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THE REPRESENTATIVENESS OF METEOROLOGICAL OBSERVATIONS

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THE REPRESENTATIVENESS OF METEOROLOGICAL OBSERVATIONS*

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INTRODUCTION

The representativeness of meteorological observations is becoming a subject of increasing concern in all branches of the atmospheric sciences. For example, in research, an understanding of representativeness is required to evaluate a large assortment of meteorological models and assess how well meteorological instruments sample atmospheric phenomena. In applications, representativeness affects interpretations of weather forecasts as functions of scale, site selection for wind and solar energy systems, and the designs of buildings and structures. It also is important in the regulation of air quality. In *Guidelines on Air Quality Models* (1), the Environmental Protection Agency (EPA) identified the need to discuss representativeness within the context of their document. In reports to the EPA, both D. Stimaitis et al. (2) and the American Meteorological Society (AMS) (3) reviewed the concepts of representativeness; and the Nuclear Regulatory Commission (NRC) referred to representativeness in Safety Guide 1.23 (4) and by reference to NUREG 0654 (5). Recently, R. E. Hanson (6) demonstrated the consequences of using nonrepresentative wind data in air quality models and showed that the meteorological station with the longest record of data is not necessarily the station with the most representative data for a given area.

To address the subject of representativeness formally, the AMS Committee on Atmospheric Measurements sponsored a workshop, which was held in Boulder, Colorado, in early summer, 1981. The workshop panel consisted of experts in the fields of atmospheric measurements, atmospheric turbulence and diffusion, numerical modeling, air quality assessment, air quality regulations, and forest management. Their task was to formulate a meaningful definition of representativeness, suggest possible ways of

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assessing it, and present some scientific examples. A summary report of this workshop (7) has been published in the AMS bulletin; however, this presentation will discuss and expand upon the workshop results, using more details and examples than appear in the summary.

GENERAL DEFINITION OF REPRESENTATIVENESS

Definitions of representativeness have been proposed in works by S. Petterssen (8), R. Geiger (9,10), and S. Teweles and J. Giraytys (11) but, typically, they were based on specific user needs and were not sufficiently general for widespread use. These studies did agree, however, that representativeness is a temporal as well as spatial concept. With this in mind, the following general definition is proposed.

> Representativeness is the extent to which a set of measurements taken in a space-time domain reflects the actual conditions in the same or different space-time domain taken on a scale appropriate for a specific application.

In constructing this definition, it was agreed that representativeness can only be determined in a relative sense and that what could be considered a representative measurement in one application might not be in another. For example, the average July rainfall measured at Station A may be representative of that measured at Station B, which is 25 km away; however, the daily rainfall observed at Station A most likely will not be representative of that observed at B. Because of the relative nature of representativeness, intervals must be established within which representativeness can be judged. A criterion for Station A measurement, q_A, to be representative of Station B measurement, q_B, can be given as

$$\Pr\{|q_A - q_B| \leq \delta\} = 0.90 \quad ; \tag{1}$$

i.e., there is a 90% probability that q_B lies within ±δ of q_A. The nature of q (e.g., spatial or temporal averages) is a matter of application.

Carrying on with the above example, if q_A and q_B are average monthly rainfalls, then Eq. 1 may be a reasonable criterion for representativeness, depending on the value of δ. However, if q_A and q_B are daily rainfall rates, then Eq. 1 may seldom be satisfied unless δ is sufficiently large. Finally, it must be noted that representativeness can only be determined in a statistical sense and that individual observations may not be representative although the probability is high that they may be.

TYPES OF REPRESENTATIVENESS

Several types of representativeness can be identified according to specific applications.

Measurement Representativeness

Measurement representativeness is the extent to which a measurement reflects the actual conditions being measured. Many factors can contribute to nonrepresentative measurements: for example, overspeeding of cup anemometers, improperly located raingauges, wind vanes with bent tails, etc. The application of data must also be considered; e.g., turbulence measurements must be made with appropriate fast-response equipment if the data analyses are to be meaningful.

Point-to-Point Representativeness

Point-to-point representativeness seeks to justify the applications of meteorological observations taken at one location for use at another location. Knowledge of this type of representativeness is often needed in air quality assessments, wind energy siting studies, wind loading studies, and air-parcel trajectory calculations. It should be noted that point-to-point representativeness is not restricted to ground-based observations or to points of equal elevation. In mountainous terrain, one may need to know how representative ridge-top winds are of valley-floor winds. Often, surface observations are extrapolated vertically upward using empirical or theoretical formulas. Here too, the question of representativeness arises.

Point-to-Volume-Representativeness

Point-to-volume representativeness addresses the question of how well a point measurement reflects the volumetric average of the quantity. This type of representativeness affects air quality studies, weather forecasting, monitoring network design, and urban meteorology. Point-to-area representativeness is a subset that concerns measurements made over horizontal surfaces such as rainfall rates, surface deposition of pollutants, planetary boundary layer heights, aerodynamic surface roughness, and surface temperature.

Temporal Representativeness

The types of representativeness listed above deal only with the spatial extension of point measurements and leave questions of time-averaging effects as matters of specific applications. Temporal representativeness asks how well measurements made at a point over a given period of time represent the conditions at the same point over a different period of time or at another time. For example, one may wish to know how representative a 5-minute-averaged wind speed is of the hourly-averaged wind speed or how long a weather station must operate to represent the climatology of the site. Considerations of temporal representativeness are important in planning field observation programs, assessing environmental impacts of air quality, and analyzing meteorological data.

SPACE-TIME VARIABILITY AND REPRESENTATIVENESS

The degree of representativeness of a measurement is ultimately determined by the temporal and spatial variability of the quantity being measured. Factors that influence space-time variability (e.g., ground surface structure, atmospheric stability, and large-scale atmospheric disturbances) also influence representativeness. Obviously, in a uniform, steady, stable flow any measurement, q, will be representative of the entire q-field. The extent to which actual conditions depart from this ideal state defines an upper limit to representativeness; i.e., a measurement cannot be expected to be more representative for a given application than the observed variability of the measurement field for the same application.

The space-time variability of atmospheric quantities can be described by various statistical measures such as bias, standard deviation, autocorrelation function and structure function. The bias, B, and standard deviation, S, are defined as follows.

$$B = \overline{[q(\zeta) - q(\eta)]} \quad , \text{and} \tag{2}$$

$$S = \{\overline{[q(\zeta) - q(\eta)]^2} - B^2\}^{1/2} \tag{3}$$

where ζ and η are either space or time coordinates and the overbar denotes ensemble averaging. Bias is a measure of the average difference between two observations, and standard deviation measures the variability of these differences about the mean difference. These values can be combined to give the total variance, σ^2, of the point-to-point differences as

$$\sigma^2 = (S^2 + B^2) \tag{4}$$

The representativeness of point-to-point measurements can now be judged according to

$$\Pr[|q(\zeta) - q(\eta)| \leq \sigma] = \varepsilon \tag{5}$$

where ε is a confidence level that can be either prescribed as a free parameter or ascertained from the distribution of the differences. For example, if the distribution of the differences is Gaussian, we know that $\varepsilon = 0.68$. However, if one requires ε to be 0.90 for a specific application, representativeness cannot be achieved. In this case, representativeness is achievable if we require

$$\Pr[|q(\zeta) - q(\eta)| \leq 2\sigma] = 0.90 \quad . \tag{6}$$

In forming the bias and standard deviations, care must be taken in calculating differences of quantities to assure that the formed averages are appropriate to the application. Thus, averages should be calculated over ensembles of observations defined, for example, by stability class, windspeed ranges, prevailing wind direction, rainfall types, etc.

In normalized form, the autocorrelation function $R(\eta)$ is given by

$$R(\eta) = \overline{[q(\zeta)][q(\zeta + \eta)]}/\overline{q^2} \tag{7}$$

where ζ and η may represent either space or time variables, and it is assumed that the statistical properties of q are invariant in some sample space and are stationary in time. The requirement of stationary and homogeneous statistics is a severe one in the atmosphere, where meso- and larger-scale fluctuations produce trends in the values of meteorological variables. This has suggested the use of the so-called structure-function $D(\eta)$ (12), where

$$D(\eta) = \overline{[q(\zeta + \eta) - q(\zeta)]^2} \tag{8}$$

The structure function is related to the autocorrelation function by

$$D(\eta) = 2\overline{q^2}[1 - R(\eta)] \quad , \tag{9}$$

which is obtained by expanding Eq. 8, taking averages, and using Eq. 7. Just as autocorrelation functions, structure functions can be defined in terms of time or space variables; but they involve only the differences between these quantities. For this reason, the structure function has certain advantages over the autocorrelation function as a practical measure of atmospheric variability. By excluding the effects of large eddies on q, the structure function more exactly describes the local structure of an atmospheric q-field, which is usually of interest in assessing representativeness.

The quantities R and $(1 - D/2\overline{q^2})$ can easily serve as measures of representativeness through the identification of some distance or time η such that $q(\zeta)$ and $q(\zeta + \eta)$ are correlated at an acceptably high level. Such a requirement for representativeness has been used by Zemel and Lyons (13). The acceptability of a level of correlation would, of course, depend on the particular application involved. In general, $\overline{q^2}R(0) = D(\infty)/2 = \overline{q^2}$ gives the total variance of q at a point; similarly, $\overline{q^2}R(\eta) = \overline{q^2} - D(\eta)/2$ gives the variance of the q-field at any other point, η space- or time-units away. Thus, these functions describe variability of q with time or distance.

EXAMPLES OF APPLICATION

Representativeness of Wind Measurements

In their study of methods for calculating the representativeness of meteorological data, T. J. Lockhart and J. S. Irwin (14) pose the question: How representative is a single station for measuring wind speed and wind direction to a radius of 10 km or 50 km at a 95% confidence level? In more formal terms, we ask what value of the total variance is required to satisfy the condition

$$\Pr[|q(o) - q(\eta)| \leq \sigma(\eta)] = 0.95 \qquad (10)$$

where q(o) is either the wind speed or direction measured at the selected station and $q(\eta)$ is the value to be represented within a radius, η, of 10 or 50 km?

For the Lockhart-Irwin study, hourly wind speeds in 1 m/s ranges and wind directions in 10° sectors for the year 1976 were taken from each of 25 stations in and around St. Louis, Missouri. These data are part of the Regional Air Monitoring System (RAMS) data base and are described in detail by F. A. Schiermeier (15). The locations of these stations, numbered from 101 through 125, are depicted in Figure 4-30. Wind speed and direction differences between the 300 pairs of stations were calculated for each hour over the whole year. All stations were treated equally and no stratification of data, for example according to stability, was attempted. Results show that for wind speed $\sigma_{WS}(10\text{ km}) = 1.6$ m/s and $\sigma_{WS}(50\text{ km}) = 2.0$ m/s; and for wind direction $\sigma_{WD}(10\text{ km}) = 38°$ and $\sigma_{WD}(50\text{ km}) = 46°$. Thus, one can conclude that winds measured at a single station in the St. Louis region will be representative of winds within a 50-km radius to within 2 m/s and 46° 95% of the time when sampled over a year's time. This is an example of point-to-point representativeness.

Using the same data, J. H. Shreffler (16) addressed the question of how well a randomly selected station in the St. Louis region represents the network resultant

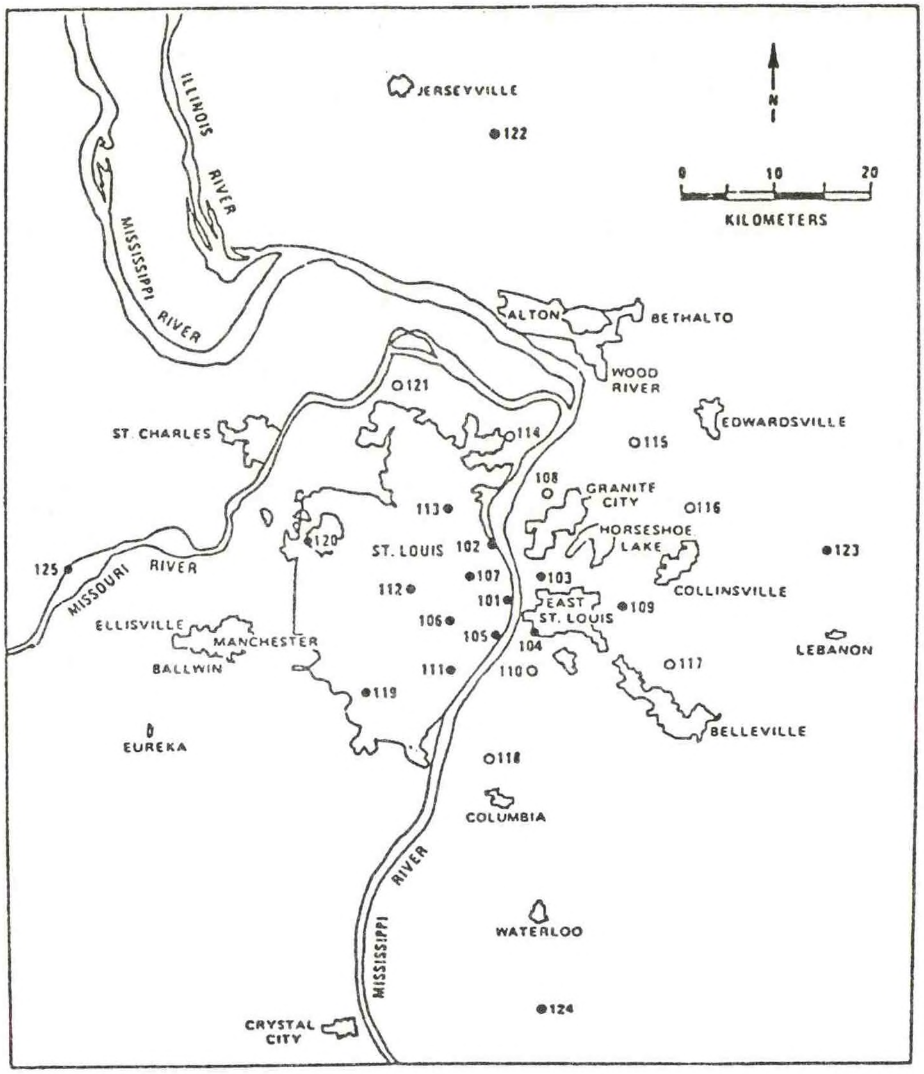

Figure 4-30. RAPS (Regional Air Pollutant Study) Network Station Locations

wind; i.e., the general flow over the region for various atmospheric stability classes. This is an example of point-to-area representativeness and can be stated as

$$\Pr[\,|q(o,s) - \overline{q}(s)| \leqq \sigma] = 0.68 \quad . \tag{11}$$

Here, q(o,s) is the wind at a selection station; s is the occurrence of some stability class; $\overline{q}(s)$ is the area average of q; and it is assumed that the differences are normally distributed.

Using Shreffler's values of station-averaged bias and standard deviation, the following values of total variance are obtained where wind speeds are expressed as percentage differences from the network resultant wind speed [i.e., $(u - \overline{u})/\overline{u}$].

P-G STABILITY CLASS

	A	C-D	D-E	F
σ_{WS} (percent)	30.8	16.1	18.2	29.7
σ_{WD} (degrees)	22.1	11.0	13.0	20.1

It is seen that maximum representativeness (i.e., minimum σ) is realized during neutral (C-D) condition; and minimum representativeness is expected during extremely unstable (A) and stable (F) conditions.

Representativeness of Precipitation Measurements

Several studies of the spatial variability of rainfall have been performed; for example, see F. A. Huff and W. O. Shipp (17,18), J. Sandsborg (19), A. A. Patrinos et al. (20), and C. J. Nappo and L. J. Gabbard (21). These studies address representativeness either in passing or by implication and do not examine the effects of sampling time (i.e., the representativeness of yearly, monthly, and daily totals and seasonal dependence). These effects will be illustrated in the following examples.

The effects of sampling time (yearly, monthly, or daily totals) and precipitation types (air mass or convective storms) on representativeness are illustrated using daily rainfall amounts for a period of 10 years (1963 to 1972). These observations were made at the Tennessee Valley Authority (TVA) Kingston and Bull Run steam plants located in the Tennessee River Valley in northeast Tennessee, a region of complex terrain. The steam plants are approximately 35 km apart and are oriented on a southwest-northeast line paralleling the valley axis (see Figure 4-31). Nappo and Gabbard observed that winter (December-February) and summer (June-August) are contrasting seasons in terms of the types of precipitation experienced in the area. Summer is characterized by weak cold-front passages, low winds, and late afternoon thunderstorms and scattered showers. Winter is characterized by warm-front passages, relatively high winds, and steady rains over large regions. If it is assumed that

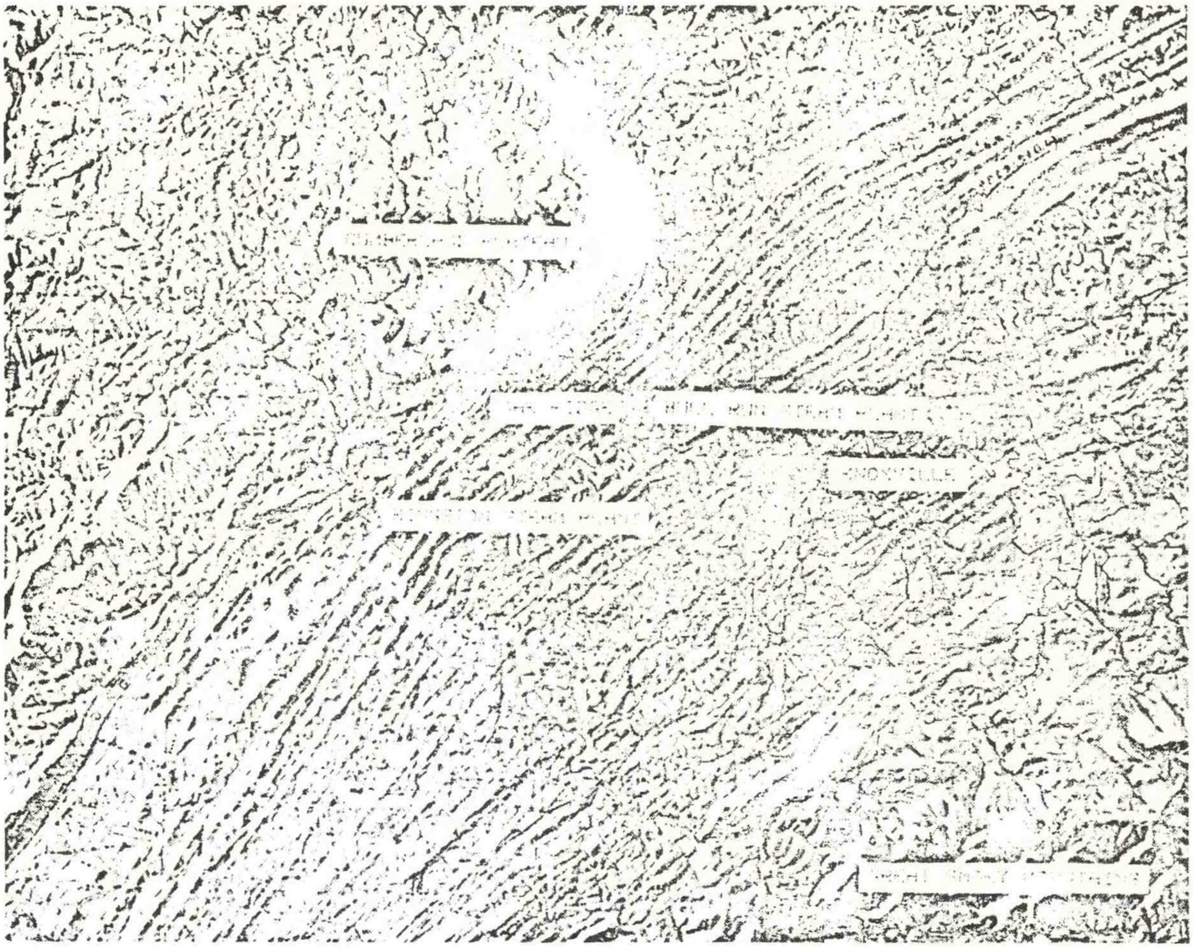

Figure 4-31. Kingston and Bull Run steam plant locations in the Tennessee River Valley region.

the precipitation differences between the Kingston and Bull Run sites are normally distributed, a criterion for representativeness can be written as

$$\Pr[|P_K(T,S) - P_B(T,S)| \leqq \sigma(T,S)] = 0.68 \quad . \tag{11}$$

where subscripts K and B refer to Kingston and Bull Run, respectively; T is sampling time; and S is season (winter or summer). The values of σ required to satisfy Eq. 11 for yearly, monthly, or daily rainfall amounts as well as winter and summer monthly and daily rainfall amounts are presented in Table 4-18 along with the observed bias for these cases.

Table 4-18

BIAS, TOTAL VARIANCE, AND NORMALIZED TOTAL VARIANCE OF RAINFALL DIFFERENCES BETWEEN KINGSTON AND BULL RUN STEAM PLANTS

Sampling Period	Bias (inches)	σ Total Variance (inches)	$\hat{\sigma}$ Normalized Total Variance
YEAR:	-4.01	5.26	0.11
MONTH:			
All Seasons	-1.96	3.21	0.78
Winter	-0.14	0.59	0.12
Summer	-0.73	2.02	0.41
DAY:			
All Seasons	-0.03	0.39	1.09
Winter	-0.04	0.29	0.07
Summer	-0.12	0.59	0.14

To compare the values of σ with each other, they have been normalized by the climatological mean precipitation for each sampling time and season. These normalized values appear in Table 4-18 under the heading $\hat{\sigma}$. It is immediately apparent that the potential for representativeness increases with increasing sampling time when rainfall types are not considered; however, when seasonal effects are taken into account, the potential for representativeness between these stations is greatest in winter. Clearly, precipitation mechanisms and sampling times must be considered in assessing representativeness of rainfall measurements.

As a final example, the use of the spatial autocorrelation as a measure of representativeness will be considered. Data for this example are taken from winter and summer rainfall amounts measured over a period of 32 years (1940-1972) at 38 stations in the central Tennessee River Valley. The locations of these stations, maintained by TVA, are shown in Figure 4-32. Contours of autocorrelation relative to the centrally located X-10 station are plotted in Figures 4-33 and 4-34 for winter and summer, respectively.

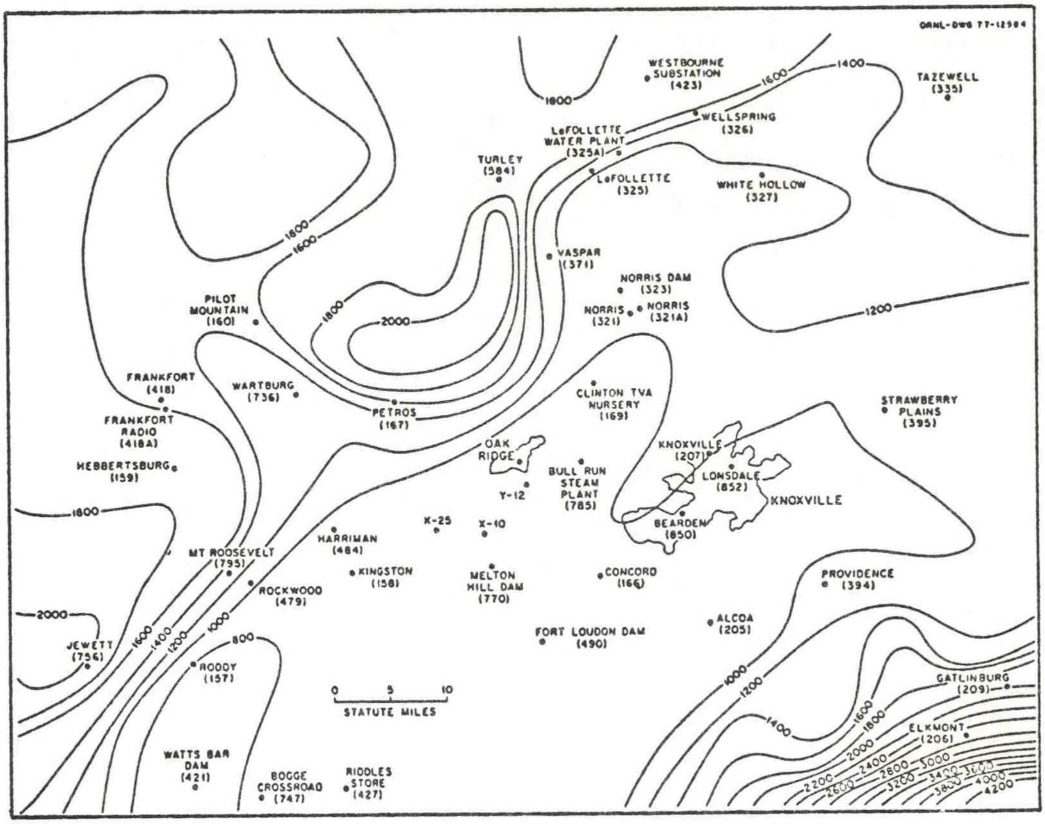

Figure 4-32. Locations of TVA Rain Gauge Stations

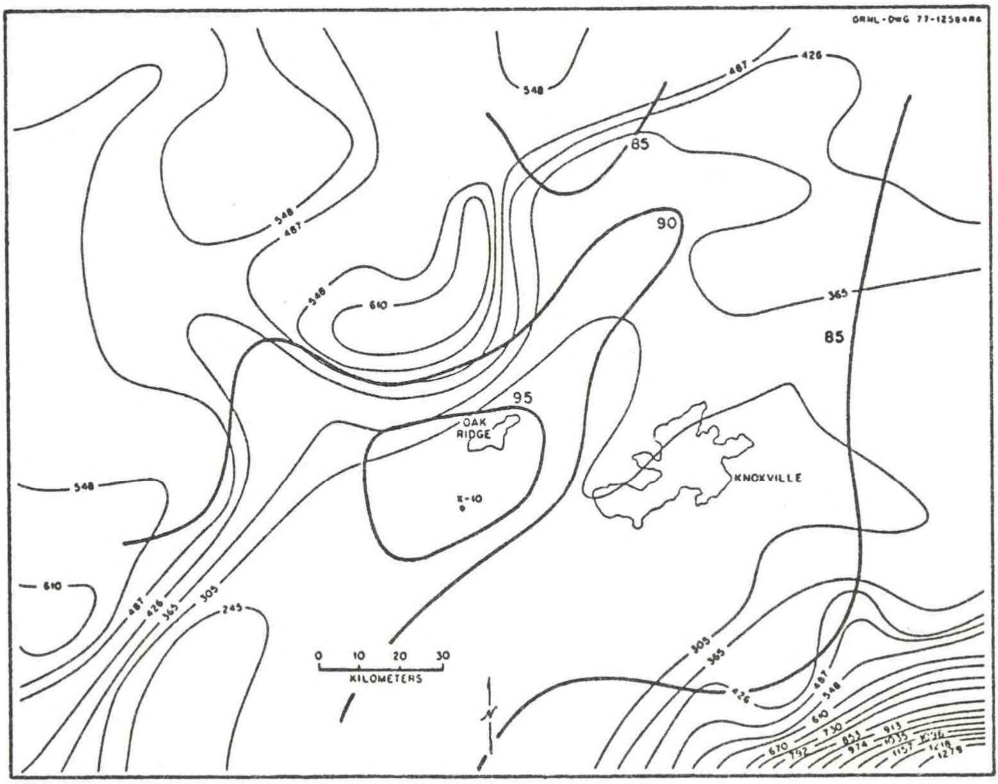

Figure 4-33. Contours of spatial autocorrelations relative to X-10 site for winter.

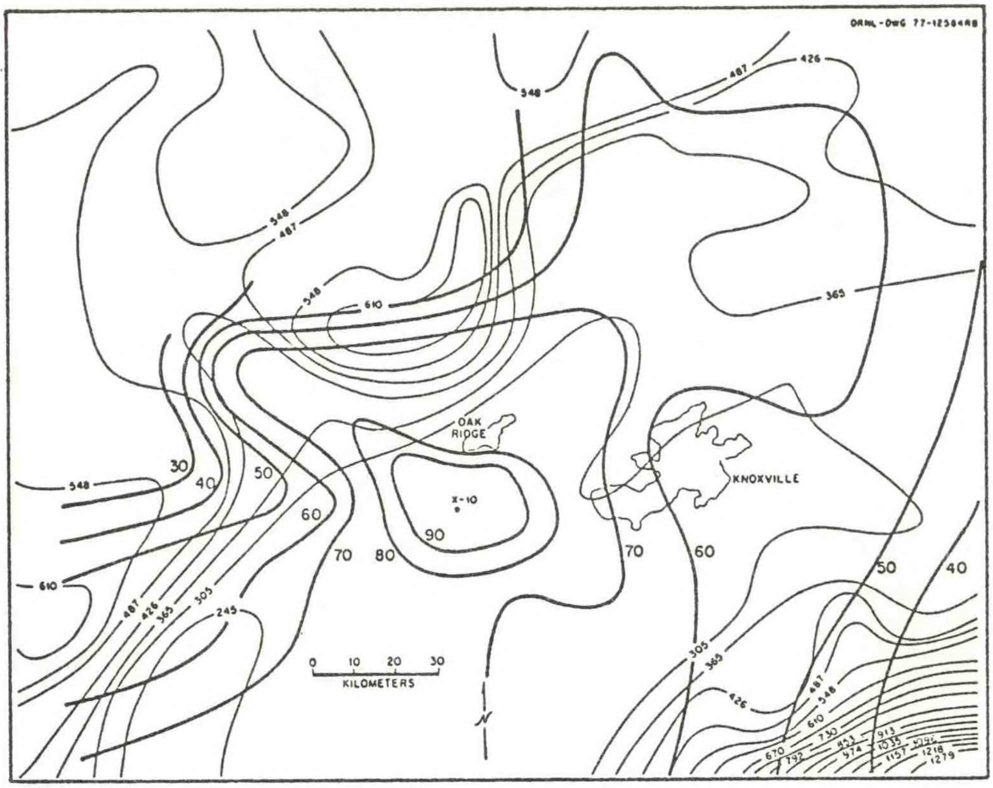

Figure 4-34. Contours of spatial autocorrelations relative to X-10 site for summer.

The decay of autocorrelation with distance is markedly different between summer and winter, and the asymmetry of the contour lines reflects complex interactions between terrain, storm tracks, and precipitation mechanisms. If the X-10 station is to be taken as representative of the area rainfall, and if the criterion for representativeness is that the autocorrelation between this and any other station be greater than 0.80, then during winter the X-10 station will be representative of the whole region (i.e., to a radius of about 100 km), while during summer it will be representative to a radius of about 30 km.

To determine the spatial extent of the representativeness of any other station, autocorrelation functions must be calculated between all possible pairs of stations and plotted against station separation distance. This was done for the summer season for station pairs aligned in the cross-valley and along-valley directions.

For comparison to the flat terrain case, the data of Huff and Shipp (18) are used. They studied rainfall variability over a high-density rain gauge network in central Illinois. These results are presented in Figure 4-35. Again, if representativeness

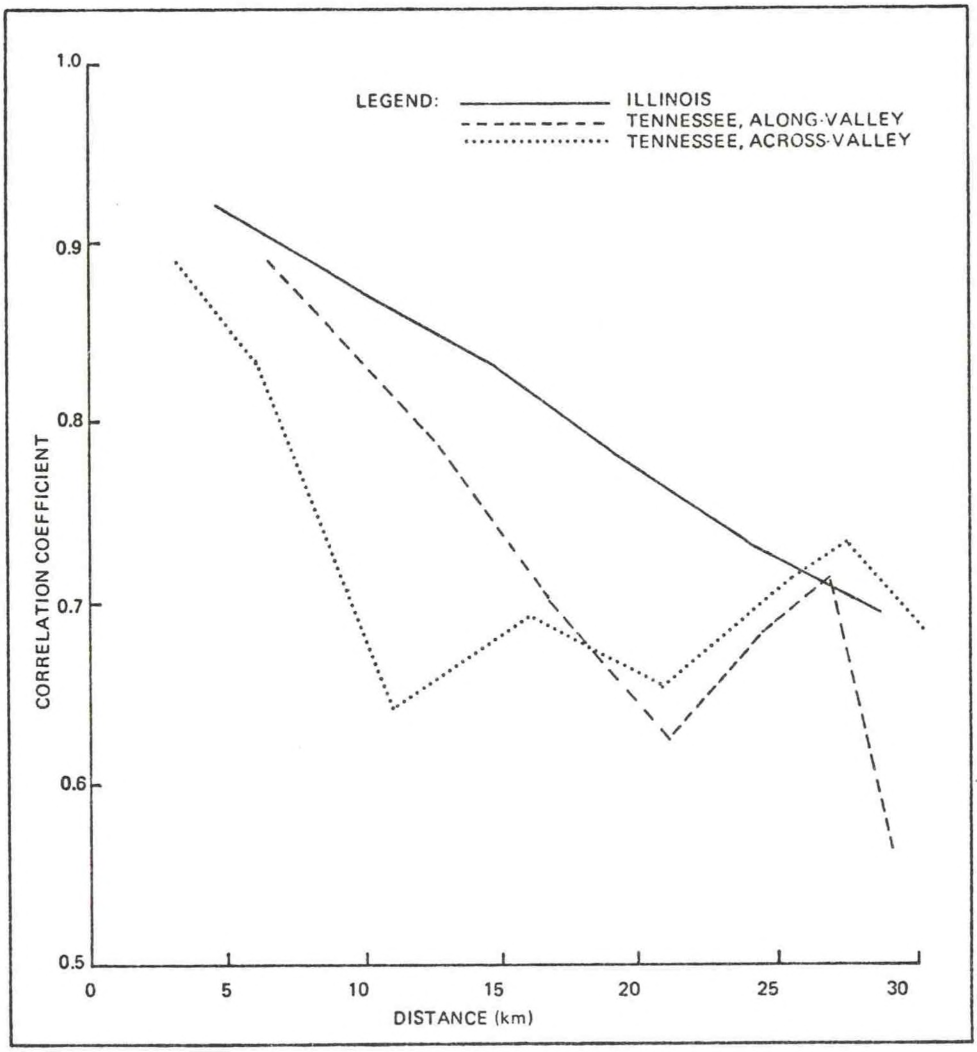

Figure 4-35. Autocorrelation functions versus distance over flat-land central Illinois and Tennessee River Valley region during summer season.

is assumed when the autocorrelation is greater than 0.80, on average a typical station in the Tennessee Valley region will be judged representative in the cross-valley direction to a distance of about 7 km and in the along-valley direction to a distance of about 11 km. Over the Illinois network, where no directional effects on station correlations are observed, this distance is about 16 km.

CONCLUSIONS AND RECOMMENDATIONS

The question of representativeness of measurements is valid in all areas of research and applications in the meteorological sciences. It arises in all discussions of integrations of observations on all time and space scales. In designing, executing, and analyzing field studies for whatever purposes, attention should be directed toward extracting information on representativeness. In this way, a general catalog of experience can be compiled on the subject.

It should be recognized that the same set of measurements may be deemed representative for some applications but not for others. Ultimately, one must decide how much risk one is willing to accept in establishing requirements for representativeness with the understanding that representativeness can only be achieved in a statistical sense; hence, the representativeness of an observation should be discussed in terms of probability.

The Representative Workshop panel made the following recommendations for the future study of representativeness.

- Conduct further research and literature review to identify additional statistical techniques and other methods such as pattern recognition to assess variability and representativeness.
- Use the aforementioned statistical techniques in appropriate applications, especially in assessing data collected during intensive field programs and from extensive meteorological monitoring networks.
- Include assessments of representativeness in the literature and scientific reports as are the standard statistical quantities used to describe a data set.
- Convene a conference or workshop to address the following topics after experience has been gained from applying the measures of representativeness to various meteorological applications.
    - Amplify the list of techniques that are available to assess representativeness.
    - List any limitations or shortcomings that have been identified through the community's experience.
    - Review the results of representativeness testing to determine if any generalized statements can be made for a specific set of applications that would either tend to limit the amount of data gathered or indicate the need for additional information to properly define the domain of interest.
    - Although value judgment will be exercised properly in the scientific community, (performance) evaluation criteria may need to be developed for specific applications for consistent regulatory use.

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