Cross-Spectral Analysis of Sunspots and Monthly Mean Temperature and Precipitation for the Contiguous United States[1]

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ABSTRACT

The finite Fourier transform method of cross-spectral analysis is used to investigate the relationship between the Zurich annual sunspot number and state monthly mean temperature and precipitation derived from the Climatological Observation Network data for most of the contiguous United States. Both the single (~11 year) and the double (~21 year) sunspot cycles are investigated. Our analyses show statistically significant relationships between the double sunspot cycle and the "January thaw" phenomenon along the East Coast and between the double sunspot cycle and "drought" (June temperature and precipitation) in the Midwest.

1. Introduction

Many researchers have examined various types of meteorological data for evidences of relationships with solar activity. The results often seem contradictory even when a common set of data is analyzed. Shapiro (1975), for example, examined a series of monthly mean temperatures for central England published by Manley (1974). He specifically comments on the absence of any evidence of the 11-year sunspot period. This same data set was examined by Bain (1975) and Dyer (1976), both of whom report evidence for an 11-year cycle, at least during certain months, as well as more compelling evidence for a 22-year (double) cycle. In these instances, the different conclusions apparently result from different analytical procedures used.

Gerety *et al.* (1977) conducted an exhaustive cross-spectral analysis of the single and double sunspot cycles and temperature and precipitation data from approximately 300 unevenly spaced stations around the world. Annual and seasonal analyses were performed. No significant evidence for a solar signal in either temperature or precipitation was found. This paper reports the results of a similar cross-spectral analysis in which the single and double sunspot cycles and state monthly mean temperatures and precipitation for most of the contiguous United States were used in place of sparse and unevenly spaced single-station data. The results of this study show several instances in which solar-weather relationships may exist.

2. Data

Temperature and precipitation data for this study were obtained from two publications containing data from the Climatological Observation Network. This network is limited to temperature and precipitation data but is far more dense than the Synoptic Network. There are more than 5000 climatological stations in the United States.

U.S.D.A. Statistical Bulletin 101, "Fluctuations in crops and weather, 1866–1948," lists the monthly mean temperature and precipitation for each state and month. These means were calculated as follows: Each state was divided into several climatological regions; regional means were calculated by averaging the values at the climatological stations in the region; and finally, a state mean was obtained by areally weighting the regional means.

Record length varies considerably among the states. Iowa has the longest record, beginning in 1873; California has the shortest, beginning in 1897. Record length was extended to 1974 by referring to the U.S. Department of Commerce (1975) publication "Areally weighted state averages of temperature and precipitation totals, 1931–1974." The values for the years 1931–48 in this publication were compared with those in Statistical Bulletin 101; no significant discrepancies were detected. Statistical Bulletin 101 does not list Maine and the New England states separately. Also, Maryland data prior to 1931 are missing from our copy. No analyses were done for these states.

Many studies involving possible relationships between solar activity and surface phenomena rely upon data from individual stations. Unfortunately, such records are subject to inhomogeneities because of re-

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location of instruments, urban growth, etc. Also, persistent local small-scale effects are not uncommon. Such inhomogeneities cannot be effectively handled by a simple linear detrending operation. Although techniques exist that will locate and remove such inhomogeneities, removal by computer requires considerable computer time and storage. Consequently, studies that use data from large numbers of stations rarely address this problem. In this study, inhomogeneities at individual stations are considered to have limited effect on state means.

3. Method

This paper reports the results of cross-spectral analyses. Analyses of monthly mean temperature and precipitation for all 12 months for 41 states were accomplished with the aid of procedure SPECTRA in the Statistical Analysis System (Barr *et al.*, 1976), a high-level programming language oriented toward statistical analysis. SPECTRA uses finite Fourier transform methods to calculate periodogram estimates, spectral densities and cross-spectral quantities as required. The data for each month were analyzed separately to eliminate high-frequency (e.g., annual) oscillations and to eliminate possible seasonal trends.

In the finite Fourier transform (FFT) method of spectral analysis, Fourier analysis is applied to the observations directly, rather than to the lagged autocovariances (or cross covariances) of these observations. The FFT method yields, for example, $N/2+1$ pairs of Fourier coefficients for each time series, where N, the number of observations, is even. Spectral and cross-spectral quantities are then calculated directly from these Fourier coefficients. These raw spectral estimates exhibit considerable variance, which may be reduced by the application of a suitable moving average to these estimates as a filter. In the selection of a filter, one encounters the same sort of trade-off between stability and resolution that one encounters in the selection of a maximum lag in the method of lagged autocovariances. However, the filter does not selectively enhance or reduce estimates at certain frequencies, as it would in the case of bandpass filtering.

In an attempt to determine the reality of a solar signal in the meteorological data, our primary concern was to avoid spurious peaks in spectral and cross-spectral densities. A number of filters were applied to the raw (univariate) spectral densities of each of certain arbitrarily selected meteorological time series without calculating cross spectra. The Hamming and Hanning filters, which are often employed in the method of lagged autocovariances, did not produce adequately smooth spectra in our FFT method. We selected a five-point uniform filter as offering the best compromise between stability and resolution. This filter was employed in the calculation of all spectral and cross-spectral quantities reported in this study.

To facilitate comparisons of results among the states, it seemed desirable to analyze the temperature and precipitation records over the same time interval for all the states. The question arose of how long an interval to use. It seemed that we would be wasting useful data by choosing an interval equal to the minimum (i.e., that of California which begins in 1897). Of the 18 states whose records begin after 1890, eight begin in 1891, and five more begin in 1892. On this basis, it was decided to run the double-sunspot-cycle analyses from 1891, giving us four complete 21-year cycles. Mean values for the series were substituted for missing values because this procedure has minimal impact on the covariance structure of the series. This procedure was deemed unnecessary in the single-sunspot-cycle analyses, and these analyses were run from 1898 (seven complete cycles).

The Zurich annual mean sunspot number was used as the index of sunspot activity. In analyses involving the double sunspot cycle, negative values were assigned to the annual mean sunspot number for alternate single cycles, the cycle beginning in 1901 being the first so assigned.

The time series were tested for linear trend in two ways. Ten time series were arbitrarily selected for examination: temperature and precipitation data for Iowa-July, Virginia-January, Colorado-June, Arizona-May and Michigan-November. In most instances the standard error of the estimated linear regression coefficient was greater than the coefficient itself, so a detrending procedure did not seem appropriate. In addition, time series showing high coherencies with one of the sunspot cycles were detrended and reanalyzed. None of the coherency estimates at the 11- or 21-year harmonics differed by more than 0.02 from the original estimates as a consequence of the detrending.

In the analysis of the effects of the single sunspot cycle, attention was directed toward the 11-year harmonics of the squared coherency (herein referred to as coherency) and phase spectra. For the double sunspot cycle, attention was directed toward the 21-year harmonics. The 10, 5 and 1% significance levels of coherency for the five-point uniform filter are 0.44, 0.53 and 0.68, respectively.

4. Results

The analyses of temperatures and the double sunspot cycle show 28 states whose temperatures have coherencies of at least 0.53 (the 5% level) at the 21-year harmonic for some month (Table 1). Sixteen of these are grouped in the eastern United States in January (Fig. 1); the rest are widely scattered in space and time. The corresponding phase estimates in the January cluster are remarkably consistent—−2.0±0.2 rad.

To interpret these results we have taken the null hypothesis that the coherency between either the single or double sunspot cycle and a temperature or precipita-

TABLE 1. Temperature and precipitation time series whose 21-year coherency harmonics with the double sunspot cycle are significant at the 5% level. Phases (rad) are in parentheses. The total area (km²) corresponding to each month is given beside the month.

Temperature				Precipitation			
January	2 223 805	August	146 194	January	151 793	August	490 806
NY	(−2.0)	IL	(−0.3)	FL	(1.5)	KS	(2.5)
PA	(−2.0)					LA	(0.5)
NJ	(−2.0)	November	1 280 717	February	1 169 359	FL	(2.0)
DE	(−2.1)	OR	(2.9)	CA	(0.4)		
OH	(−2.0)	ID	(2.7)	UT	(0.4)	September	1 180 057
WV	(−2.1)	TX	(2.1)	WV	(−0.2)	CA	(0.2)
VA	(−2.1)	LA	(1.8)	VA	(0.2)	NE	(2.2)
TN	(−2.1)			NC	(0.6)	SD	(2.1)
NC	(−2.1)	December	286 531	SC	(0.7)	MN	(2.1)
SC	(−2.0)	NV	(0.4)	GA	(0.7)	MI	(1.8)
GA	(−2.0)						
FL	(−2.2)			April	322 608	October	199 714
AL	(−2.0)			VA	(−1.0)	SD	(−3.1)
MS	(−2.0)			NC	(0.2)		
LA	(−1.9)			SC	(0.8)	November	917 990
KY	(−2.1)					CA	(2.5)
MT	(1.2)			June	2 156 664	NV	(2.2)
WA	(0.7)			WY	(2.4)	UT	(2.4)
				SD	(1.9)		
February	428 144			IA	(2.7)	December	655 332
WA	(1.7)			NE	(2.2)	NM	(1.6)
OR	(1.9)			CO	(2.3)	OH	(−2.8)
				KS	(2.2)	SC	(3.1)
June	490 330			MO	(2.5)	GA	(2.8)
UT	(−0.4)			TX	(1.0)		
CO	(−0.6)						
				July	232 291		
				SC	(1.1)		
				FL	(2.0)		

tion time series is zero. Thus it can be stated with 95% confidence that 24.60±9.48 of the 492 time series in each study should have a coherency estimate at or above 0.53. However, because the time series are not strictly normal and also are not independent, results in terms of numbers of states must be interpreted with caution. The results may also be presented in terms of areas, i.e., it can be stated with 95% confidence that states representing $4.58\times10^6\pm1.74\times10^6$ km² of the total area for each study should have a coherency estimate at or above 0.53.

Another pattern occurs in the analyses of precipitation and the double sunspot cycle. In this case, there

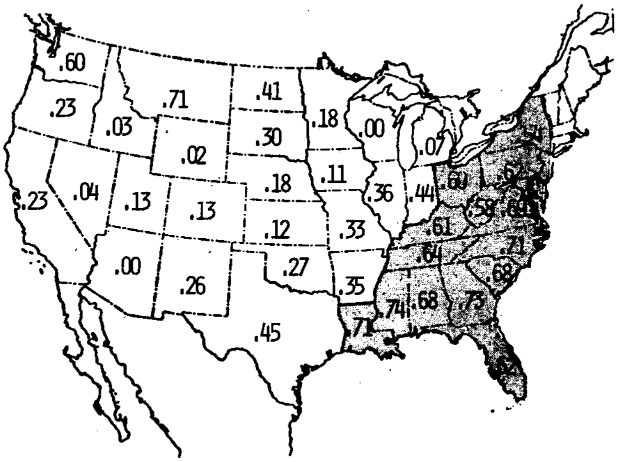

FIG. 1. January temperatures and the double sunspot cycle. The 21-year coherency harmonic is given for each state in the analysis. Contiguous states having coherencies significant at the 5% level are shaded in Figs. 1–7.

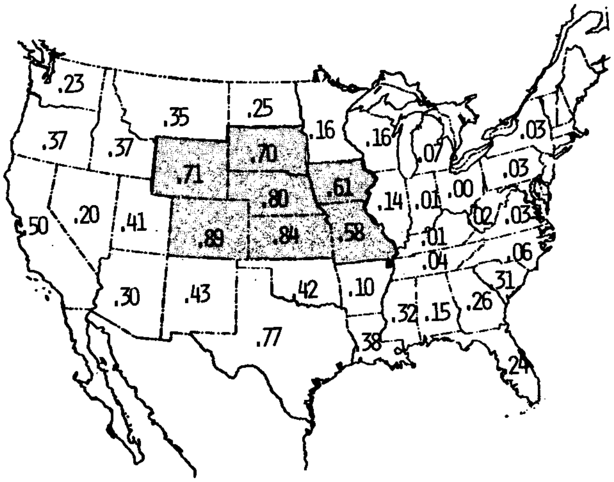

FIG. 2. June precipitation and the double sunspot cycle. The 21-year coherency harmonic is given for each state in the analysis.

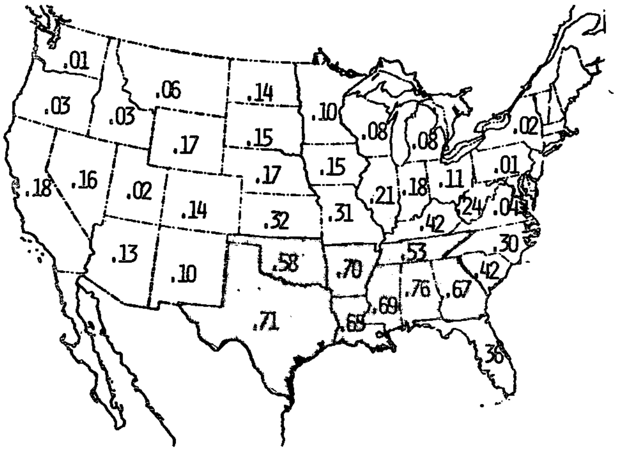

FIG. 3. April temperatures and the single sunspot cycle. The 11-year coherency harmonic is given for each state in the analysis.

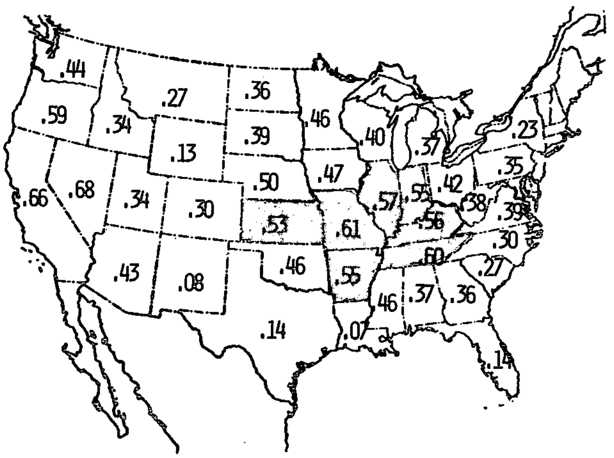

FIG. 5. June temperatures and the single sunspot cycle. The 11-year coherency harmonic is given for each state in the analysis.

are 37 state-month time series having a 21-year coherency harmonic significant at the 5% level (Table 1). Of these, seven occur in the Great Plains area in June. Phase relationships in this cluster are consistent and the coherencies are near the 1% significance level (Fig. 2).

In the analyses of temperatures and the single sunspot cycle, we observed 40 state-month time series whose 11-year coherency harmonics are significant at the 5% level (Table 2). Twenty-eight of these occur in one of four clusters (Figs. 3–6). Three clusters in May, June and July seem associated in space, and phase relationships are consistent among, as well as within, these clusters.

Finally, in the analyses of precipitation and the single sunspot cycle we find 39 state-month time series with coherencies at 11 years significant at the 5% level (Table 2). Eleven of these are clustered in the eastern and central United States in June (Fig. 7). In this case, the phases are not entirely consistent; they range over 1.6 rad (or 2.8 years).

The maps in Figs. 1–7 depict only the results that have geographical groups at the 5% level. Tables 1 and 2 provide complete lists of the temperature and precipitation time series that show coherency harmonics at 11 or 21 years significant at the 5% level with the single or double sunspot cycles. Phase estimates at the appropriate harmonic are also given.

The results in terms of numbers of states are summarized in Table 3. Here the number of states whose temperature and precipitation time series have 11- or 21-year coherency harmonics with the single or double sunspot cycles significant at the 10, 5 and 1% levels are presented. For the 492 time series in each study the expected number of states in a 95% confidence interval are 49±13, 25±9 and 5±4 for the 10, 5 and 1% levels, respectively. Because states represent different

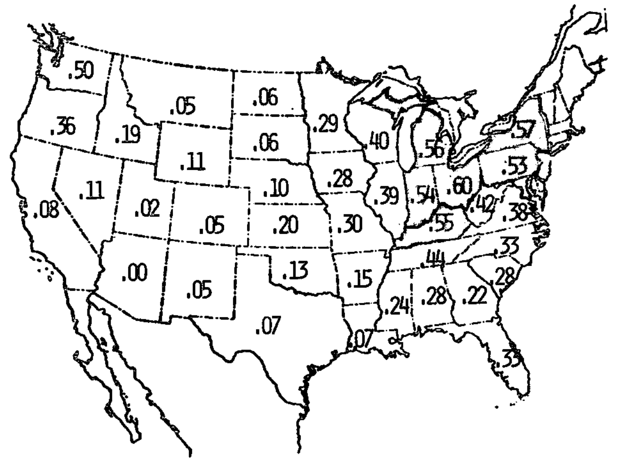

FIG. 4. May temperatures and the single sunspot cycle. The 11-year coherency harmonic is given for each state in the analysis.

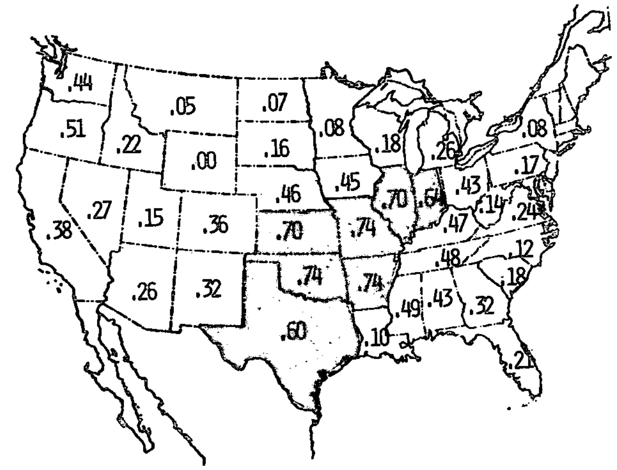

FIG. 6. July temperatures and the single sunspot cycle. The 11-year coherency harmonic is given for each state in the analysis.

TABLE 2. As in Table 1 except where the 11-year coherency harmonics with the single sunspot cycle are significant at the 5% level.

Temperature				Precipitation			
January	176 760	July	1 645 991	February	428 144	July	1 058 868
WA	(−2.3)	KS	(−2.4)	WA	(0.7)	CA	(−1.2)
		OK	(−2.3)	OR	(0.6)	KS	(1.2)
March	220 111	TX	(−2.3)			OK	(0.9)
UT	(0.0)	MO	(−2.6)	March	776 003	IL	(0.6)
		AR	(−2.7)	ND	(−2.7)	OH	(0.1)
April	1 657 207	IL	(−2.6)	NY	(−2.9)		
OK	(−2.3)	IN	(−2.7)	PA	(−2.7)	August	263 417
TX	(−2.3)			VA	(3.1)	IA	(2.8)
AR	(−1.7)	October	707 485	KY	(−2.8)	PA	(−1.6)
LA	(−1.6)	ID	(−2.9)	NC	(2.8)		
MS	(−1.7)	MT	(−2.7)			September	216 588
TN	(−1.4)	TN	(1.4)	May	270 219	ID	(0.7)
AL	(−1.4)			CO	(−0.8)		
GA	(−1.2)	November	1 087 443			October	632 921
		KS	(−2.6)	June	2 277 385	LA	(0.2)
May	792 546	OK	(−2.6)	WY	(−1.1)	AR	(0.5)
NY	(2.3)	TX	(−2.7)	ND	(−2.0)	MS	(0.2)
PA	(2.6)			TX	(1.3)	TN	(0.1)
OH	(2.7)	December	220 111	OK	(0.5)	NC	(−0.3)
IN	(2.8)	UT	(−0.6)	AR	(0.2)		
KY	(−3.0)			MO	(−0.2)	November	211 560
MI	(2.4)			TN	(0.7)	KY	(0.5)
				KY	(0.7)	OH	(0.6)
June	1 935 257			IN	(0.3)		
OR	(0.5)			OH	(0.1)	December	286 388
CA	(0.5)			WV	(1.4)	AL	(2.4)
NV	(0.7)			VA	(1.0)	GA	(2.3)
KS	(3.0)			NC	(1.1)		
MO	(3.0)						
AR	(−3.0)						
IL	(2.9)						
IN	(3.0)						
KY	(3.0)						
TN	(3.0)						

areas, it is appropriate to present the results in terms of the total areas corresponding to these states. These are shown in Table 4.

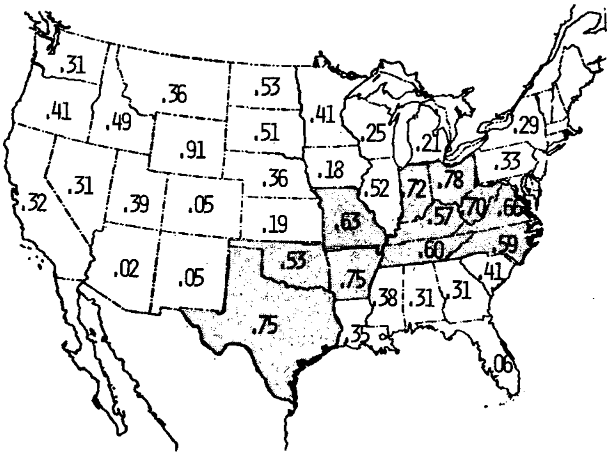

FIG. 7. June precipitation and the single sunspot cycle. The 11-year coherency harmonic is given for each state in the analysis.

5. Discussion

The implications of these results for the United States as a whole may be examined. Three of our studies, temperature versus the single cycle, precipitation versus the double cycle and precipitation versus the single cycle, involve more than 6.32×10^6 km^2 (the upper 95% bound) of area significant at the 5% level. The other study, temperature versus the double cycle,

TABLE 3. Numbers of states whose 1% temperature and precipitation time series have 11- or 21-year coherency harmonics with the single or double sunspot cycles significant at the 10, 5 and 1% levels.

Significance level	21 Year Precipitation	21 Year Temperature	11 Year Precipitation	11 Year Temperature	95% Confidence interval*
10%	64	49	68	80	49±13
5%	37	28	39	40	25± 9
1%	13	9	14	12	5± 4

* 95% confidence interval for the expected number of states having coherencies significant at this level.

Table 4. Total areas (10^6 km²) corresponding to states whose temperature and precipitation time series have 11- or 21-year coherency harmonics with the single or double sunspot cycles significant at the 10, 5 and 1% levels.

Significance level	21 Year Precipitation	21 Year Temperature	11 Year Precipitation	11 Year Temperature	95% Confidence interval*
10%	12.16	8.38	13.14	14.98	9.16±2.43
5%	7.48	4.86	6.42	8.35	4.58±1.75
1%	3.52	1.98	2.64	2.56	0.92±0.81

* 95% confidence interval for the expected total state areas (10^6 km²) having coherencies significant at this level.

has a total area (4.86×10^6 km²) consistent with that which would be expected by chance at the 5% level of significance. Similar statements could be made concerning the 10% and 1% levels of significance.

A cluster of states in the central United States has June precipitation records that show coherencies at 21 years significant at the 5% level with the double sunspot cycle (Fig. 2). The (approximate) 20-year drought cycle in this region is virtually a part of folklore and has been discussed by a number of authorities (e.g., Thompson, 1973; Roberts and Olson, 1975; Harrison, 1976). Drought in the central United States is usually found to be the result of a strengthening of the summer continental anticyclone, generally accompanied by an eastward displacement from its more usual position in the southwest. This effect was first observed by Reed (1937), was described in detail by Allen *et al.* (1940) and was mentioned by Holland (1954). The theory also requires above-average temperatures in the region. The results of our analyses of June temperatures and the double sunspot cycle are not as dramatic as the January temperature relationship for the eastern United States, but there is a cluster of six states in this region whose temperature records have 21-year coherencies significant at the 10% level with the double sunspot cycle (Fig. 8). The phase relationships for the precipitation cluster are such that a precipitation minimum would occur around the time of the sunspot minimum following a negative cycle. The phase angles for states in the temperature cluster are roughly 180° out of phase (Fig. 9) with those for precipitation, a circumstance conducive to a drought cycle.

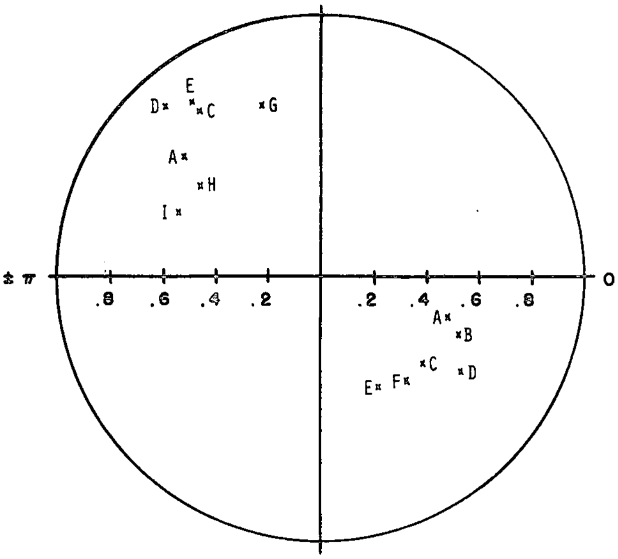

Fig. 9. June temperatures and precipitation. This is a polar plot of the 21-year harmonics of coherency and phase for June temperatures and precipitation and the double sunspot cycle. Only states in the regions of interest in Figs. 2 and 8 are plotted. All temperatures are located within the second quadrant; all precipitations are located within the fourth.

(A) Wyoming
(B) Utah
(C) Nebraska
(D) Colorado
(E) Kansas
(F) New Mexico
(G) South Dakota
(H) Missouri
(I) Iowa

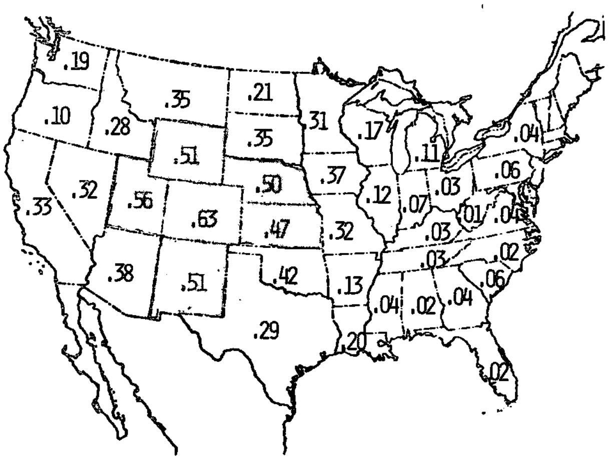

Fig. 8. June temperatures and the double sunspot cycle. The 21-year coherency harmonic is given for each state in the analysis. In this case, contiguous states having coherencies significant at the 10% level are shaded.

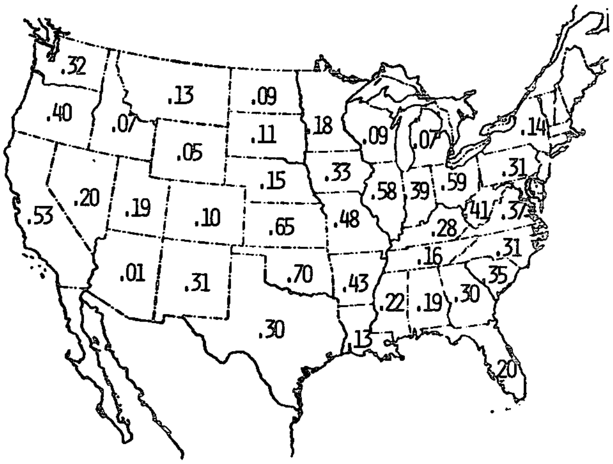

Fig. 10. July precipitation and the single sunspot cycle. The 11-year year coherency harmonic is given for each state in the analysis.

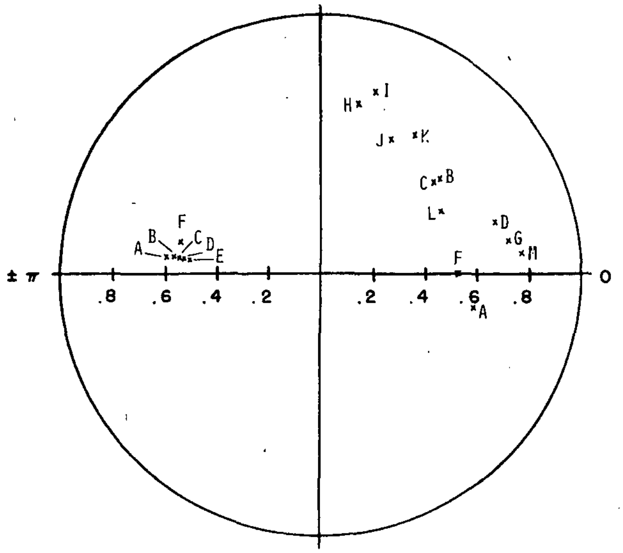

FIG. 11. June temperatures and precipitation. This is a polar plot of the 11-year harmonics of coherency and phase for June temperatures and precipitation and the single sunspot cycle. Only states in the regions of interest of Figs. 5 and 7 are plotted. Temperatures are located near $\pm\pi$; precipitations are located within (or near) the first quadrant.

(A) Kansas
(B) Indiana
(C) Kentucky
(D) Tennessee
(E) Missouri
(F) Illinois
(G) Arkansas
(H) West Virginia
(I) Texas
(J) North Carolina
(K) Virginia
(L) Oklahoma
(M) Ohio

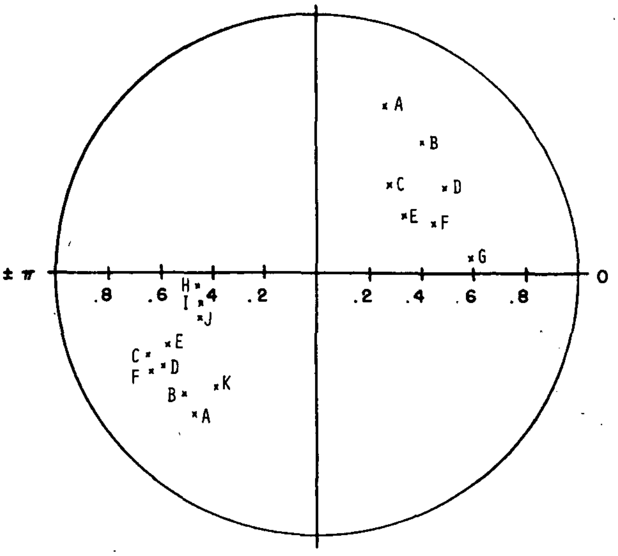

FIG. 12. July temperatures and precipitation. This plot is similar in notation to Fig. 11. The regions of interest in Figs. 6 and 10 are compared. Precipitations are located with the first quadrant; temperatures are located within the third.

(A) Oklahoma
(B) Kansas
(C) Arkansas
(D) Illinois
(E) Indiana
(F) Missouri
(G) Ohio
(H) Mississippi
(I) Kentucky
(J) Tennessee
(K) Texas

The analysis of temperatures and the double sunspot cycle provides further statistical evidence for a sunspot-weather relationship. Of the 16 states shown in Fig. 1 with coherencies significant at the 5% level, seven of these are also significant at the 1% level. Mock and Hibler (1976) investigated 10 stations in eastern North America by using maximum entropy spectral analysis and found a prominent 20-year peak only in the winter spectrum and, of the winter months, only in January. They also observed that the 20-year oscillation was substantially in phase over the region.

The geographical progression of clusters of states having 11-year coherencies significant at the 5% level in May, June and July (Figs. 4–6) in the analyses of temperature and the single sunspot cycle is quite striking. This progression is suggestive of a dynamical cause.

The corresponding precipitation analyses also show a cluster of states having 11-year coherencies significant at the 5% level, but only in June (Fig. 7). There is fragmentary evidence that the effect persists until July (Fig. 10). Although the phase relationships in the June precipitation cluster are not tightly consistent, they are roughly 180° out of phase (Fig. 11) with the phase angles for the June temperatures in the same vicinity. This relationship between the phase angles for temperature and precipitation is clearer for the July analyses (Fig. 12), even though the precipitation coherencies are on the whole somewhat lower. This circumstance could produce periodic crop stress, a contention that receives some support from Harrison's (1976) study of crop yields. His analysis of Illinois corn yields showed significant decreases near sunspot minima.

6. Conclusion

Our results show several instances for both the single and double sunspot cycles in which clusters of states have precipitation or surface-temperature relationships with sunspot activity that are significant at least at the 5% level and that also have common phases. Certain of these relationships support biological drought indicators such as tree rings or crop yields.

This type of research needs to be extended to other parts of the world with a caution that single-station data may not be satisfactory for identifying a signal. Because some of the clusters of states having common high coherencies cover substantial geographic areas, the results reported here should be of some help to those who study solar-terrestrial relationships from the point of view of atmospheric dynamics.

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