THE INVESTIGATION OF RELATIONSHIP BETWEEN HYDROLOGIC TIME SERIES AND SUNSPOT NUMBERS

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Several departments at Colorado State University have substantial research and graduate programs oriented to hydrology. These Hydrology Papers are intended to communicate in a fast way the current results of this research to the specialists interested in these activities. The papers will supply most of the background research data and results. Shorter versions will usually be published in the appropriate scientific and professional journals, or presented at national or international scientific and professional meetings and published in the proceedings of these meetings.

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ABSTRACT

The relationship of hydrologic series of monthly precipitation, annual precipitation and annual runoff to sunspot numbers has been investigated by cross-correlation analysis for various time lags (zero lag included) and by cross-spectral analysis. Eighty-eight series of monthly precipitation and 173 series of annual precipitation (stations from western North America), and 16 series of annual flows (stations from several parts of the world) were used as research data. No significant correlation was found between these hydrologic series and sunspot numbers. In fact, the spectrum of sunspot numbers proved to be nearly identical to the spectrum of residuals which were obtained by deducting values of hydrologic series from values of sunspot series. The coherence graphs worked out are within confidence limits of two independent time series, that indicate there is no relationship between hydrologic time series and sunspot numbers. Sampling fluctuations of cross-correlation coefficients between hydrologic series and sunspot numbers increase when both series are smoothed by moving average schemes. Therefore, when the confidence limits of unsmoothed series are used in the smoothed series approach, incorrect conclusions may be drawn about the significance of correlation.

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Chapter I

INTRODUCTION

1. Extraterrestrial effects on hydrologic processes. No periodic movement with cycles longer than one year has been discovered for hydrologic time series. As far as is presently known, from all extraterrestrial activities, only sunspot phenomena, which approach periodicity, are likely to affect precipitation and runoff. Whether or not there is a connection between sunspot fluctuations and hydrologic processes on earth is, at present, an unsettled problem and, therefore, a point of controversy. As a result, two questions may arise:

A. Is there any significant relationship between hydrologic time series and sunspot numbers which can be proven either by statistical analysis and tests or by physical relationship?

B. If no such significant relationship can be established by these methods, a second question arises: Are the erroneous correlations between hydrologic series and sunspot numbers attributable to some error in previous researchers' analyses?

It is known that phenomena in the upper atmosphere are affected by sunspot activities. For example, the upper atmosphere is subject to surplus ionization; it is conjectured that this extra ionization may affect the rainfall condensation process in the lower atmosphere during the maximum sunspot activities by bringing about an increase in the number of nuclei in clouds. One may ask, however, whether diffusion would likely be so effective that a significant number of additional nuclei would be brought down into the lower atmosphere where the precipitation and evaporation processes occur. Moreover, it has been shown that the augmentation of nuclei in clouds may have either of two opposite effects: It can cause an increase or a decrease in precipitation. Thus, the diffusion downward of too many nuclei will decrease precipitation, while the diffusion of the right number should increase it. This fact leads to the hypothesis that sun activities, as measured by sunspot numbers, may both increase and decrease precipitation, depending on the content of nuclei, the geographical position of the area under study and the type of precipitation producing air masses.

At this point, the following legitimate question might well be raised: How well do sunspot numbers represent phenomena in sun activites which might affect hydrologic processes in the lower atmosphere? Sunspot numbers follow a movement that is nearly periodic. This means that both sunspot number amplitude and length of cycle randomly change about their means from one cycle to the next with high stochastic components superimposed, but that, nevertheless, an average cycle and an average amplitude are used to describe the sunspot process.

For the study of the effect of sunspots on hydrologic processes close to the earth's crust, two approaches are feasible: the physical (analyzing the physical processes themselves and their relationships) and the statistical (relating the data on hydrologic time series to data on sunspot series). The approach taken for this paper was to correlate both precipitation and runoff series--using their monthly and annual values--with sunspot numbers. Thus, the objective was to determine whether any of the cross-correlations would prove significant, and if not, to examine the correlations obtained by authors in previous research for evidence of faulty techniques or improper application or interpretation of adequate techniques.

2. Physical approach to study of sunspot effects on hydrologic processes. The physical approach must necessarily start from the measurements and investigation of the quantity of ions in the upper atmosphere as a function of sunspot activites. However, a better insight is needed into how well the sunspot numbers represent those activities on the sun which affect the additional ionization in the upper atmosphere.

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The next problem, in the physical approach, is to obtain the necessary information of how long the ions persist and how they are diffused from the highest levels of atmosphere to the lowest levels where the processes of evaporation, moisture movement through the air and precipitation occur. If one finds a relatively high positive correlation between the number of sunspots and the number of ions in the upper atmosphere and between the number of ions in the upper atmosphere and their number per unit of air volume in the lower atmosphere, where the processes of precipitation occur, the physical process may be established for an eventual relationship between condensation nuclei in clouds and the sunspot numbers.

The diffusion process of ions between the upper and lower atmosphere must be slow because of the tremendous storage possibilities between these extremes of atmosphere. If ions, as precipitation condensation nuclei, are not the only factor which affects precipitation, then any other relevant phenomenon in the uppermost atmosphere must become substantially attenuated or changed in the diffusion process down to the lowest layers of atmosphere. In other words, any phenomenon which fluctuates in the upper atmosphere similarly to the sunspots will have much smaller fluctuations (much smaller amplitudes) at the levels of precipitation condensation.

Let us assume a hypothesis; namely, that for given cloud conditions, there is a unit volume content of ice (or other) nuclei for the precipitation condensation which gives the maximum precipitation. If there are less condensation nuclei, the process will be less efficient and the total precipitation will be smaller. If there are more nuclei than that optimal content, the coalescence of very fine rain drops or the growth of ice crystals will be slower than under the best concentration of nuclei, and the total precipitation will be smaller than the above maximum. This hypothesis is based on the assumption that there is a nuclei content per unit volume of clouds which produces the maximal effect in precipitation. Any content smaller or greater than that will produce less precipitation. This hypothesis, whether or not it is correct, should be a basis for the study of effect of sunspot activities on hydrologic processes.

The consequence of this hpothesis is that the increase in ion-nuclei during sunspot activities and the decrease during the relative quiescence of the sun should vary from region to region, from season to season and from one type of cloud formation to another. The logical conclusion would be that, in areas of consistent lack of ice or other nuclei (like in orographic and thunderstorm types of precipitation), the sunspot activities would mean precipitation greater than the average amount and the quiescent sun would mean precipitation smaller than the average amount. In areas, seasons or moist air masses containing clouds of usually sufficient content of nuclei, any increase of ions in the lower atmosphere during sunspots would mean a decrease in precipitation in comparison with the amounts during the quiescent sun. Therefore, the above hypothesis would lead one to expect either an increase or a decrease of precipitation during the peak of sunspots in comparison with precipitation during their lowest values. It should be expected, however, that many cases of precipitation generation may be between these two cases with minimal or no effects of sunspots on precipitation amounts and patterns.

This physical approach to the establishment of an eventual dependence of hydrologic processes on sunspot activities awaits yet a rigorous scientific scrutiny and analysis and such analysis is much beyond the scope of this paper.

3. Statistical approach to study of sunspot effects on hydrologic processes. Many scientists feel that there may be some effect of sunspots on precipitation, but that it is masked by the preponderance of other effects. In other words, sunspot activities have an effect on hydrologic processes, but are too small to detect by simple and classical physical or statistical techniques. The significance of this effect represents the main contemporaneous controversy of the subject.

If the simple and already classical statistical techniques of the relationship between two physical processes cannot detect a statistically significant dependence between these two phenomena, assuming that various mathematical models of dependence have been applied, then the effect must be relatively small. Refined discrimination techniques may be used; however, the probability is very small that a significant or large dependence would be discovered by this refinement. This position is taken by the writers of this paper in their investigations. If the techniques, like cross-correlation and cross-spectral analysis, do not show a significant relationship between hydrologic processes of precipitation and runoff and sunspot numbers, it is unlikely that any new technique would detect anything other than a small effect of sunspots on hydrologic phenomena. This small effect cannot be a serious basis for the prediction of water resources available in the near future when predicting the forthcoming activities of the sun or its quiescence. There is a degree of uncertainty in the prediction of sunspots because of the noise contained in their fluctuation; this fact decreases, even more, the predictability of hydrologic processes from sunspot activity.

The present study of sunspot effects on precipitation and runoff is a reaction to the following two tendencies: (a) An overemphasis on the study of sunspots from the hydrologic point of view, justifying it by the expected prediction possibility in water resources field, and (b) An inclination among some hydrologists to spend their energies searching for extraterrestrial causal factors of fluctuations of hydrologic time series instead of seeking the causes of these fluctuations, namely in terrestrial phenomena, especially in the state, variations and evolution of conditions of large bodies of water on the earth, like oceans, seas, snow and ice accumulation, and similar.

Another point should be considered when one reviews the literature on the relationship between hydrologic phenomena and sunspot numbers. Researchers who find a relationship considered significant between hydrologic time series and sunspot numbers usually report their findings in the scientific or professional journals. Those who do not find any significant relationship do not report their findings, because it is not as customary to report negative results. These negative results seem preponderant.

The idea of whether or not the percentage of "discovered correlations" may be just the number of cases which would be outside the confidence limits of correlation of two independent processes may be interesting for investigation. When the improper (usually narrower) confidence limits are used, the number of "positive correlations" may be increased by this bias, as will be shown later in the particular case of using the smoothing procedure of the moving average scheme.

Chapter II

SUNSPOTS AND THEIR ARGUED EFFECT ON TERRESTRIAL PHENOMENA

1. What are sunspots? Without intending to go into a description of sunspots and their causes, it seems proper to give a very brief introduction to the terms used in this paper. For an extensive exposition of sunspots, their measure and their causes, the reader is referred to the works of Kiepenheuer (1962) and Bray and Loughhead (1965), which are only a part of the extensive literature on this topic.

A single spot starts its life as a small round pore of 1,500 to 3,000 km. diameter. Such a pore does not differ from the dark areas between the solar granules, except in its greater life time. Sometimes, these pores increase in size; in the majority of such cases, they develop rapidly into small spot groups extending over 5-10 square degrees. In most cases, pores and groups disappear after a few hours or within a day. The majority of spot groups has a lifetime of less than a day (Kiepenheuer, 1962).

In 1849 R. Wolf of Zurich introduced the "sunspot number" as a measure of the frequency of sunspots. It is defined as: if there are on the solar disk f individual spots which are collected into g groups, the Wolf number is

$$R = k(10g + f) .$$

The factor k depends on the conditions of observation, the subjective judgment of the observer, his decisions as to grouping, the effects of fatigue, the instrument used, and the method of observation (Kiepenheuer, 1962).

The particular combination of g and f is somewhat arbitrary and is no ideal measure of spottiness. The definition is accepted mainly because it has been used for more than a century and forms one of the largest time series of interest in geophysical problems. Although better ways of measuring solar activity have been devised, the Wolf's number has proved its worth in the study of solar-terrestrial relations.

Wolf, who used a Fraunhofer refractor 8 cm. in aperture and 64x magnification, set $k = 1.00$. Efforts have been made throughout the years to keep the scale homogeneous. Since a complete series requires the cooperation of numerous observers in different climates and conditions, the counts must be reduced to a common standard; yet this reduction clearly remains somewhat uncertain.

The arbitrary nature of the Wolf sunspot number does not appear to have serious consequences. Kiepenheuer (1962) calculated the daily values for 1949 of the expressions: f, $(g+f)$, $(10g+f)$ and g. The first three curves differ little; only the g curve has a different character.

In 1908, George Hale discussed the nature of the physical actions which take place on the sun during periods of sunspot activity by demonstrating that sunspots are giant cyclones or whirlpools in the sun's atmosphere, similar in formation to the tropical hurricanes which very often occur on the earth (Parmelee, 1960).

A completely satisfactory theory for the physical causes of sunspots does not yet exist. Many scientists have postulated that outside forces acting on the sun are the primary cause of sunspots. Their usual assumption, in favor of planetary influence, is that the attraction of the planets for the sun causes tides in the solar atmosphere as the moon causes tides in the oceans of the earth (Arakwa, 1956). Jupiter's size and distance from the sun make this planet most capable of influencing these "solar tides," although it may take years for its tide-raising force to bring the solar atmosphere into maximum oscillation (Stetson, 1937). It is easy to show mathematically that the tide-raising forces decrease with the cube of the distance, so that the total effect of Jupiter on the sun may be only a little more than twice that of the earth. The variation in this tide-raising force, on account of the changing distance of the planets from the the sun, is six times as great with Jupiter as it is with the earth. If Jupiter has an effect on the sun, it is obvious that the other planets, likewise, must influence tides in the solar atmosphere. The influence will, in each case, vary according to the mass of the planet and the inverse cube of the distance (Stetson, 1937).

Perhaps the most notable attempt made to combine the effects of the planets in the tide-raising force was that of E. W. Brown. In 1900 he called attention to the fact that approximately every 9.93 years Saturn is in line with Jupiter and the sun, so that the tide-raising force of Saturn, which is approximately one-third that of Jupiter, is added to Jupiter's effect. Brown combined this 9.93 year interval between conjunctions and oppositions of the planets with the period of Jupiter's revolution about the sun, which is 11.86 years, and found that he could reproduce most of the times of the occurrences of maxima of sunspots. By 1900, however, his curve deviated so much from the sunspot curve that the author himself expressed doubt as to the reality of agreement (Stetson, 1937).

Another theory suggests looking for the cause of sunspots in the own nature of the sun. This theory assumes that the vertical winds producing the sunspots on the surface of the sun are caused by uprushes of gases from inside the sun due to the accumulation of stresses that, for some reason, periodically disturb the equlibrium of the sun.

2. The sunspot cycle. While it is customary to speak of an 11-year sunspot cycle, many fail to realize that the distance between the peaks or between the troughs may vary in length from a minimum of 8 years to a maximum of 16 years (Williams, 1961). Because of insufficient knowledge about the physical nature of sunspots, it is better to predict them on the basis of statistical models than on the basis of their physical origin. Many attempts have been made to represent the irregular spot cycle by a superposition of periods; even correlations with planetary periods have been studied. These attempts have failed.

Granger (1957) has shown the sunspot period to be distributed in a rectangular distribution, with a mean of 132 months and a semi-range of 30 months In the same paper, Granger proposes a simple two-parameter statistical model which explains 88 percent of the total variation found in Wolf's sunspot number data.

3. The controversy of hydrologic processes being dependent on sunspots. H. C. Willet stated in 1933: "There can be no doubt at the present time, but that changes of the world weather patterns are significantly related to sunspots, to the eleven-year cycle, to the Hale or double-sunspot cycle, and to longer cycles." Few feel that terrestrial weather is not influenced by the sun and its solar activity. There is reason to doubt the sunspot number is a good measure of solar activity. It seems to the writers that it is also justified to question the "significant relations" between weather and sunspots. The term "significant relations" is, scientifically, a very vague expression. A relation between two phenomena can be called "significant" from a physical or explanatory point of view, but the same relation may be "not significant" from a statistical point of view. The explanatory meaning is a subjective one and, as such a relation, can be significant for one scientist and not significant for another. On the other hand, statistical comparison is the objective method for judging the significance of a relationship.

Researchers, through many years, have looked for correlations between sunspot numbers and various earth phenomena such as tree rings, barometric pressure, temperature, rainfall, lake levels, thickness of varves, (layers of sediment deposited each year in old lakes and estuaries), river flows, etc. Many of these investigators claim these correlations exist in their analysis. It would be a very long task to critically analyze all these studies, but it is instructive to take, as an example, the thickness of tree rings.

The most famous study in the field of tree rings is perhaps that of A. E. Douglass of the University of Arizona. In 1933, Professor Douglass noted, in many of the tree rings he studied in his extensive investigation, that sequences of periods of rapid growth were followed by periods of retarded growth and then rapid growth again. Believing that the growing conditions under which the trees survive might be varying with the sunspot cycle, he began an intensive study counting tree rings to discover if his assumption could be verified. The result of these investigations is summarized by Stetson (1937) in the following words: "However skeptical some scientists may have been in regard to Professor Douglass' theory of sunspots and tree growth during the early days of his investigation, there are few well informed scientists today who have not accepted the connection."

Studying the same problem, Abetti (1957) presents a chart showing 2.8 to 44.0 year cycles obtained by F. Vercelli from an analysis of the dendrological sequence of a Sequoia gigantea from 274 B.C. to 1914 A.D. Abetti states: "Extremely obvious, however, are the oscillations of about 11.1 years, which must be traced to solar causation, and the way in which the curve of relative sunspot numbers if suppressed for a certain number of years, later to be resumed with increasing amplitude."

In 1961, Bryson and Dutton presented the results of an investigation in the variance spectra of tree rings and varves. They showed that "none of the tree-ring spectra exhibits significant peaks near 11 years, and as many show minima as show minor maxima." They continue, "from this we might conclude that the so-called sunspot periods are not important features of tree-ring spectra. Summing up the variance-spectrum evidence on 'hidden' periodicities, we must conclude that they are well hidden, if present at all. Certain short periods seem to be preferred in most tree-ring spectra, and in a spectrum of July rainfall for the southwestern United States as well (Sellers, 1960). For example, the 2+ - and the 3+ - year period periodicities, which appear frequently in the spectra of this study, are also present in Southwestern July rainfall spectrum. Other than this slight indication of some relatively universal variance excess at 2+ and 3+ years, we must conclude that there are no demonstrably important frequencies in the tree-ring record, and that at higher frequencies the variance is distributed nearly as 'white noise'."

Similarly, to the discussion given above, there has been a long controversy about the relation between precipitation and sunspots. One of the most extensive studies on this topic is the one by Abbot (1955). By using a family of periods discovered to exist in variations of the solar constant of radiation, Abbot predicted, with moderate success, values of future precipitation and temperature at St. Louis, Missouri. Twenty-three periods were used, all of them multiples of 22 3/4 years within one percent. In his paper, Abbot states that "these 23 periods exist in temperature and precipitation however they may be produced." This conclusion does not appear valid to the writers. Extensive studies conducted by Yevjevich (1964) at Colorado State University have shown that the correlograms and variance spectra of annual runoff values of 140 stations from many parts of the world, of annual precipitation values of about 1600 stations and of annual runoff values of about 450 river stations all in western North America do not have any significant cycle or peak, respectively for correlograms and variance spectra, of periods longer than a year. Roesner (1965), using monthly data of precipitation and runoff of many stations, found peaks only at the one year cycle and its subharmonics with the rest of the spectrum showing either white noise (for monthly precipitation or independence) or red noise (for monthly runoff or stochastic time dependence).

Many examples of contradictory findings like the ones mentioned may be found in the literature. It is a fact that, in the search for cycles, different results have been obtained when analyzing the same or similar data by different mathematical techniques. This poses the question of whether the cycles really exist or are artificially introduced by the particular technique used. The same question arises when looking for correlations between two time series, and it will be shown later that certain measures of correlation can be deeply altered by some mathematical procedures.

Chapter III

SUMMARY OF THE MATHEMATICAL TECHNIQUES USED IN THIS INVESTIGATION

To reach the objectives of this study, techniques of cross-correlation and cross-spectral analysis between two time series were used. A detailed exposition of these methods may be found elsewhere (Rodriguez-Iturbe, 1967). Only a brief summary of the theory is presented here.

Consider two arbitrary random processes $[x_k(t)]$ and $[y_k(t)]$ with mean values

$$\mu_x(t) = E[x_k(t)] \tag{1}$$

$$\mu_y(t) = E[y_k(t)] \tag{2}$$

Their autocovariance functions are defined at arbitrary values of t and $t-\tau$ by

$$\alpha_x(t, t-\tau) = E\left[\left(x_k(t) - \mu_x(t)\right)\left(x_k(t-\tau) - \mu_x(t-\tau)\right)\right] \tag{3}$$

$$\alpha_y(t, t-\tau) = E\left[\left(y_k(t) - \mu_y(t)\right)\left(y_k(t-\tau) - \mu_y(t-\tau)\right)\right] \tag{4}$$

Similarly, the cross-covariance function of the lag τ is defined by

$$\alpha_{xy}(t, t-\tau) = E\left[\left(x_k(t) - \mu_x(t)\right)\left(y_k(t-\tau) - \mu_y(t-\tau)\right)\right] \tag{5}$$

In the most general case, all the preceding quantities vary with t and τ.

Other statistical quantities can be defined over the ensemble of these two series by fixing three or more times instead of two. The probability structure is thus described in finer and finer detail by increasing the number of fixed times. If all possible joint probability distributions involving $x_k(t)$ are independent of the absolute times $t_1, t_2, \ldots, t_n, \ldots$, and are only functions of the intervals $\tau_1, \tau_2, \ldots, \tau_n, \ldots$, then the process is said to be strongly stationary. If only the first n joint probability distributions involving $x_k(t)$ are independent of the absolute times, the process is called n^{th}-order stationary. In order to prove n^{th}-order stationarity, it is only necessary to prove that the joint n^{th}-probability density is independent of absolute times, because the joint first (n-1) probability densities are obtained from the joint n^{th}-density by successive integrations.

In the special case of a Gaussian independent process, the mean value and the covariance function provide a complete description of the underlying probability structure. In this case, second order stationarity or weak stationarity is equivalent to strong stationarity, because the former implies that the mean and covariance function are independent of absolute times. This, in turn, implies that all the possible joint probability distributions are independent of absolute times, because all of them may be derived from the mean value and the covariance function.

It will now be assumed that for the two stationary processes $[x_k(t)]$ and $[y_k(t)]$, the functions $\alpha_x(\tau)$, $\alpha_y(\tau)$ and $\alpha_{xy}(\tau)$ exist and have Fourier transforms $S_x(f)$, $S_y(f)$ and $S_{xy}(f)$ given by

$$S_x(f) = \int_{-\infty}^{\infty} \alpha_x(\tau)\, e^{-2\pi f\tau i}\, d\tau \tag{6}$$

$$S_y(f) = \int_{-\infty}^{\infty} \alpha_y(\tau)\, e^{-2\pi f\tau i}\, d\tau \tag{7}$$

$$S_{xy}(f) = \int_{-\infty}^{\infty} \alpha_{xy}(\tau)\, e^{-2\pi f\tau i}\, d\tau \tag{8}$$

where $S_x(f)$ and $S_y(f)$ are defined as the variance (density) or power spectra of the stochastic processes $[x_k(t)]$ and $[y_k(t)]$. $S_{xy}(f)$ is defined as the cross-spectrum function between these two processes.

It is convenient to define the so-called physically realizable one-sided variance spectra and cross-spectrum functions. These functions are given by

$$G_x(f) = 2S_x(f),\quad 0 \le f < \infty \text{, otherwise zero} \tag{9}$$

$$G_y(f) = 2S_y(f),\quad 0 \le f < \infty \text{, otherwise zero} \tag{10}$$

$$G_{xy}(f) = 2S_{xy}(f),\quad 0 \le f < \infty \text{, otherwise zero} \tag{11}$$

and are the quantities determined by direct procedures in practice.

In the case of real-valued process, all the previous equations may be simplified. The real valued two-sided variance spectrum is obtained from Eq. (6) by making the imaginary part equal to zero, so that

$$S_x(f) = \int_{-\infty}^{\infty} \alpha_x(\tau) \cos 2\pi f\tau\, d\tau . \tag{12}$$

Due to the fact that the covariance $\alpha_x(\tau)$ is an even function

$$S_x(f) = 2\int_{0}^{\infty} \alpha_x(\tau) \cos 2\pi f\tau\, d\tau \tag{13}$$

and

$$G_x(f) = 4\int_{0}^{\infty} \alpha_x(\tau) \cos 2\pi f\tau\, d\tau, \text{ for } 0 \le f < \infty, \tag{14}$$

otherwise zero. A similar expression is valid for $G_y(f)$.

The physically realizable one-sided cross-spectrum function expressed as

$$G_{xy}(f) = 2\int_{0}^{\infty} \alpha_{xy}(\tau)\, e^{-2\pi f \tau i}\, d\tau \qquad (15)$$

and, being a complex number, can be written as

$$G_{xy}(f) = C_{xy}(f) + i\,Q_{xy}(f) \qquad (16)$$

where $C_{xy}(f)$ is the co-spectrum which is a measure of the in-phase covariance, and $Q_{xy}(f)$ is the quadrature spectrum which is a measure of the out-of-phase covariance. In more practical words, the co-spectrum measures the contribution of oscillations of different frequencies to the total cross-covariance at the lag zero between the two time series. The quadrature spectrum measures the contribution of different frequencies to the total cross-covariance between the series when all frequencies of the series $x(t)$ are delayed by a quarter period, while those of the series $y(t)$ remain unchanged (Panofsky and Brier, 1958).

From Cramer's spectral representation (1940-1942), any stationary time series can be considered as a sum of frequency components, each component being statistically independent of the others. One of the important things about the theory of stationary processes is that not only is the component with the frequency f_j independent of all the other components of the process, but it is also independent of all components of another process except for the component with the frequency f_j.

A direct measure of the square of amplitude correlation at the frequency f is given by the coherence function

$$\gamma^2_{xy}(f) = \frac{|G_{xy}(f)|^2}{G_x(f)\,G_y(f)} = \frac{C^2_{xy}(f) + Q^2_{xy}(f)}{G_x(f)\,G_y(f)} \qquad (17)$$

where $0 \leq \gamma^2_{xy}(f) \leq 1$. In this manner, when the coherence between two time series is calculated, one looks for correlations in small ranges of frequencies. On the other hand, with the cross-covariance function, one is looking for correlations between the two processes considering each one as a whole.

Even if the amplitudes are fully correlated, it is possible that the corresponding frequency components will have different phases. The phase lag at each frequency is given by

$$\theta_{xy}(f) = \text{arc tang}\left[\frac{Q_{xy}(f)}{C_{xy}(f)}\right]. \qquad (18)$$

Representing $x(t)$-series by the type $x(t) = a \cos(2\pi ft + \zeta)$, it is possible to perform a linear regression between the series $x(t)$ and $y(t)$ at each frequency f as

$$y(t) = a\frac{|G_{xy}(f)|}{G_x(f)} \cos[2\pi ft + \zeta + \theta(f)] + \eta(t) \qquad (19)$$

where the term $\frac{|G_{xy}(f)|}{G_x(f)}$ is called the gain factor and is equivalent to a regression coefficient at each frequency f. The spectrum of the residual terms $\eta(t)$ is given by Jenkins (1963) as

$$G_\eta(f) = G_y(f)\,[1 - \gamma^2_{xy}(f)]\ . \qquad (20)$$

$G_\eta(f)$ will give an idea of possible other periodicities in the series $y(t)$ which are not shared by $x(t)$.

The theory has been outlined assuming that one is dealing with continuous time series. For the case of discrete time series, the procedure of estimation used in this paper is the same one used by Rodriguez-Iturbe (1967).

Chapter IV

DATA ASSEMBLY AND PROCEDURE FOR THE ANALYSIS

1. Principles used in sampling of stations. The stations used in this study form part of the research data assembly of the Hydrology Program at Colorado State University. The characteristics of this data have been discussed in detail by Yevjevich (1963), and only some of the most relevant features will be mentioned here.

The smaller the area and the greater the number of selected gaging stations, the larger is the average regional correlation coefficient among the data of stations taken pairwise. The larger this average coefficient, the smaller is the effective number of independent stations, and the less is the information which can be derived. The effective number of independent stations, in the case of correlated stations, is defined here as the number of uncorrelated stations that would be statistically equivalent. From previous considerations, it is concluded that there is no advantage in the selection of a very large number of stations within a limited area.

Two scales were selected for the area: global and continental. The global scale meant the use of stations from many parts of the world. The continental scale was limited to western North America, because the data on both annual flow and annual precipitation were readily available and sufficiently reliable. This general sampling scheme was thus aimed to compensate, as much as possible, for the disadvantages of a limited period of observation by sampling stations over large areas.

2. Precipitation data. Precipitation gaging stations used in these investigations are located in the continental region of western North America. Annual and monthly precipitation data were used in this study with the location of the stations being shown in Fig. 1.

Annual precipitation. Research data on annual precipitation, used in this study, consisted of annual values for 174 stations, each with 70 or more years of observation. For all stations, the average length of these series is 79 years.

Monthly precipitation. The monthly precipitation data used include 88 series, with each series having more than 60 years of observation, and with the total series having an average length of 73 years.

The criteria used for the selection of series of annual precipitation were (Yevjevich, 1963):

a. Total number of monthly estimates by correlation and regression analysis with neighboring stations is small;

b. Records of large sample are stationary in the practical limits of stationarity tests;

c. Data for the annual precipitation were taken from the publications or from official records of weather services;

d. Records are reliable.

Appendices 1 and 2 give information about the individual stations used for precipitation data in this study.

3. Runoff data. Data on annual runoff made up of annual values for 16 runoff stations selected from several parts of the world were used for investigations. For all stations, the average length of the series is 94 years. Both runoff, corrected for water carryover from year to year (or series of annual effective precipitation), and observed annual runoff were analyzed. Appendix 3 gives names and characteristics of these series. The criteria used for the selection of series of annual flow were (Yevjevich, 1963):

a. Estimated monthly flows, by using correlation and regression analysis with neighboring stations, did not exceed a small percentage of all monthly values available;

b. River stations with very changeable conditions and significant continuous changes of virgin flows, were avoided;

c. The records obtained at a station were not used when the diversions into or out of the river basin exceeded one percent of the total river flow and the diversions could not be accounted for by corrections;

d. In the case of large irrigation areas, with the change during the period of observation of net consumptive use of water greater than approximately two to three percent of annual mean flow, the records of such affected stations were not usually selected for the study;

e. If large storage reservoirs have had a great influence either on overyear flow distribution or on evaporation, and could not be accounted for easily, the stations were not selected for this study;

f. Data of annual flows were taken from the publications or from official records of hydrologic services; and

g. Only stations having records with available monthly or daily flows, which allowed the computation of stored water volumes in the river basin at given times, were used.

4. Sunspot data. Sunspot data were the monthly and annual values of the Zurich sunspot relative number introduced by Rudolf Wolf, in 1848, as a measure of sunspot activity. The sunspot values used in this study have been the same ones given by Waldemier (1961).

5. Procedure for the analysis. Cross-correlograms and complete cross-spectral analyses were made between each of the hydrologic series considered and the corresponding sunspot numbers. For the annual hydrologic data, the analysis was made with the corresponding annual sunspot numbers for the same year of the hydrologic data. With monthly precipitation data, monthly sunspot numbers were used.

When working with annual data there were 33 lags throughout the analysis. For the monthly data, 132 lags were used. This high number of lags was necessary in order to study the possible effects of the sunspot cycle which has an average period of 11 years.

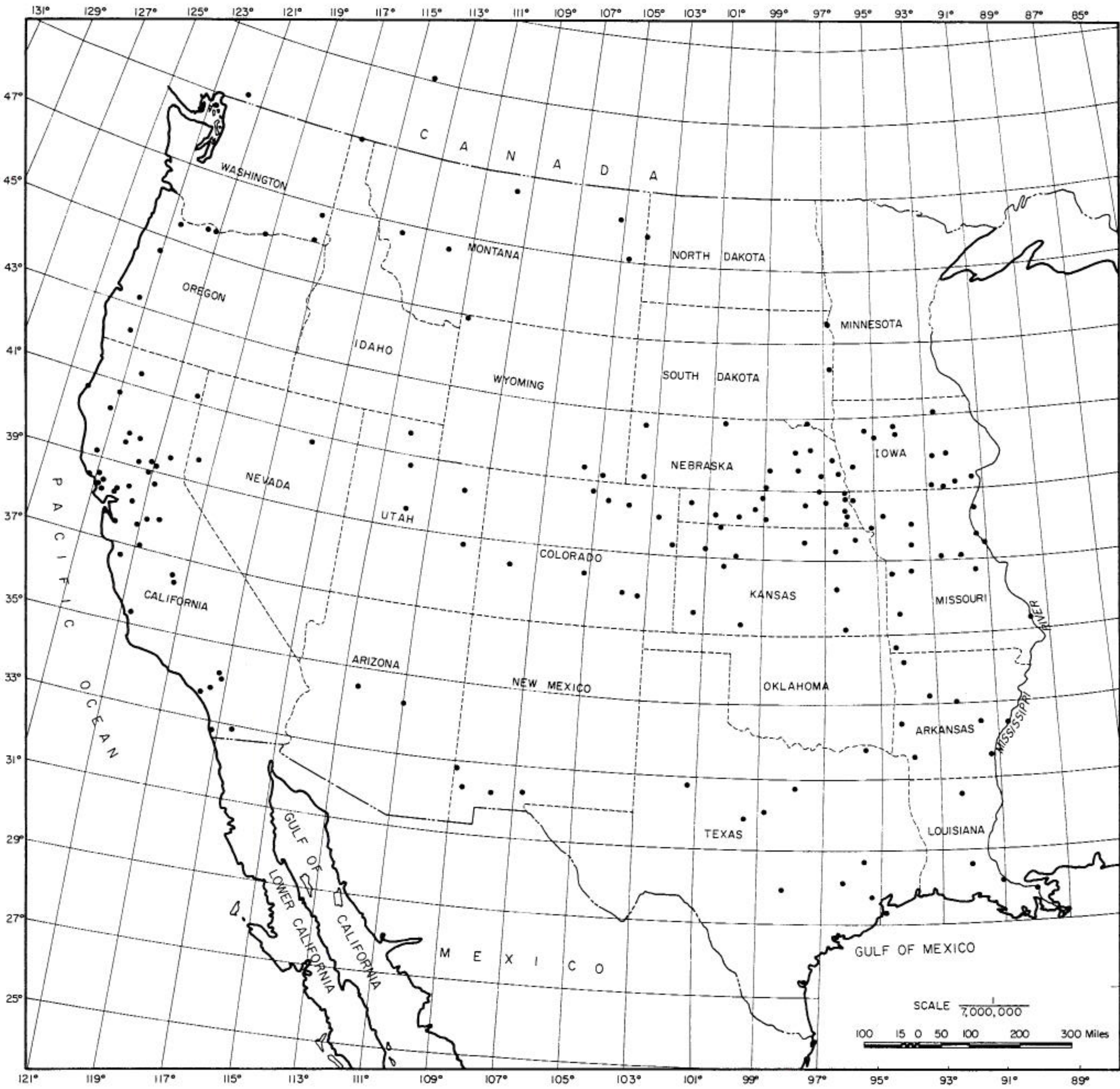

Figure 1 Location of precipitation stations in Western North America, for which the annual and monthly data are used in this study.

Chapter V

ANALYSIS OF RESULTS

1. Average cross-correlation functions for the series analyzed. Figure 2 shows the average cross-correlograms between hydrologic series and sunspot series (average cross-correlation coefficients as functions of $\pm\tau$) for annual precipitation (line 1), for annual runoff (line 2), and for annual effective precipitation (line 3). Figure 3 gives the average cross-correlogram between monthly precipitation and monthly sunspot numbers. These average cross-correlograms are estimates of cross-correlation functions which are obtained by correlating each individual series with sunspot numbers and averaging the cross-correlation coefficients for each τ, or 173 series for line 1 and 16 series for lines 2 and 3 in Fig. 2 and 88 series for the line in Fig. 3.

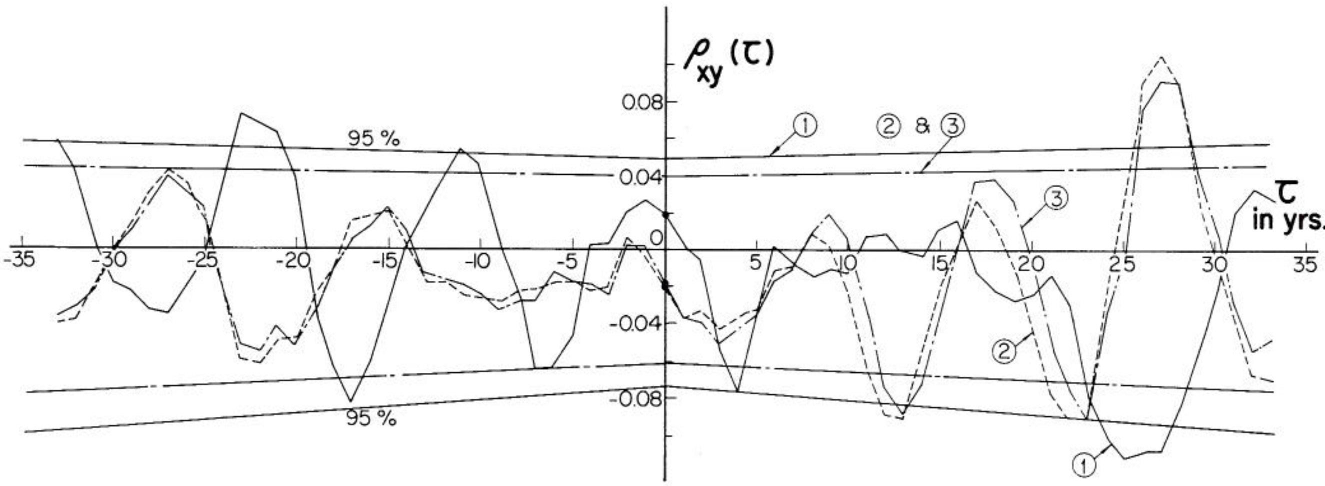

Figure 2 Average cross-correlograms between the annual values of precipitation, runoff and effective precipitation and the annual sunspot numbers for $-35 \leq \tau \leq 35$: (1) average cross-correlation coefficients of 173 precipitation stations; (2) average cross-correlation coefficients of 16 runoff stations; and (3) average cross-correlation coefficients of effective precipitation obtained for the above 16 runoff stations. The outside confidence limits at the 95 percent probability level refer to annual precipitation (1), while the inside limits are for annual runoff and annual effective precipitation (2) and (3).

The proper confidence limits of ρ_τ are also computed and plotted in Figs. 2 and 3. For line 1 in Fig. 2 and for Fig. 3, the effective number of independent stations (equivalent number of independent stations) was computed following the procedure applied in CSU Hydrology Paper No. 4 (Yevjevich, 1964), Eq. 2.74, because of a high regional correlation either between annual precipitation of various stations or between monthly precipitation of various stations. These effective numbers (12.2 for the series of annual precipitation and 13.16 for the series of monthly precipitation) were used in determining the confidence limits at 95 percent probability level.

Figures 2 and 3 show that about 5 percent or fewer of the average cross-correlation coefficients are outside the confidence limits. It is expected that this will be the case for uncorrelated time series when they are investigated for cross-correlation at various lags. The cross-correlogram for $+\tau$ is for sunspots preceding precipitation or runoff and has a physical meaning and justification. On the other hand, the cross-correlogram for $-\tau$ corresponds to precipitation or runoff preceding sunspots. It results from the formal approach but has no physical meaning.

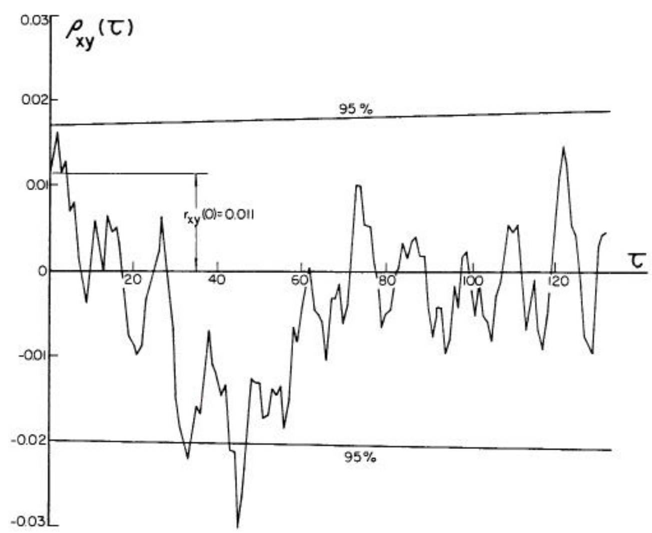

Figure 3 Cross-correlogram between the monthly values of precipitation and the monthly sunspot numbers, as an average of 88 stations in western North America, with the confidence limits at the 95 percent probability level.

On the basis of Figs. 2 and 3, the statistical inference shows that, on the average, no significant relationship exists between hydrologic time series and sunspots. Because hydrologic time series do not show periodic movements longer than a year, the movements in cross-correlograms, which are still within the confidence limits, only point out the periodicity existing in one series--in this case in the sunspot series.

Figure 3 of the average cross-correlogram of monthly precipitation and monthly sunspot numbers shows for $\tau \geq 0$, or for rainfall following sunspots, that nearly all ρ_k - values are within the confidence limits at the 95 percent level; only 3 out of 132 values are outside. In other words, about 99 percent are within. Therefore, statistically speaking, the cross correlogram of Fig. 3 is not significantly different from zero or from two uncorrelated time series.

The lag $\tau = 11$ of Fig. 2 and $\tau = 132$ of Fig. 3 correspond approximately to the average sunspot cycle. For annual series, the average values of cross-correlation coefficients at the lag $\tau = 11$ are: annual precipitation (173 stations), $\rho_{11} = 0.00678$; annual runoff (16 stations), $\rho_{11} = 0.06289$; and annual effective precipitation (16 stations), $\rho_{11} = -0.03107$. For monthly precipitation, the average value of cross-correlation coefficients (88 stations) at the lag $\tau = 132$ is $\rho_{132} = -0.00024$. All these ρ - values are very small.

The variance of the above average cross-correlation coefficients are shown in Figs. 4 and 5 for the annual and monthly series, respectively.

2. Frequency distribution of the cross-correlation coefficients of the series analyzed. If sunspots affect precipitation, a detectable effect of sunspots on series of annual precipitation should show up in the lag correlation coefficients ranging from zero to about three years. The frequency histograms of ρ_0, ρ_1, ρ_2, and ρ_3 for the annual series of precipitation are shown in Fig. 6. In this case, the confidence limits at the 95 percent level for the series of an average length of 79 years are plotted for all four distributions. From the graphs in Fig. 6, it can be concluded that the cross-correlation coefficients are not significantly different from zero for the lags 0, 1, 2, and 3. In all cases, less than 5 percent of the correlation coefficients fall outside the confidence limits, showing that for these lags, the series can be considered uncorrelated.

The frequency histograms of ρ_0, ρ_1, ρ_2, and ρ_3 for the series of annual flow and annual effective precipitation are not shown here, though they have also been plotted with the 95 percent level confidence limits for the series of an average length of 94 years. On the average, one of sixteen values was outside of the confidence limits, this being in agreement with the level of significance used in the graphs.

3. Cross-correlograms for series of annual precipitation. Figure 7, given as Appendix 4, presents the cross-correlograms between the annual precipitation of individual precipitation stations and the annual sunspot numbers.

The graphs for the individual stations, as presented in Fig. 7, Appendix 4, are given with the purpose to show how the cross-correlograms of individual precipitation stations may deviate from the cross-correlograms of two uncorrelated series. The average correlogram of Fig. 2 (line 1) gives only a general picture in the sense that there is no general pattern of relationship between the annual precipitation and the annual sunspot numbers whose pattern is valid for a large region. Figure 2 (line 1) supports the hypothesis that the effect, if any, of sunspot activities on the precipitation is likely to be different from station to station, or from region to region, or from one type of precipitation to another. Therefore, Fig. 2 does not show a general dependence law between the two phenomena being investigated for the cross-correlation. The cross-correlograms of individual precipitation stations may show some other properties which cannot be discriminated by the average cross-correlograms.

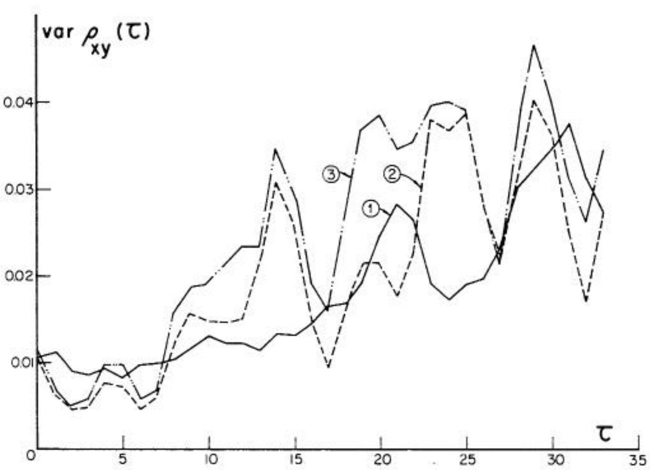

Figure 4 The variance of the average cross-correlation coefficients between the annual values of hydrologic time series and the annual sunspot numbers: (1) annual precipitation; (2) annual runoff; and (3) annual effective precipitation.

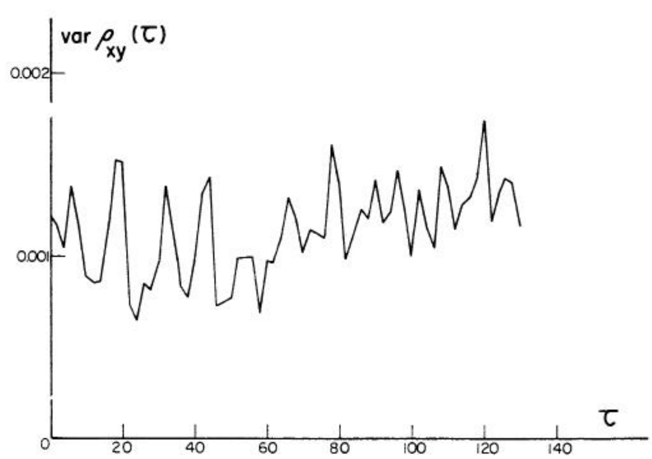

Figure 5 The variance of the average cross-correlation coefficients between the monthly precipitation and the monthly sunspot numbers.

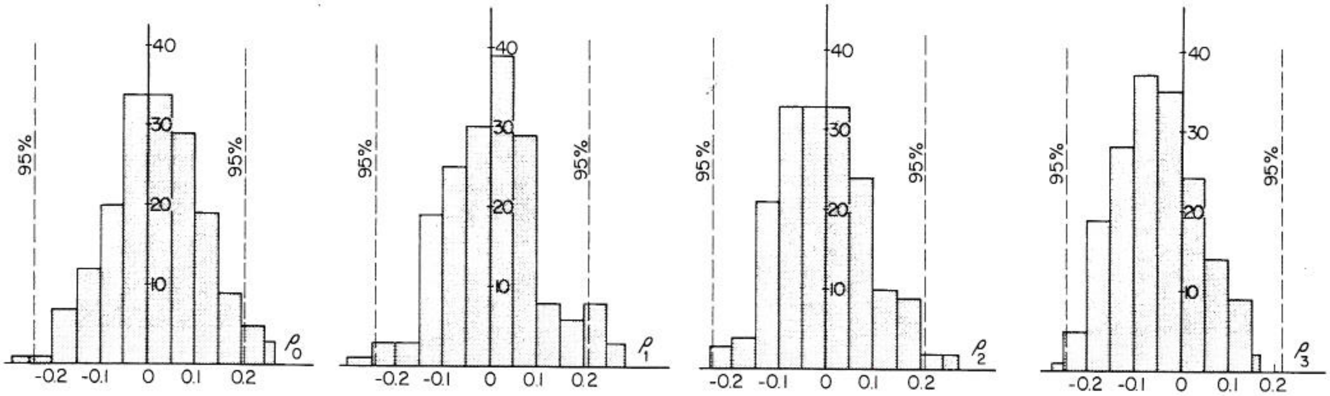

Figure 6 The frequency histograms of cross-correlation coefficients ρ_0, ρ_1, ρ_2 and ρ_3 (sunspots preceding precipitation) for annual precipitation of 173 stations related to sunspot numbers, with the confidence limits of uncorrelated time series at the 95 percent probability levels shown as the vertical dashed lines.

Although the left side of the cross-correlograms (negative τ, or the precipitation proceeds the sunspots) has no physical meaning, it serves a useful purpose. It can be assumed with a high probability that the sunspots are independent of precipitation of previous years. A comparison between the left side (negative τ) with the right side (positive τ) of the cross-correlograms for many individual precipitation station may be a measure of the small effects that the sunspots may have on the hydrologic time series. For this purpose, it was considered useful to present the cross-correlograms of all precipitation stations and both their positive and negative sides of τ, in Appendix 4.

The confidence limits at the 95 percent probability level are plotted for the cross-correlogram of each individual precipitation station.

By the definition of 95 percent confidence interval, three ρ_τ values (or 5 percent) should be outside the confidence limits in each cross-correlogram, if each series and the sunspot series are not correlated. This is, in general, the case observed in Fig. 7, Appendix 4, where most of the cross-correlation coefficients which fall outside the confidence interval correspond to a large lag interval for which the variability of the estimates is larger and its physical significance smaller. One cannot expect with a reasonable probability that the effect of sunspots of a given year may affect the annual precipitation 10 or 20 years hence.

As was shown in Fig. 7, Appendix 4, there are cases where ρ_τ values are significantly different from zero even for short lag intervals; these cases were shown to be a small minority of all 173 cases and do not provide a statistical evidence that sunspots have a significant or large influence on annual precipitation. However, a comparison between the left and right sides of cross-correlograms show a particular pattern. Namely, the right side usually has a larger fluctuation about the cross-correlation coefficient value of zero than the left side, though mainly staying in the confidence limits. These layer fluctuations are usually related to the lag values of $\tau > 15$, or mainly for $\tau = 15$-33. This could lead one to conclude that there may be still a small dependence between the annual precipitation at some stations and the annual sunspot numbers. The fact that most values of cross-correlation coefficients which fall outside the confidence limits are located at large positive values of τ (15-33) works against giving any special and important meaning to the conclusion.

4. Cross-correlograms for series of annual flows and annual effective precipitation. Figure 8, Appendix 5, shows cross-correlograms between the annual runoff of individual runoff stations and the sunspot numbers. The confidence limits at the 95 percent level of significance are also given in the graphs. Figure 9, Appendix 6, gives similar cross-correlograms between the annual effective precipitation of individual runoff stations (basins of these stations) and the sunspot numbers.

The series of annual flows and annual effective precipitation display somewhat larger cross-correlation coefficients with sunspot numbers than the series of annual precipitation previously analyzed. Although, on the average, the cross-correlograms were shown to be non-significantly different from zero, there are individual series like the one of annual flows of the Tennessee River at Chattanooga, which display many cross-correlation coefficients significantly different from zero. It should be stressed that the confidence limits have been determined under the assumption that two series are both mutually uncorrelated and also each individually serially uncorrelated. This last assumption was approximately justified for the annual precipitation (Yevjevich, 1964) because the average first serial correlation coefficient of annual precipitation is about 0.05. However, the annual runoff has an average first-serial correlation coefficient of approximately 0.20 (mainly because of varying water carryover from year to year in river basins), while this approximate average coefficient for the annual effective precipitation on river basins is about 0.15.

When one of the two series is not significantly serially correlated (like annual precipitation) and the other is serially correlated (like annual sunspot numbers), the distribution of their cross-correlation coefficients are not basically affected. However, when both series are serially correlated (like the annual runoff and the annual sunspot numbers, or the annual effective precipitation and the annual sunspot numbers) then the distribution of cross-correlation coefficients is different, and usually the confidence limits at the 95 percent probability level are much wider than for the case of one or both series being serially uncorrelated.

It can be assumed that some of the cross-correlograms in Fig. 7, Appendix 4, with a relatively greater number of cross-correlation coefficients than 5 percent being outside the confidence limits, may be due to the serial correlation of the corresponding series of annual precipitation. The practice of using the confidence limits of two uncorrelated series with one or both of them also being serially uncorrelated and applying them to the case when both series are serially correlated is a biased approach to statistical inference. For the above example of the Tennessee River at Chattanooga, the first serial coefficient of annual runoff is 0.186, which is not a negligible dependence. The first serial correlation coefficients of annual runoff for 16 stations used in this study are given in the last column of Appendix 3. The average of 16 values is 0.253, which clearly shows that the confidence limits in Fig. 8 of Appendix 5, and Fig. 9 of Appendix 6 are too narrow for the cases treated. There is a general tendency in Figs. 8 and 9 for the cross-correlograms to be better located inside the confidence limit the closer the first serial correlation coefficient of a given series of annual runoff or of annual effective precipitation is to zero.

A general conclusion may be advanced at this point. Regardless that the confidence limits were used for the cross-correlograms of the two serially uncorrelated variables, the graphs in Figs. 8 and 9 do not show any significant correlation either between the annual runoff and the annual sunspot numbers or between the annual effective precipitation and the annual sunspot numbers. This is particularly the case for the cross-correlation coefficients ρ_0, ρ_1, ρ_2 and ρ_3.

A second conclusion should also be advanced here; namely, that the confidence limits in the graphs of Figs. 7, 8 and 9 must be determined as soon as a hydrologic time series is serially correlated, because the series of annual sunspot numbers is already serially correlated. In the absence of the exact or approximate theoretical distributions of $\rho_{xy}(\tau)$ as functions of parameters of mathematical models of serial correlation for each of the two cross-correlated series, the data generation method (Monte Carlo Method) may be used to develop the approximate distributions of $\rho_{xy}(x)$ in each particular case. It will be later shown in the example of a precipitation station that the moving average scheme, applied to the two cross-correlated series, produces by its smoothing effect, a distribution of $\rho_{xy}(\tau)$ which has a greater variance than the distribution of $\rho_{xy}(\tau)$ of two mutually uncorrelated time series. It will also be shown that the series of annual sunspot numbers has a cyclic component (of the average cycle of about 11.3 years) and a dependent stochastic component. Even if the cycle is removed, the stochastic component left is a dependent component.

5. Cross-correlograms for series of monthly precipitation. Figure 10, Appendix 7, shows cross-correlograms between individual stations, the monthly precipitation data of individual precipitation stations and the monthly sunspot numbers. The confidence limits at the 95 percent level of significance are also given in the graphs for the case that either one or both of the series are not serially correlated. In this case, there were 132 lags throughout the analyses. This means, from the definition of 95 percent confidence interval of serially uncorrelated time series, that 13 ρ_τ values, or 5 percent of 264 values in each cross-correlogram, should be outside the confidence limits, if each series and the monthly sunspot numbers are not correlated. This is, in general, the observed case although there exist series which show more than 13 correlation coefficients significantly different from zero.

Only the right side of cross-correlograms is shown in Fig. 10, which for the monthly sunspot number preceding the monthly precipitation or being concurrent with them, is the basic hypothesis of their physical relationship. These graphs are given in this study to show the type of cross-correlation of many individual stations in contrast to the average cross-correlogram of monthly precipitation related to monthly sunspot numbers, given in Fig. 3.

All cross-correlograms, either those in Fig. 3 or in Fig. 10, show the effect of a 12-month cycle inside the monthly precipitation. However, this cyclic fluctuation is mainly contained inside the confidence limits.

By inspecting the graphs in Fig. 10, Appendix 7, and taking into account that both the monthly precipitation series and the monthly sunspot numbers are serially correlated (therefore the confidence limits are too narrow for these types of series), it can be concluded that there is no significant statistical relationship between the monthly precipitation and the monthly sunspot numbers.

6. Cross-spectral results of the analyses. Complete cross-spectral analyses were made between each series of the different ensembles and the corresponding sunspot numbers. Only the more significant results, together with some individual examples, will be given in this paper.

7. Frequency distribution of coherence coefficients. There are two coherence coefficients that have special significance: the coherence at the frequency of 1/11 cycles per year and the coherence at 1/22 cycles per year. These frequencies correspond to the sunspot cycle and the double-sunspot or Hale cycle, respectively. The distribution histograms for the coherence at the frequencies previously mentioned are presented in Figs. 11 and 12, for the 173 series of annual precipitation investigated by the cross-spectral analysis. The confidence limits at the 95 percent probability level for the coherence are computed for the average length of cross-correlated time series of 79 years. Similar distribution histograms of coherence were also computed for the annual runoff and annual effective precipitation of 16 stations, but because of the small sample of 16, the results are less important than the above sample of 173 for the annual precipitation.

Due to the relatively large number of lags used in the analysis, the significance levels are extremely high, with none of the coherence coefficients falling outside the confidence interval. Until larger hydrologic series become available, this problem will have to be faced by any researcher interested in detecting large period cycles in hydrology by spectral

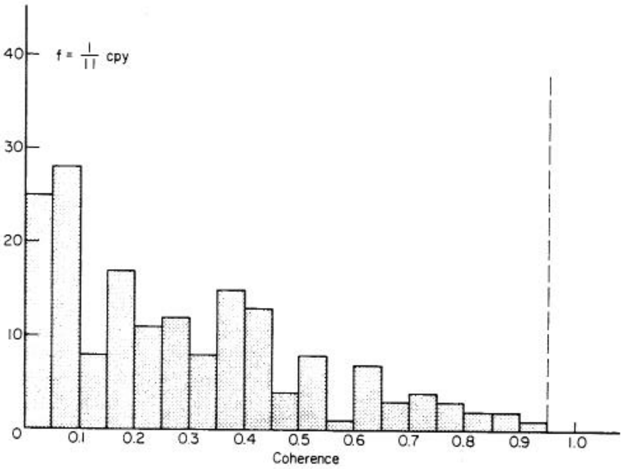

Figure 11 The distribution histogram of the coherence for the 173 series of annual precipitation investigated by the cross-spectral analysis with the series of annual sunspot numbers for the basic frequency 1/11 cycles per year, with the confidence limit of coherence at the 95 percent level (for the average time series length of 79 years) falling far outside the graph.

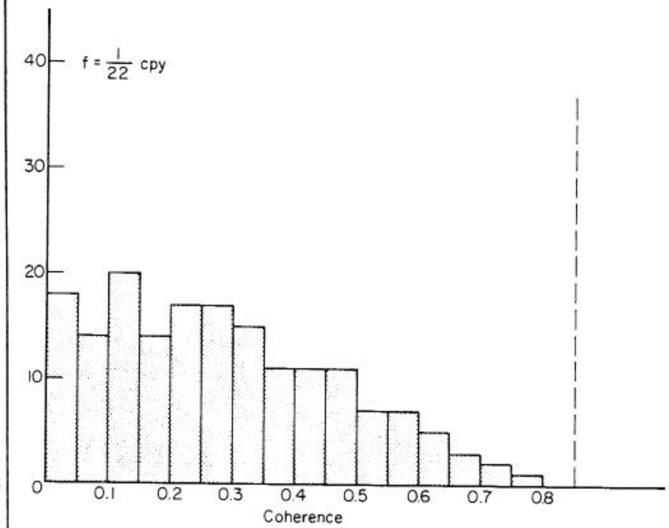

Figure 12 The distribution histogram of the coherence for the same conditions except the basic frequency is 1/22 cycles per year.

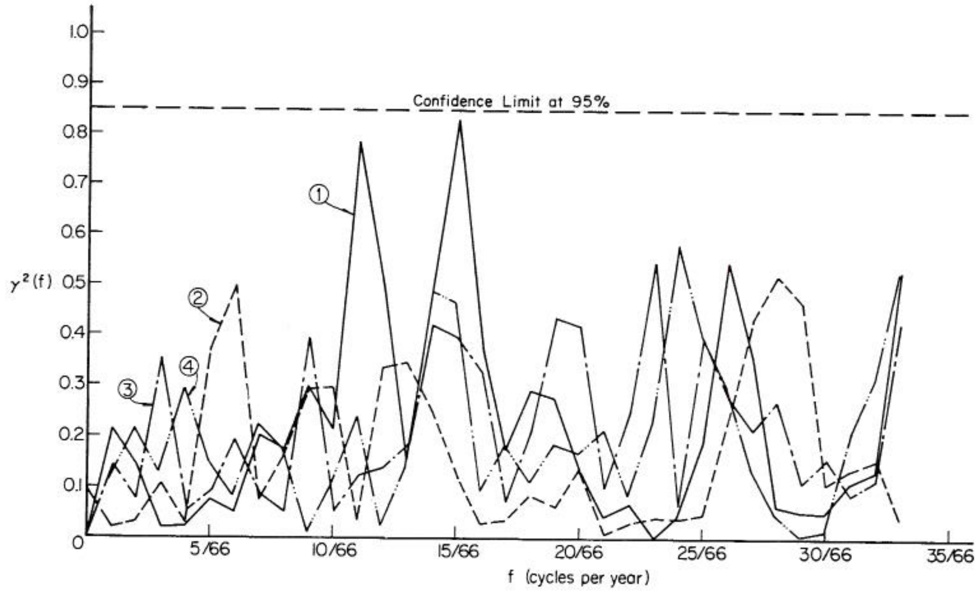

Figure 13 The function of the square of coherence to the frequency in cycles per year for four individual series of annual runoff and the annual sunspot numbers, with the confidence limit at the 95 percent level (0.85): (1) The Nemunas River at Smolinkai; (2) The Gota River at Vanersburg; (3) The Danube River at Orshava; and (4) The Rhine River at Basle.

methods. Due to the large significance levels obtained, the coherence results obtained here can be considered only as tentative.

Examples of coherence functions (the function of the square of coherence to the frequency in cycles per year) for seven individual hydrologic series of annual values and the annual sunspot numbers are given in Fig. 13 (four river stations) and in Fig. 14 (three precipitation stations). The confidence limits at the 95 percent probability level show that there is no frequency for which the square of coherence is significant, especially 1/11 and 1/22.

8. Examples of spectra of residuals. As explained in Chapter III, the spectra of residuals (a standardized hydrologic time series minus the standardized sunspot numbers), $G_\eta(f)$, will give an idea of the periodicities in the sunspot series which are not shared by the hydrologic series. The seven time series, which are examined for the coherence function in Figs. 13 and 14, also serve as examples for the spectra of residuals. Figure 15 gives the spectrum of the annual sunspot numbers, clearly showing the cycle of about 11 years, as well as some stochastic dependence of the stochastic component when the

cycle of 11 years is removed. The spectra of residuals for the four series of annual runoff (the Nemunas, the Gota, the Danube and the Rhine) are given in Fig. 16, and those of the three series of annual precipitation (Elko, Walla-Walla, Dalles) in Fig. 17.

It may be observed from the spectra of residuals of Figs. 16 and 17 that the large peak at 1/11 cycles per year for each of seven cases do not differ from the peak of the spectrum of sunspot numbers as given in Fig. 15. This suggests, indirectly, that the 11-year cycle of sunspots does not exist in the hydrologic time series.

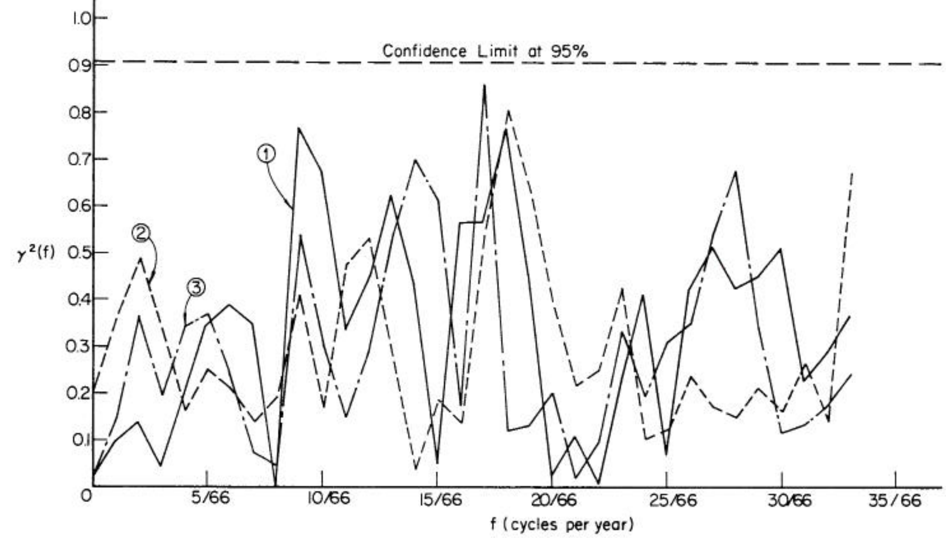

Figure 14 The function of the square of coherence to the frequency in cycles per year for three individual series of annual precipitation and the annual sunspot numbers, with the confidence limit at the 95 percent level (0.91): (1) Elko - 26.2573; (2) Walla-Walla - 14.8931; and (3) The Dalles - 35,8407.

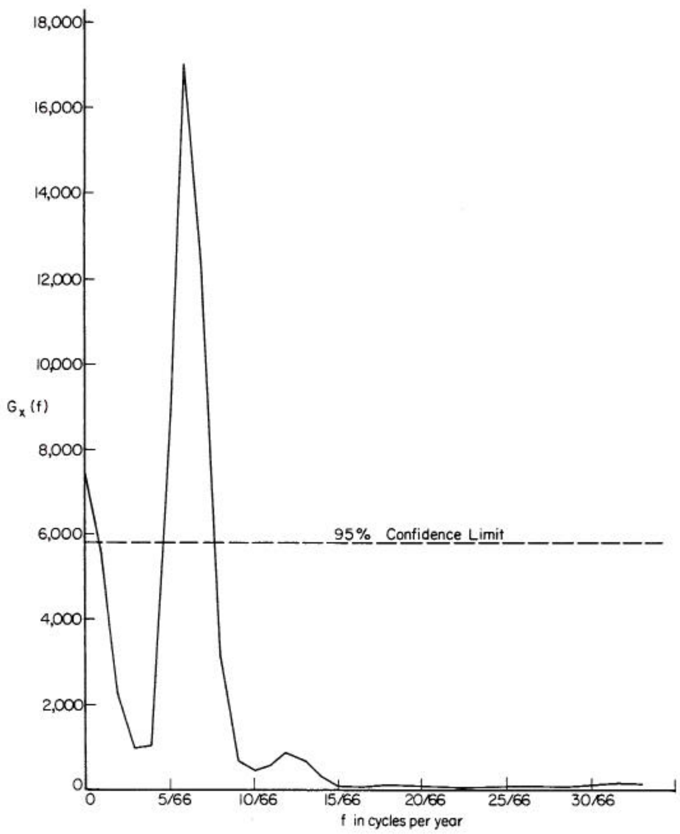

Figure 15 The spectrum of the annual values of sunspot numbers.

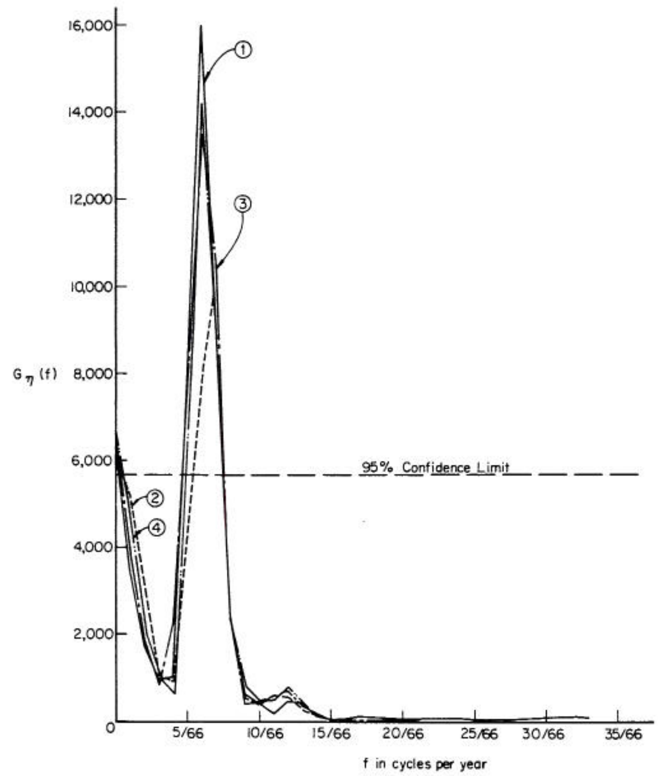

Figure 16 The spectrum of residuals (standardized annual runoffs minus standardized annual sunspot numbers) for four rivers (1) The Nemunas; (2) The Gota; (3) The Danube; and (4) The Rhine.

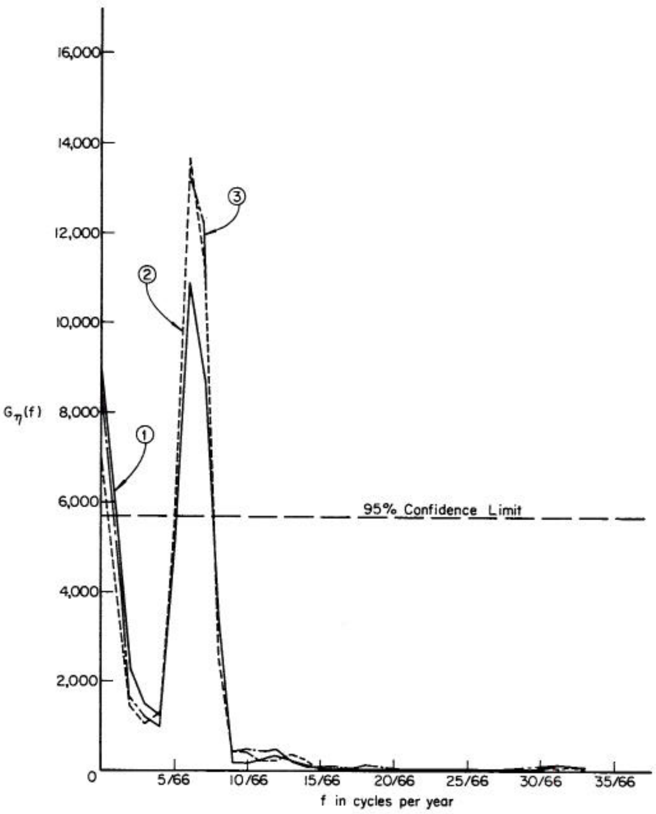

Figure 17 The spectrum of residuals (standardized annual precipitation values minus standardized annual values of sunspot number) for three precipitation stations: (1) Elko; (2) Walla-Walla; and (3) Dalles.

Chapter VI

THE EFFECT OF SMOOTHING TIME SERIES ON CROSS-CORRELATION

1. Effect of smoothing on cross-correlation. The smoothing of time series by moving average schemes and other types of smoothing filters is a common practice in hydrology, but it has not been always realized that the use of this method may sometimes affect the results of an investigation. The effect of linear filters on the cross-correlation function between two time series will be briefly investigated in this chapter.

Consider two random input functions $x_1(t)$ and $x_2(t)$ related to two output functions $y_1(t)$ and $y_2(t)$ through a linear filter function $h(t)$ by means of a simple convolution:

$$y_1(t) = \int_{\infty}^{\infty} x_1(t-u)\, h_1(u)\, du \tag{21}$$

$$y_2(t) = \int_{\infty}^{\infty} x_2(t-s)\, h_2(s)\, ds \tag{22}$$

Conceptually, $h(\tau)$ represents the way the system responds to being hit with a unit impulse at $(\tau + t)$ and is the impulse response function.

In order to simplify the notation, assume $E[x_1(t)] = E[x_2(t)] = 0$. The cross-covariance between the outputs can be written as

$$\alpha_{y_2 y_1}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} y_1(t)\, y_2(t+\tau)\, dt\ , \tag{23}$$

or by replacing $y_1(t)$ and $y_2(t)$ with their expressions from Eqs. (21) and (22)

$$\alpha_{y_2 y_1}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} dt \int_{-\infty}^{\infty} x_1(t-u)\, h_1(u)\, du \cdot$$

$$\cdot \int_{-\infty}^{\infty} x_2(t+\tau-s)\, h_2(s)\, ds =$$

$$= \int_{-\infty}^{\infty} h_1(u)\, du \int_{-\infty}^{\infty} h_2(s)\, ds \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x_1(t-u)\, x_2(t+\tau-s)\, dt$$

or

$$\alpha_{y_2 y_1}(\tau) = \int_{-\infty}^{\infty} h_1(u)\, du \int_{-\infty}^{\infty} h_2(s)\, ds\ \alpha_{x_2 x_1}(\tau + u - s). \tag{24}$$

Putting $t = s - u$ in Eq. (24), one gets

$$\alpha_{y_2 y_1}(\tau) = \int_{-\infty}^{\infty} h_1(u)\, du \int_{-\infty}^{\infty} h_2(t+u)\, dt\ \alpha_{x_2 x_1}(\tau - t)$$

$$= \int_{-\infty}^{\infty} \alpha_{x_2 x_1}(\tau - t)\, dt \int_{-\infty}^{\infty} h_1(u)\, h_2(t+u)\, du\ . \tag{25}$$

The integral $\int_{-\infty}^{\infty} h_1(u)\, h_2(t+u)\, du$ represents the cross-covariance of the impulse response functions $h_1(t)$ and $h_2(t)$:

$$\alpha_{h_2 h_1}(\tau) = \int_{-\infty}^{\infty} h_1(t)\, h_2(t+\tau)\, dt, \tag{26}$$

so, one can write

$$\alpha_{y_2 y_1}(\tau) = \int_{-\infty}^{\infty} \alpha_{x_2 x_1}(\tau - t)\ \alpha_{h_2 h_1}(t)\, dt \tag{27}$$

Equation (27) shows that the cross-covariance function of the filtered series is equal to the convolution of the cross-covariance function of the original series and the cross-covariance function of the filters $h_1(t)$ and $h_2(t)$.

The cross-correlation function between $y_2(t)$ and $y_1(t)$ is obtained by dividing Eq. (27) by the product of the standard deviations of $y_2(t)$ and $y_1(t)$:

$$\rho_{y_2 y_1}(\tau) = \frac{\int_{-\infty}^{\infty} \alpha_{h_2 h_1}(t)\ \alpha_{x_2 x_1}(\tau - t)\, dt}{\sigma_{y_2}\ \sigma_{y_1}} \tag{28}$$

where

$$\sigma^2_{y_2} = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} y^2_2 (t)\, dt$$

and

$$\sigma^2_{y_1} = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} y^2_1 (t)\, dt .$$

From Eq. (27), it is seen that the cross-correlogram of the smoothed series is, in general, different from the cross-correlogram of the unsmoothed series. It is also observed that if the expected cross-correlation coefficient of two original series is zero at every lag τ, the expected coefficient of the two smoothed series will also be zero at every lag. However, two finite uncorrelated series have a cross-correlogram with correlation coefficients which oscillate around the expected values of zero within the confidence limits of a given variance of coefficient distributions. Thus, when two uncorrelated series are smoothed and the confidence limits used are the same as for serially uncorrelated series, many of the cross-correlation coefficients may be significantly different from zero when determined by the probability level of confidence limits.

2. Example. An example is presented in Fig. 18 by using the Karachi precipitation station. In this case, both series, the July precipitation in Karachi and the annual sunspot numbers, were smoothed by the simple linear moving average scheme $x_t = \frac{1}{3}x_t + \frac{1}{3}x_{t+1} + \frac{1}{3}x_{t+2}$. Smoothing the series produced the cross-correlation coefficients which fluctuate in a larger range than do the cross-correlation coefficients of the original series of precipitation in July at Karachi (Nagvi, 1958) and the annual sunspot numbers.

On the other hand, it has been proven by Rodriguez-Iturbe (1967) that the use of linear filters does not affect the coherence function between the two time series.

Because many researchers have used the moving average of 10-30 members of the series, their confidence limits should be much wider than Fig. 18 points out for only a 3-member simple moving average scheme. The confidence limits should be wider with greater smoothing.

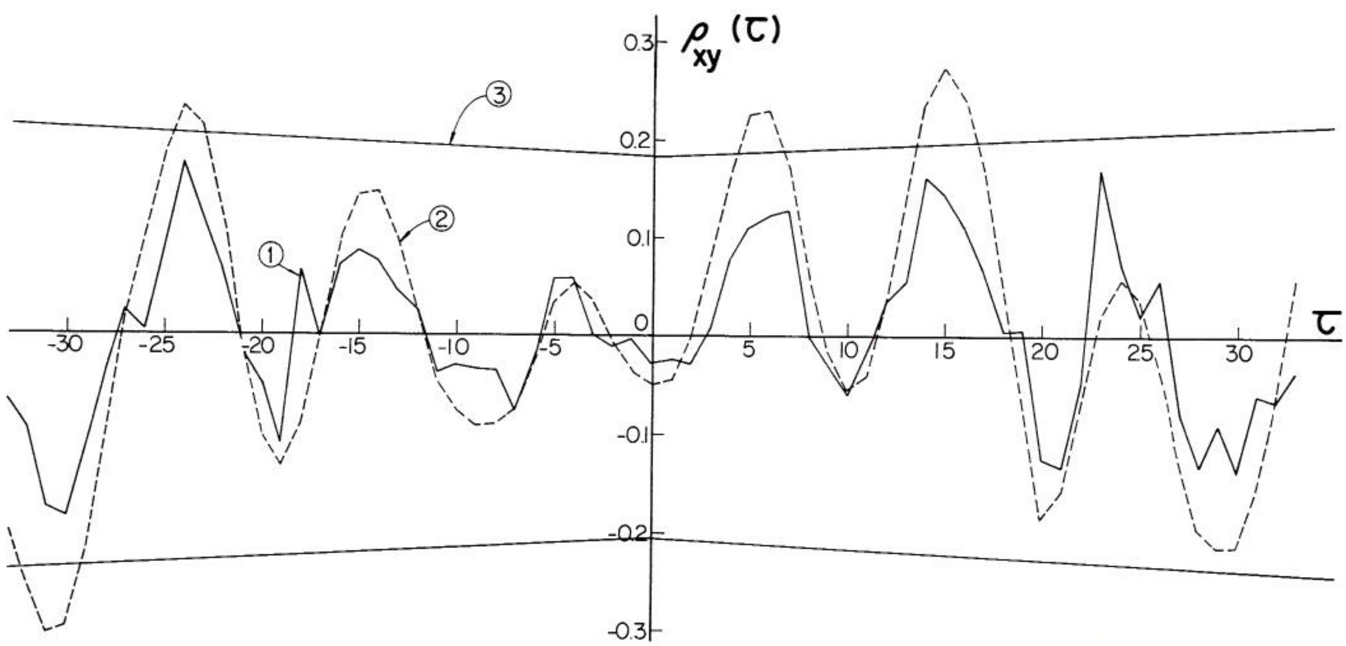

Figure 18 A comparison of cross-correlograms between the series of July precipitation in Karachi (Pakistan) and the series of annual sunspot numbers: (1) original unsmoothed series; (2) series smoothed by the simple (linear) moving average scheme of three successive values; and (3) confidence limits at the 95 percent probability level for unsmoothed series.

Chapter VII

CONCLUSIONS

The main results of this investigation led to the following conclusions:

1. On the average, no statistical evidence exists, either for the simultaneous correlation or the lag correlation, that proves any significant correlation between precipitation or runoff series and sunspot numbers.

2. The eleven-year sunspot cycle does not appear to be present in the series analyzed in this paper.

3. The smoothing of original time series by linear filters (a practice sometimes applied), if carried out before cross-correlation analysis is undertaken, increases sampling fluctuations (or confidence limits) of the cross-correlation function. If this result is not taken into account and if the confidence limits of unsmoothed series are used, incorrect conclusions may be reached about the significance of the relationship between hydrologic time series and sunspot numbers.

4. Since the hydrologic time series are sometimes serially correlated, while the sunspot numbers are always serially correlated, it is not necessary to smooth time series in order to perform a biased statistical test. In developing confidence limits for two mutually uncorrelated time series, it is implicitly assumed that at least one series is not serially correlated. When both series are serially correlated, the confidence limits must be changed by increasing the confidence interval for the same level of probability.

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APPENDICES

1 through 7

TABLE 1

APPENDIX 1

ANNUAL PRECIPITATION STATIONS USED FOR THE INVESTIGATIONS

Station Number	Name	Latitude	Longitude	Number Years
2. 6796	Prescott	34. 5500	112. 4500	87
2. 8815	Tuscon U of Arizona	32. 2333	110. 9500	85
3. 0234	Arkansas City	33. 6167	91. 2000	74
3. 1596	Conway	35. 0833	92. 4667	77
3. 1838	Dardanelle	35. 2167	93. 1500	74
3. 2444	Fayetteville Exp. Station	36. 1000	94. 1667	71
3. 2670	Fulton	33. 6167	93. 8000	75
3. 3242	Helena	34. 5333	90. 5833	87
3. 4756	Mena	34. 5833	94. 2500	71
3. 6918	Stuttgart	34. 4833	91. 5333	73
4. 0227	Antioch F. Mills	38. 0167	121. 7667	82
4. 0383	Auburn	38. 9000	121. 0667	90
4. 0693	Berkeley	37. 8667	122. 2500	74
4. 1018	Bowman Dam	39. 4500	120. 6667	75
4. 1715	Chico Exp. Station	39. 7000	121. 7833	90
4. 1912	Colfax	39. 1000	120. 9667	91
4. 2239	Cuyamaca	32. 9833	116. 5833	73
4. 2294	Davis 1 WSW	38. 5333	121. 7500	89
4. 2910	Eureka WB City	40. 8000	124. 1667	74
4. 3157	Fort Bidwell	41. 8500	120. 1333	72
4. 3191	Fort Ross	38. 5167	123. 2500	86
4. 3571	Grass Valley	39. 2000	121. 0333	88
4. 3875	Healdsburg	38. 6167	122. 8667	84
4. 4022	Hollister	36. 8500	121. 4000	87
4. 5118	Los Banos	37. 0500	120. 8500	88
4. 5385	Marysville	39. 1500	121. 6000	90
4. 5738	Modesto	37. 6500	121. 0000	79
4. 5983	Mount Shasta WB City	41. 3167	122. 3167	73
4. 6074	Napa State Hospital	38. 2833	122. 2667	82
4. 6305	Oakdale Woodward Dam	38. 8667	120. 8667	72
4. 6506	Orland	39. 7500	122. 2000	78
4. 6826	Petaluma Fire Station No. 2	38. 2333	122. 6333	70
4. 6960	Placerville	38. 7333	120. 8000	84
4. 7077	Porterville	36. 0667	119. 0167	72
4. 7306	Redlands	34. 0500	117. 1833	72
4. 7470	Riverside Fire Station No. 3	33. 9500	117. 4000	80
4. 7723	San Bernardino	34. 1333	117. 2667	90
4. 7740	San Diego WB AP	32. 7333	117. 1667	111
4. 7851	San Luis OBISPO POLY	35. 3000	120. 6667	91
4. 7912	Santa Clara University	37. 3500	121. 9333	79
4. 7965	Santa Rosa	38. 4500	122. 7000	72
4. 8353	Sonora	37. 9833	120. 3833	73
4. 9087	Tustin Irvine Ranch	33. 7333	117. 7833	84
4. 9122	Ukiah	39. 1500	123. 2000	84
4. 9177	Upper Mattole	40. 2500	124. 1833	74
4. 9200	Vacaville	38. 3667	122. 0000	81
4. 9367	Visalia	36. 3333	119. 3000	81
4. 9490	Weaverville RS	40. 7333	122. 9333	71
4. 9699	Willows	39. 5333	122. 2000	82
5. 1121	Burlington	39. 3000	102. 2667	70
5. 1294	Canon City	38. 4333	105. 2267	72
5. 3005	Fort Collins	40. 5833	105. 0833	80
5. 3038	Fort Morgan	40. 2500	103. 8000	72

TABLE 1 (continued)

APPENDIX 1 - Continued

ANNUAL PRECIPITATION STATIONS USED FOR THE INVESTIGATIONS

Station Number	Name	Latitude	Longitude	Number Years
5.3546	Greeley	40.3333	194.6833	72
5.4834	Las Animas	38.0667	103.2167	94
5.5722	Montrose No. 2	38.4833	107.8833	72
5.7167	Rocky Ford	38.0333	103.7000	72
5.9295	Yuma	40.1167	102.7333	71
10.7264	Porthill	49.0000	116.5000	71
13.0112	Albia	41.0333	92.8000	70
13.0173	Alta	42.6667	95.3000	71
13.0205	Ames 3SW	42.0000	93.6500	85
13.0576	Atlantic 1 NE	41.4167	95.0000	74
13.0600	Belle Plaine	41.9000	92.2667	71
13.1402	Charles City	41.0667	92.6833	78
13.1731	Columbus Junction	41.2833	91.3667	70
13.2789	Fairfield	41.0167	91.9500	79
13.2999	Fort Dodge	42.5167	94.1667	70
13.3473	Grinnell	41.9167	92.7333	77
13.3985	Humbolt No 2	42.7167	94.2167	77
13.4381	Keokuk L and D No. 19	40.4000	91.3667	90
13.4894	Logan	41.6333	95.8000	95
13.6243	Onawa	42.0353	96.1000	76
13.6391	Ottumwa	41.0000	92.4333	71
13.7312	Sac City	42.4333	94.9833	84
14.0365	Ashland DDC 8	37.2000	99.7667	72
14.0405	Atchison	39.5667	95.1167	70
14.1699	Colby 1 SW	39.3833	101.0667	71
14.1769	Concordia WB City	39.5667	97.6667	76
14.2541	Emporia 1S	38.3833	96.1833	80
14.3527	Hays 1S	38.8667	99.3333	93
14.4972	Manhattan No. 2	39.2000	96.5833	103
14.5906	Oberlin	39.8167	100.5333	74
14.7305	Sedan	37.1167	96.1667	76
14.8287	Ulysses	37.5833	101.3500	70
14.8495	Wakeeney	39.0167	99.8833	78
16.1411	Calhoun Exp. Station	32.5167	92.3333	70
16.2534	Donaldsonville	30.1000	91.0000	72
16.6117	Melville	30.6833	91.7500	74
16.6659	New Orleans WB City	29.9500	90.0667	114
23.1037	Brunswick	39.4167	93.1333	80
23.1822	Conception	40.2500	94.6833	75
23.2823	Fayette	39.1500	92.6833	75
23.3601	Hannibal W W	39.7167	91.3667	75
23.3649	Harrisonville	38.6500	94.3333	81
23.3793	Hermann	38.7000	91.4500	86
23.4226	Jackson	37.3833	89.6667	71
23.4705	Lamar	37.5000	92.2667	78
23.4904	Lexington	39.1833	93.8833	79
23.5093	Louisiana Starks N	39.4333	91.0667	78
23.5541	Mexico	39.1833	91.9000	83
23.5976	Neosho	36.8667	94.3667	78
23.6357	Oregon	39.9833	95.1333	105
23.8712	Warrensburg	38.7667	93.7333	78
24.3581	Glendive	47.1000	104.7167	71
24.3994	Harve WB City	48.5667	109.6667	81

TABLE 1 (continued)

APPENDIX 1 - Continued

ANNUAL PRECIPITATION STATIONS USED FOR THE INVESTIGATIONS

Station Number	Name	Latitude	Longitude	Number Years
24.4055	Helena WB AP	46.6000	112.0000	79
24.5740	Missoula 2WNW	46.8833	114.0333	78
24.6660	Poplar	48.1167	105.2000	71
25.0640	Beaver City	40.1333	99.8333	79
25.2020	Crete	40.6167	96.9500	81
25.2065	Culbertson	40.2167	100.8333	73
25.3015	Fort Robinson	42.6667	103.4667	77
25.3015	Franklin	40.1000	98.9500	72
25.3050	Fremont	41.4333	96.4833	79
25.3175	Geneva	40.5333	97.6000	70
25.3185	Genoa	41.4500	97.7333	85
25.3910	Holdredge	40.4333	99.3833	71
25.4110	Imperial	40.5167	101.6333	70
25.4335	Kearney	40.7000	99.0833	84
25.4440	Kimball	41.2333	103.6667	72
25.5805	Nebraska City 1WNW	40.6833	95.8833	85
25.5990	Norfolk	42.0333	97.4167	75
25.6040	North Loup	41.5000	98.7667	77
25.6135	Oakdale	42.0667	97.9667	72
25.7040	Ravenna	41.0333	98.9167	83
25.7715	Seward	40.9000	97.1000	70
25.8395	Syracuse	40.6500	96.1833	79
25.8410	Table Rock 5 N	40.2500	96.0833	72
25.8465	Tecumseh	40.3667	96.1833	80
25.8760	Valentine WB AP	42.8667	100.5500	72
25.9090	Weeping Water	40.8833	96.1333	83
25.9200	West Point	41.8333	96.7167	74
25.9510	York	40.8667	97.6000	72
26.2573	Elko WB AP	40.8333	115.7833	91
26.6779	Reno WB AP	39.5000	119.7833	90
29.2436	Deming	32.2667	107.7500	79
29.3265	Fort Bayard	32.8000	108.1500	92
29.5079	Lordsburg	32.3500	108.7000	80
29.8535	State University	32.2833	106.7500	74
35.0078	Albany	44.6500	123.1000	82
35.3445	Grants Pass	42.4333	123.3167	72
35.4003	Hood River Exp. Station	45.6833	121.5167	77
35.6761	Portland WB City	45.5333	122.6667	89
35.7326	Roseburg WB AP	43.2333	123.3667	83
35.8407	The Dalles	45.6000	121.2000	94
35.8734	Umatilla	45.9167	119.3500	73
39.1076	Brookings 1 NE	44.3333	96.7667	72
39.5536	Milbank	45.2167	96.6333	71
41.0120	Albany	32.7333	99.3000	79
41.0367	Arthur City	33.8833	95.5000	70
41.1048	Brenham	30.1667	96.3833	72
41.1875	Coleman	31.8333	99.4333	70
41.2019	Corsicana	32.0833	96.4667	81
41.3430	Galveston WB City	29.3000	94.8333	90
41.4305	Houston WB City	29.7667	95.3667	82
41.4382	Huntsville	30.7333	95.5667	73
41.6276	New Braunfels	29.7000	98.1167	71
41.9532	Weatherford	32.7500	97.8000	70

TABLE 1 (continued)

APPENDIX 1 - Continued

ANNUAL PRECIPITATION STATIONS USED FOR THE INVESTIGATIONS

Station Number	Name	Latitude	Longitude	Number Years
42. 1731	Corinne	41. 5500	112. 1167	91
42. 2996	Fort Duchesne	40. 2833	109. 8500	71
42. 5065	Levan	39. 5500	111. 8667	70
42. 5733	Moab	38. 6000	109. 6000	71
42. 7598	Salt Lake City WB AP	40. 7667	111. 9667	86
45. 1586	Colfax 1 NW	46. 8833	117. 3833	71
45. 6096	Olga 2 SE	48. 6167	122. 8000	71
45. 8931	Walla Walla WB City	46. 0333	118. 3333	93
48. 1675	Cheyenne WB AP	41. 1500	104. 8167	87
48. 5410	Laramie	41. 3000	105. 5667	78
48. 9905	Yellowstone Park	44. 9667	110. 7000	72
91. 0050	Agassiz	49. 2333	121. 7667	71
91. 9320	Victoria Gonzales Hts. (S)	48. 4167	123. 3167	72
92. 1200	Calgary	51. 0667	114. 0167	76

TABLE 2

APPENDIX 2

MONTHLY PRECIPITATION STATIONS USED FOR THE INVESTIGATIONS

Station Number	Name	Latitude	Longitude	Number Years
2.6561	Pinal Ranch	33.35	110.98	65
2.8815	Tuscon University of Arizona	32.23	110.95	66
3.0234	Arkansas City	33.62	91.20	72
3.0460	Batesville L. and D. No. 1	35.75	91.63	61
3.1596	Conway	35.08	92.47	77
3.2444	Fayettesville Exp. Station	36.10	94.17	70
3.5820	Pocahontas	36.27	90.98	67
3.6928	Subiaco	35.30	93.65	63
4.0227	Antioch F. Mills	38.02	121.77	81
4.0383	Auburn	38.90	121.07	61
4.3161	Fort Bragg	39.95	123.80	61
4.3191	Fort Ross	38.52	123.25	85
4.4022	Hollister	36.85	121.40	87
4.6118	Needles	34.77	114.62	69
4.7740	San Diego WB Apt.	32.73	117.17	111
4.7851	San Luis OBISPO POLY	35.30	120.67	91
4.8353	Sonora	37.98	120.38	73
4.9087	Tustin Irvin Ranch	33.73	117.78	84
4.9452	Wasco	35.60	119.33	61
4.9490	Weaverville RS.	40.73	122.93	71
4.9699	Willows	39.53	122.20	82
5.1294	Cannon City	38.43	105.27	67
5.1564	Cheyenne Wells	38.82	102.35	64
5.2432	Durango	37.28	107.88	66
5.3005	Fort Collins	40.58	105.08	63
5.4834	Las Animas	38.07	103.22	94
5.5722	Montrose No. 2	38.48	107.88	70
5.9295	Yuma	40.12	102.73	71
10.6542	Oakley	42.23	113.88	67
13.0364	Atlantic 1 NE	41.42	95.00	70
13.2208	Des Moins WB City	41.58	93.62	83
13.6391	Ottumwa	41.00	92.43	68
13.7161	Rockwell City	42.40	94.62	65
14.1769	Concordia WB City	39.57	97.67	75
14.5173	Medicine Lodge	37.27	98.58	68
14.6374	Phillipsburg	39.77	99.32	69
14.7305	Sedan	37.12	96.17	76
14.8186	Toronto	37.80	95.95	64
16.1411	Calhoun Exp. Station	32.52	92.33	69
16.4700	Jennings	30.23	92.67	63
16.6117	Melville	30.68	91.75	74
16.6659	New Orleans WB City	29.95	90.07	91
16.7344	Plain Dealing	32.90	93.68	67
23.2823	Fayette	39.15	92.68	76
23.3793	Hermann	38.70	91.45	86
23.5976	Neosho	36.87	94.37	78
23.7720	Shelbina	39.68	92.05	67
23.8712	Warrensburg	38.77	93.73	77
25.0930	Blair	41.55	96.13	91
25.1145	Bridge Port	41.67	103.10	63
25.2020	Crete	40.62	96.95	81
25.2805	Ewing	42.25	98.35	68
25.3015	Fort Robinson	42.67	103.47	77
25.3185	Genoa	41.45	97.73	85

TABLE 2 (continued)

APPENDIX 2 - Continued

MONTHLY PRECIPITATION STATIONS USED FOR THE INVESTIGATIONS

Station Number	Name	Latitude	Longitude	Number Years
25.3630	Hartington	42.62	97.27	69
25.7040	Ravenna	41.03	98.92	83
26.2573	Elko WB Apt.	40.83	115.78	91
26.6779	Reno WB Apt.	39.50	119.78	90
29.3265	Fort Bayard	32.80	108.15	90
29.8535	State University	32.28	106.75	100
32.2188	Dickenson Exp. Station	46.88	102.80	69
32.3621	Grand Forks U.	47.92	97.08	69
32.4418	Jamestown St. Hosp.	46.88	98.68	68
32.6025	Mohall	48.77	101.52	67
34.9445	Webber Falls	35.52	95.13	62
35.3445	Grants Pass	42.43	123.32	72
39.0290	Armour	43.32	98.35	63
39.4661	Ladelle 7 NE	44.68	98.00	64
39.5536	Milbank	45.22	96.63	71
39.7667	Sioux Fall WB AP	43.57	96.73	70
41.0120	Albany	32.73	99.30	79
41.0611	Beaumont	30.08	94.10	68
41.1138	Brownwood	31.72	98.98	68
41.2019	Corsicana	32.08	96.47	75
41.3430	Galveston WB City	29.30	94.83	89
41.4780	Kerrville	30.03	99.13	65
41.5018	Lampasas	31.05	98.18	66
41.9532	Weatherford	32.75	97.80	67
42.2101	Dessert	39.28	112.65	61
42.2996	Fort Duchesne	40.28	109.85	71
42.8771	Tooele	40.53	112.30	64
45.1350	Chelan	47.83	120.03	69
45.1586	Colfax 1 N W	46.88	117.38	69
45.7507	Sedro Wolley 1 E	48.50	122.22	64
45.8207	Sunnyside	46.32	120.00	66
45.8332	Tatoosh Island WB	48.38	124.73	77
48.5830	Lusk	42.77	104.43	62
48.9905	Yellowstone Park	44.97	110.70	72

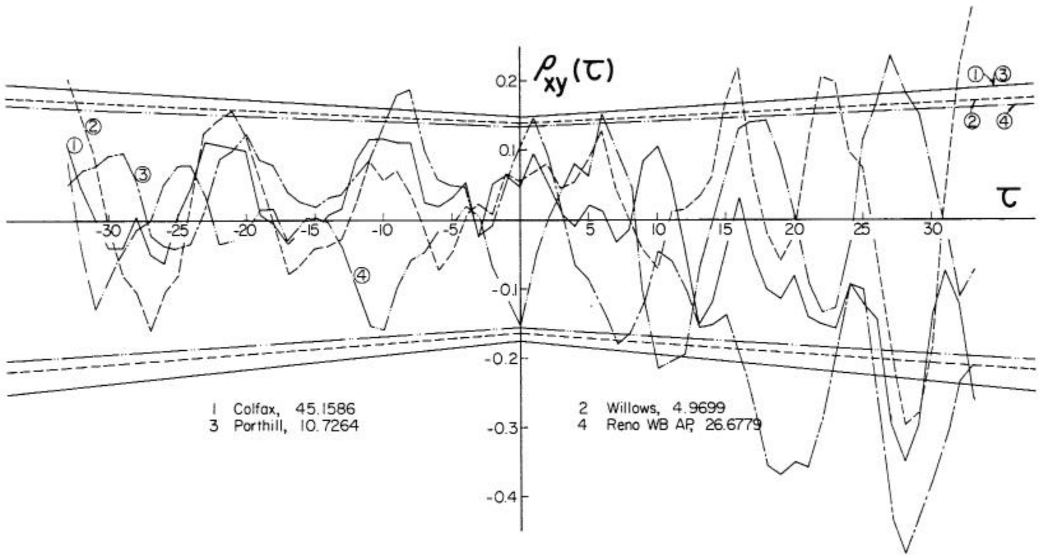
TABLE 3

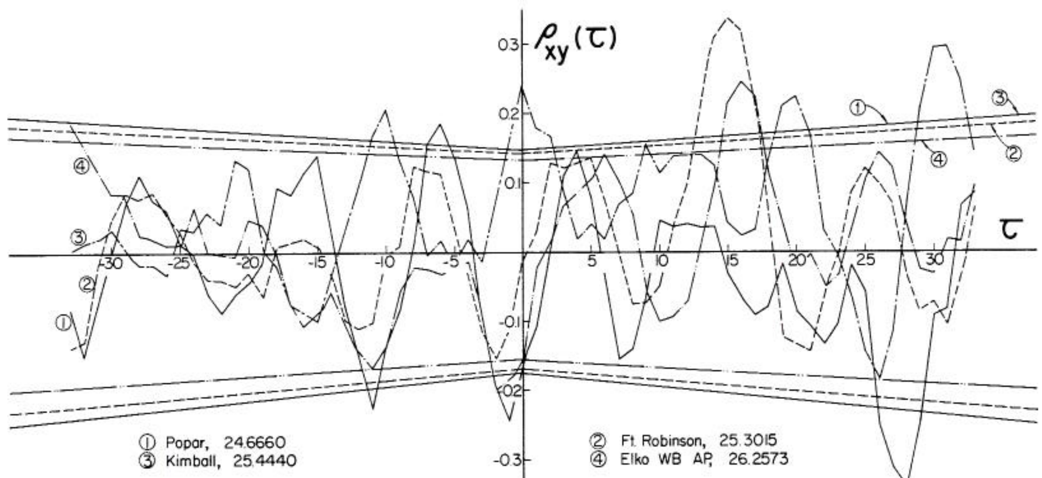
APPENDIX 3

RUNOFF STATIONS USED FOR THE INVESTIGATIONS

River	Station	Country	Mean Discharge cfs	Period of Records	First Serial Corr. Coeff. of Annual Runoff
Tennessee	Chattanooga	Tennessee, U. S. A.	36,876	1874-1956	0.186
Kanawha	Kanawha Falls	West Virginia, U. S. A.	12,712	1877-1957	0.039
St. Lawrence	Ogdensburg	New York, U. S. A.	240,820	1860-1957	0.705
Mississippi	Keokuk	Iowa, U. S. A.	61,177	1878-1957	0.415
Mississippi	St. Louis	Missouri, U. S. A.	175,119	1861-1957	0.294
Thames	Teddington	Great Britain	2,223	1883-1954	0.140
Rhine	Basel	Switzerland	36,253	1807-1957	0.077
Danube	Orshava	Romania	189,455	1837-1957	0.096
Mures	Arad	Romania	5,906	1876-1955	0.247
Gota	Sjotorp-Vanersburg	Sweden	18,921	1807-1957	0.463
Dal	Norslund	Sweden	12,249	1852-1922	0.093
Nemunas	Smalininkai	U. S. S. R.	19,253	1811-1943	0.185
Neva	Petrokrepost	U. S. S. R.	91,462	1859-1935	0.534
Dnieper	Dnieperpetrovsk	U. S. S. R.	56,904	1881-1955	0.112
Goulburn	Murchison	Australia, Victoria	3,175	1881-1957	0.169
Kiewa	Kiewa	Australia, Victoria	729.7	1885-1957	0.290

Figure 7 The following pages of cross-correlograms present the relationships between the annual precipitation of individual precipitation stations and the annual sunspot numbers. The ordinates represent the cross-correlation coefficients $\rho_{xy}(\tau)$ and the abscissas represent the lag τ between the correlated pairs of annual precipitation and annual sunspot numbers. Every graph except one contains four cross-correlograms corresponding to four individual precipitation stations. For each cross-correlogram, the confidence limits at the 95 percent probability level are plotted depending on the length of each precipitation time series. The limits are obtained under the assumption that the annual precipitation series are serially uncorrelated, and are not cross-correlated with the sunspot numbers.





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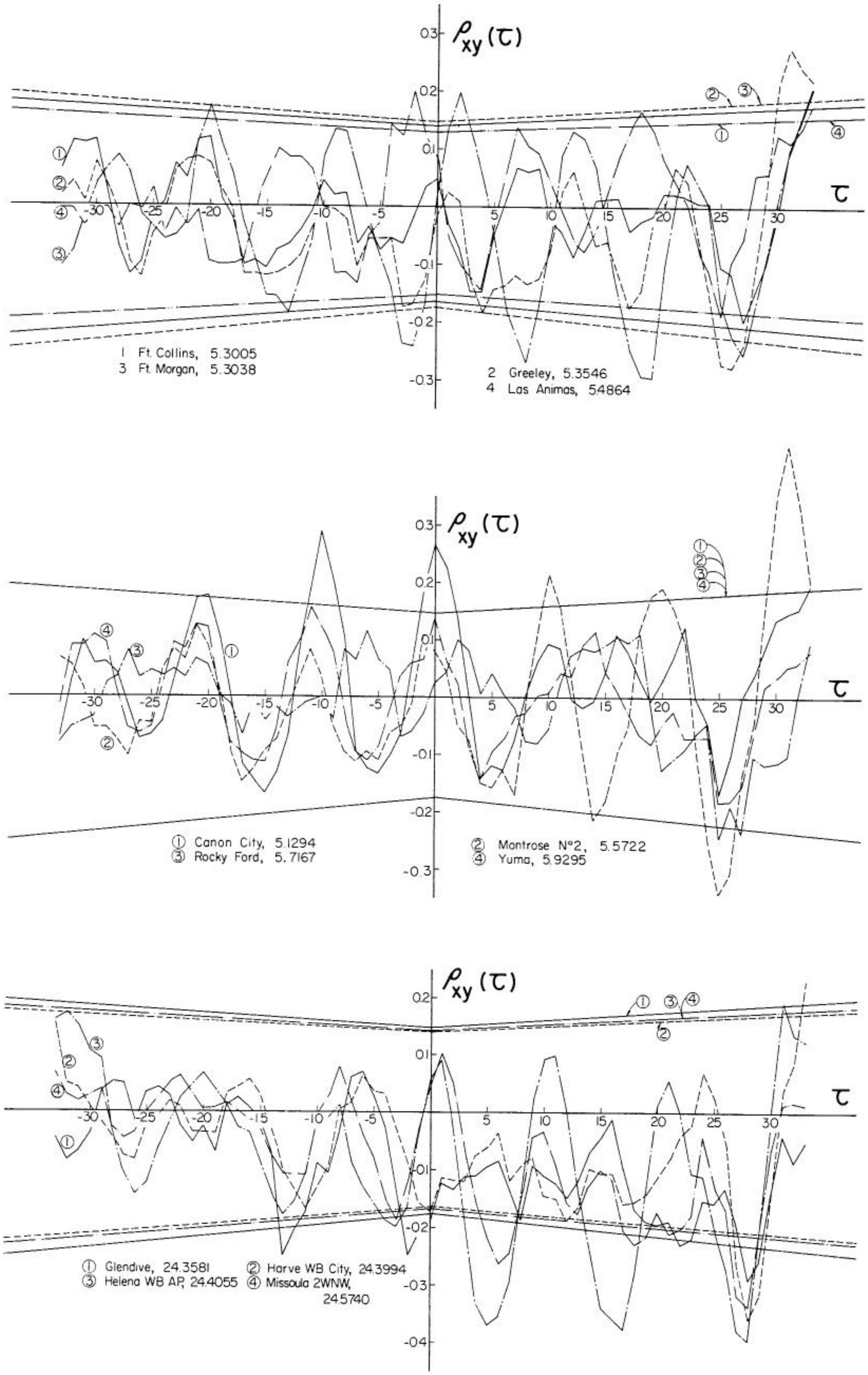
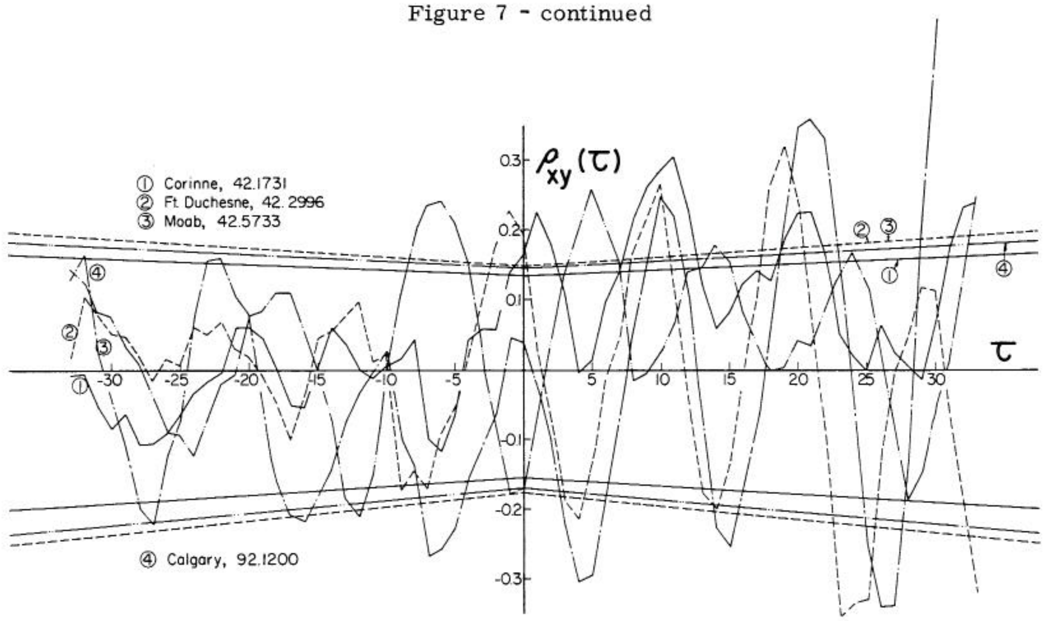
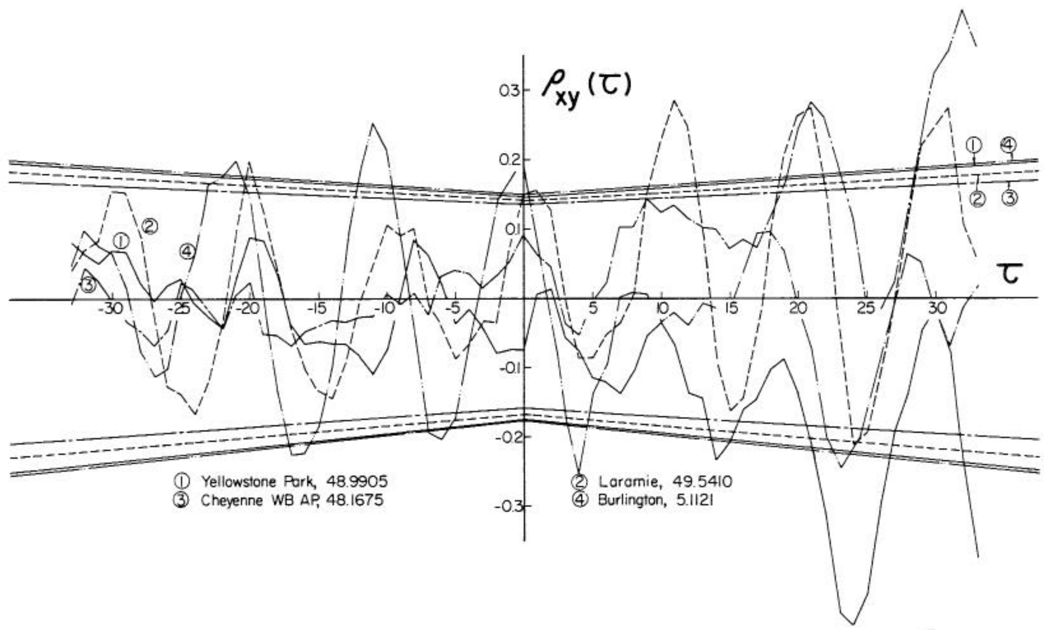

ρxy (τ)
τ
1 Ft. Collins, 5.3005
3 Ft. Morgan, 5.3038
2 Greeley, 5.3546
4 Las Animas, 54864
ρxy (τ)
τ
① Canon City, 5.1294
③ Rocky Ford, 5.7167
② Montrose N°2, 5.5722
④ Yuma, 5.9295
ρxy (τ)
τ
① Glendive, 24.3581
② Harve WB City, 24.3994
③ Helena WB AP, 24.4055
④ Missoula 2WNW, 24.5740

continued

Figure 7 - continued





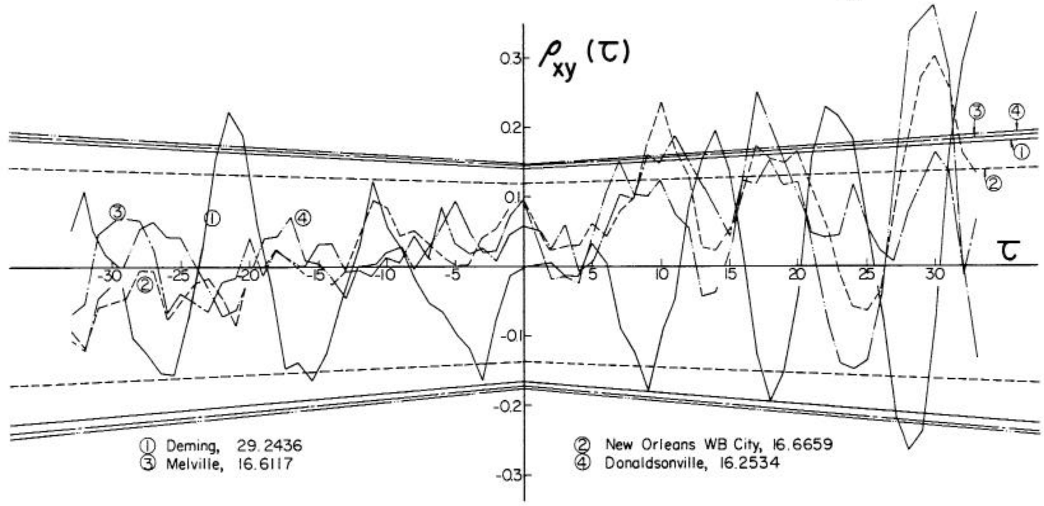


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Figure 7 - continued

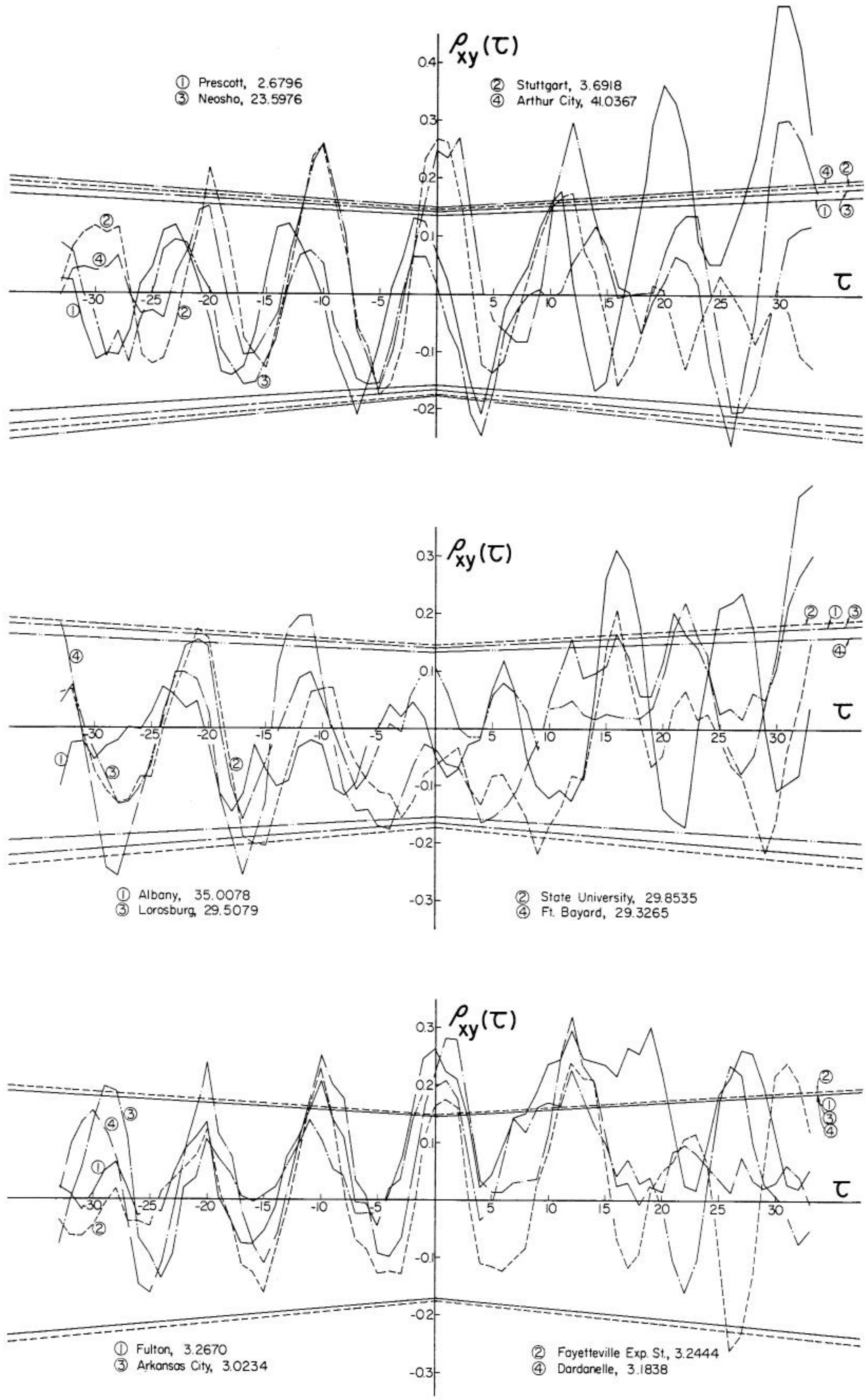

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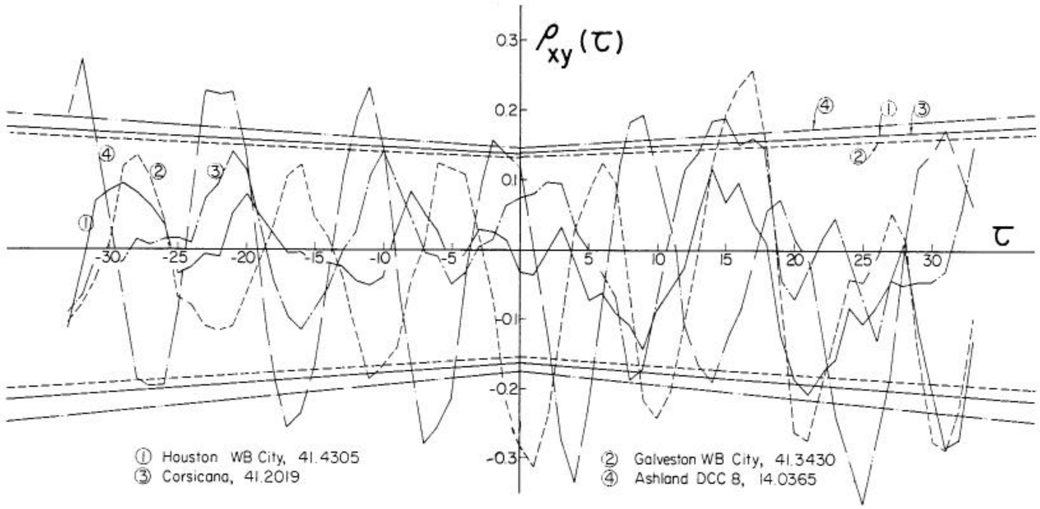
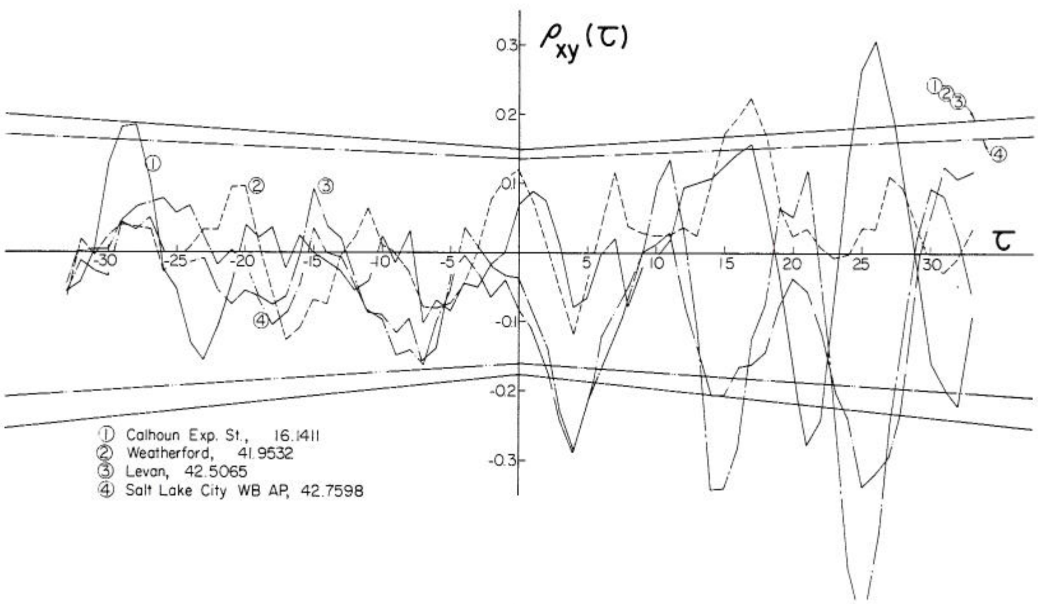
Figure 7 - continued





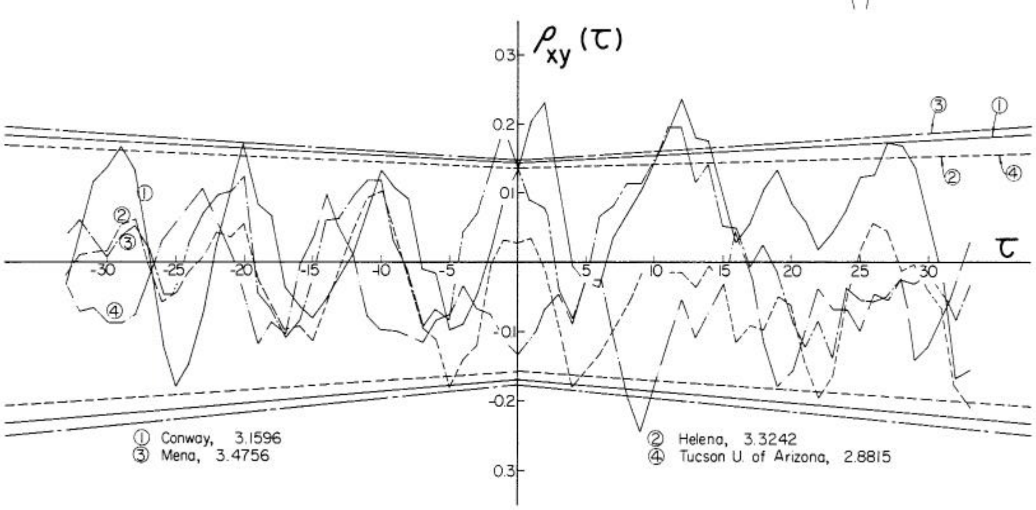


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Figure 7 - continued

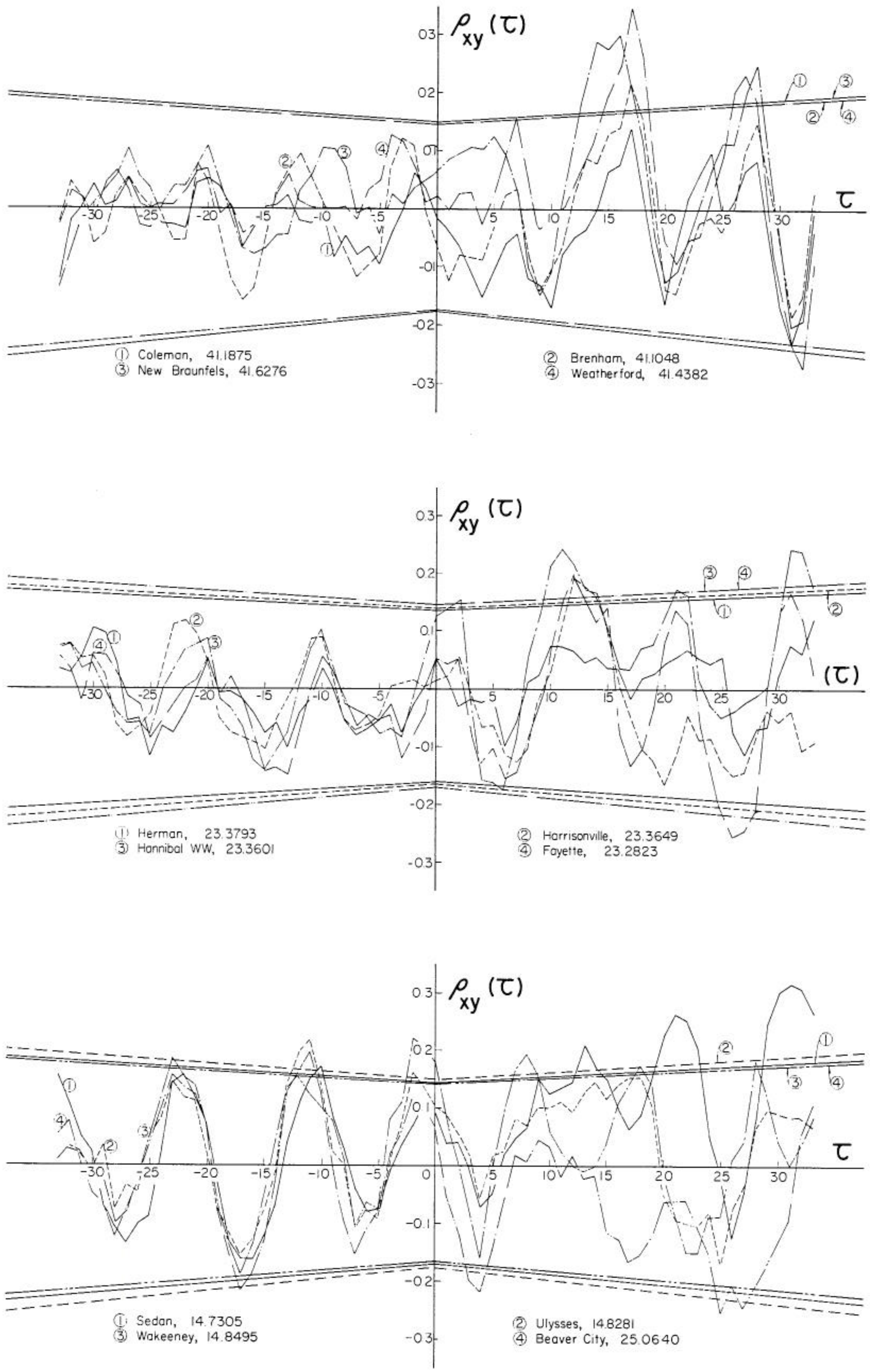

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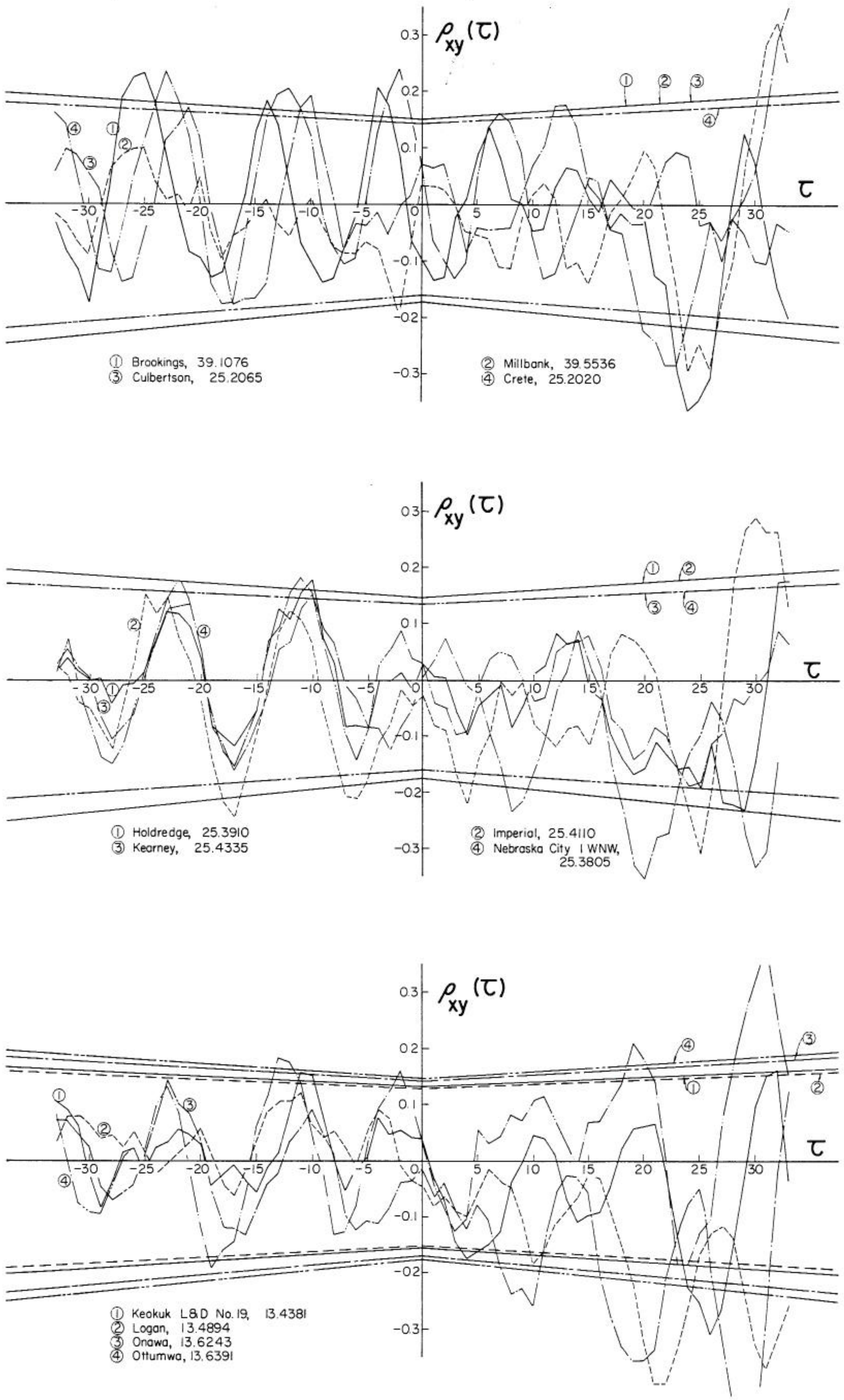
Figure 7 - continued



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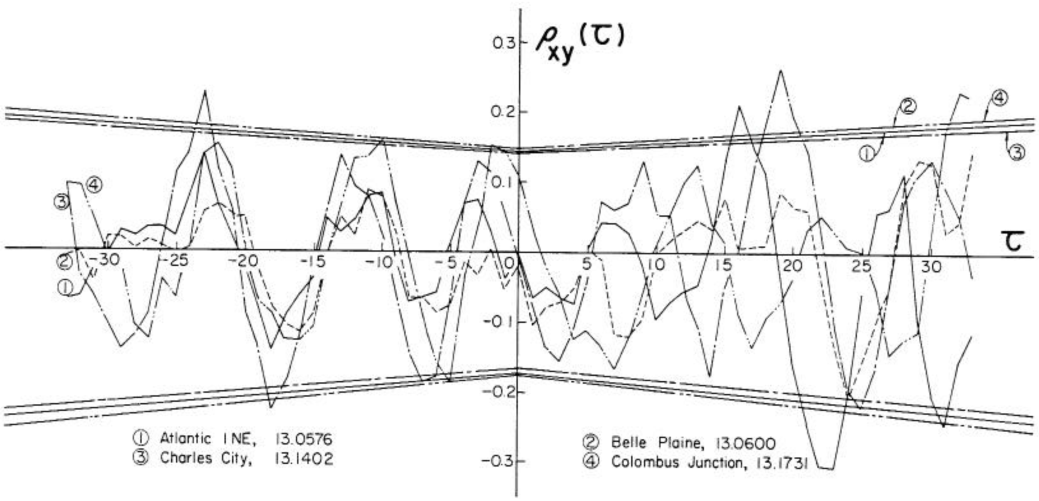

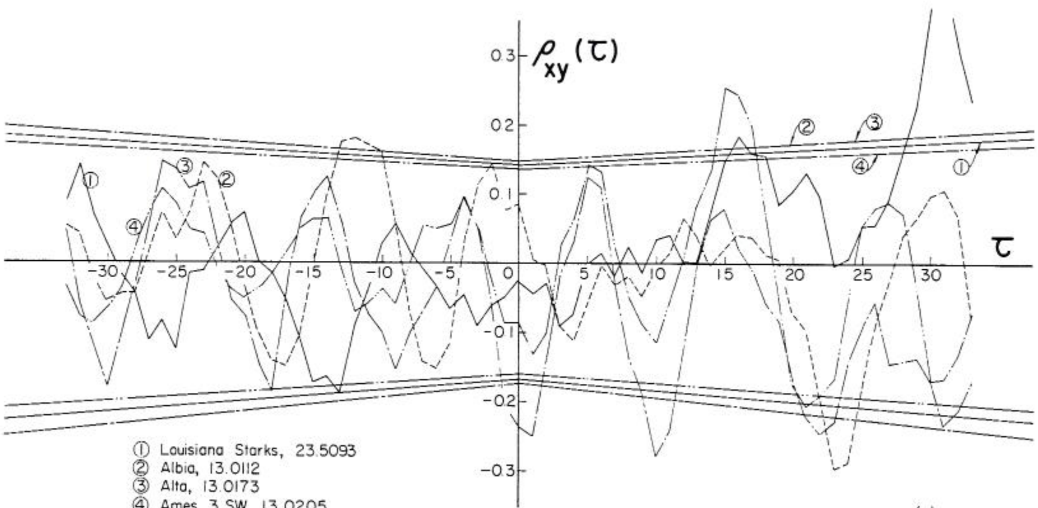

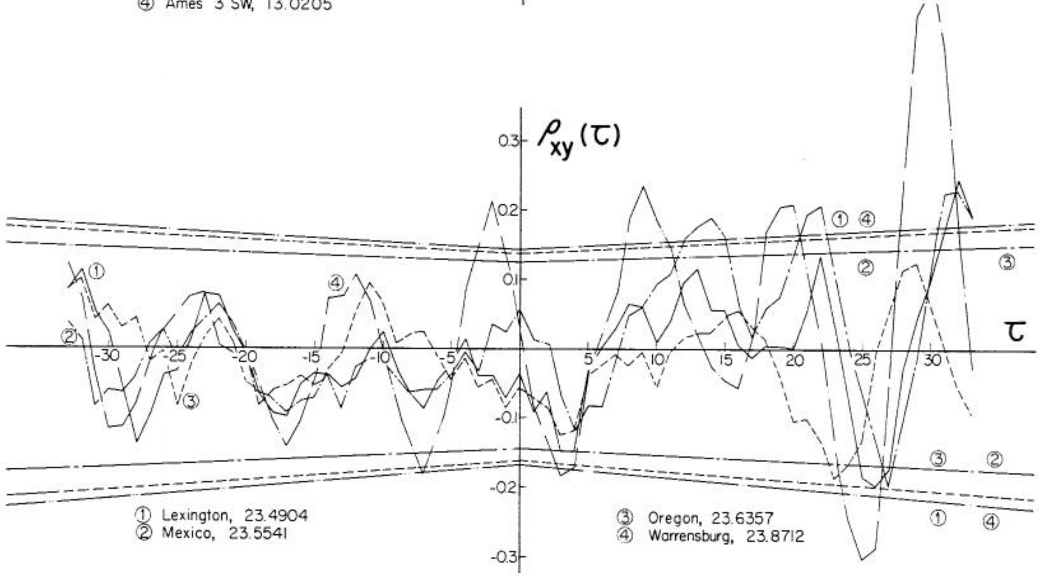

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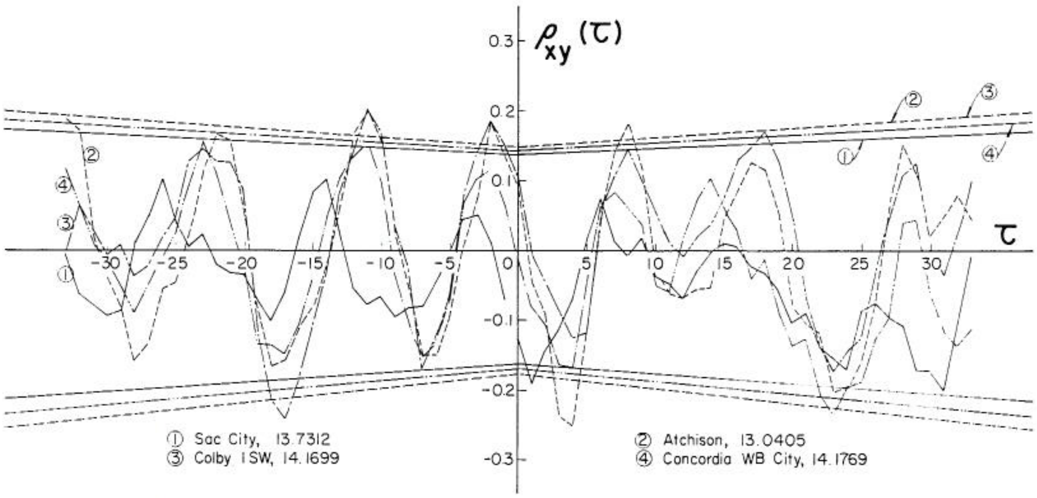
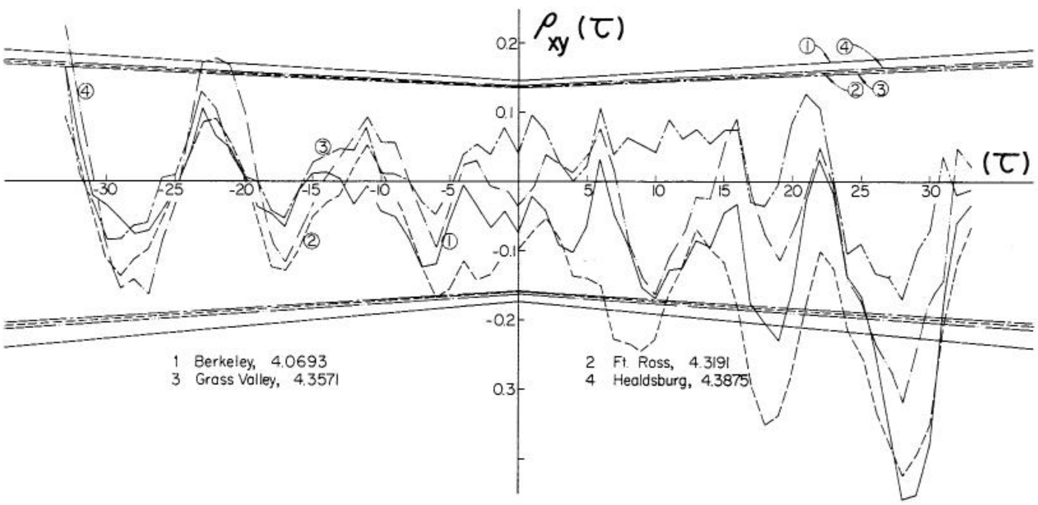
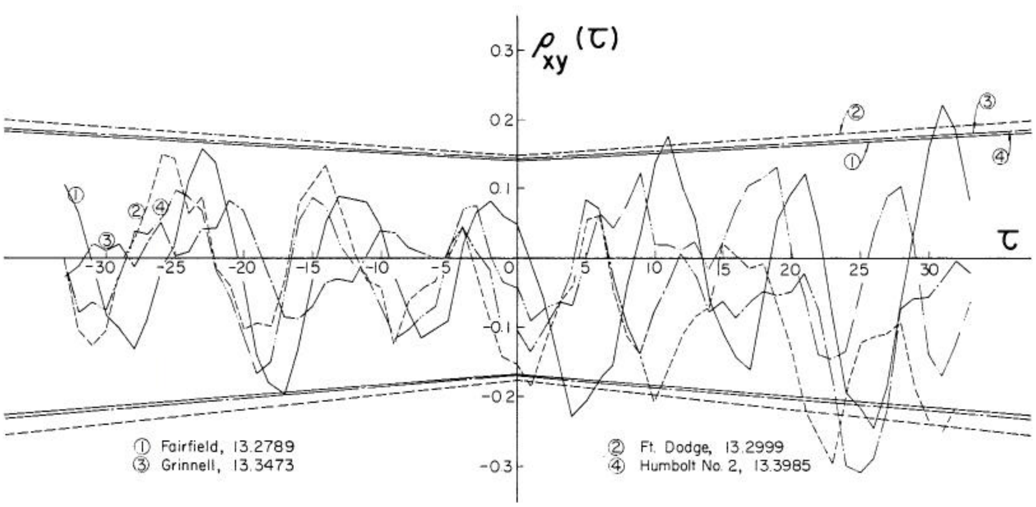
Figure 7 - continued







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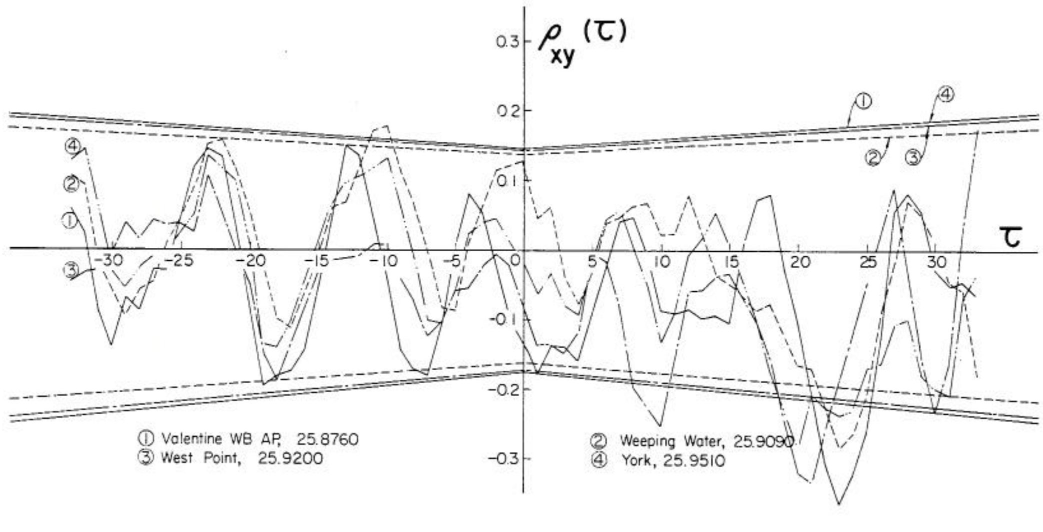

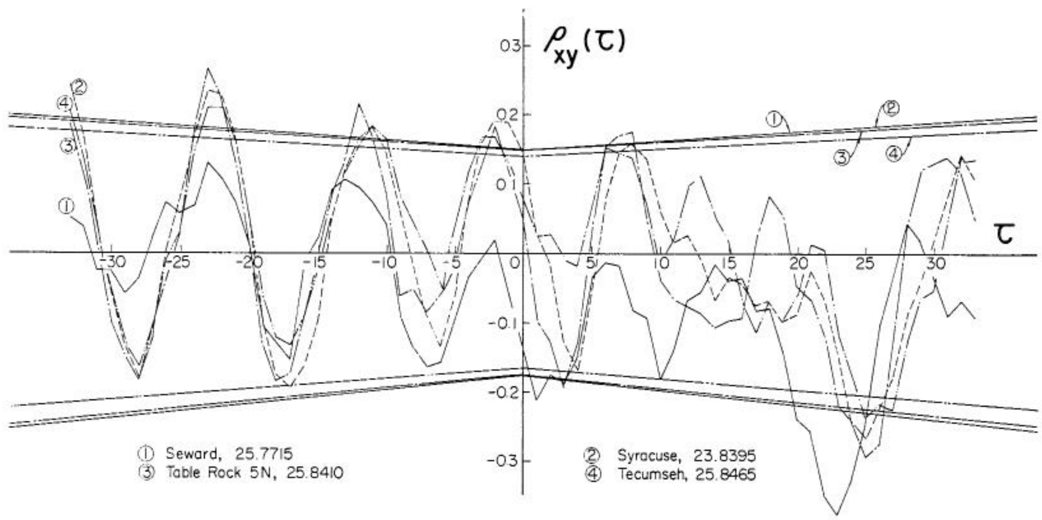

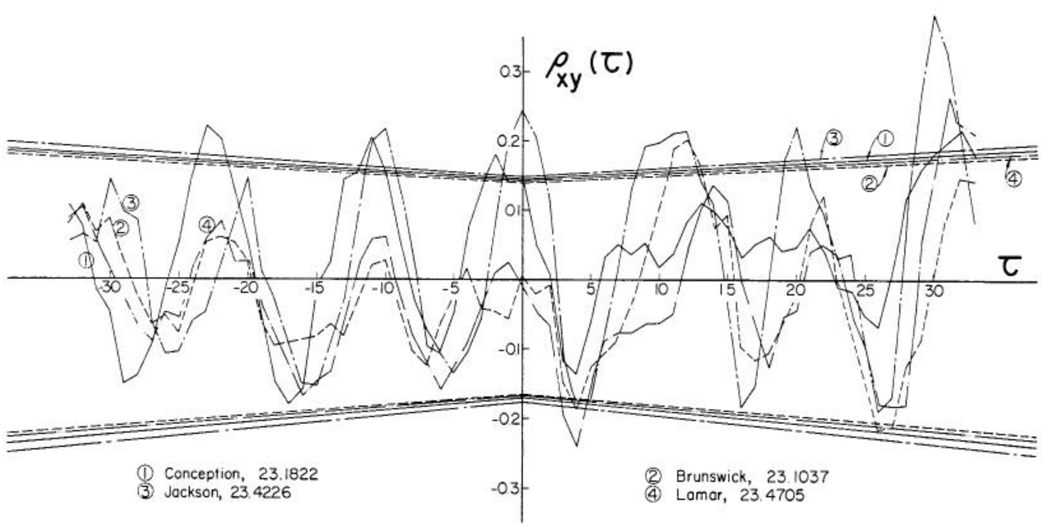

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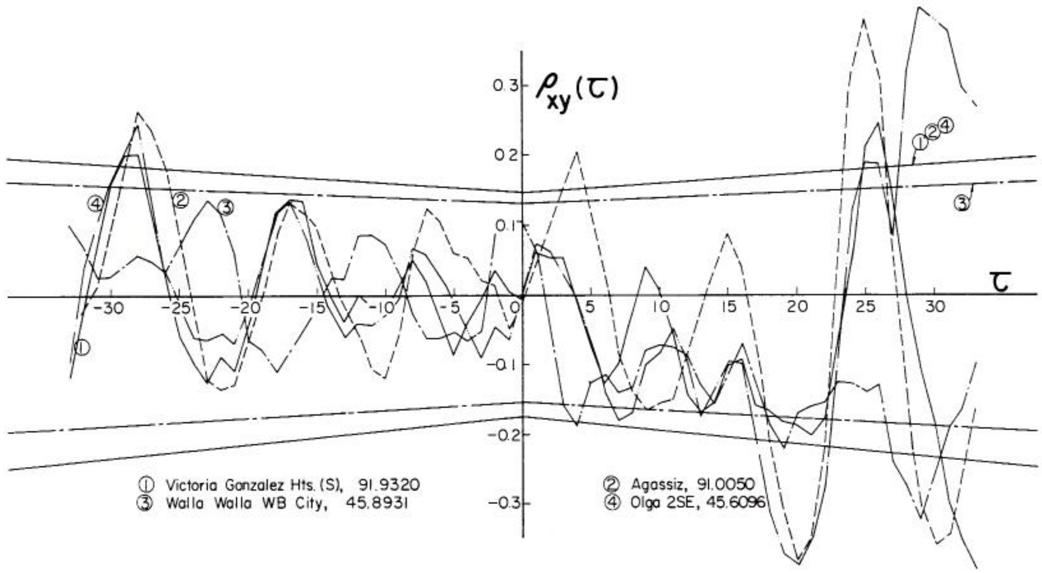

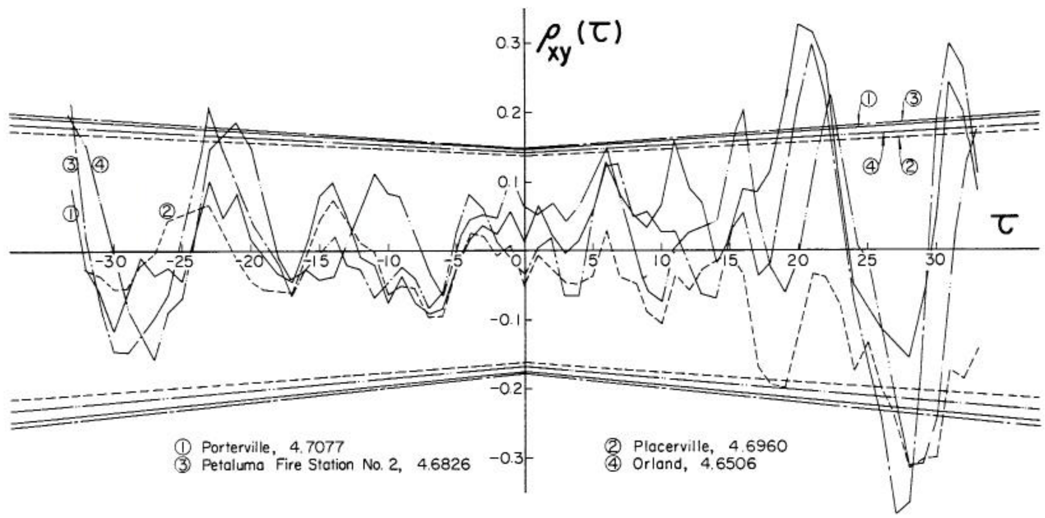

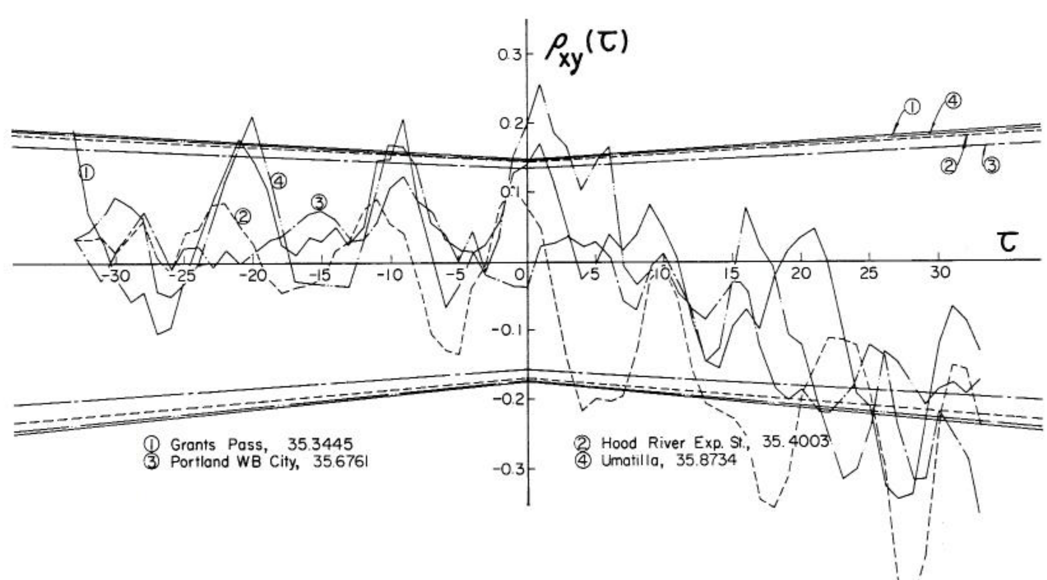

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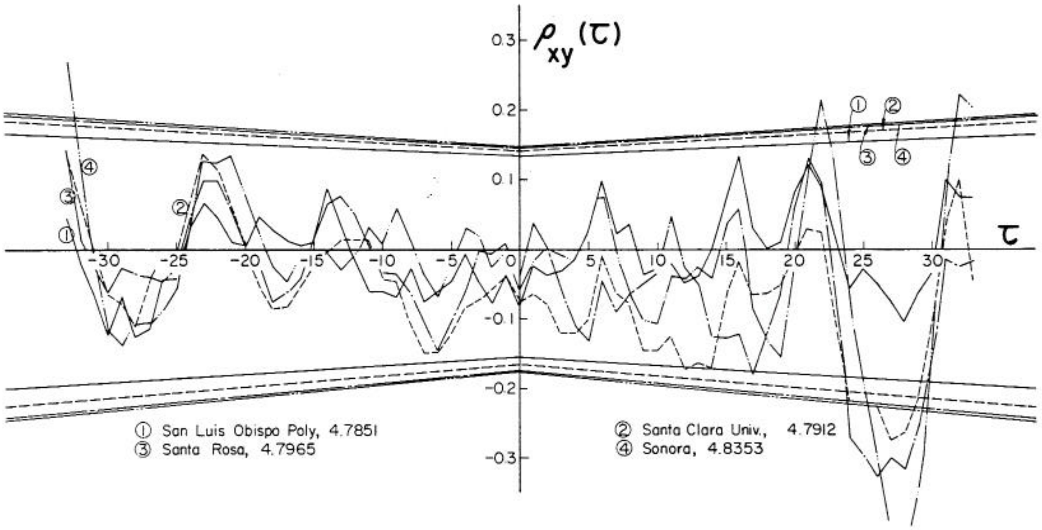

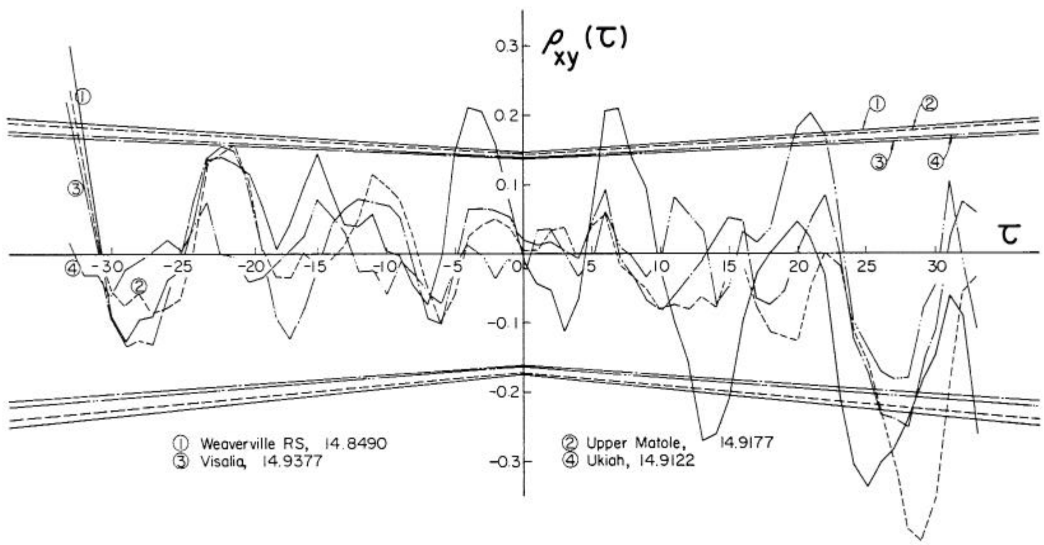

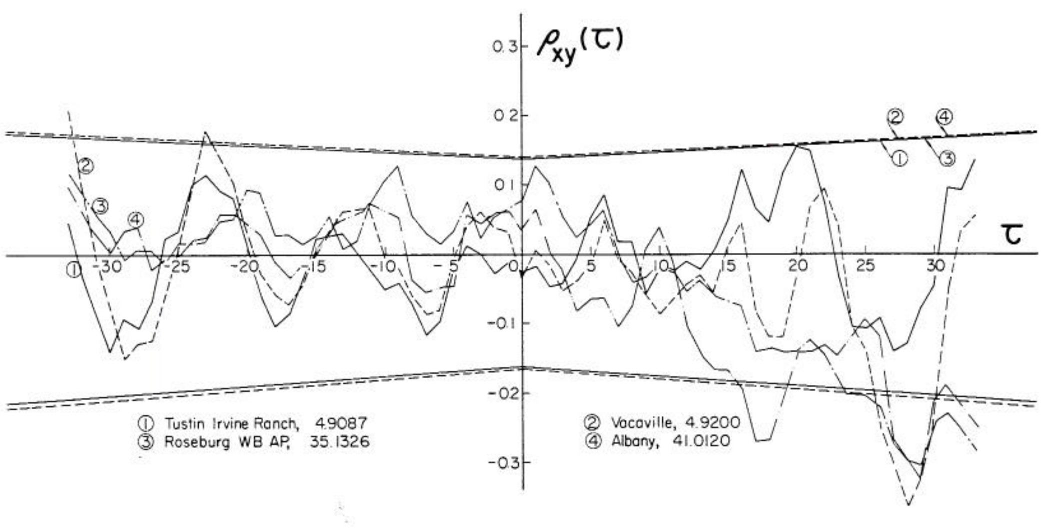

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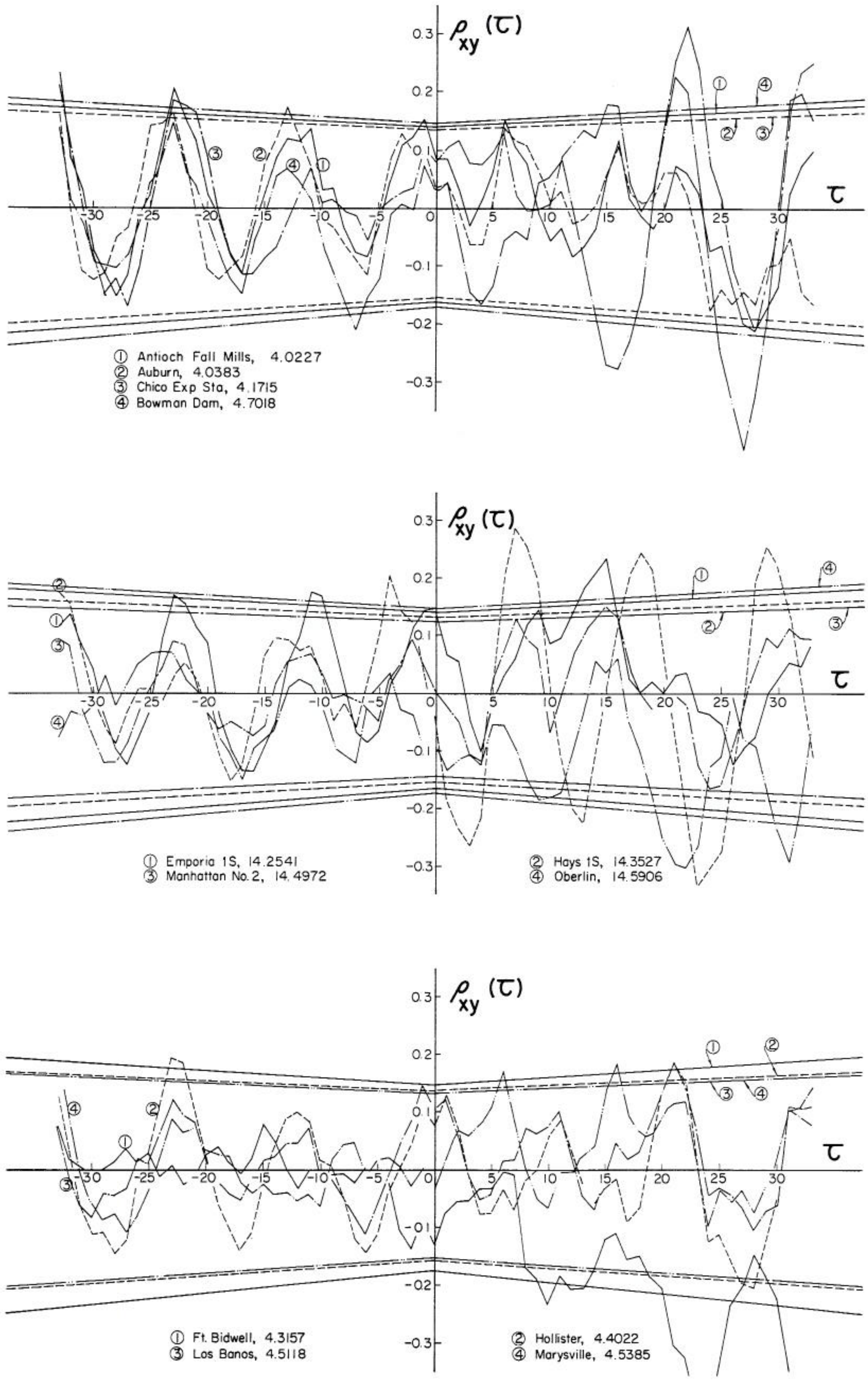
Figure 7 - continued



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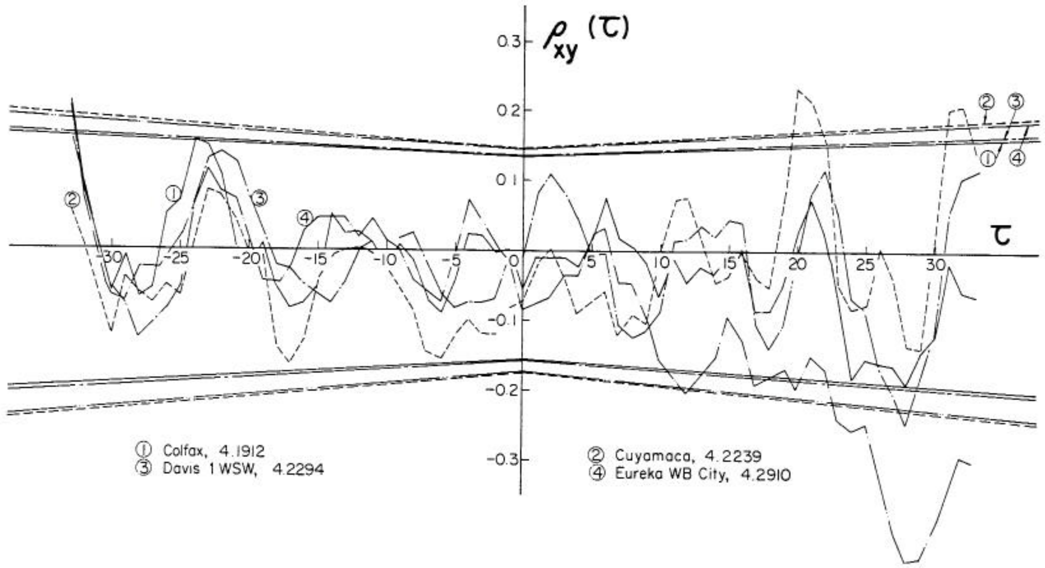

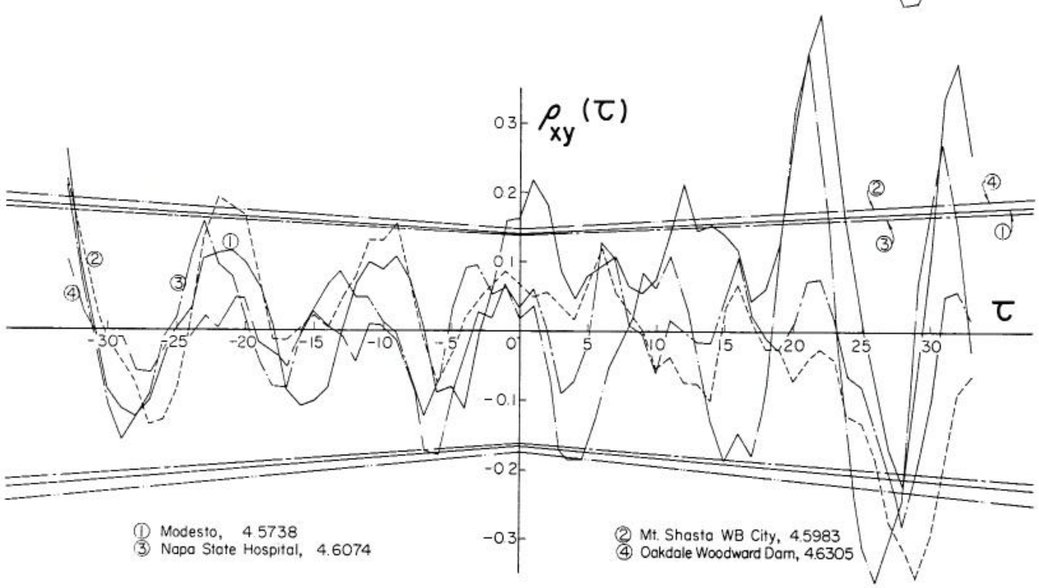

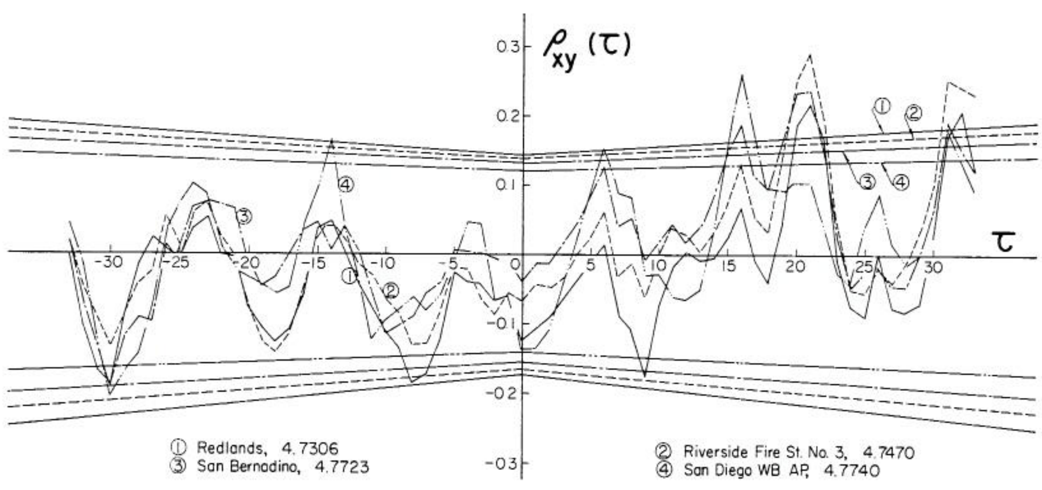

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Figure 7 - continued

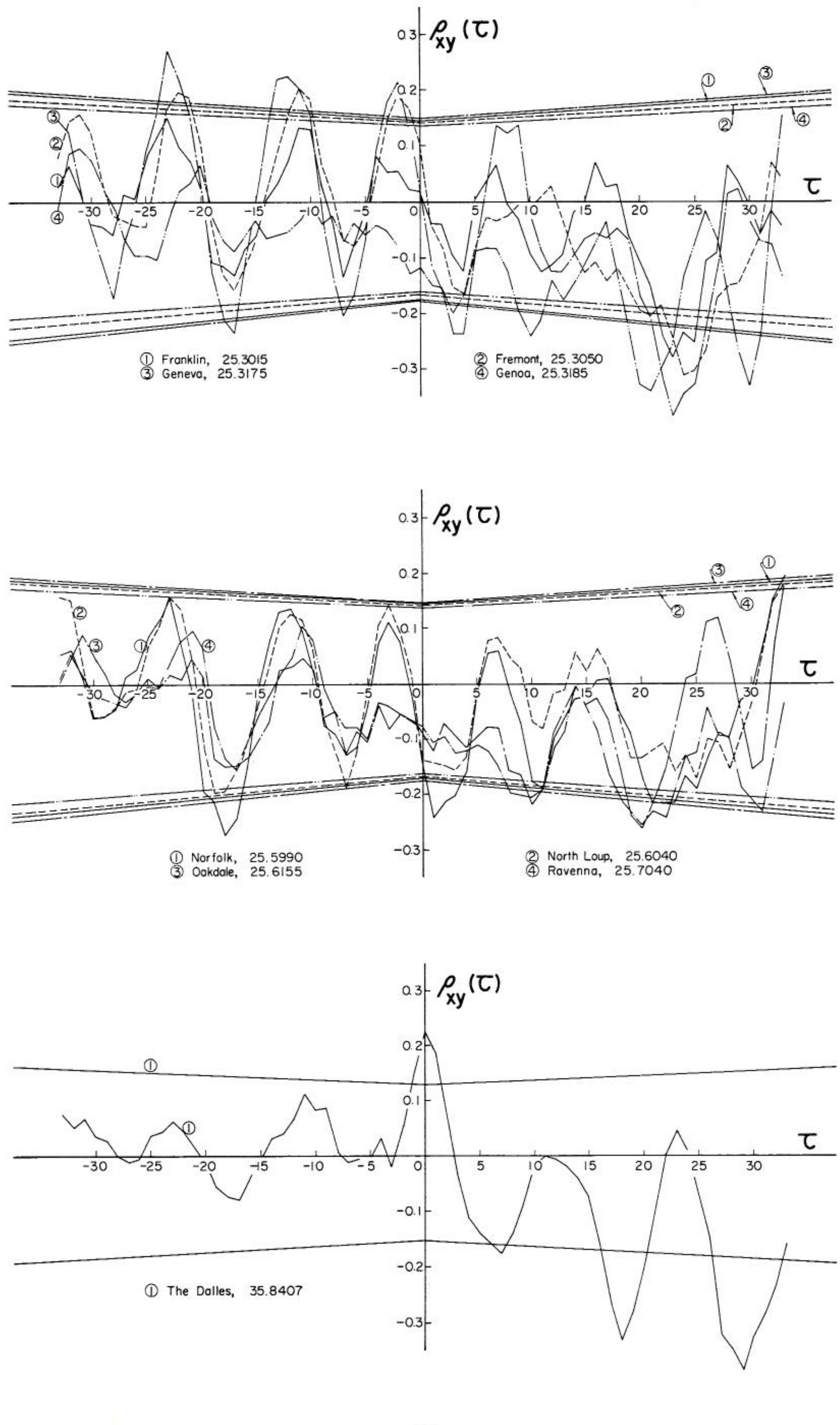
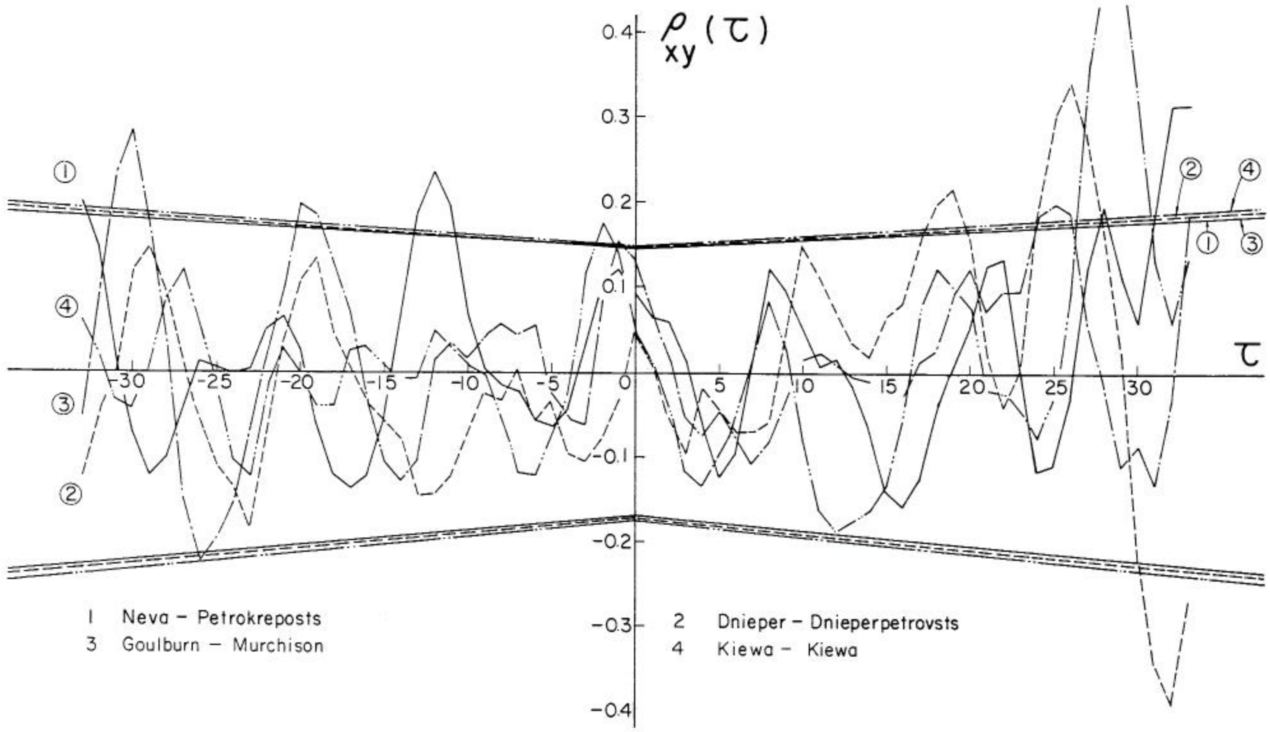


Figure 8 The following four graphs present 16 cross-correlograms between the annual runoff and the annual sunspot numbers, for the 16 river stations investigated (see Appendix 3). The ordinates are cross-correlation coefficients $\rho_{xy}(\tau)$ and abscissas are the lag τ between the correlated pairs.

The confidence limits at the 95 percent probability level refer to the two series both uncorrelated in cross-correlation and one or both serially uncorrelated. This hypothesis is a very strong test for the annual runoff because both the runoff series and the sunspot series are serially correlated.



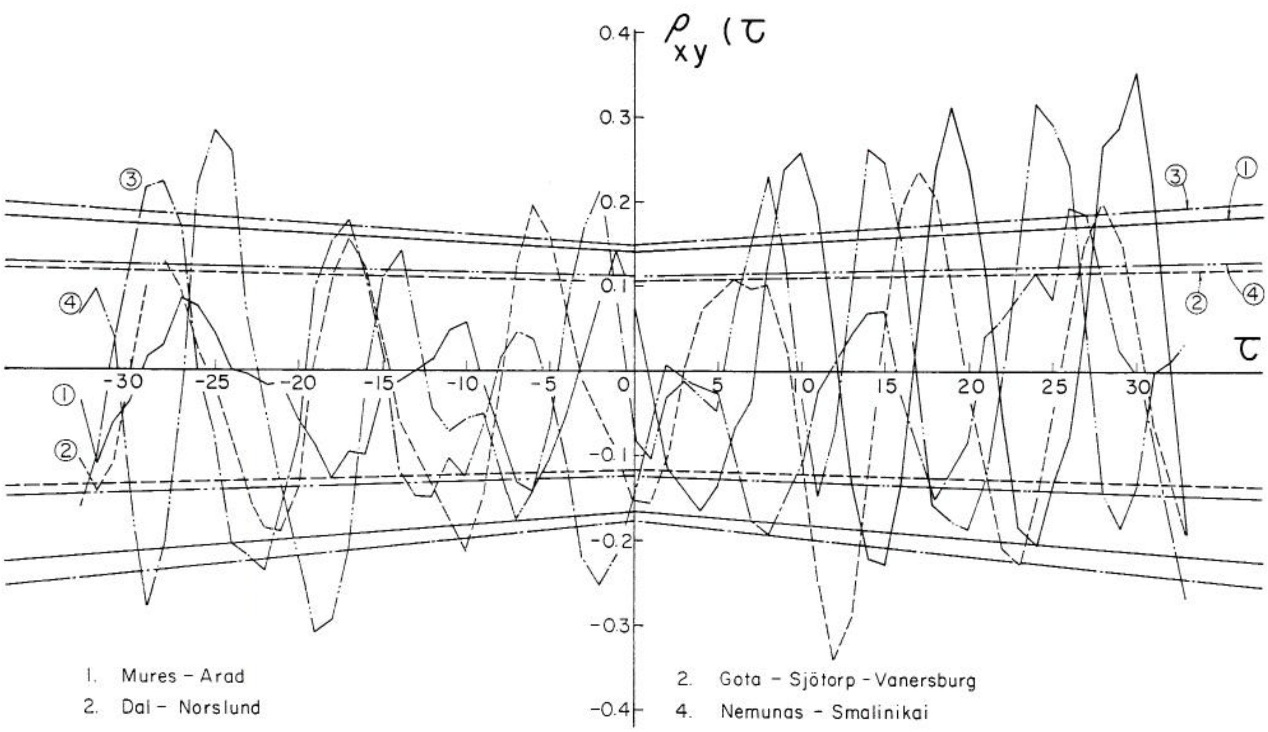


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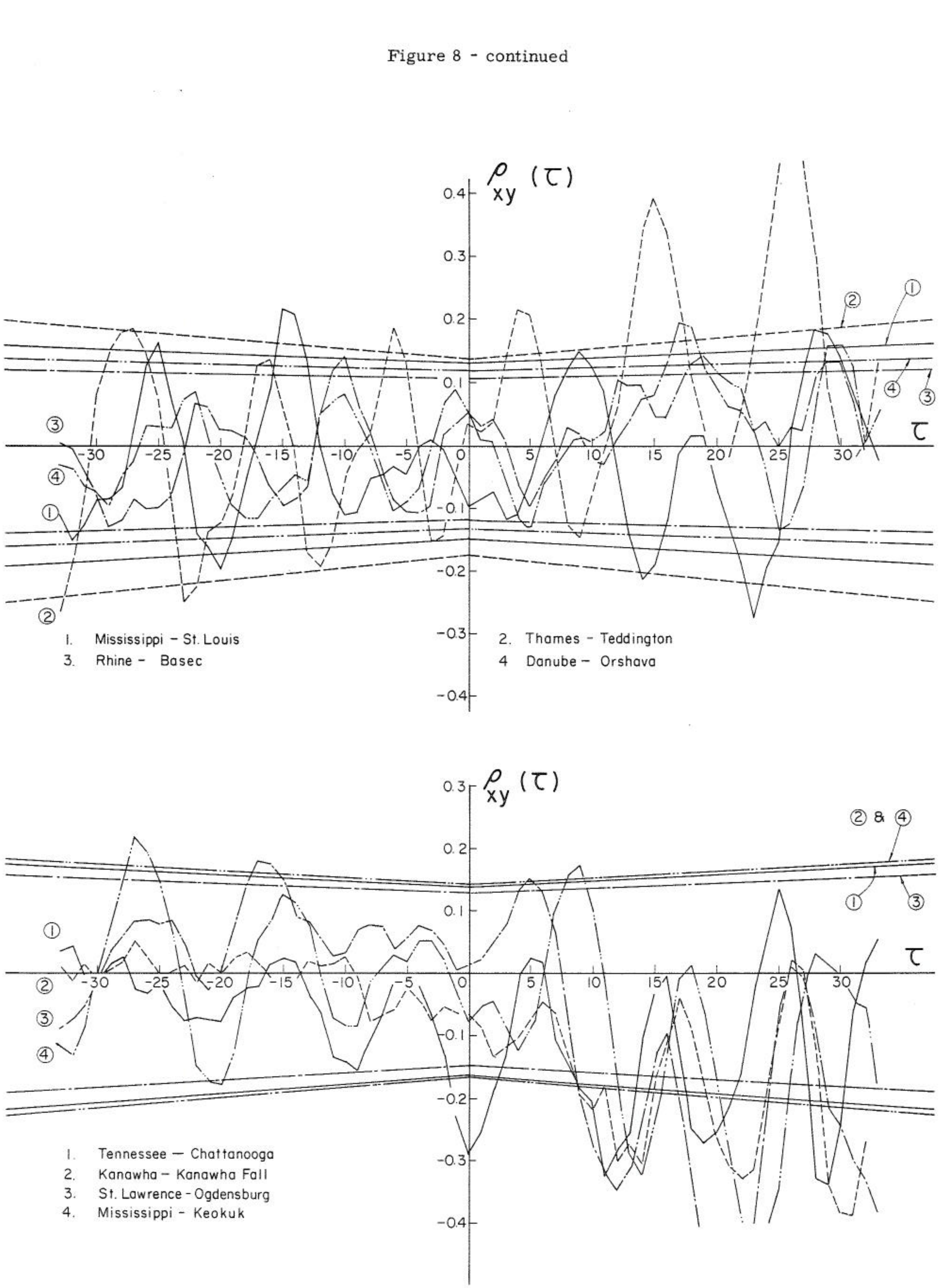
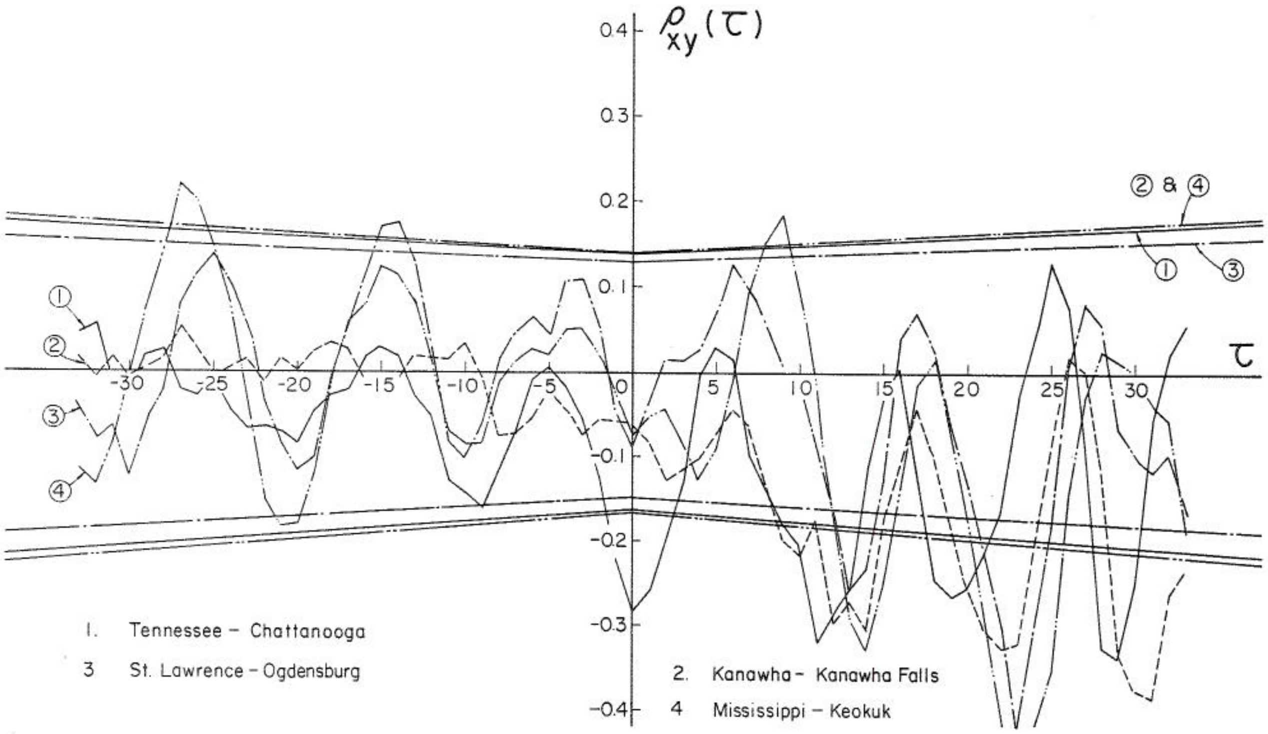
Figure 8 - continued



APPENDIX 6

Figure 9 The following four graphs present 16 cross-correlograms between the annual effective precipitation and the annual sunspot numbers, for the river basin of 16 river stations investigated (see Appendix 3). The ordinates are cross-correlation coefficients $\rho_{xy}(\tau)$ and abscissas are the lag τ between the correlated pairs. The confidence limits at the 95 percent probability level refer to the two series both uncorrelated in cross-correlation and one or both serially uncorrelated. This hypothesis is a very strong test for the annual effective precipitation because both the effective precipitation series are serially correlated.



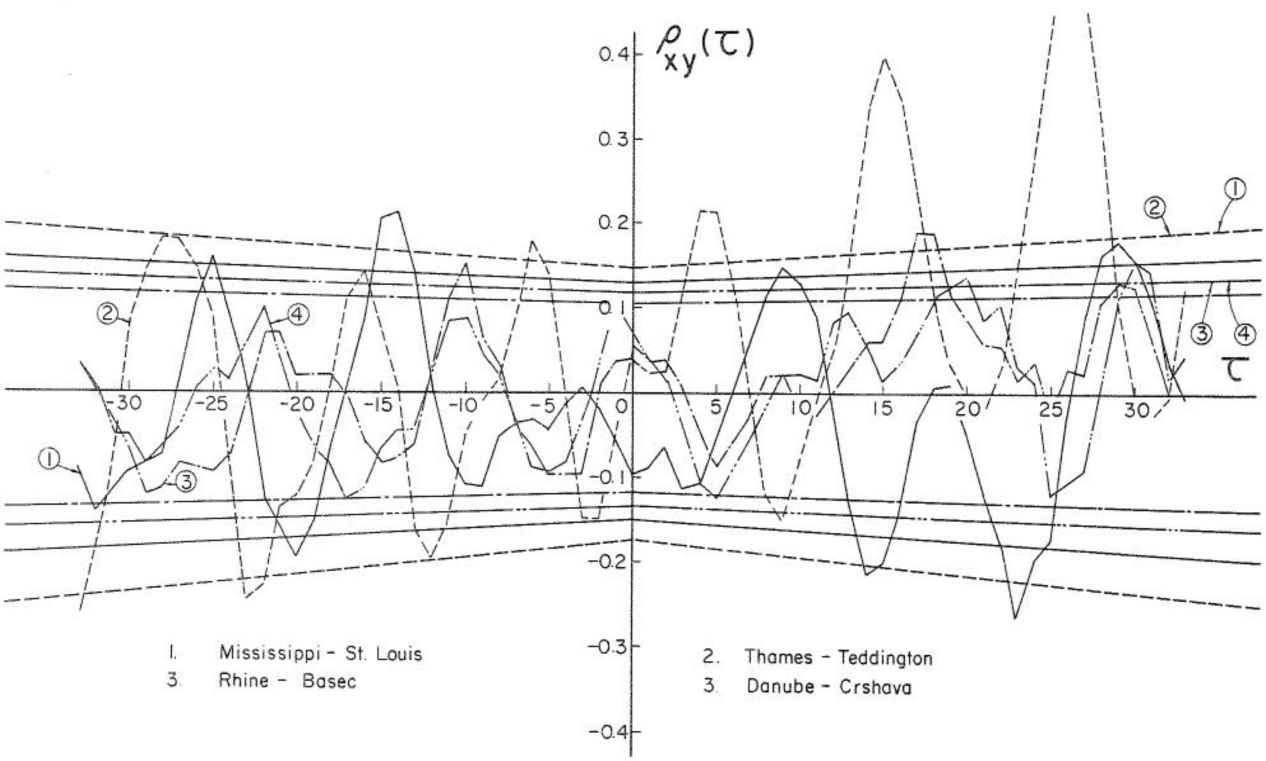


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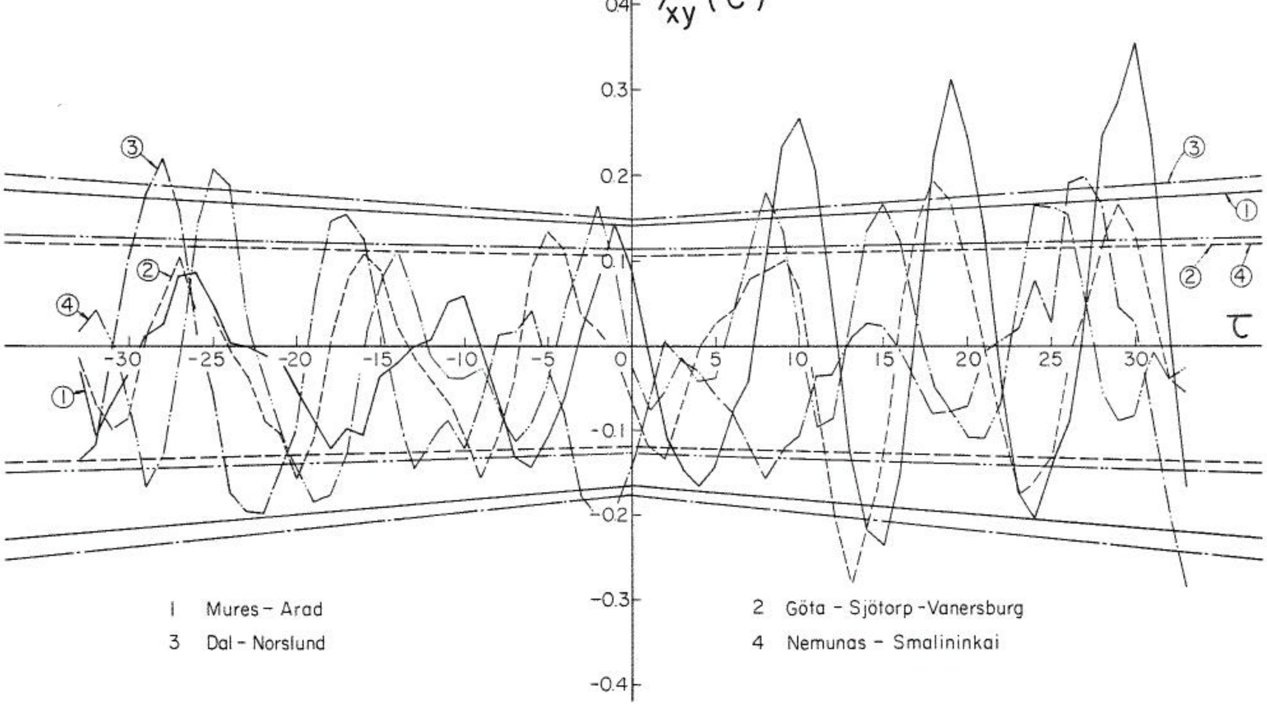
Figure 9 - continued



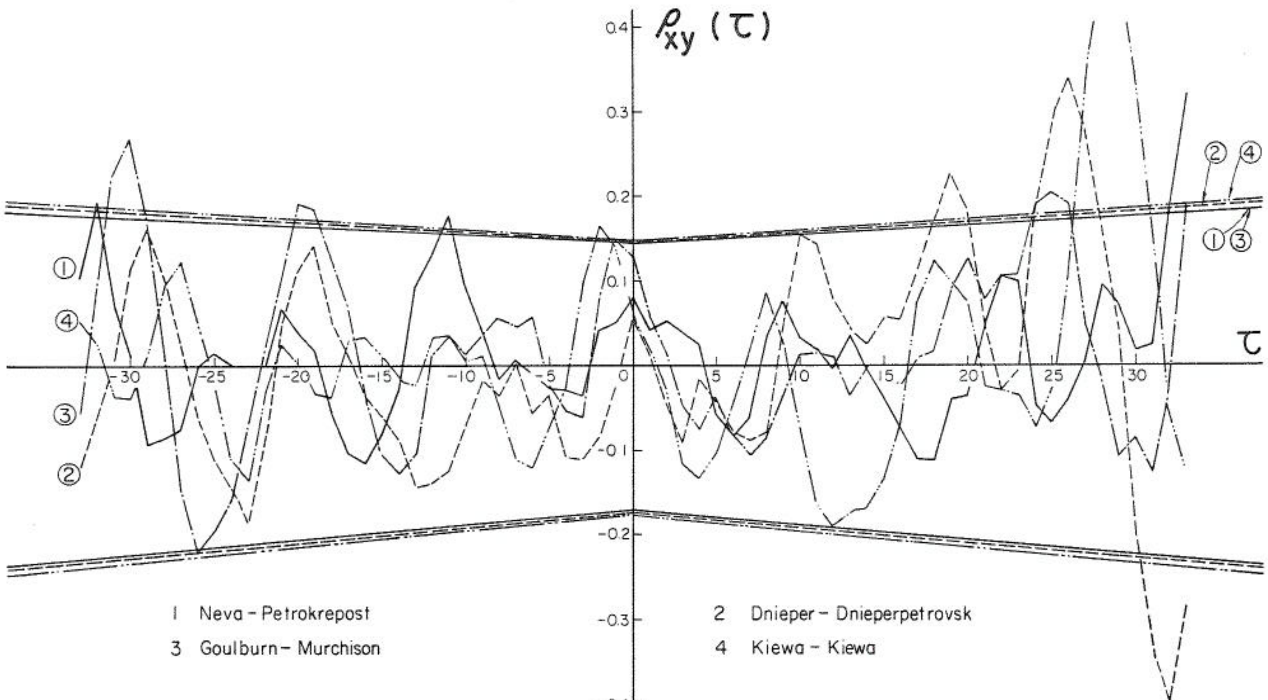
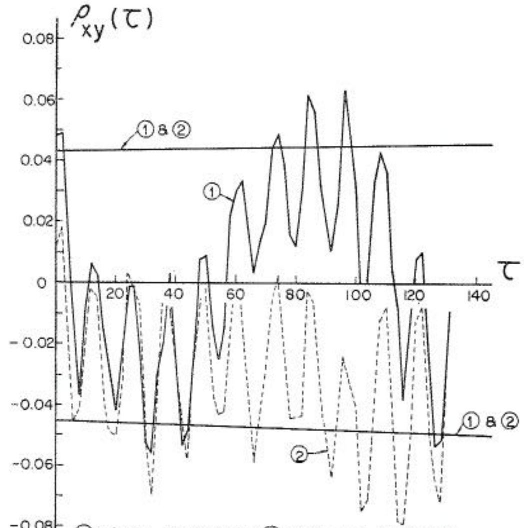
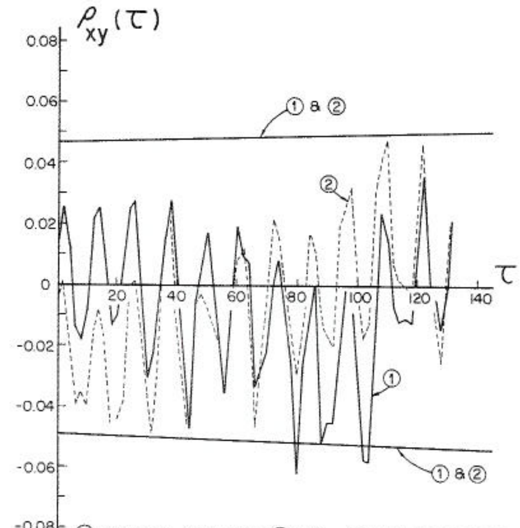


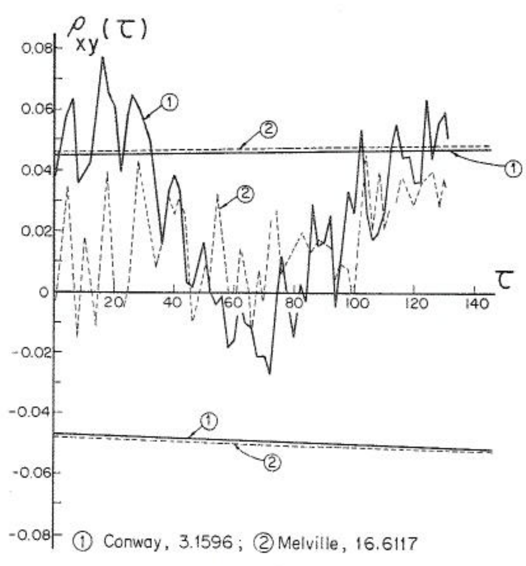
Figure 10 The following pages of cross-correlograms present the relationship between the monthly precipitation series of individual precipitation stations and the monthly sunspot numbers. The ordinates are the cross-correlation coefficients $\rho_{xy}(\tau)$ and the abscissas are the lag τ between the correlated pairs of values. Each graph contains two cross-correlograms corresponding to two individual precipitation stations. For each cross-correlogram the confidence limits at the 90 percent probability level are plotted, depending on the length of each precipitation time series. The confidence limits are obtained under the assumption that the monthly precipitation time series are serially uncorrelated (which is not correct because they usually follow a periodic movement of the 12-month periodicity), and that this series is not cross-correlated with the monthly sunspot numbers.



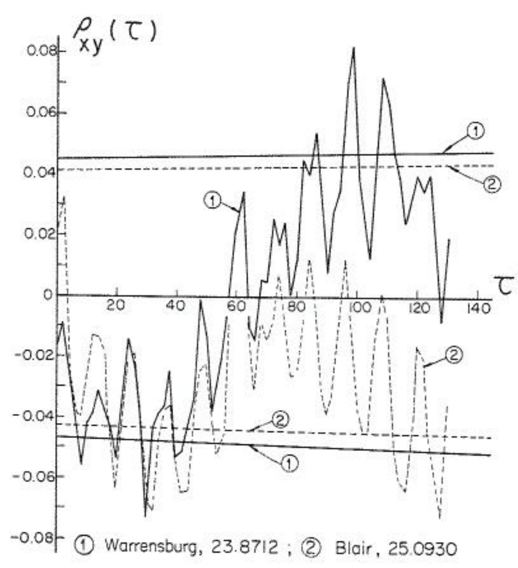
① Crete, 25.2020; ② Ravenna, 25.7040



① Milbank, 39.5536; ② Sioux Fall WB AP, 39.7667



① Conway, 3.1596; ② Melville, 16.6117



① Warrensburg, 23.8712; ② Blair, 25.0930

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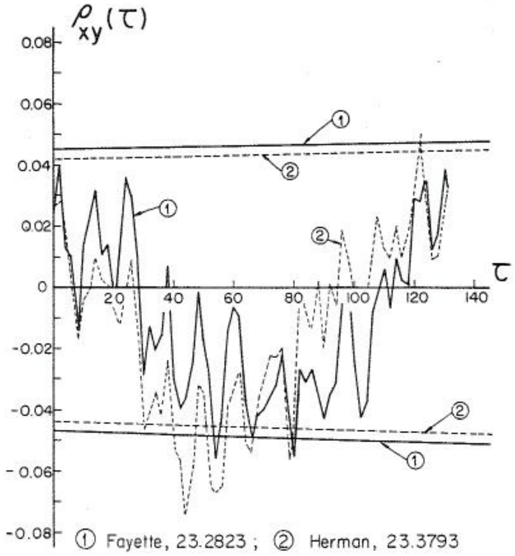
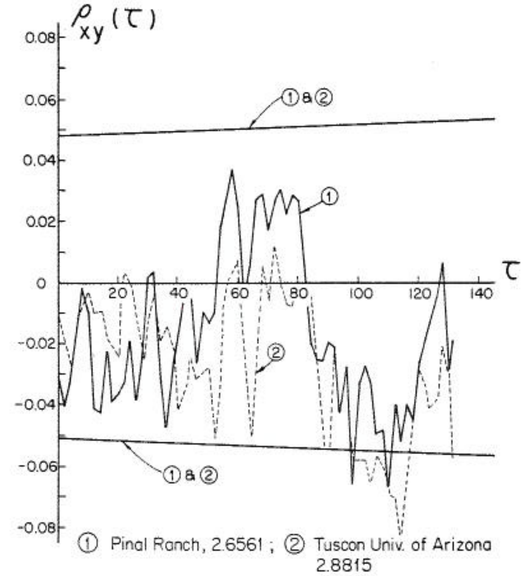
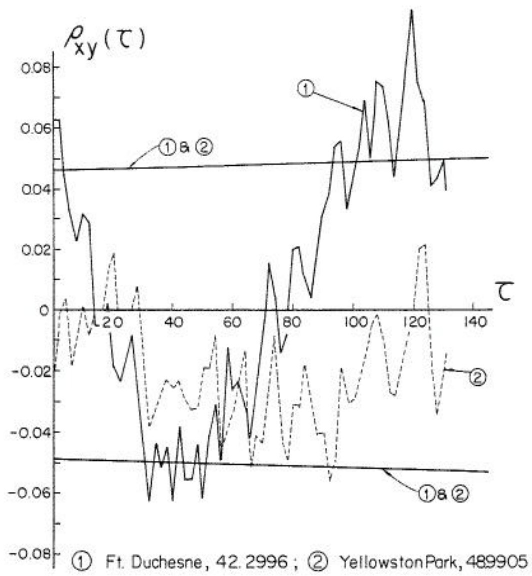
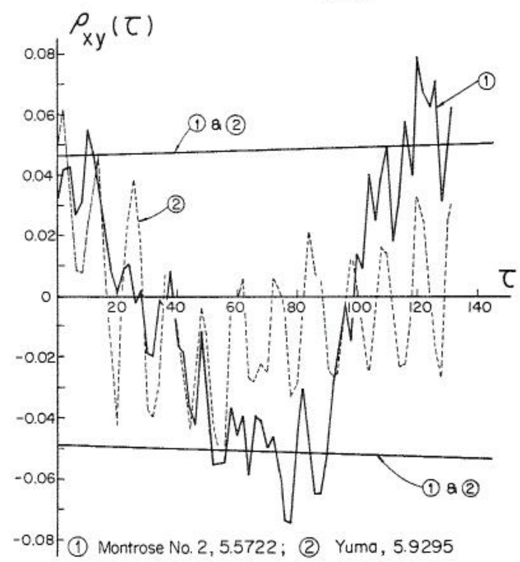
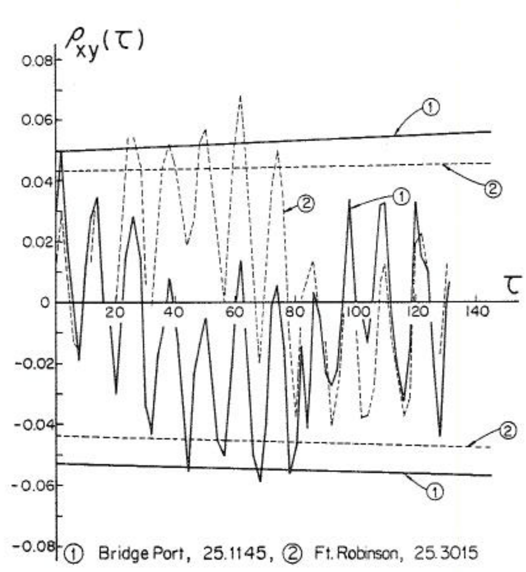
Figure 10 - continued

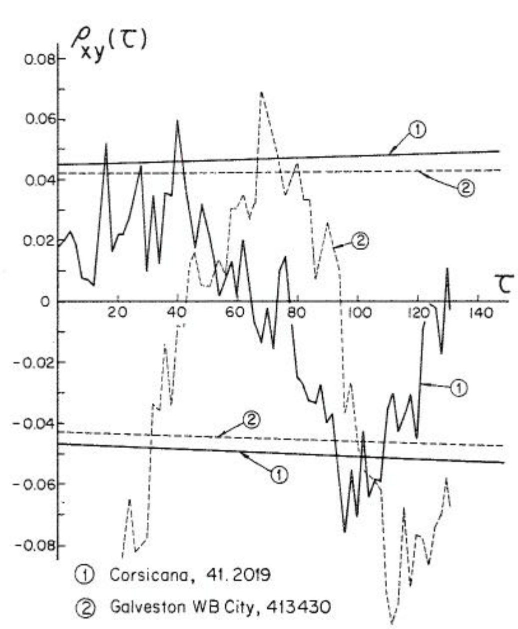












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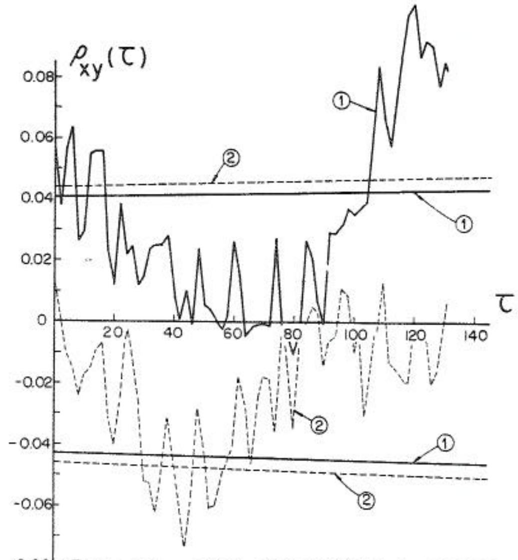
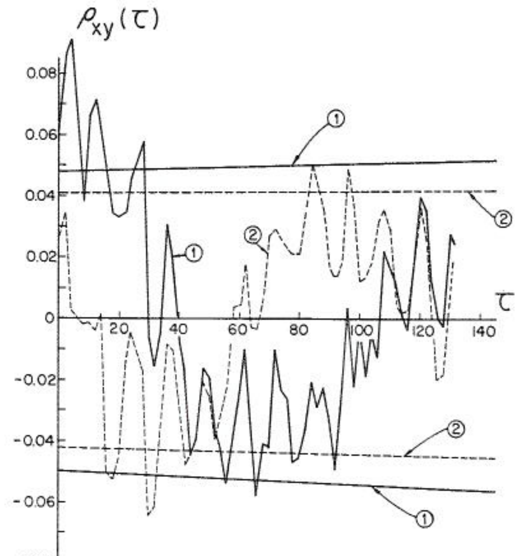
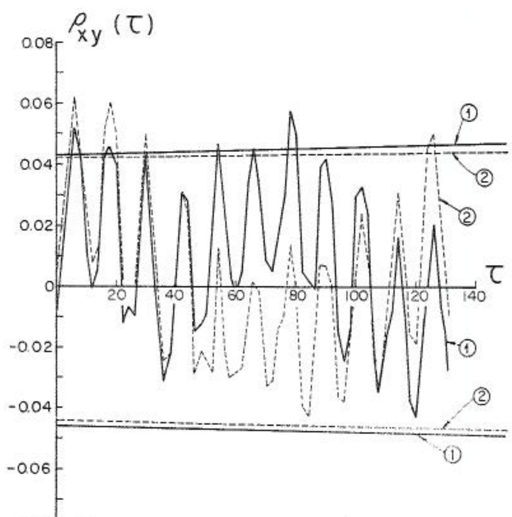


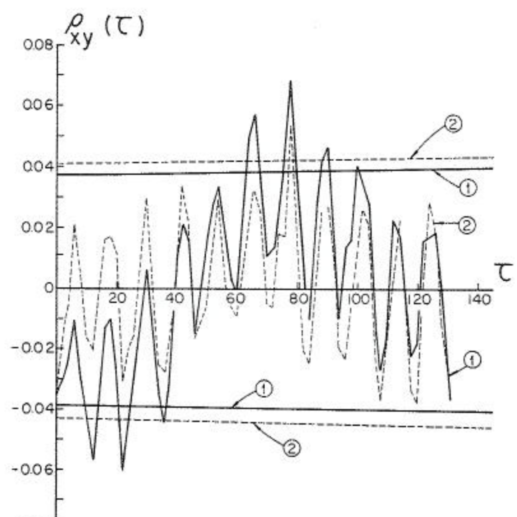
① New Orleans WB City, 16.6659 ; ② Neosho, 23.5976



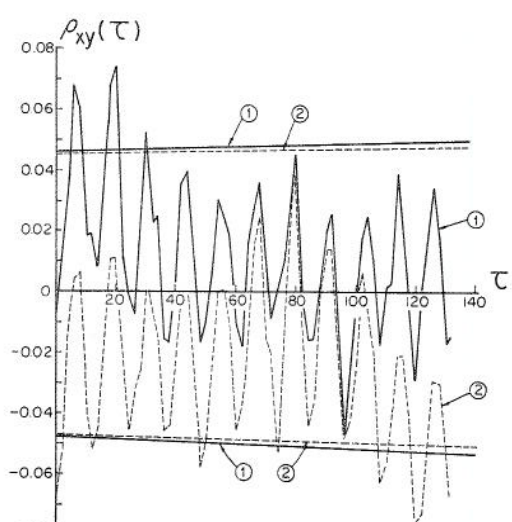
① Cannon City, 5.1294; ② Las Animas, 5.4834



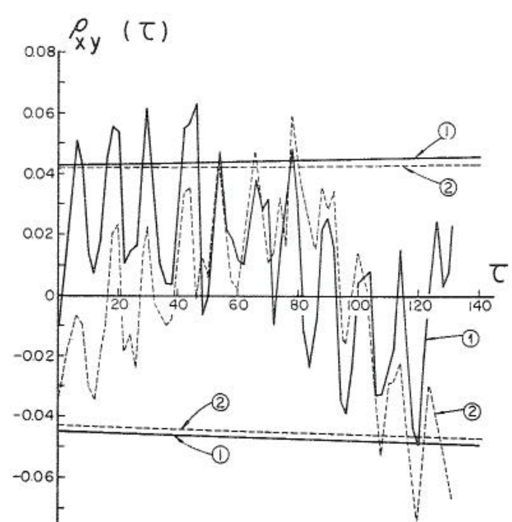
① Antioch F. Mills, 4.0227; ② Hollister, 4.4022



① San Diego WB Apt., 4.7740 ; ② San Luis OBISPO Poly 4.7851



① Grants Pass, 35.3445 ② Tatoosh Island WB 45.8332



1 Willows, 4.9699 ; 2 Reno WB AP, 26.6779

Key Words: Sunspot effects, hydrology, extraterrestrial effects on hydrology, cross-correlation in hydrology, cross-spectral analysis in hydrology

Abstract: The relationship of hydrologic series of monthly precipitation, annual precipitation and annual runoff to sunspot numbers has been investigated by cross-correlation analysis for various time lags (zero lag included) and by cross-spectral analysis. Eighty-eight series of monthly precipitation and 173 series of annual precipitation (stations from western North America), and 16 series of annual flows (stations from several parts of the world) were used as research data. No significant correlation was found between these hydrologic series and sunspot numbers. In fact, the spectrum of sunspot numbers proved to be nearly identical to the spectrum of residuals which were obtained by deducting values of hydrologic series from values of sunspot series. The coherence graphs worked out are within confidence limits of two independent time series, that indicate there is no relationship between hydrologic time series and sunspot numbers. Sampling fluctuations of cross-correlation coefficients between hydrologic series and sunspot numbers increase when both series are smoothed by moving average schemes. Therefore, when the confidence limits of unsmoothed series are used in the smoothed series approach, incorrect conclusions may be drawn about the significance of correlation.

References: Ignacio Rodriguez-Iturbe and Vujica Yevjevich, Colorado State University Hydrology Paper No. 26 (April 1968), "The Investigation of Relationship Between Hydrologic Time Series and Sunspot Numbers."

Key Words: Sunspot effects, hydrology, extraterrestrial effects on hydrology, cross-correlation in hydrology, cross-spectral analysis in hydrology

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References: Ignacio Rodriguez-Iturbe and Vujica Yevjevich, Colorado State University Hydrology Paper No. 26 (April 1968), "The Investigation of Relationship Between Hydrologic Time Series and Sunspot Numbers."

Key Words: Sunspot effects, hydrology, extraterrestrial effects on hydrology, cross-correlation in hydrology, cross-spectral analysis in hydrology

Abstract: The relationship of hydrologic series of monthly precipitation, annual precipitation and annual runoff to sunspot numbers has been investigated by cross-correlation analysis for various time lags (zero lag included) and by cross-spectral analysis. Eighty-eight series of monthly precipitation and 173 series of annual precipitation (stations from western North America), and 16 series of annual flows (stations from several parts of the world) were used as research data. No significant correlation was found between these hydrologic series and sunspot numbers. In fact, the spectrum of sunspot numbers proved to be nearly identical to the spectrum of residuals which were obtained by deducting values of hydrologic series from values of sunspot series. The coherence graphs worked out are within confidence limits of two independent time series, that indicate there is no relationship between hydrologic time series and sunspot numbers. Sampling fluctuations of cross-correlation coefficients between hydrologic series and sunspot numbers increase when both series are smoothed by moving average schemes. Therefore, when the confidence limits of unsmoothed series are used in the smoothed series approach, incorrect conclusions may be drawn about the significance of correlation.

References: Ignacio Rodriguez-Iturbe and Vujica Yevjevich, Colorado State University Hydrology Paper No. 26 (April 1968), "The Investigation of Relationship Between Hydrologic Time Series and Sunspot Numbers."

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