Hurricane Climatic Fluctuations. Part I: Patterns and Cycles

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ABSTRACT

Hurricane records for 1899 through 1978 are used to determine the numbers of hurricanes during the period August through October of each year that were present in the Atlantic. The Atlantic basin is subdivided into four geographic regions: the Central Atlantic, East Coast, Gulf of Mexico and Caribbean. An empirical orthogonal function (EOF) analysis is made of the time series of hurricane occurrence in each region to derive the dominant uncorrelated modes of interannual variability of seasonal hurricane incidence. The first EOF mode, accounting for 68% of the variance, represents the overall activity of the hurricane season. The second mode, accounting for 16% of the variance, represents the shift of hurricane incidence between the Gulf plus Caribbean, and the East Coast regions.

A coherency spectrum between the time variations of the first and second modes indicates a significant coherence at periods of about 2.5 and 4.5 years. The coherence at 2.5 years corresponds to the quasi-biennial oscillation (QBO). The results are related to the QBO in monthly hurricane numbers and in the strength and position of the North Atlantic subtropical high found by Angell *et al.* (1969). It is found that the maximum in East Coast hurricane incidence occurs at the phase of the QBO when the subtropical high is at its farthest northeastern displacement. The relation of the coherence at 4.5 years to the QBO is discussed.

1. Introduction

Global climatic variations have come under increased attention in recent years. Interannual fluctuations in hurricane activity and track form one part of the global picture. The 1940s was a decade of frequent hurricanes in Florida, the 1950s on the east coast of the United States, and the 1960s and 1970s in states on the Gulf of Mexico (Hebert and Taylor, 1979). The clustering of active hurricane periods in time has been noted in all formation areas of the globe (Gray, 1979). Several investigators have analyzed monthly or annual numbers of tropical cyclones in order to find periodic cycles and relationships between different geographic regions (Angell *et al.*, 1969, hereafter AKC; Jordan and Ho, 1962). Apparent relations between Atlantic hurricane incidence and large-scale wind or pressure anomaly patterns have been diagnosed by Namias (1955) and Ballenzweig (1959), among others. These analyses have been limited by the lack of an objective determination of dominant patterns of hurricane incidence, and by the absence of a statistical test of the apparent relations found between incidence and large-scale features.

The method of Empirical Orthogonal Functions (EOFs) will be used in this paper to determine dominant patterns of variability in seasonal hurricane incidence within the Atlantic basin. Spectral and cross-spectral analysis will be made of independent measures of overall activity and regional shifts in incidence. The results will be related to periodic cycles in monthly hurricane numbers and in the strength and position of the North Atlantic subtropical high found by AKC. In Part II (Shapiro, 1982) hurricane incidence EOFs will be related to sea-level pressure, sea-surface temperature and 500 mb height EOFs. This latter analysis specifies the statistically significant correlations that exist between the large-scale circulation patterns and cycles in seasonal Atlantic hurricane incidence.

2. Patterns of hurricane incidence

The data used in this analysis were derived from a compilation of tropical cyclone tracks made for the North Atlantic basin by the National Hurricane Center (Neumann *et al.*, 1981). This is the most comprehensive and reliable set of cyclone tracks for any area of the world. The Atlantic basin has been further subdivided by Dr. H. Hawkins into four regions, shown in Fig. 1: Central Atlantic (1), East Coast (2), Gulf of Mexico (3), and Caribbean (4). This geographic breakdown is a logical one in terms of hurricane threat. Regions 3 and 4 are essentially the same as those used by Ballenzweig (1959) to define areas of hurricane formation. Region 2 encompasses hurricanes that are a threat to the east coast of the United States. Region 1 encompasses Atlantic storms. Other boundaries could be selected.

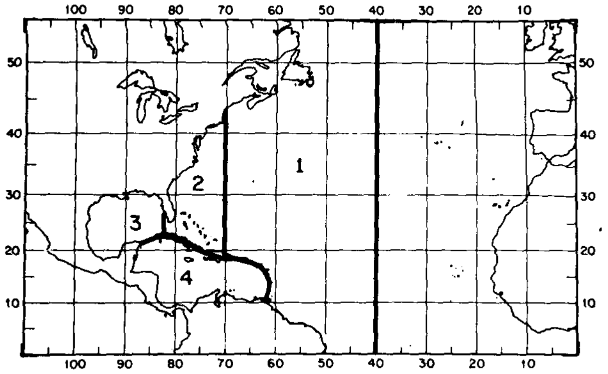

FIG. 1. Regions used for determining patterns of hurricane incidence: (1) Central Atlantic; (2) East Coast; (3) Gulf of Mexico; (4) Caribbean.

However, the use of many more regions to better define the "tracks" of the systems would reduce the average number of hurricanes in some regions to much less than one per year. August, September and October (ASO) are the three most active months of the hurricane season, contributing about 85% of the yearly activity. The number of tropical cyclones that occurred in each of the four regions during ASO was counted for each year from 1899 through 1978. This period was chosen so that the hurricane record would correspond to the period covered by sea-level pressure data (cf., Part II). Only tropical cyclones that attained hurricane strength (maximum wind $\geqslant 33$ m s^{-1}) were included. As long a track as possible was taken to define the cyclone path. Tropical storm tracks have been tabulated for the entire 80-year record. The path of each cyclone was followed during the time it was a named tropical storm (maximum wind $\geqslant 17.5$ m s^{-1}). The use of hurricane instead of storm stage to define the path would not significantly alter the results. A storm that passed through more than one region was counted once in each region it entered. If it was present in a given region more than one time, as in a recurving storm, the hurricane was counted only once. The four time series of hurricane numbers, each 80 years in length, were used to derive dominant patterns of variability in seasonal hurricane incidence.

The method of EOFs was applied by Lorenz (1956) to efficiently represent the time variations of meteorological data fields by use of a limited number of parameters. The properties of EOFs are developed by Lorenz (1956) and are discussed in Appendix B of Davis (1976). A data field $\phi(i, t)$, defined at N points $i = 1, \ldots, N$ and T times $t = 1, \ldots, T$ (for total of $N \times T$ observations) is decomposed into N modes:

$$\phi(i, t) = \langle \phi(i, t) \rangle + \sum_{n=1}^{N} a_n(t) e_n(i), \qquad (1)$$

where the sample mean

$$\langle \phi(i, t) \rangle \equiv \sum_{t=1}^{T} \phi(i, t)/T.$$

The N eigenmodes $\{e_n(i)\}$ are defined to be orthonormal, with uncorrelated amplitudes $\{a_n(t)\}$. The modes are ordered with respect to their contribution to the total variance in ϕ, the first mode explaining the greatest portion of the variance. The EOFs form an efficient representation of the data field for use in statistical prediction. This property is exploited in Part II. For the present analysis, the important feature of the EOFs is that they describe the uncorrelated modes of variability in the field.

In this paper the data to be analyzed are the number of hurricanes $\phi(i, t)$ present in Region i during ASO of year t. Here $N = 4$ and $T = 80$. The first EOF accounts for 68% of the total variance of ϕ. The remaining three EOFs account for 16, 11 and

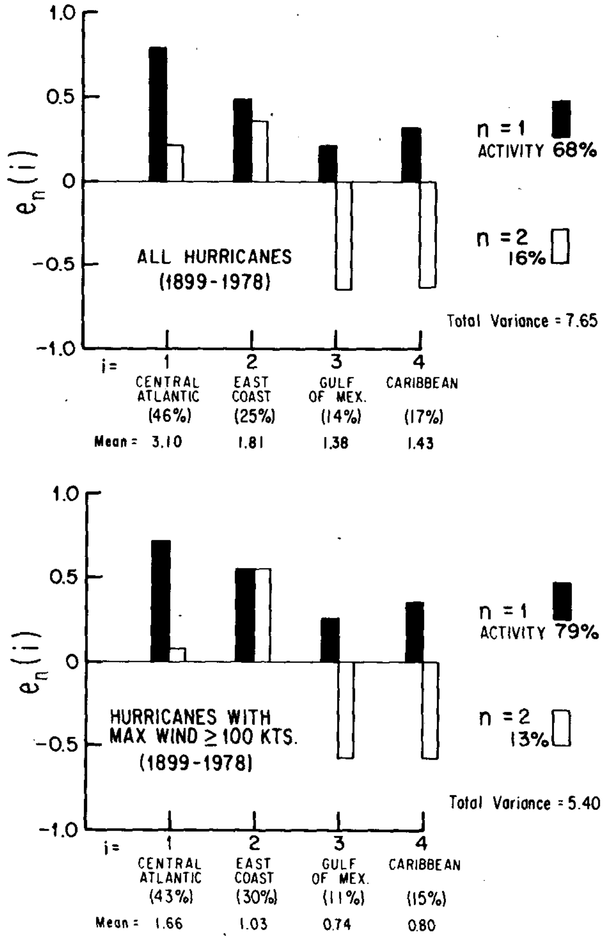

FIG. 2. Eigenmodes corresponding to dominant EOFs $n = 1$ and $n = 2$. Top panel is based on all hurricanes for ASO. Bottom panel is for hurricanes $\geqslant 100$ knots. Percentages are contributions to total variance in hurricane incidence.

5% of the variance, respectively. The eigenmodes corresponding to the first two EOFs, $n = 1$ and $n = 2$, are shown in the top panel of Fig. 2. $e_1(i)$ is positive in all regions, indicating a mode in which all regions vary in phase. The amplitude of $e_1(i)$ in a given region is approximately proportional to the contribution of the region to the total variance. In fact, the correlation coefficient between $a_1(t)$ and the total number of hurricanes occurring during ASO is 0.94. Thus, EOF $n = 1$ represents the overall hurricane activity for the entire Atlantic basin.

The remaining modes can be interpreted as the shift of storm activity from region to region. The second eigenmode $n = 2$ is by definition uncorrelated with $n = 1$. The importance of this property will be evident in Section 3. The mode $e_2(i)$ is positive in the Central Atlantic ($i = 1$) and East Coast ($i = 2$), and negative in the Gulf ($i = 3$) and Caribbean ($i = 4$). Thus, this mode represents the shift between East Coast and Gulf storms evident in climatological studies, such as Hebert and Taylor (1979). The prominence of this mode of variability in regional shifts in hurricane incidence follows directly from the EOF analysis. Of the three EOFs that represent the shift of hurricane incidence from one region to another, it is the mode that explains the greatest portion of the total variance. The third EOF mode ($n = 3$, not shown) represents the shift of incidence due to early recurving storms. Only the first two EOFs are considered in the present analysis. The contribution of these modes to the variance in hurricane incidence for each of the four individual regions is shown in Fig. 3. The first mode $n = 1$ contributes a substantial fraction of the variance in the Central Atlantic and East Coast regions; the contribution to the variance in the other two regions is much less. Thus the second mode ($n = 2$) must be included for a good representation of fluctuations of hurricane incidence in the Gulf of Mexico and Caribbean regions.

The lower panel of Fig. 2 shows the first two eigenmodes derived from the paths of cyclones that became hurricanes with maximum wind speed > 100 knots (51.5 m s^{-1}, Category $\geqslant 3$ on the Saffir-Simpson intensity scale; cf. Neumann *et al.*, 1981, Table 5). The dominant EOF ($n = 1$), explaining 79% of the total variance, represents the overall activity as it did for all hurricanes. The second EOF ($n = 2$) explains 13% of the variance; it shows a stronger negative relation between the East Coast ($i = 2$) and Gulf ($i = 3$) than did the analysis for all hurricanes. The third EOF ($n = 3$) explains only 6% of the variance. The first and second modes together account for 93% of the variance in ϕ while for all hurricanes they accounted for 83%. Thus, $n = 1$ and $n = 2$ together form a more complete representation of hurricane incidence that is more distinctly separated from higher modes when only Category $\geqslant 3$ hurricanes are included. In fact, Category $\geqslant 3$ hurricanes were used by Hebert and Taylor (1979) to illustrate the decades of Gulf and Caribbean vs. East Coast storms, since the cycles were much less evident when all hurricanes were included (Paul Hebert, personal communication, 1981). The EOF analysis of Category $\geqslant 3$ hurricanes will therefore be used in the present paper to evaluate periodic cycles and relationships in hurricane incidence. The analysis for all hurricanes is used in Part II.

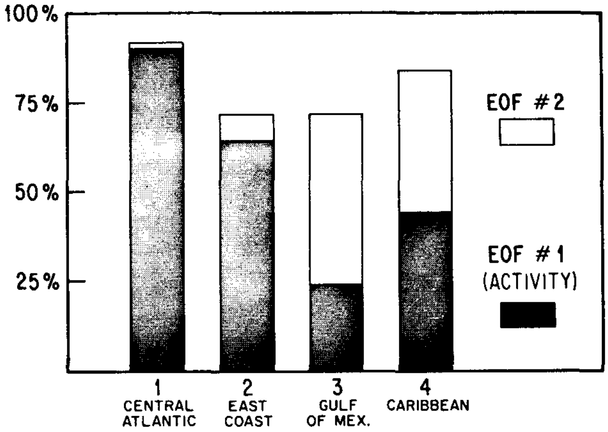

FIG. 3. Contribution of EOFs $n = 1$ and $n = 2$ to hurricane incidence in each of four regions. Values are percent of variance.

The amplitudes $a_1(t)$ and $a_2(t)$ of the first two EOFs for Category $\geqslant 3$ hurricanes are shown as functions of year in the upper bar graphs of Figs. 4 and 5. $\langle a_1(t)\rangle = \langle a_2(t)\rangle = 0$ by (1) and the orthogonality of the eigenmodes. The lower graph of Fig. 4 shows the number of Category $\geqslant 3$ hurricanes occurring in the Atlantic basin during ASO of each year. The average number is 1.93. $a_1(t)$ is large and positive in active years and negative in inactive years. The lower graph of Fig. 5 shows the number of hurricanes occurring in the East Coast ($i = 2$), and the Gulf ($i = 3$) plus Caribbean ($i = 4$) regions. $a_2(t)$ is positive when hurricane incidence has shifted towards the East Coast, as in the 1950s; it is negative during periods of Gulf and Caribbean activity, as near 1910. These trends are evident in the study by Hebert and Taylor (1979). Thus, the amplitudes give objective measures of hurricane activity and regional shifts in incidence that are consistent with previous climatologies. The time series, representing uncorrelated modes of variability, will be used in the following section.

3. Periodic cycles and relationships in hurricane activity and regional shifts in incidence

AKC performed an harmonic analysis of series of monthly hurricane numbers for the Atlantic basin. They found maxima in harmonic amplitude at periods of 28.8 months (2.4 years), 20.1 months (1.67

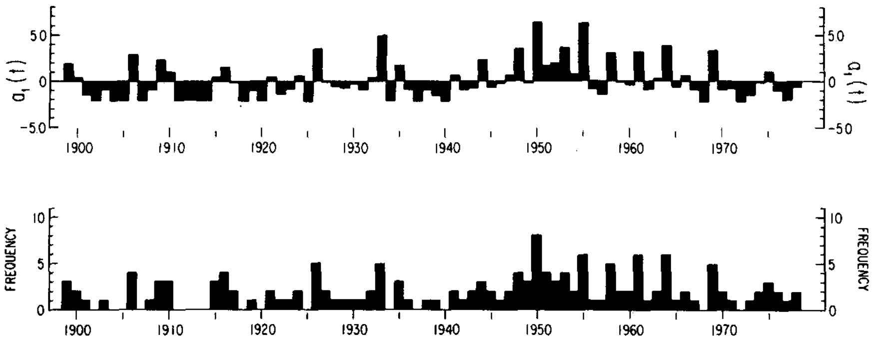

FIG. 4. Upper graph shows amplitude of EOF $n = 1$, representing ASO activity, for hurricanes $\geq$ 100 knots. Lower graph shows total number of ASO hurricanes occurring in Atlantic basin.

years), and about 15 months (1.25 years). Fig. 6 is drawn after AKC's Fig. 5. They attributed the first periodicity to the quasi-biennial oscillation (QBO), which they also found in harmonic analysis of the strength and position of the North Atlantic subtropical high. On the average, hurricane activity was a maximum 0.6 months after the pressure maximum of the High. The physical significance of the 20-month periodicity was not apparent.

The spectra of $a_1(t)$, representing overall hurricane activity, and $a_2(t)$, representing shifts between East Coast and Gulf plus Caribbean incidence were both computed. The spectrum of $a_2(t)$ had no significant peaks. A broad spectral peak was evident for activity, $a_1(t)$, centered on 0.35–0.40 year^{-1}. This peak, which may be associated with the QBO in hurricane activity found by AKC, was marginally significant at the 95% level. There is more information in the time series than is evident from the individual spectra. The two series representing activity and regional shifts are by definition uncorrelated at zero lag, $\langle a_1(t)a_2(t)\rangle = 0$. Thus, these are independent measures; there are no artificial relationships between the two series, solely based upon the means of quantifying cycles. When activity increases (or decreases), the measure of regional shifts does not vary in any correlated manner.

The series are not, however, uncorrelated at nonzero lag. AKC found a QBO in both hurricane activity and the position of the North Atlantic subtropical high. We expect oscillations in the position of the high to influence hurricane tracks and therefore regions of increased incidence. Thus we will investigate the correlation between $a_1(t)$ and $a_2(t)$ for evidence of the QBO. The cross-correlation function (ccf) between the two series (Jenkins and Watts, 1968, hereafter JW, Chapter 8) is shown in Fig. 7. A cubic polynomial fit was removed from each series before the correlations were computed. Thus, there is small negative correlation at zero lag. The long-period fluctuations removed account for less than 20% of the variance of each of the series. Fig. 7 shows the ccf as a function lag τ. $a_1(t)$ leads $a_2(t)$ for positive lag. The smoothed squared coherency spectral estimate at frequency f, $\bar{K}^2(f)$ (JW, Chapter 9) and

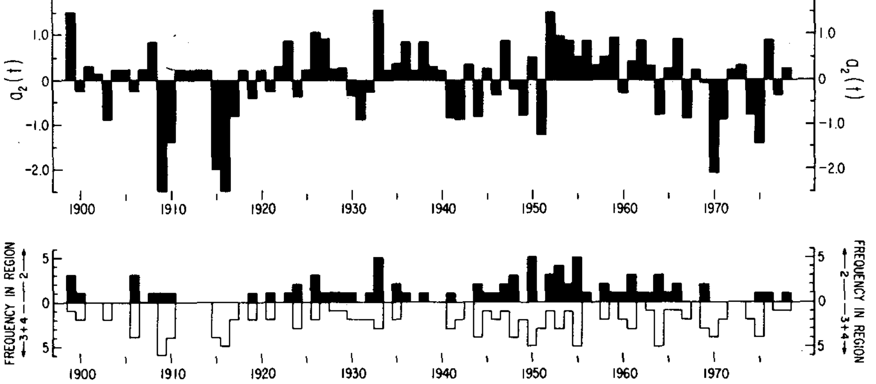

FIG. 5. Upper graph shows amplitude of EOF $n = 2$, representing regional shifts in ASO incidence; for hurricanes $\geq$ 100 knots. Lower graph shows number of East Coast ($i = 2$) hurricanes (solid bars) and number of Gulf ($i = 3$) plus Caribbean ($i = 4$) hurricanes (open bars).

phase spectral estimate $\bar{F}(f)$ between $a_1(t)$ and $a_2(t)$ are shown in Figs. 8a and 8b. A bandwidth of 0.167 year^{-1} is used.

We can reject the null hypothesis that the true coherence is zero at a given significance level if the squared coherence estimate is greater than a critical value that depends on the bandwidth (or equivalent degrees of freedom). The critical squared coherence value can be computed from Eq. (10.3.17) of JW. For a bandwidth of 0.167 year^{-1} (or 27 degrees of freedom), the critical value of $\bar{K}^2$ is 0.14 at the 15% level and 0.21 at the 5% level. These values are valid for determining the significance of the coherence in a given frequency band that is specified prior to the analysis. Since we are looking for evidence of a QBO, the critical value determined in this *a priori* manner is relevant to the frequency band centered on about 0.4 year^{-1}. The peak near f = 0.45 year^{-1} in Fig. 8a is significant at the 15% level, with $\bar{K}^2$ (critical) = 0.14. Since we have no prior expectation of a coherence between the series at other frequencies, an *a posteriori* level is appropriate in that part of the frequency domain (Julian, 1971). Since there are roughly three independent spectral estimates for the given bandwidth, a 15% *a posteriori* level is equivalent to about the 5% *a priori* level (see Julian, 1971, Section 1). The peak near f = 0.20 year^{-1} in Fig. 8a is thus significant at the 15% (*a posteriori*) level, with $\bar{K}^2$ (critical) = 0.21.

A narrower bandwidth of 0.083 year^{-1} is used to better define the frequency of the significant coherence peaks. The results are summarized in Fig. 9. The significant peaks in $\bar{K}^2$ are shown, together with the bandwidths. There is a significant relation between overall activity and regional shifts in incidence at periods of both about 4.5 and 2.5 years. The phase differences between a_1 and a_2 are also shown, as determined from Fig. 8b. 80% confidence limits on the phase are indicated. These limits are computed from Eq. (10.4.4) of JW. For the peak at 4.5 years, the East Coast maximum (a_2) leads activity (a_1) by about 175° (2.1 years). For the peak at 2.5 years, a_2 leads a_1 by approximately 65° (0.5 years). Since a_2 leads a_1 by about 0.5 years, in the given frequency band a_1 leads a_2 by about 2.5 − 0.5 = 2.0 years. This phase is consistent with the peak in the ccf (Fig. 7) at 2 years lag.

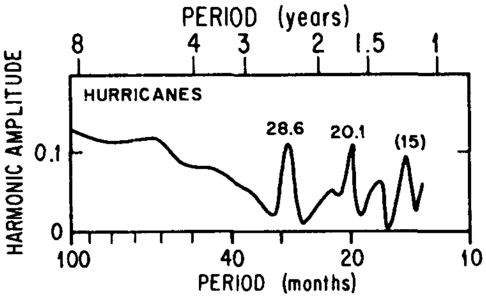

FIG. 6. Harmonic amplitude of monthly mean frequency of North Atlantic hurricanes (after Fig. 5 of Angell *et al.*, 1969).

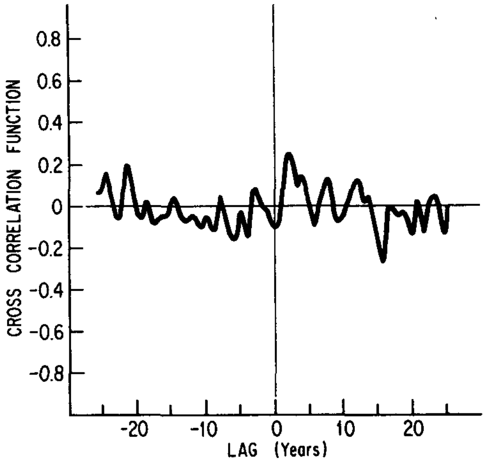

FIG. 7. Cross-correlation function between $a_1(t)$ and $a_2(t)$. For positive lag, a_1 leads a_2. Lags greater than 25 years are not shown.

The results of the present analysis are consistent with those of AKC, and suggest an explanation for the 20-month periodicity found in their analysis. The results also highlight the coupling between the motion of the subtropical high and the activity and tracks of Atlantic hurricanes. The significant peak coherence at a period of 2.5 years in the present analysis corresponds to the quasi-biennial oscillation found by AKC. The frequency of the QBO (0.4 year^{-1}) is about twice that of the peak coherence at 0.22 year^{-1}. Thus, the QBO could be the second harmonic of the oscillation at 0.22 year^{-1}. There is another possible relation between the two oscillations, however. The frequency of the second harmonic of the QBO is 2 × 0.40 = 0.80 year^{-1}. The frequency of 0.80 year^{-1} corresponds to a period of 1.25 years (15 months), the third peak found by AKC. This frequency is not detected with a sampling rate of once a year, and is aliased into a frequency 1.0 − 0.8 = 0.2 year^{-1}. In other terms, the second harmonic of the peak at 2.5 years is modulated by the annual cycle in hurricane activity to a period of 5 years. The significant peak coherence found in the present analysis at 4.5 years is near this period. The uncertainties in the phase estimate are too large to reject either possible relation between the two oscillations. The uncertainties are large enough that the association of the 4.5-year peak with the annual modulation of the second harmonic of the QBO can be considered only suggestive. The annual modulation of the QBO itself, found by AKC at 28.8 months, is an oscillation at 20.5 months. The second periodicity at 20.1 months found by AKC is apparently a manifestation of the modulated oscillation. This conclusion is supported by the analysis made by AKC

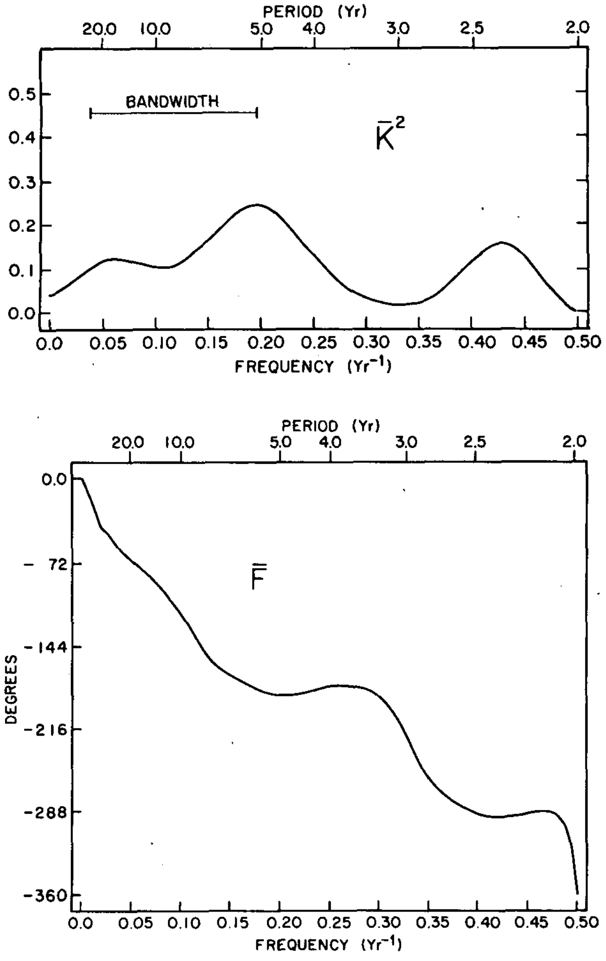

FIG. 8. Smoothed spectral estimates of $a_2(t)$ against $a_1(t)$. (a) Squared coherency, (b) phase. a_2 leads a_1 for positive values.

for North Pacific typhoons. They found a QBO in monthly numbers of typhoons at a period of 27.3 months. The annual modulation of this oscillation is at a period of 21.4 months, very close to AKC's peak in harmonic amplitude for typhoons at 21.8 months (cf., top panel of AKC's Fig. 5). Thus, all three peaks in the harmonic analysis of Atlantic hurricane numbers found by AKC may be related to the QBO.

The phase relation found in the present analysis between overall activity and regional shifts may be related to the QBO in the North Atlantic subtropical high found by AKC. They found that the High underwent a northeast–southwest oscillation in position, and that the pressure maximum of the High fell about four months after it was at the farthest northeastern part of its oscillation. The maximum in hurricane activity was thus about 4.5 months, a phase of about 60°, after the northeasternmost part of the high's QBO. In the present analysis, the maximum in hurricane activity occurs about 65° after the maximum in East Coast incidence. Thus, the maximum in East Coast incidence falls at about the phase of the QBO when the subtropical High is at its farthest northeastern displacement. This relation is quite reasonable in terms of steering: when the subtropical high is displaced most towards the northeast, it will tend to steer storms away from the Gulf and towards the East Coast. A northeastward displacement of the subtropical high from its normal position is evident in both Namias' (1955) and Ballenzweig's (1959) composite maps of 700 mb height anomalies for the seasons with maximum tropical cyclone incidence in the northeastern United States.

4. Conclusion

The average number of Atlantic hurricanes during ASO is about four. The series $a_1(t)$, corresponding to the dominant pattern of seasonal hurricane incidence, provides a measure of activity for the Atlantic basin as a whole. Since this first EOF mode accounts for 68% of the variance for all hurricanes (79% for hurricanes $\geqslant$ 100 kt), the geographic shifts represented by the other modes account for less than a third of the total variance in incidence for all regions together. The contribution of EOF $n = 1$ to the variance in individual regions varies considerably, however. As can be seen from Fig. 3, overall activity plays a much smaller role in the hurricane threat for the Gulf and Caribbean than for the other regions. In that area the regional shift contributes a larger portion of the variance. The presence of the shift between the East Coast and the Gulf and Caribbean

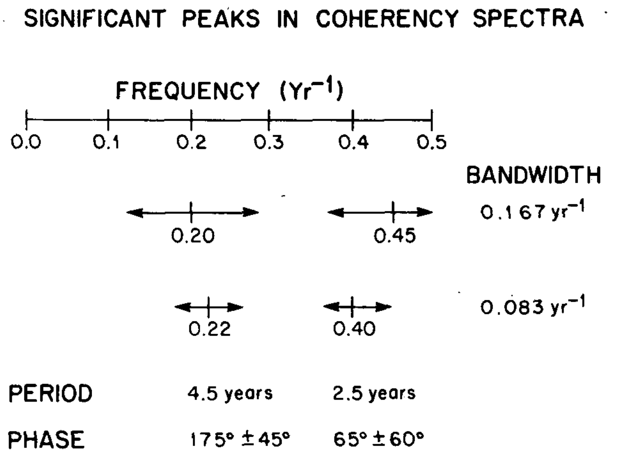

FIG. 9. Summary of coherency spectra results. Frequency (year^{-1}) of significant peaks in squared coherency are shown. The peak near 0.40 year^{-1} is significant at the 15% *a priori* level. The peak near 0.2 year^{-1} is significant at the 15% *a posteriori* (5% *a priori*) level. See text for details. Peaks for bandwidths of 0.167 year^{-1} and 0.083 year^{-1} are indicated. For the latter case, the corresponding periods are given. The bounds on phase are 80% confidence limits.

as the EOF mode explaining the second greatest fraction of the total variance in hurricane incidence provides a quantitative confirmation of previous climatologies.

The independence of the series that measure overall activity and shift in activity from region to region is a valuable consequence of the EOF analysis. The coherence found between the series is not an artificial relationship due to the method of quantifying the cycles. It is inferred that hurricane activity and regional shifts are physically related in the frequency band of the quasi-biennial oscillation. A quasi-biennial oscillation in sea-level pressure and other atmospheric properties will modulate both activity and track. The quasi-biennial oscillation in strength and position of the North Atlantic subtropical high found by AKC is one contribution to this modulation. It should be noted, however, that the QBO explains only a very small portion of the total variance of hurricane incidence. Part II more explicitly correlates changes in the large-scale circulation to Atlantic hurricane cycles.

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