Spectral Analysis of Station Pressure as an Indicator of Climatological Variations in Synoptic-Scale Activity in the Eastern United States

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ABSTRACT

A substantial decline in North American cyclone and anticyclone activity has been documented by several recent studies based on counts of disturbance tracks. An independent method of assessing long-term trends in synoptic-scale activity based on sequential spectral analysis of station pressure is suggested. The efficacy of this approach is supported by previous studies relating the spatial distribution of variance of band-pass filtered pressures to preferred cyclone tracks. However, examples of a preliminary application of the spectral method to three widely separated stations using approximately 30 years of winter data fail to reveal any significant long-term trends in the variance of pressure for synoptic-scale time periods.

1. Introduction

The familiar daily weather events of middle latitudes are closely associated with the cyclones and anticyclones of the near-surface weather maps and with the waves in the westerlies aloft. The long-recognized significance of cyclones as carriers of cloud and weather systems and as features of the general circulation has resulted in many studies of the spatial distribution of cyclone activity. In recent years a somewhat more modest effort has been made to examine temporal variations in synoptic-scale disturbance activity, for the most part applying the techniques of counting cyclones or cyclone tracks. Within the last decade, these studies have accumulated significant evidence for a substantial decline in cyclone and anticyclone frequency over North America.

The profound implications of significant changes in cyclone frequency for precipitation climatology and for the general circulation have received little attention. Furthermore, no studies of long-term trends in cyclone frequency appear to have been done independent of the cyclone track data base. The present study applies spectral analysis techniques to station pressure data in an effort to shed additional light on this important problem. This approach is independent of changing methods of map analysis and interpretation as well as changing data density. In fact, it is based on the single most accurate and robust measurement made in meteorology: the station pressure. Following a brief survey of the work based on cyclone tracks, we discuss the details of the method, the results of a preliminary application of the method and some implications of the results.

2. Recent studies

The spatial distribution of cyclone activity has been documented by the well-known studies of Petterssen (1950) and Klein (1957). These studies are based on counts of individual cyclones on daily weather maps. More recent work by Reitan (1974), Hayden (1981), and others has been based on published cyclone track maps. The interannual variation of cyclone frequency and long-term trends in cyclone activity have been studied by Saucier (1949), Hosler and Gamage (1956), Reitan (1974), Resio and Hayden (1975), Reitan (1979), Zishka and Smith (1980), Hayden (1981) and Whittaker and Horn (1981). With the exception of the earliest of these studies, all are based on the cyclone track method. Hosler and Gamage noted quite remarkable interannual variations in cyclone frequency, but no obvious longer period trends.

The more recent studies have quite consistently shown a distinct downward trend in cyclone activity. Fig. 1 from Zishka and Smith (1980) combines the results of their study with the earlier work of Hosler and Gamage. The more recent work indicates a decrease of 45% in the numbers of January cyclones over North America and its environs during the 28 year period ending in 1977. This result is largely consistent with Whittaker and Horn (1981). Furthermore, Zishka and Smith note a similar downward trend in anticyclone frequency.

Hayden (1981) used principal components analysis to define the spatial and temporal variations in annual cyclone frequencies. His data consist of annual frequencies of cyclone tracks passing through each of 74 grid cells covering 2.5° latitude by 5° longitude. The

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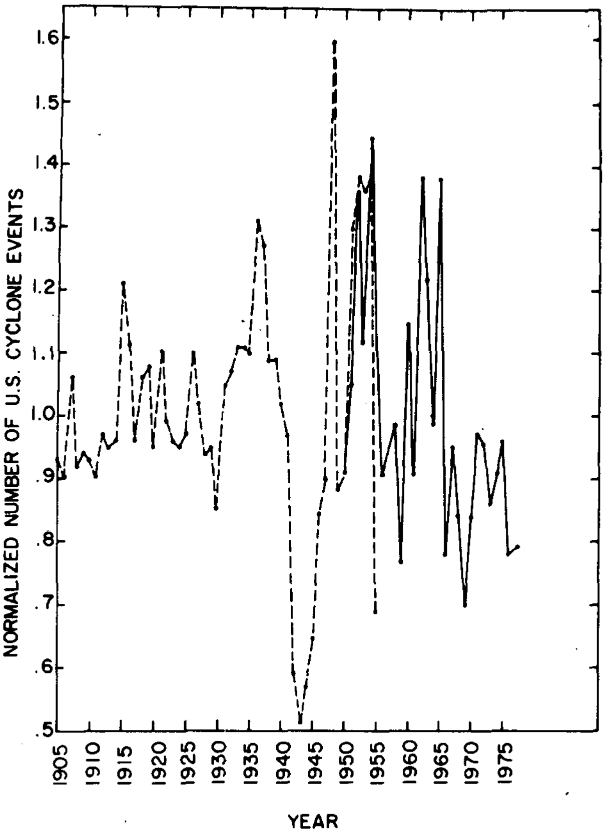

FIG. 1. Normalized yearly fluctuations of cyclone events over the United States (solid line from Zishka and Smith, 1980; dashed line from Hosler and Gamage, 1956). Entire figure from Zishka and Smith, 1980.

study encompasses the area of eastern North America and the western North Atlantic Ocean for the period between 1885 and 1978.

The first component obtained by Hayden distinguishes between continental and marine cyclones, while the second component is interpreted by Hayden to represent an east coast cyclogenesis function. Both components exhibit a century-long secular variation which suggests a relative increase of cyclone frequency over marine areas and a relative decrease over the continent along with a decrease in coastal cyclogenesis following a peak in the 1950's.

The cyclone-track counting method has been questioned by Peyrefitte and Astling (1981). They point out that the analysis interval for isobars on the operational analyses, upon which the cyclone tracks are based, has changed. The more recent analyses are effectively, coarser analyses. In their reply Zishka and Smith (1981) point out that no sudden change in their frequencies occurred at the time the changes in analysis interval took place. They argue that their inclusion only of systems which lasted a minimum of 24 h renders their results relatively insensitive to the analysis interval. Tests by Whittaker and Horn (1982), based on reanalyzed maps, support this contention.

While the cyclone track data base does appear to be fairly reliable, there are both obvious and subtle problems with its use. For example, particularly with the older data, we are often quite uncertain of the criteria used to define cyclones and of the philosophy of the analyses upon which the tracks are based. For example, the decision of whether or not to draw a closed isobar in a sparsely observed region of generally low pressure is a common analysis problem. Over long periods of time, an overall predilection to draw or not to draw such closed isobars without direct observational evidence will have important consequences for cyclone track statistics. Obviously, the time interval between operational analyses, and whether or not fronts are analyzed on the maps will also influence analyses of cyclone centers.

While we have not explored the question in detail, we have examined the relationship of cyclone tracks published in the *Monthly Weather Review* to cyclones appearing in the *Historical Weather Map* series for a few years of January cases. We found that in January of 1943 there are at least six well-defined cyclones over and near the United States for which tracks do not appear on the track maps; only five of at least eleven tracks are shown. Note from Fig. 1 that 1943 represents a remarkable minimum in the cyclone counts by Hosler and Gamage. In other years the counts based on these independent sources are generally quite consistent, suggesting difficulties with operational analysis under wartime security restrictions or possibly inexperience on the part of analysts. Whatever the cause of this one discrepancy, we believe that it further supports our contention for the importance of a study of disturbance activity that does not depend on more-or-less subjectively determined cyclone counts.

What is required is a meteorological variable which is both objectively determined and intimately related to cyclone activity. In this connection, analyses of the variances of pressure and other variables have been examined by many investigators. When variance in an appropriate "synoptic scale" frequency window is mapped over large geographic regions, results suggest a close relationship with disturbance activity.

For instance, Klein (1951a) combined new data with earlier results from the later 1800s to the mid-1900s and mapped the mean interdiurnal pressure change over much of the Northern Hemisphere. Areas with large interdiurnal pressure change correspond closely with cyclone tracks. Blackman *et al.*, (1977) extended the work of Sawyer (1970) and found that variance of several quantities for the 2.5–6 day period over the Northern Hemisphere is related closely to cyclone activity. For example, regions with high variance of geopotential height at 1000, 500 and 300 mb and the meridional wind component and relative vorticity at

500 mb—all coincide with the two major Northern Hemisphere storm tracks.

These studies and other works (Hartmann, 1974; Chiu, 1973) suggest a spatial correspondence between cyclone tracks and variance of station pressure, but the connection is not without ambiguities. For example, as Klein (1951b) notes, regions of high variance correspond well with tracks of anticyclones as well as cyclones.

Furthermore, it is not clear that temporal changes in cyclone frequency over a particular region correspond with temporal changes in the variance of station pressure within a fixed synoptic-scale frequency window. There is some suggestion that this is so, however. In his discussion of the weather for December 1951, Klein (1951b) notes that displacement of the location of preferred storm tracks over the United States from their normal position was accompanied by a corresponding displacement of the zone of maximum interdiurnal pressure change at sea level.

The results of earlier studies thus suggest that the variance of station pressure in certain frequency bands might be a suitable index of disturbance activity and that temporal trends in cyclone and anticyclone activity might be accompanied by trends in the pressure variance. Furthermore, basing the study on the variances at individual stations makes the results independent of changes in data density and map analysis techniques.

3. The data base and analysis techniques

To test the hypothesis that significant trends in disturbance frequency should be accompanied by trends in pressure variance, station pressure data observed every 3 h at Boston, Nashville and New Orleans for 25 to 34 winter seasons (1 December to 28 February) were used in this study (Table 1) to calculate the variance spectrum at each location and for each season. Spectral results were compared over time for a given station and among stations.

Station selection was based in part on data availability and partly on obtaining a widely dispersed sample of data over the eastern United States. The suitability of this selection is supported by Table 2 showing the eigenvector weights obtained by Hayden (1981) for grid boxes encompassing each of the stations. The greater the magnitude of the weights, the greater the response at a given location to the temporal variations shown by Hayden. The relatively large weights at Boston, Nashville and New Orleans clearly indicate that these stations should be representative of the trends revealed by Hayden's analysis.

TABLE 1. Three-hourly station pressures used in this study.

Station	Seasons used	Missing seasons	Total number of seasons
Boston	Dec 1945–Feb 1946 through Dec 1979–Feb 1980	Dec 1964–Feb 1965	34
Nashville	Dec 1954–Feb 1955 through Dec 1979–Feb 1980	Dec 1957–Feb 1958	25
New Orleans	Dec 1948–Feb 1949 through Dec 1979–Feb 1980	Dec 1964–Feb 1965	31

TABLE 2. Eigenvector weights determined by Hayden (1981).

Station	Eigenvector weights 1	Eigenvector weights 2
Boston	−0.08	+0.12
Nashville	−0.14	+0.10
New Orleans	−0.08	+0.09
Range of land values east of 90 W	−0.16–+0.08	0.00–+0.20

These conclusions are further substantiated by the raw cyclone frequency data for these same grid boxes discussed in Section 4. Thus while a larger number of stations would certainly be desirable, these three should provide a reasonably representative sample for present purposes.

The variance spectrum for each winter season was computed directly from the original data values using the fast Fourier transform (FFT).

The major steps followed in calculating the variance spectrum from a set of D observations of $x'(j)$, a sample of $x(j)$, are outlined, along with the theoretical foundations of spectral analysis, in Rayner (1971). The specific steps are:

1) Remove the mean.

2) Apply the tapering window functions $h[j]$, described by Blackman and Tukey (1959). Blackman and Tukey suggest that a cosine taper be used over 10% of each end of the data with the number of tapering points (G) equal to about $D/10$; the form of $h[j]$ is given as:

$$\left.\begin{aligned} h[j] &= \frac{1}{2}\left\{1 - \cos\left(\frac{\pi j}{G}\right)\right\}, & 0 \leqslant j < G \\ &= 1, & G \leqslant j \leqslant D - G \\ &= \frac{1}{2}\left\{1 - \cos\left[\frac{\pi(D - j)}{G}\right]\right\}, & \\ & & D - G < j \leqslant D - 1 \end{aligned}\right\} .$$

As a result, $\hat{x}(j) = x'(j)h[j]$.

3) If required, zeros may now be added to the end of $\hat{x}(j)$ to aid in factoring for the fast Fourier transform. The addition of zeros also allows the user to adjust the frequency bands to the desired central frequencies. The number of zeros added plus D is defined as n.

4) Calculate the coefficients $\hat{a}[k]$ and $\hat{b}[k]$ from

$$\left.\begin{aligned} \hat{a}[k] &= \frac{2}{n}\sum_{j=0}^{n-1} \hat{x}[j]\cos\left(\frac{2\pi jk}{n}\right) \\ \hat{b}[k] &= \frac{2}{n}\sum_{j=0}^{n-1} \hat{x}[j]\sin\left(\frac{2\pi jk}{n}\right) \end{aligned}\right\}.$$

5) Calculate the variances $\widehat{XX}[k]$ and sum over blocks which are $2z + 1$ in width (where z is any integer) centered at r, to give the $\widehat{XX}[r]$ estimates, i.e.,

$$\left.\begin{aligned} \widehat{XX}[0] &= \hat{\hat{a}}^2[0] + \sum_{k=1}^{z} \frac{\hat{a}^2[k] + \hat{b}^2[k]}{2} \\ \widehat{XX}[r] &= \sum_{k=r(2z+1)-z}^{r(2z+1)+z} \frac{\hat{a}^2[k] + \hat{b}^2[k]}{2} \\ \widehat{XX}[m] &= \sum_{k=n/2-z}^{n/2-1} \frac{\hat{a}^2[k] + \hat{b}^2[k]}{2} \\ &\qquad + \hat{\hat{a}}^2\left[\frac{n}{2}\right] \end{aligned}\right\} ,0 < r < m,$$

$$\hat{a}[k] = \frac{a[k]}{2}$$

for

$$k = 0 \quad \text{and} \quad k = \frac{n}{2},$$

where n equals the number of observations D plus the number of zeros added, and m equals the number of spectral estimators. With n even, $2z + 1$ odd, and $(n/2)/m = 2z + 1$, the derived frequency bands are centered at $0, \frac{1}{2m\Delta t}, \frac{2}{2m\Delta t}, \ldots, \frac{r}{2m\Delta t}, \ldots, \frac{1}{2\Delta t}$, where, in the present case, m is 75, $2z + 1$ is 5, and Δt is 0.125 day. Selection of the above parameters, yields variances in periods ranging from 0.25 to 18.75 days. The results constitute a one-sided spectrum.

The statistical significance of the year-to-year variations in band variances has been assessed using 90% confidence limits calculated from

$$\frac{N\sum\hat{\sigma}^2}{\chi^2_{N,0.05}} \leqslant \sum\sigma^2 \leqslant \frac{N\sum\hat{\sigma}^2}{\chi^2_{N,0.95}},$$

where $\Sigma\,\hat{\sigma}^2$ is the variance in each frequency interval summed over the frequency band to be tested, and N is the equivalent degrees of freedom in the band. The value of N is computed from

$$N = 2B_eT,$$

where T is the total band period, and B_e is the equivalent bandwidth (Blackman and Tukey, 1959) obtained from

$$B_e = \frac{(\sum\hat{\sigma}^2)^2}{\sum(\hat{\sigma}^2)^2}.$$

Visual inspection of data plots indicated that slight trends in the pressure data existed in some seasons; however, neglecting them did not appreciably affect the variance in the 2–10 day period range.

Dates of changes in station elevation during the years used in the study were checked in Local Climatological Data (1980) and compared with the time series of station pressure. The effects of elevation changes were found to be negligible for the stations in question.

For the most part, missing or questionable data were not a problem. When a large portion of the pressure data for a month were missing, this season was not used in the study. Usually, however, only single, isolated data points were missing or questionable. Prior to 1965, hourly data were available for all stations, whereas after 1965 only 3-hourly data were available. Thus, when one 3-hourly observation was missing prior to 1965, the average of the pressure values one hour before and after the missing value was used. After 1965 adjacent 3-hourly data were averaged.

4. Results

Of the three sites, the largest magnitude and interannual variability of total pressure variance is evident at Boston, as illustrated in Fig. 2. The importance of the activity at this site agrees with data on cyclone tracks and storm frequency by Zishka and Smith (1980), for example, where a maximum in the cyclone frequency in January for 1950–77 is located in the waters off the New England coast. The large interannual winter variability is well represented in both studies. Of note in Fig. 2, however, is the conspicuous lack of long term trend in variance at any of the sites.

The importance which the 2 to 10 day period variation (the approximate time scale of cyclone activity) plays in shaping the total spectrum is illustrated for Boston in Fig. 3. The variance in each frequency band is multiplied by the appropriate frequency and plotted against the log of the frequency. Thus, the area under each curve is a measure of the total variance, and the relative contribution of variance in any frequency band can be compared to that in other bands. Neglecting for a moment the year-to-year differences in the spectrum, one can see the large contribution from the activity in the 2 to 10 day period.

In the winter season the synoptic-scale variance dominates the total spectrum and there are no major peaks in variance at longer or shorter periods. Even in summer the synoptic-scale dominates, although the well-known decrease in synoptic activity characteristic of midlatitude summers causes an appreciable decrease in magnitude of the spectrum.

Year-to-year fluctuations in the relative variance in selected frequency bands are illustrated for Boston in Fig. 4. Here the variance is simply summed for periods of 7.5 days or more (long period), periods between 2

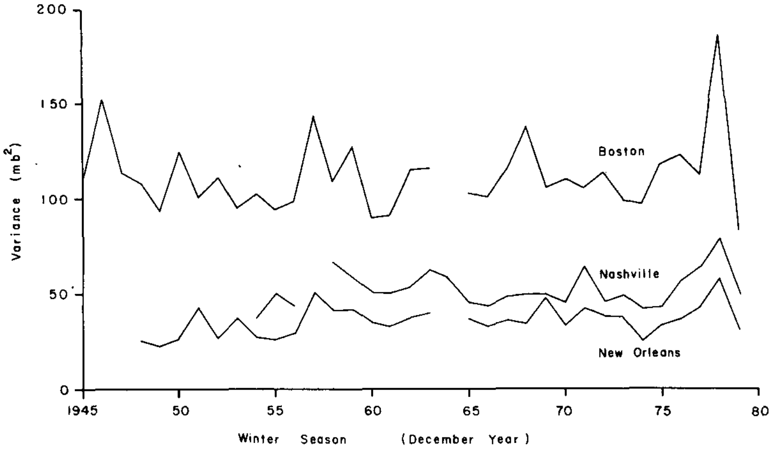

FIG. 2. Total variance of 3-hourly station pressure at three National Weather Service stations.

and 7.5 days ("band-pass" period) and for periods less than 2 days (short period). To aid in assessing the statistical significance of year-to-year variations, 90% confidence intervals are included for each band pass and selected total variances.

Much of the year-to-year variation in total variance, such as that depicted for 1951 through 1956, is not statistically significant. Differences are highly significant statistically where confidence intervals do not overlap, as in the total variance for 1957 and 1958, for example.

In the band-pass region there is important year-to-year variability also, but again, there is no significant long-term trend. A few short-term trends appear in the time series, as from 1950 to 1956 and from 1967 to 1972, for example, but a few such trends are a likely result of chance, especially in view of the width of the confidence intervals.

Results for Nashville and New Orleans in Figs. 5 and 6 are similar to those for Boston. Year-to-year variability in the band-pass and total variance is sometimes significant, but there is a conspicuous absence of a long-term trend.

The variance in any particular winter at one site does not appear to be well correlated with the variance at the other sites for any of the frequency bands, as careful inspection of Figs. 4, 5 and 6 reveals. However, it is interesting to note that the peak total variance at

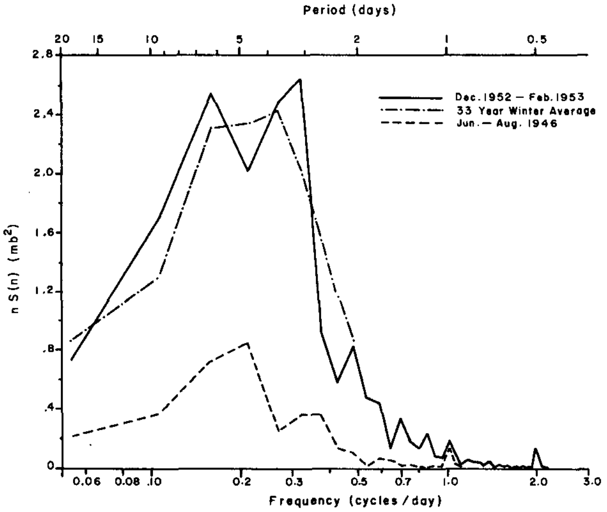

FIG. 3. The station pressure spectrum for Boston for selected seasons. Variance $S(n)$ in each frequency band is multiplied by the appropriate frequency n.

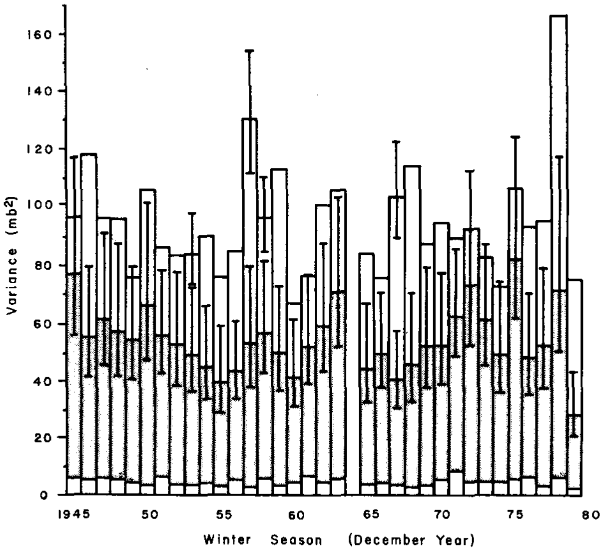

FIG. 4. Year-to-year variance during winter (December through February) for Boston. Variance for total, band-pass period (between 2 and 7.5 days), and short period (<2 days) is given for each year. The 90% confidence intervals are included for each band-pass period and selected total variance.

all three sites occurred in the winter of 1978–79. Also, the following winter was characterized by very low band-pass activity at all three locations. These extremes of pressure variance are associated with remarkable precipitation anomalies. During the "active" winter of 1978–79, Nashville experienced its wettest December on record, Boston its wettest January and New Orleans it second wettest February (Taubensee, 1979; Wagner, 1979; Dickson, 1979). On the other hand, January of 1980 was the driest and second least snowy on record at Boston (Wagner, 1980) where band-pass variance was at its lowest for the period of our study.

Raw cyclone frequency data for Hayden's cells over Boston, Nashville and New Orleans were obtained for December through February for the period 1945–80. At Boston and Nashville where seasonal counts ranged from 0 to 14, there was a downward trend in cyclone counts from ~1950 to the early to mid-1960s followed by an increase until the mid-1970s. Interestingly, there is no correlation at either station between the 2 to 10 day spectral variance and the seasonal cyclone counts. The only relation is that which might have been expected form Klein (1951a), namely, that Boston, with the largest 2 to 10 day variance experienced more cyclones over the 30 year period. Likewise, New Orleans had both the lowest variance and the lowest average number of cyclones.

The lack of any temporal relationship between cyclone counts and spectral variance is puzzling. Inspection of the individual pressure traces reveals that there are often many more pressure minima resembling cyclone passage than the cyclone counts indicate. This is probably because the cyclones were counted in 2.5° latitude by 5° longitude sectors, while the scale of cyclones is roughly eight times larger. Thus, cyclones passing by beyond the borders of the grid box produce distinct pressure minima at the center of the box. Therefore, it seems that direct comparison of variances with cyclone counts will require careful selection of a cyclone-scale sector within which cyclones are to be counted.

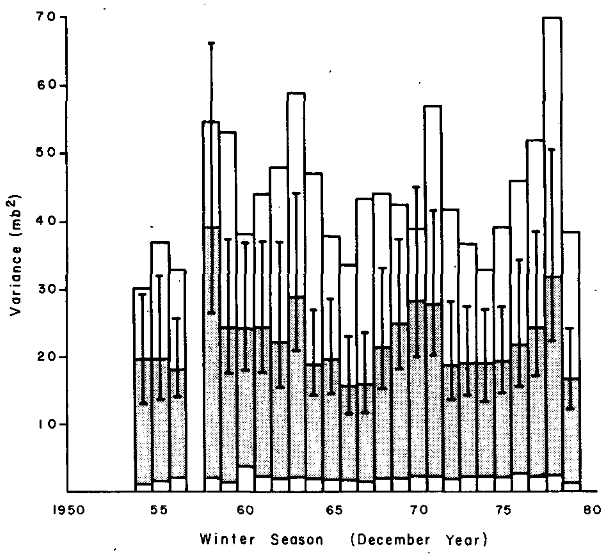

FIG. 5. As in Fig. 4 but for Nashville.

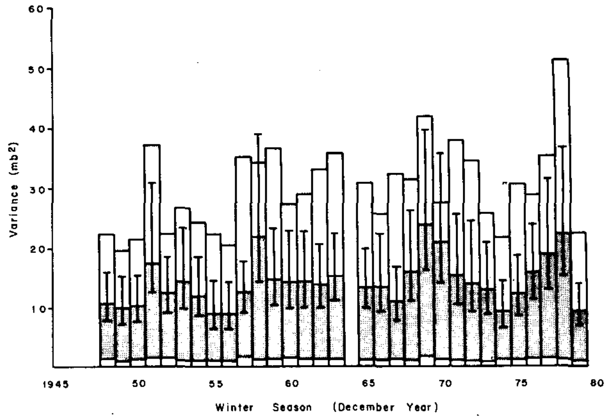

FIG. 6. As in Fig. 4 but for New Orleans.

5. Conclusions

While there were sometimes large changes in variance from year-to-year and four-to-six year trends in total and synoptic-scale variance, the long-term down trend in cyclone and anticyclone activity since 1950 based on track data was not confirmed by spectral analysis of station pressure in winter at Boston, Nashville or New Orleans.

Since data from only three sites were used in this analysis, and in particular, since the variations do not generally correlate well among the sites, it is possible that the three happen to be nonrepresentative of the eastern United States; however comparison with Hayden's analysis does not support this argument. Furthermore, given the synoptic space-scale and the results presented here for the synoptic period variance, the possibility seems remote. Most likely, either the cyclone-track data base is suspect, or a real decrease in the frequency of passage of cyclone centers has been compensated either by an accompanying increase in the frequency of open waves of synoptic time-scale, as frontal troughs, for example, or by an increase in mean cyclone intensity. Some evidence for the last possibility has been presented by Mather *et al.* (1967) and Zishka and Smith (1980).

We plan to extend this preliminary study by including more stations in the analysis, and we expect correlations and spectral coherence to increase, especially for long-period variance. If the interval between adjacent stations were reduced to the synoptic scale, the agreement should increase at the synoptic period also.

The implications of changes in synoptic-scale activity are fundamental to our perception of climatic change, and several questions raised here should be addressed. First and most obvious is the question of the relation between actual disturbance frequency and variance in the synoptic-scale period. Further comparison of spectrum analyses for a group of sites within a region with cyclone counts for that region for several test periods might clarify this question. Second, what is the spatial continuity of spectral coherence for various frequency bands? This is a question somewhat related to the first in that it can be used to quantify the synoptic or long-wave scale in the statistical sense.

The spatial bounds of the year-to-year trends in variance can also be ascertained. Results of this study show that, for locations as far apart as Boston, Nashville and New Orleans, variance trends are dissimilar for the most part. However, they are interesting and should be investigated for a longer data set and at more locations, since the persistence of trends and the similarities or differences in trends at synoptic versus longer-scale periods have important forecast applications.

Finally, if identifiable wave structures associate with preferred periods, what is the wave speed and where do the disturbances intensify or weaken? Techniques of Wallace and Dickerson (1972) and Wallace (1972) applied to a more complete data set might begin to provide answers to the question. We plan to explore these questions in future studies.

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