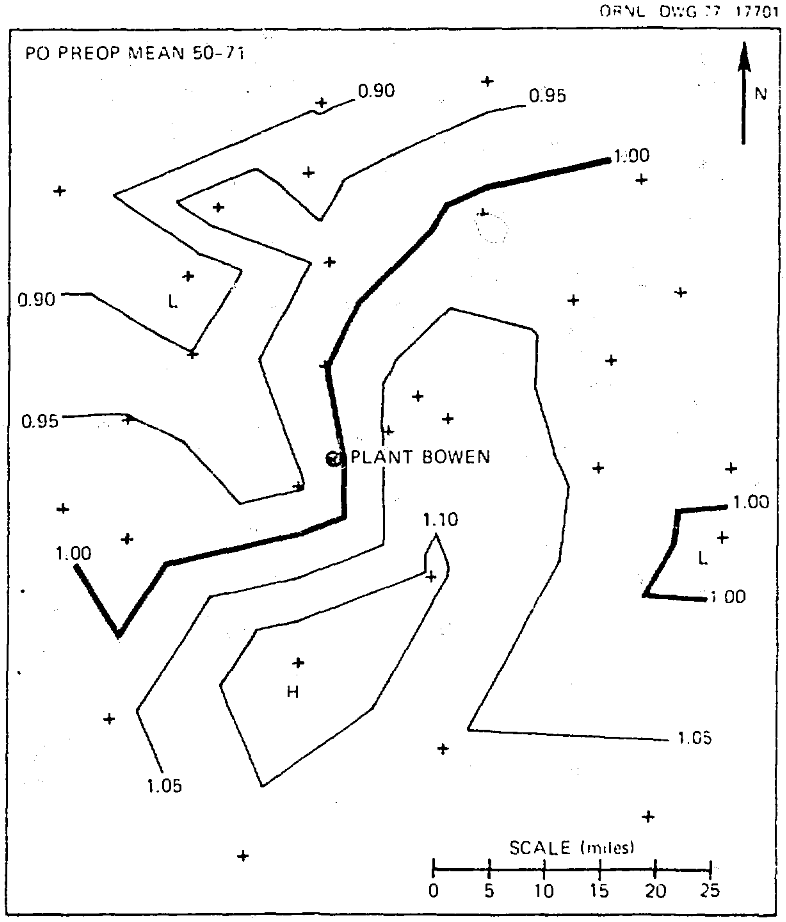

Fig. 6. Contour map of ratios of postoperational (PO: 1972-1976) to preoperational (PREOP: 1950-1971) normalized precipitation means (winter).

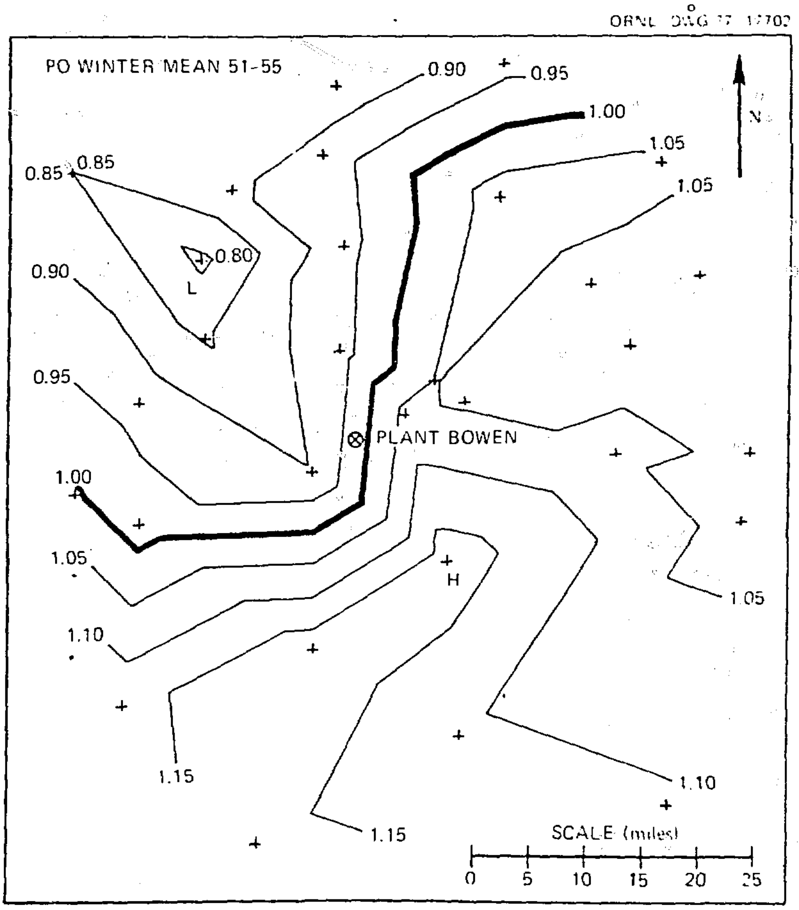

Fig. 7. Contour map of ratios of postoperational (PO: 1972-1976) to preoperational (PREOP: 1951-1955) normalized precipitation means (winter).

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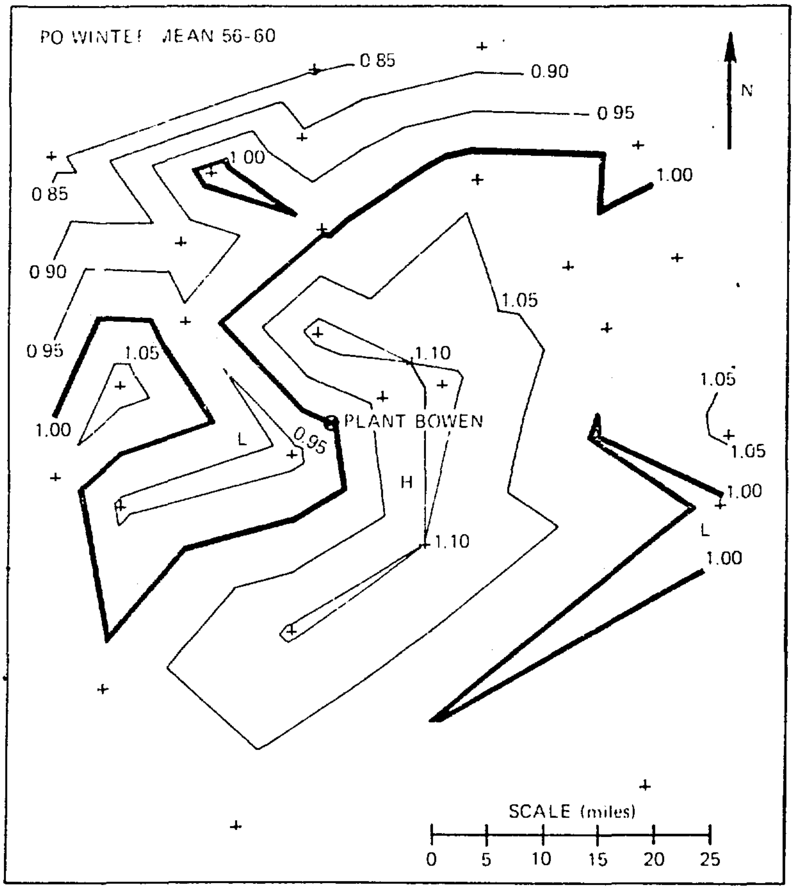

Fig. 8. Contour map of ratios of postoperational (PO: 1972-1976) to preoperational (PREOP: 1956-1960) normalized precipitation means (winter).

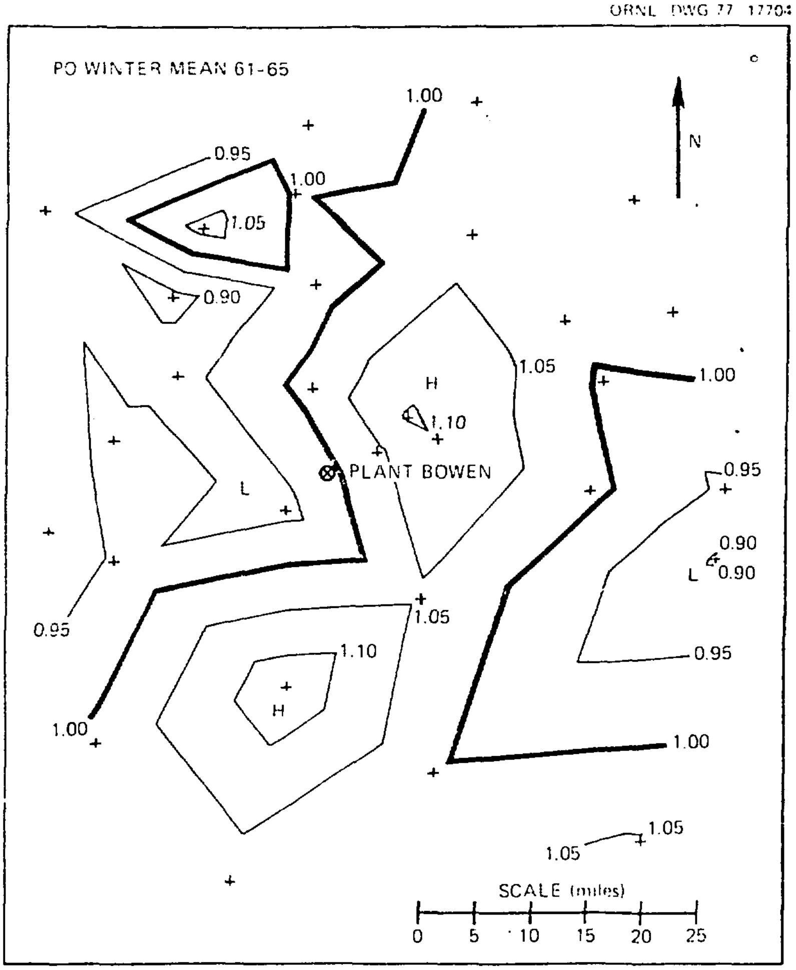

Fig. 9. Contour map of ratios of postoperational (PO: 1972-1976) to preoperational (PREOP: 1961-1965) normalized precipitation means (winter).

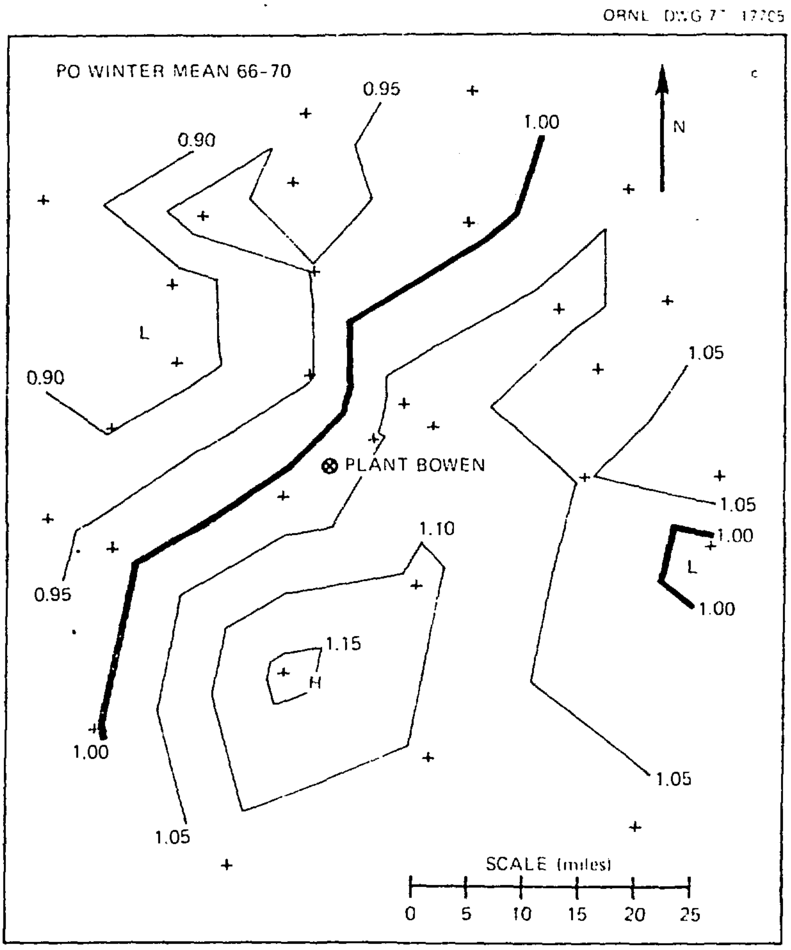

Fig. 10. Contour map of ratios of postoperational (PO: 1972-1976) to preoperational (PREOP: 1966-1970) normalized precipitation means (winter).

periods in the numerator for comparison. The plots displayed considerable random behavior with no persistent patterns in the precipitation highs and lows. Figure 11 displays the equivalent of Fig. 6 for an enlarged network (the stations within a 60-mi radius of Plant Bowen) and for the postoperational period 1972-1978. The basic patterns of the contour plots is the same in both figures. A series of statistical tests were then applied to the data to test the significance of the result. Apart from the rank (Wilcoxon T) test mentioned above, parametric tests such as the Student's t-test were attempted with limited success. The roots of the difficulty lie in the use of monthly rainfall totals which exhibit unwieldy frequency distributions and resist treatment by standard parametric statistical techniques. Current research includes attempts to characterize these frequency distributions by more complex techniques.

2.3 Spatial Correlations

The use of the spatial correlation as a tool to investigate rainfall modification effects is quite controversial.[13] One proposed method (not described in this paper) attempts to utilize the spatial correlation for that purpose by establishing the background natural variability of the spatial correlation function. Spatial correlations have also been used to characterize the local climatology and to produce quantitative measures of rainfall relationships between stations.[14,15,16] Figures 12-14 display the correlation coefficient contour plots we obtained for three stations ("Beaverdale 1E," Ball Ground," and "Atlanta Airport") computed on the basis of 300 consecutive common months. It is noteworthy that the correlation coefficient isopleths have a predominant direction along the WSW-ENE. This direction coincides with the direction of the predominant storm tracks;[17,18,19] a plausible explanation of the phenomenon is that storm systems moving along a given direction produce precipitation amounts along that direction with consistent relationships (these relationships are probably a function of topography, storm type, etc.). Moreover, the possibility exists that a storm moving along a given direction would produce rain along a relatively narrow strip in that direction with no rain elsewhere. This is translated into high correlations along that direction with low correlations in the perpendicular direction. Since the correlation coefficients presented here are computed on the

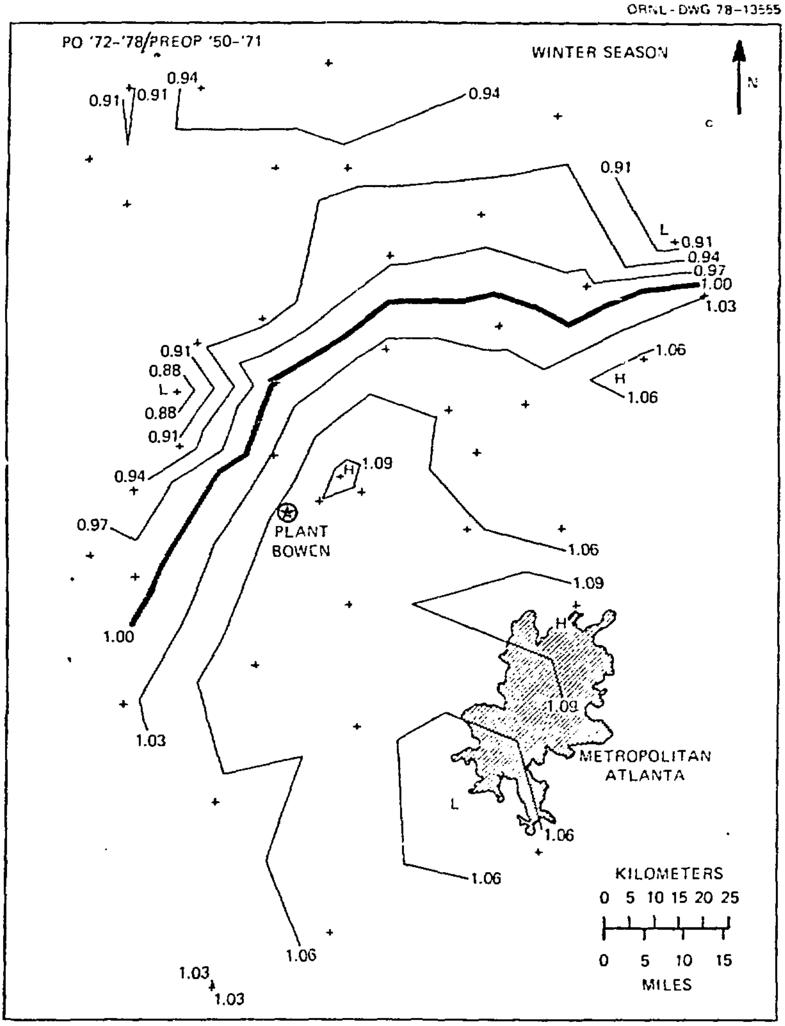

Fig. 11. Contour map of ratios of postoperational (PO: 1972-1978) to preoperational (PREOP: 1950-1971) normalized precipitation means (winter).

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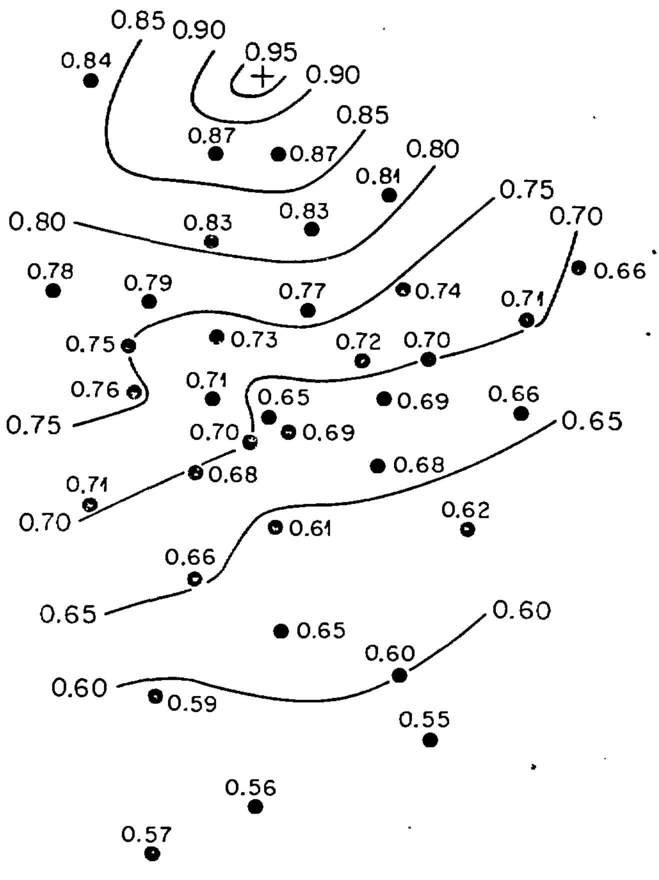

Fig. 12. Contour map of the spatial correlation coefficients for the Beaverdale 1E station (based on 300 monthly totals).

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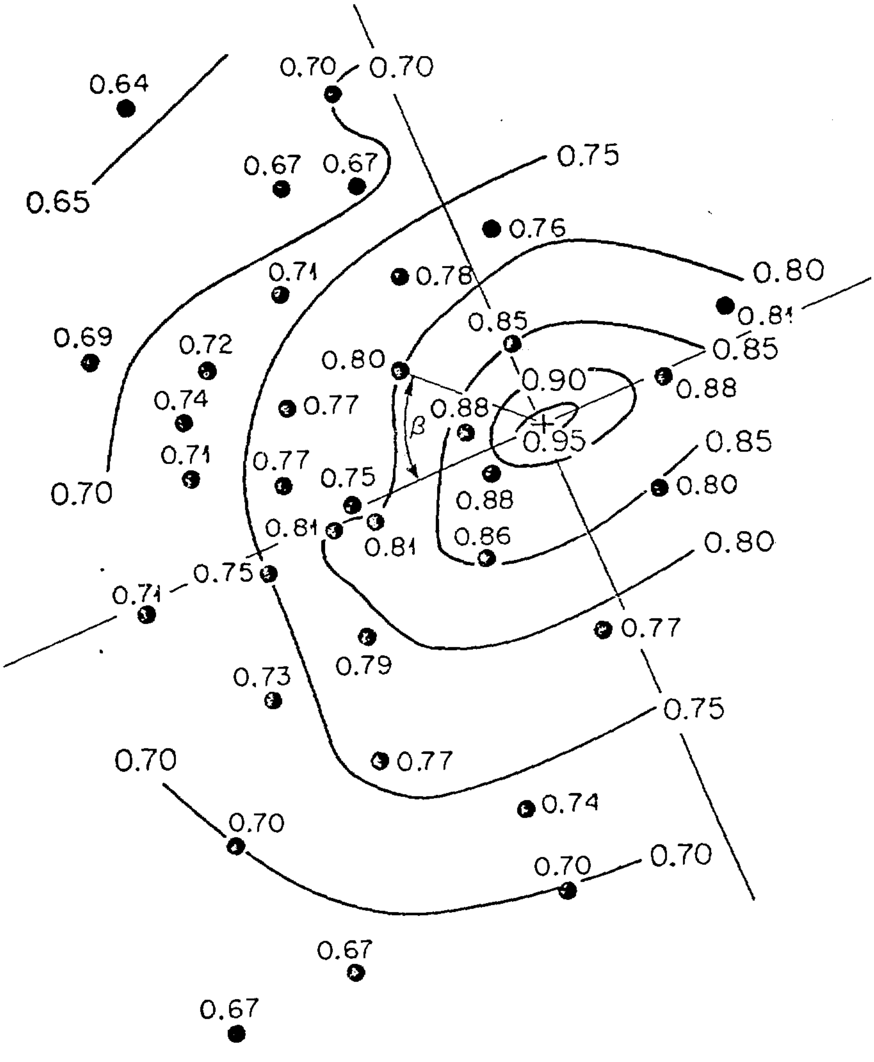

Fig. 13. Contour map of the spatial correlation coefficients for the Ball Ground station (based on 300 monthly totals).

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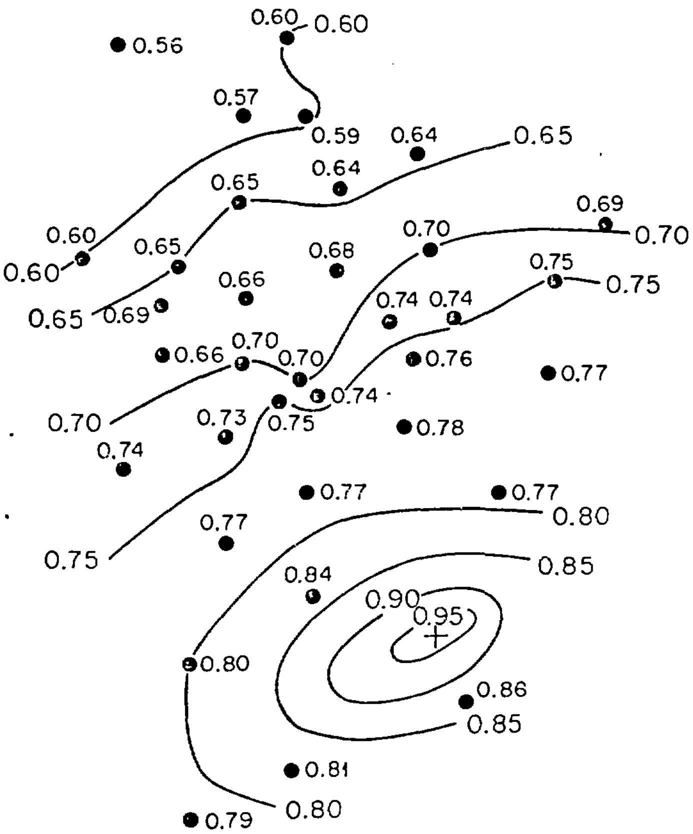

Fig. 14. Contour map of the spatial correlation coefficients for the Atlanta Airport station (based on 300 monthly totals).

basis of monthly totals, the above-mentioned sharp differences are to some extent smoothed out over the various storms. Nevertheless, the observed patterns support this theory to a satisfactory degree.

The relationship between the correlation coefficient and distance was investigated by displaying all computed correlation coefficient values vs the normalized distances between stations (the distances were normalized by the distance between the "Beaverdale 1E" and "Franklin 2" stations). A coordinate system was established in which the x-axis was aligned with the direction of the prevailing storm tracks (Fig. 13), and the origin was located at the respective station; β is defined as the angle ($0° \leq \beta \leq 90°$) which the position vector for every other station forms with the x-axis. Figure 15 contains the results, where stations with $0° \leq \beta < 20°$ are depicted by a •, with $20 \leq \beta \leq 70°$ by a o, and with $70° < \beta \leq 90°$ by a +. As expected from the patterns of the correlation plots, stations with small β have larger correlation coefficients when compared with equidistant stations with large β. Despite the considerable scatter of points, there is evidence of a quasilinear relationship between the two quantities beyond a certain distance. It remains to be seen whether that relationship is intrinsic to the network area, is dependent on the type of predominant storms, or obeys some universal law.

2.4 The Plant Bowen Field Study

The Plant Bowen field study was felt to be necessary for several reasons. The current state-of-the-art in precipitation studies recommends a rain gauge density of about 1 gauge per 16 sq mi; the NWS network falls short of that number of an order of magnitude. This density requirement becomes particularly important for rainfall events of the convective type (summer rainfall), and our speculation is that precipitation modification would maximize during such events. The second reason for carrying out the field study was that the potential effect was believed to be sufficiently small so that higher resolution instrumentation (recording rain gauges) would be necessary to investigate rainfall on a storm event basis. An additional dimension of the problem was the need for a concise knowledge of the prevailing winds in the vicinity of the plant during the rainfall events for the implementation of the control-target area technique.[10]

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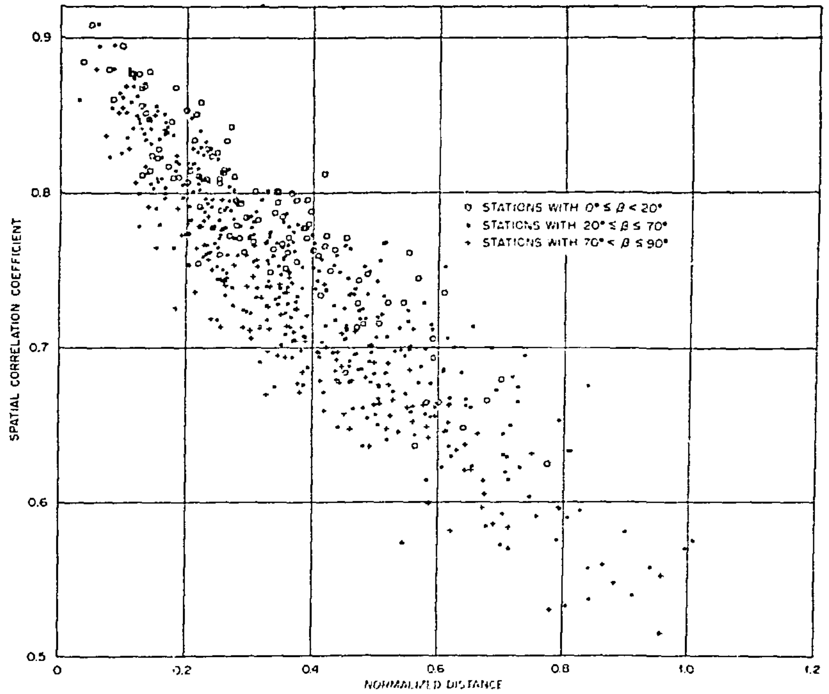


Fig. 15. Spatial correlation coefficients vs normalized distances for all stations satisfying the 300 common-month requirement.

The METER-ORNL precipitation network was installed in February 1978. Figure 16 depicts the present network against the topographical map of the area. It is composed of 49 recording rain gauges and 4 recording windsets. The rain gauges are of the weighing-bucket type continuously recording on a weekly chart. The windsets include a cup-anemometer, a wind-vane, and a strip-chart recorder operating on a monthly basis. Three-hr weather maps obtained from the NWS provide information regarding the prevailing synoptic conditions (storm type, storm movement, etc.). In addition, the power plant's thermal output (on an hourly basis) during the rainfall events is obtained from the Georgia Power Company. Additional wind data are recorded at the power plant's meteorological station located a few miles from the cooling towers. The above information is being accumulated on a storm-by-storm basis. Precipitation events are considered distinct storm events when they are separated by at least two hrs with no rain over the entire network. The complete data base, thus, is composed of "storm profiles," such as those presented in Figs. 17 and 18 for two storms in March 1978.

The Bowen Plant field study is currently underway and is expected to continue for five years with a data base of approximately 600 storms.[20] It is believed that this data base will be sufficient to detect any plant-induced effect and provide its qualitative description as well as a quantitative measure of its magnitude.

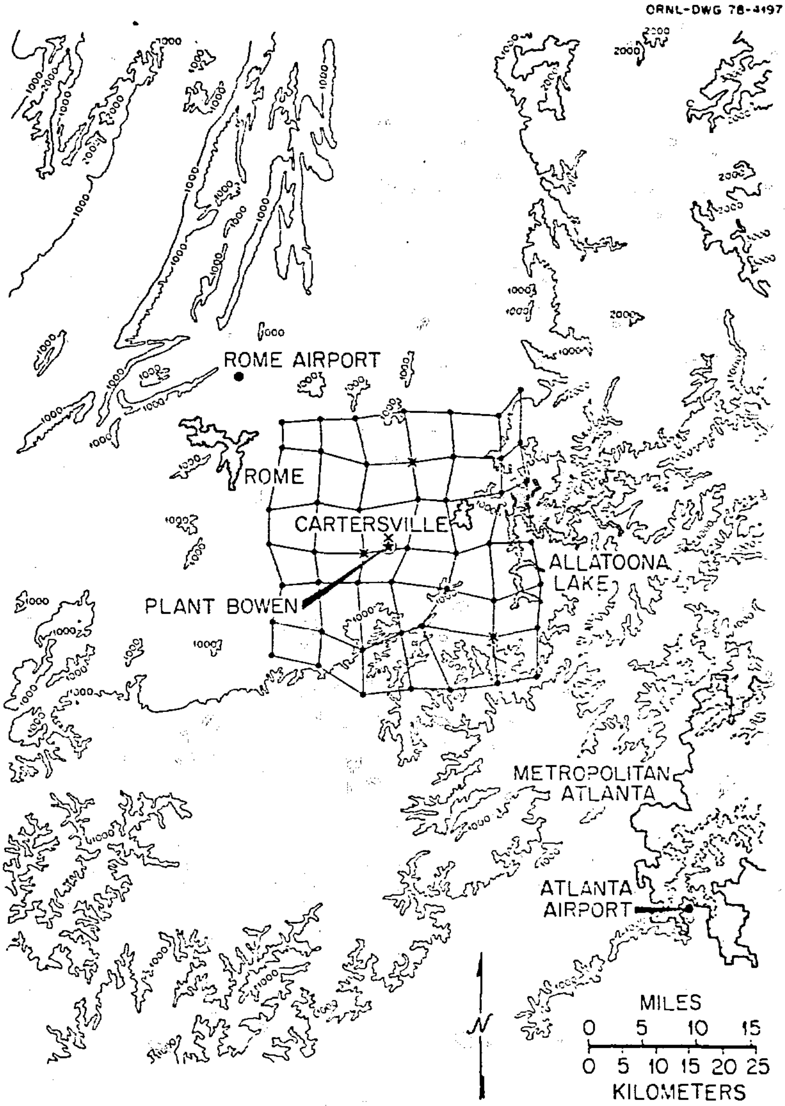
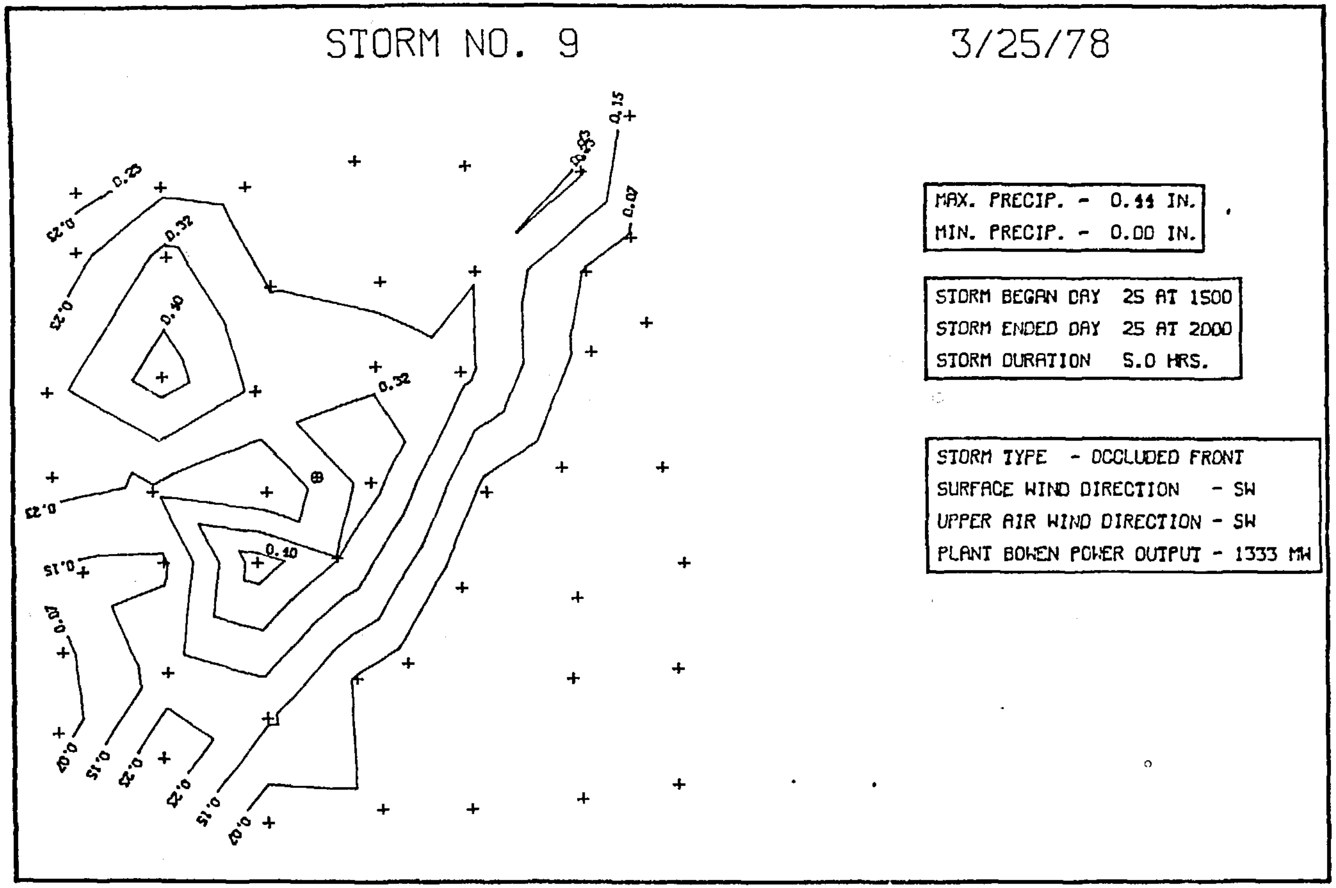


Fig. 16. The METER-ORNL network superimposed on the topographical map of NW Georgia. The minimum elevation in the valley is about 600 ft above mean sea level. Dots denote the rain gauge stations and crosses depict the wind-set locations.

METER - ORNL NETWORK PRECIPITATION CONTOURS



STORM NO. 9 3/25/78

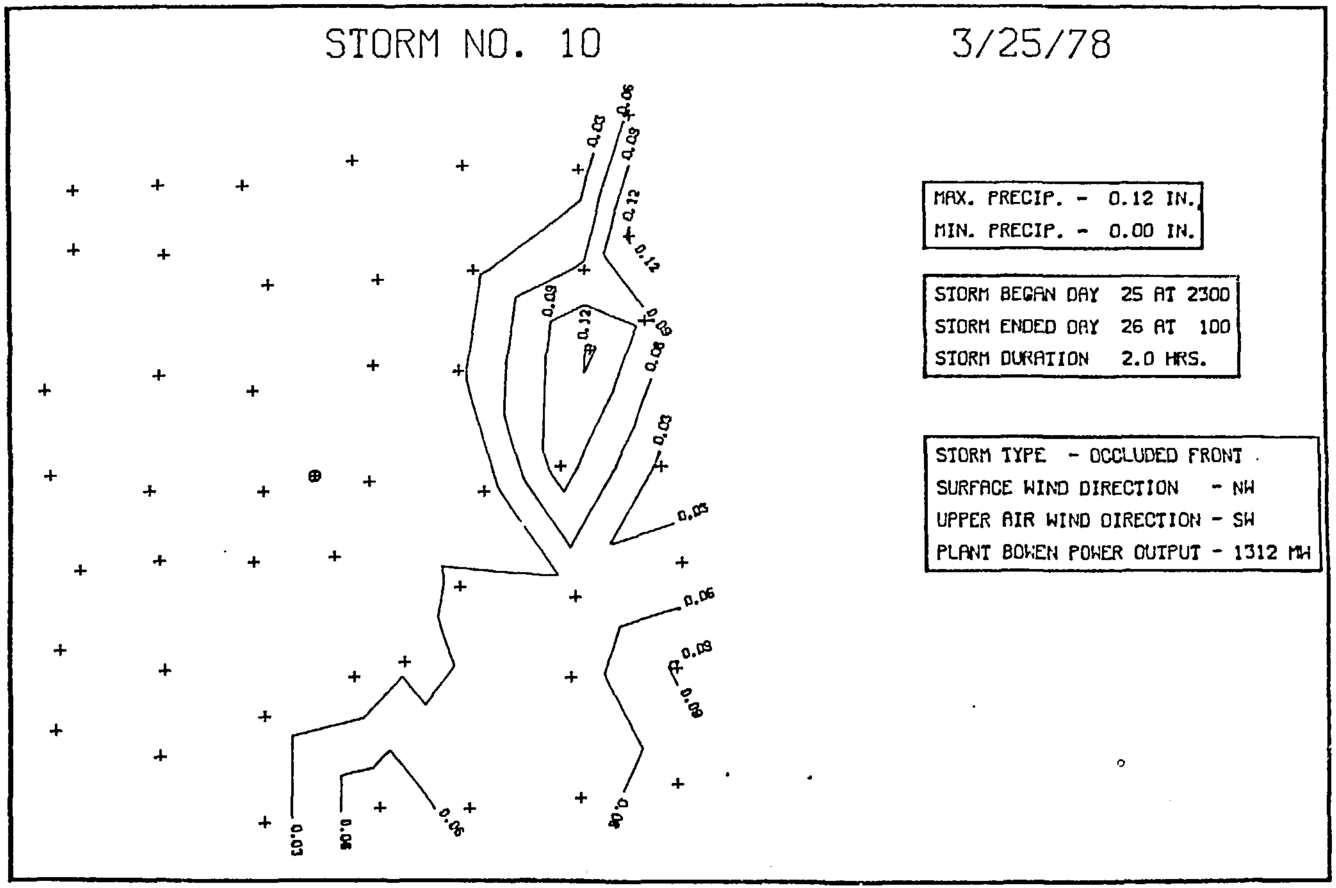
MAX. PRECIP. - 0.44 IN.
MIN. PRECIP. - 0.00 IN.

STORM BEGAN DAY 25 AT 1500
STORM ENDED DAY 25 AT 2000
STORM DURATION 5.0 HRS.

STORM TYPE - OCCLUDED FRONT
SURFACE WIND DIRECTION - SW
UPPER AIR WIND DIRECTION - SW
PLANT BOWEN POWER OUTPUT - 1333 MW

Fig. 17. Storm Profile No. 9.

METER - ORNL NETWORK PRECIPITATION CONTOURS



STORM NO. 10

3/25/78

MAX. PRECIP. - 0.12 IN.
MIN. PRECIP. - 0.00 IN.

STORM BEGAN DAY 25 AT 2300
STORM ENDED DAY 26 AT 100
STORM DURATION 2.0 HRS.

STORM TYPE - OCCLUDED FRONT
SURFACE WIND DIRECTION - NW
UPPER AIR WIND DIRECTION - SW
PLANT BOWEN POWER OUTPUT - 1312 MW

Fig. 18. Storm Profile No. 10.

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