Hurricane Climatic Fluctuations. Part II: Relation to Large-Scale Circulation

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ABSTRACT

Correlations are computed between interannual fluctuations of hurricane incidence in the Atlantic basin and large-scale patterns of seasonally-averaged sea-level pressure (SLP; 1899–1978), sea-surface temperature (SST; 1899–1967), and 500 mb heights (Z500; 1946–1978). Dominant modes of interannual variability in average August–September–October (ASO) hurricane incidence are used as measures of overall activity and shifts in activity from region to region. These uncorrelated modes are derived using an empirical orthogonal function (EOF) analysis, as described in Shapiro (1982). The hurricane modes are related to dominant modes of variability in seasonal SLP, SST and Z500, also derived using an EOF analysis. Correlations between the amplitudes of the EOF modes are tested for significance using a measure of artificial skill.

May–June–July (MJJ) large-scale SLP anomalies have predictive skill for ASO hurricane activity, significant at the 1.0% level. The correlation predicts about 17% of the variance in activity. Lower SLP precedes more active seasons.

Other significant correlations are found: High SST just west of Africa precedes more active seasons, but adds little predictive skill to that of SLP. Relationships between Z500 and hurricane track are consistent with steering concepts, and the results of previous investigators. Weaker westerlies are concurrent with more active seasons.

1. Introduction

Several studies have proposed that changes in large-scale circulation features could be related to hurricane activity or track on a monthly or seasonal basis. Namias (1955) proposed that the vulnerability of coastal regions to hurricanes is directly related to time-averaged planetary wave patterns, and that the prediction of genesis as well as track could be related to large-scale pressure patterns. He found physically reasonable differences between composites of seasonal 700 mb height anomaly patterns from seven "maximum threat" years and six "minimum threat" years for the New England coast. Simple indices, based upon height anomalies and their gradients, were found to correlate well with vulnerability. Ballenzweig (1959) produced composite 700 mb height anomaly charts to characterize months and seasons of maximum and minimum tropical storm incidence in five regions of the Atlantic, Caribbean and Gulf of Mexico, as well as the Atlantic basin as a whole. For the five seasons of maximum storm incidence, the Atlantic subtropical high was found to be farther north, and the westerlies south of about 45°N weaker, than for the five seasons of minimum incidence. The anomaly map for the seasons of maximum vulnerability for the northeastern United States was quite compatible with Namias' (1955) results.

The composite charts were considered to have value in diagnosis, and possibly prediction, of storm formation and track for both individual seasons and shorter periods. Due to the small number of maps making up the composite, however, no tests of the statistical significance of the differences found among the maps could be made. Without such tests, no definitive statement can be made as to the utility of time-averaged maps for the diagnosis or prediction of hurricane incidence for individual seasons. This test is especially needed in the case of hurricane formation, since the physical link between the large-scale circulation and the genesis of storms has not been fully established.

Dickson (1975) found a significant correlation between southeastern North Pacific tropical storm frequency in August and several parameters based on 700 mb heights and meridional height gradients. Nicholls (1979) found that seasonal Australian tropical cyclone activity is significantly correlated with Darwin pressure anomalies for the preceding winter.

Thermodynamic effects have a direct influence on the development of tropical systems. An apparent correlation was found by Carlson (1971) between the sea-surface temperature (SST) in a 10° square region of the tropical Atlantic and the number of Atlantic storms that developed in a given season. Wendland (1977) also related SST to the numbers of Atlantic tropical storms and hurricanes.

In Part I (Shapiro, 1982), an empirical orthogonal

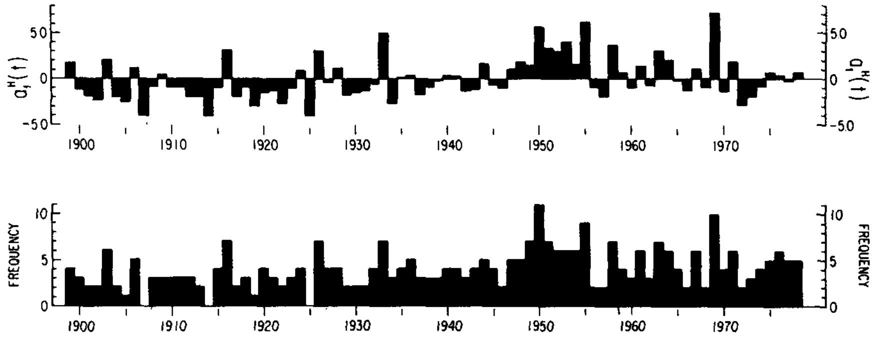

FIG. 1. Upper graph shows amplitude of EOF mode $n = 1$, representing ASO activity for all hurricanes, 1899–1978. Lower graph shows total number of ASO hurricanes occurring in Atlantic basin.

function (EOF) analysis was made of hurricane incidence during August-September-October (ASO) of the years 1899 through 1978. The numbers of hurricanes present in each of four regions: Central Atlantic, East Coast, Gulf of Mexico and Caribbean (Part I, Fig. 1) were used to derive uncorrelated modes of interannual variability of hurricane incidence. The first EOF (Part I, Fig. 2) represents a mode in which all four regions vary in phase. The amplitude, $a_1^H(t)$, of the first EOF mode, measures the activity of the hurricane season for the entire Atlantic basin, and is shown in the upper graph of Fig. 1. This figure is similar to Fig. 4 of Part I but includes all hurricanes, rather than only hurricanes $\geqslant 100$ kt. The superscript "*H*", denoting hurricanes, has been added for compatibility with later notation. The average number of ASO hurricanes is 4.00.

In Section 2 of the present analysis, hurricane activity is first related to large-scale patterns of seasonally-averaged sea-level pressure (SLP). Dominant modes of variability of SLP are derived using an EOF analysis; the amplitudes of the dominant modes are correlated with hurricane activity. Following Davis (1976, 1977) the correlations are tested for significance using a measure of artificial skill. In Section 3 the analysis is repeated for SST instead of SLP. In Section 4 both hurricane activity and regional shifts in incidence are related to seasonal patterns of 500 mb geopotential height (Z500) and its meridional gradient. The relationships are compared with those found by Namias and Ballenzweig. Section 5 summarizes and discusses the results.

2. Sea-level pressure (1899–1978) and hurricane activity

The SLP data are derived from monthly-averaged Northern Hemisphere analyses on a 5° latitude–longitude grid, archived by the National Center for Atmospheric Research (NCAR) for the years 1899–1978. Documentation is available from the Data Support Section/Computing Facility, NCAR. Daily historical maps from the National Climatic Center (1899–1939), the Massachusetts Institute of Technology (1939–1944), Scripps Institution for Oceanography (1945), and the Navy (1946–1978) form the basis for the monthly grids. Further reduction of the data was made by averaging over two adjacent longitudinal grid points. The area 20–50°N, 110°W–0° was then analyzed for the 7 × 12 = 84 points on the 5° latitude × 10° longitude grid. The average SLP for ASO is shown in Fig. 2. The presence of the subtropical high centered near 35°N is clearly visible. The variance in ASO SLP for the 80-year record (Fig. 3) is lower in the southern part of the domain. To equalize the contribution of each point to the total variance in seasonal SLP, the data are normalized by these variances.

a. Correlations

In order to relate year to year variations in SLP to hurricane activity, the correlation coefficient is computed between a_1^H and ASO SLP at each grid point. The distribution of correlation coefficients is shown in Fig. 4. Large negative correlations are present near the Gulf, with maximum correlation

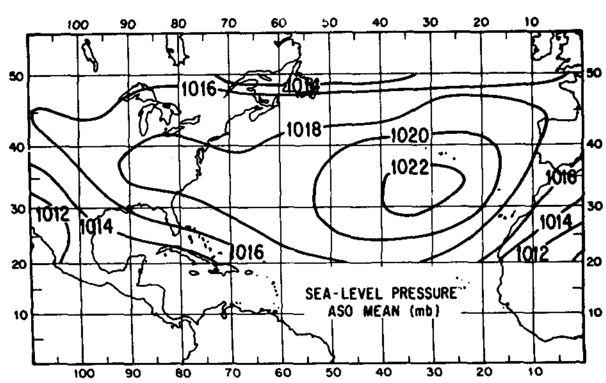

FIG. 2. Average SLP for ASO, 1899–1978.

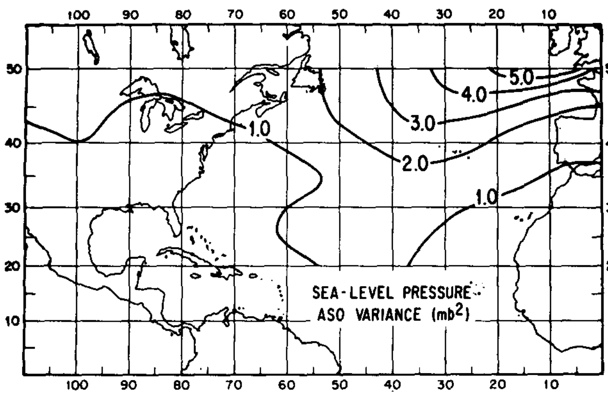

FIG. 3. Variance of ASO SLP, 1899–1978.

~ −0.7. This is a region of relatively frequent tropical storm incidence. The SLP is analyzed for ASO, the same period for which hurricane activity is evaluated. Thus, there is potentially a large effect of the hurricanes on the SLP. Fig. 4 alone cannot separate that portion of the correlation that is due to the presence of the hurricanes themselves.

So as to avoid questions of causality [Were the large correlations due to the influence of the hurricanes?] correlations are computed between ASO hurricane activity and average SLP for May–June–July (MJJ), the three months preceding the given hurricane season. There is still a large negative correlation, shown in Fig. 5, with maximum value ~ −0.5. The use of the lagged SLP guarantees that these correlations are not influenced by the presence of the hurricanes. Thus, there is potential predictive skill in MJJ SLP for ASO hurricane activity. Low SLP correlates with a more active season.

On the average there are only about 0.5 hurricanes per year occurring in MJJ. The correlation between the number of MJJ and ASO hurricanes is negligible. Moreover, almost none of the MJJ hurricanes is present in the central Atlantic. Thus, MJJ hurricanes have very little influence on the large correlations between MJJ SLP and ASO hurricanes.

The statistical significance of the correlations is a question of fundamental importance. If the observed correlations could easily have occurred by chance, then there would be no real predictive content in the SLP field. Since a large number of correlation coefficients are computed, one for each of the 84 grid points, the possibility of finding a high correlation purely by chance is greatly increased. The probability of finding a statistically significant correlation is in proportion to the number of correlation coefficients computed.

The method of EOFs was used by Lorenz (1956) for the express purpose of minimizing the number of predictors in a linear statistical forecast model. The essential mathematical properties of EOFs were discussed by Davis (1976) and briefly summarized in Part I. By selecting a limited number of modes that account for a large fraction of the variance, the number of predictors used in the statistical models can be reduced in an *a priori* manner, independent of the correlations deduced.

An EOF analysis is made of the normalized MJJ SLP. Here $N = 84$. The number of observations is $T = 80$. A linear trend is removed from the SLP data before the EOFs are determined. The reason for removing the trend is given in Section 2b. The area-averaged SLP decreased during the 80 years of record. The first 10 EOFs, accounting for 86% of the total SLP variance, are selected as potential predictors of ASO hurricane activity. Table 1 lists the EOFs, in the order of their contribution to the total variance of SLP. The correlation coefficient between the amplitude a_n^{SLP} of the nth SLP EOF and hurricane activity is denoted $r(a_1^H, a_n^{SLP})$. An increasing linear trend was removed from a_1^H before the correlations were computed. This trend may be partly due to the improvements in observations during the 80 years (cf., Neumann *et al.*, 1981). However, there may also be a real increasing trend in hurricane activity associated with decreases in SLP and increases in SST (cf., Section 3) during the same period. The variance of hurricane activity explained by the nth

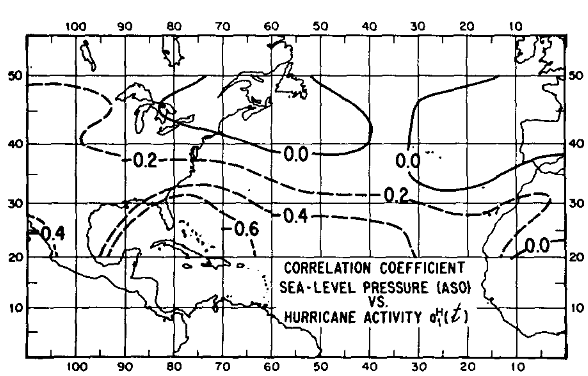

FIG. 4. Correlations between ASO SLP and hurricane activity, 1899–1978.

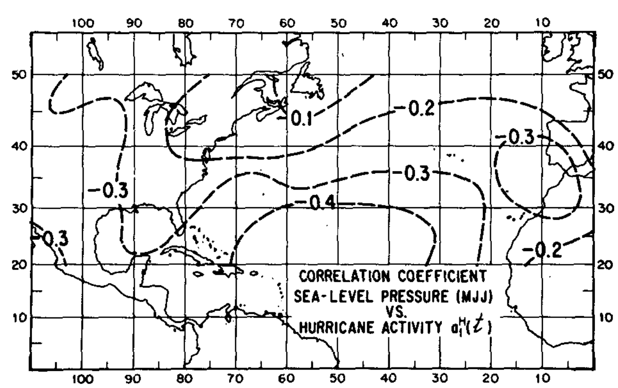

FIG. 5. As in Fig. 4, but for MJJ SLP.

mode is r^2. r^2 is a measure of the prediction hindcast skill $S_H \equiv r^2$, based on the 80 years of available data [Davis, 1976, Eq. (4a)].

Since the SLP EOFs are mutually uncorrelated, their contribution to S_H is additive. SLP EOF $n = 1$ alone accounts for 36% of the SLP variance. The spatial distribution of this eigenmode is given in Fig. 6. The correlation between activity and the amplitude of EOF $n = 1$ is $r = 0.44$ (i.e., a hindcast skill of $S_H = 0.19$). As expected from the negative correlations in Fig. 5, hurricane activity is positively correlated with an SLP EOF eigenmode that is negative. The mode shown in Fig. 6 is quite uniform over the region. In fact, this mode closely resembles the variation of the area-averaged (normalized) SLP.

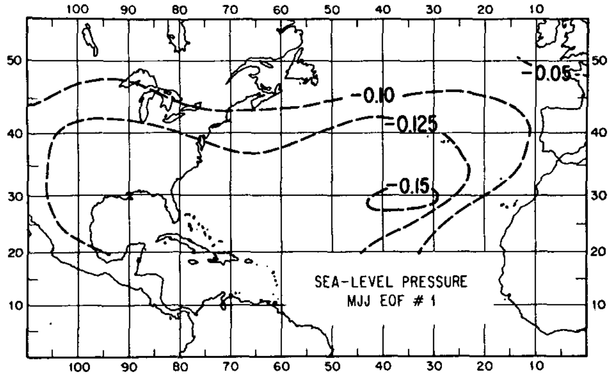

FIG. 6. MJJ SLP eigenmode $n = 1$.

b. Significance of correlations

If the predictor (a_1^{SLP}) and predictand (a_1^{H}) are each normally distributed and serially uncorrelated, the significance of the correlation $r = 0.44$ between the two series could be tested using the "F" statistic (e.g., Kleinbaum and Kupper, 1978). The number of degrees of freedom is computed from the number of serially independent observations in the series. The series of the predictand is not normally distributed. In fact, hurricane activity tends to follow a Poisson distribution (Neumann *et al.*, 1981, Section 8). The test statistics tend to be relatively insensitive (robust) to departures from normality, however (e.g., Kleinbaum and Kupper, 1978, Chapter 5). A more important difficulty arises because the series are serially correlated. Correlations between observations from one year to another reduce the effective number of independent observations T^* and thus the equivalent degrees of freedom. This is a potentially serious problem when long time scale variations are present and correlations are large at substantial lags. As emphasized by Davis (1976, 1977), correlations among variations on long time scales increase the artificial skill S_A contributing to the hindcast. In particular, if the linear trends in the SLP and hurricane data were not removed, the correlation between the series would be larger than that computed after detrending. Since the time scale associated with the trend is greater than the length of the record, however, the effective number of cases is very small. Thus, the series must be detrended to increase the effective number of observations contributing to the observed correlation, thereby reducing the artificial skill. True skill $S = S_H - S_A$. A method for computing the effective number of degrees of freedom when serial correlations are present in both series of predictor and predictand is given by Davis (1976, 1977). The method is based on an integral correlation time scale, computed from the series auto- and cross-correlation functions.

In practice, a_1^{SLP} is selected *a priori* as the first potential predictor, based upon its largest contribution to the MJJ SLP variance. As the other nine EOFs in Table 1 are entered in order as potential predictors, the number of correlation coefficients computed increases. As noted in Section 2a, the probability of finding a high, statistically significant correlation by chance increases in proportion to the number of correlations computed. Thus, the expected value of the artificial skill $\langle S_A \rangle$ (Davis, 1976), which is the predictive skill expected purely by chance, increases with the number of available predictors. For M predictors, $\langle S_A \rangle \approx M/T^*$ (Davis, 1976).[1] This relation is based upon the approximation that T is large, the series are joint normally distributed, the correlation time scales are nearly equal and much shorter than the length of the record, and S_H is small. $\langle S_A \rangle$ increases both as the effective number of independent observations T^* decreases, and as the

TABLE 1. MJJ SLP dominant EOF modes and their correlation with ASO hurricane activity, 1899–1978.

EOF n	Contribution to SLP variance (%)	Hindcast skill $S_H = r^2(a_1^H, a_n^{SLP})$
1	36	0.194
2	11	0.002
3	8	0.035
4	6	0.001
5	6	0.001
6	6	0.010
7	5	0.001
8	3	0.004
9	3	0.026
10	2	0.002
	86	

[1] The derivation of a more general expression for $\langle S_A \rangle$ for M predictors and for the critical value of hindcast skill given in this Section appear in a manuscript, "Effects of Sampling Errors in Statistical Estimation," by D. B. Chelton (1982), which has been submitted to *Deep Sea Res.*

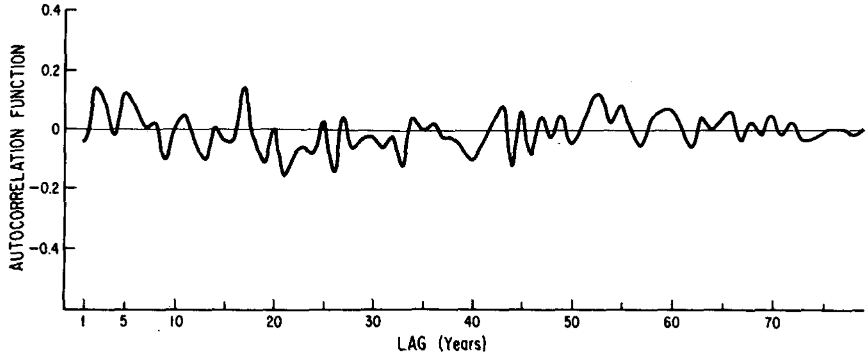

FIG. 7. Auto-correlation function of hurricane activity a_1^H, 1899–1978.

available number of predictors M increases. The first EOF mode is a reliable predictor only if $\langle S_A \rangle \ll S_H$ so that there is a high probability that $S \neq 0$. A subsequent EOF is included as a predictor if the increase in S_H is greater than the increase in $\langle S_A \rangle$ so that the mode contributes to the estimate of S.

Fig. 7 shows the autocorrelation function (acf) for hurricane activity a_1^H. At one year lag the acf is small and negative. The cross-correlation function (ccf) between the amplitude of MJJ SLP EOF $n = 1$, a_1^{SLP}, and hurricane activity is given in Fig. 8. Using Eq. (12b) of Davis (1977), valid for small S_H, the "equivalent number of degrees of freedom" $T^* \approx 54$, less than the record length $T = 80$. The correlation time scale is $T/T^* = 1.5$ years. In the present case, $M = 1$ and $\langle S_A \rangle \approx 0.019$. True skill at large lag is assumed zero. Then, as suggested by Davis (1977, Section 8), the average of S_H at many such lags gives an alternate upper-bound estimate of artificial skill. As seen in Fig. 8, the ccf is small even at lags of a few years. Thus, in practice, artificial skill is estimated by averaging S_H from lags from ±1 year to ±40 years, half the record length. By this method, $\langle S_A \rangle \approx 0.020$, slightly larger than the value computed from T^*. A conservative estimate of artificial skill chooses the latter, higher value.

Since the expected artificial skill is much less than the hindcast skill $S_H = 0.19$, the observed correlation probably did not occur by chance. D. B. Chelton has derived a more quantitative estimate of the statistical significance of the sample S_H estimate. For M predictors, the observed hindcast skill is significantly different from zero at the α significance level if $S_H \geq S_H\,\text{(critical)} = \langle S_A \rangle R_M(\alpha)/M$, where $R_M(\alpha)$ is the $100\alpha\%$ point of the chi-squared distribution with M degrees of freedom (D. Chelton, personal communication). In the present case, with $\langle S_A \rangle = 0.020$, $S_H/\langle S_A \rangle \approx 10$. From the chi-squared distribution (e.g., Kleinbaum and Kupper, 1978, Table A-3), the hindcast predictive skill, and thus the observed correlation, is significant at the 1.0% level. It is therefore inferred that MJJ SLP EOF $n = 1$ is a very reliable predictor of ASO hurricane activity. The estimate of true predictive skill is $S_H - \langle S_A \rangle \approx 0.17$. As discussed in Section 5, this predictive skill has little utility for actually predicting the activity of a given hurricane season. Moreover, the predictive skill for hurricane incidence in an individual region is less than that for overall activity; $S_H - \langle S_A \rangle \approx 0.16$, 0.06, 0.06 and 0.13 for the Central Atlantic, East Coast, Gulf and Caribbean regions, respectively. The contribution of the EOFs $n = 2, \ldots, 10$ to S_H does not add to true skill. February–March–April correlations (not shown) add less than 0.02 to true predictive skill over MJJ.

3. Sea-surface temperature (1899–1967) and hurricane activity

An analysis similar to that of SLP is made for SST. The data are obtained from monthly-averaged SSTs on a 5° latitude × 10° longitude grid, provided

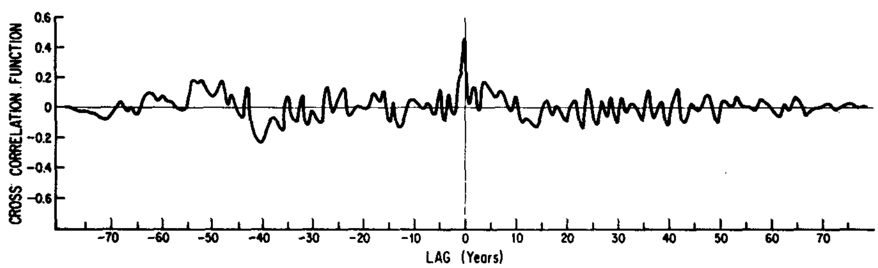

FIG. 8. Cross-correlation function between hurricane activity and amplitude of MJJ SLP EOF $n = 1$. For positive lag, a_1^H leads a_1^{SLP}.

by NCAR. The data were processed by the Meteorological Office, Bracknell, England for three ocean areas for the years 1854–1967, from data provided by the National Climatic Center. Data processing included quality control checks. Low-order harmonics were used to fill in missing values. The present study is restricted to the area 10–45°N, 110°W–0°, on an 84-point grid for the years 1899–1967. Averages for MJJ are computed for each year. The seasonal SSTs are normalized by the variance, as was SLP. So that the years covered by the series would correspond, $a_1^H(t)$ is recomputed for ASO hurricanes for the period 1899–1967, a shorter record than was used for SLP. The series a_1^H was changed very little by this process during the common period covered.

Correlations between a_1^H, measuring hurricane activity, and MJJ SST are shown in Fig. 9. The values are positive, indicating that higher SSTs in MJJ correlate with greater activity in the immediately following hurricane season. The maximum correlation is ~ 0.55, in a region near the area used by Carlson (1971). An EOF analysis is made of the normalized MJJ SST to determine the dominant patterns of variability and limit the number of predictors of hurricane activity. As with SLP, a linear trend is first removed. Both SST and hurricane activity increase during the 69 years.

The hindcast skill for each of the first 10 EOF's, accounting for 74% of the SST variance, is shown in Table 2. Artificial skill is estimated as the larger of the values based on the effective number of degrees of freedom and the average of S_H at large lag (cf., Section 2). $\langle S_A \rangle \approx 0.025$ for EOF $n = 1$ and 2. Since $\langle S_A \rangle \ll S_H$, each of these modes contributes to true skill. EOF $n = 3$ does not add to S since $\langle S_A \rangle \approx S_H$ for that mode. S_H for each of EOFs $n = 4, \ldots, 10$ is very small and does not contribute to S. With the first two EOF's as predictors of activity, total $S_H = 0.15$ and $\langle S_A \rangle \approx 0.05$. By the chi-squared test ($M = 2$), S_H is significant at the 10% level. Subtracting low-order polynomial fits, or high-pass filtering to remove long-period oscillations from the SST data, decreases artificial skill. The significance of the results, however, does not increase. In the remainder of the paper S_H will be considered significant if it passes the chi-squared test at the 10% level. Less stringent application of the test, at the 20% level, will be noted. In the latter case, there is still only a one in five probability that the correlation occurred by chance.

MJJ SST eigenmodes $n = 1$ and 2 are shown in Fig. 10. Both are positively correlated with activity. The first mode is strongly positive in the eastern Atlantic, just west of Africa. For the first mode, the anomalies in this area are negatively correlated with

TABLE 2. MJJ SST dominant EOF modes and their correlation with ASO hurricane activity, 1899–1967.

EOF n	Contribution to SST variance (%)	Hindcast skill $S_H = r^2(a_1^H, a_n^{SST})$
1	27	0.087
2	12	0.066
3	8	0.023
4	7	0.000
5	6	0.010
6	4	0.001
7	3	0.003
8	2	0.014
9	2	0.014
10	2	0.001
	74	

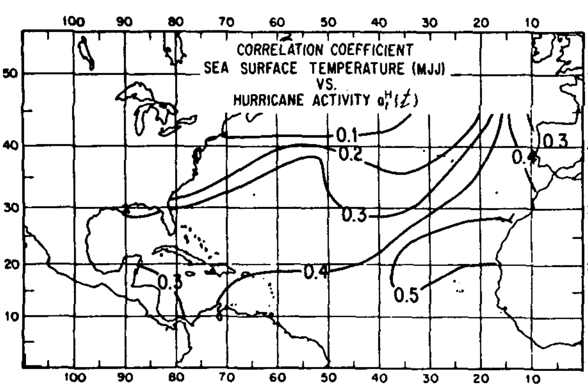

FIG. 9. Correlations between MJJ SST and hurricane activity, 1899–1967.

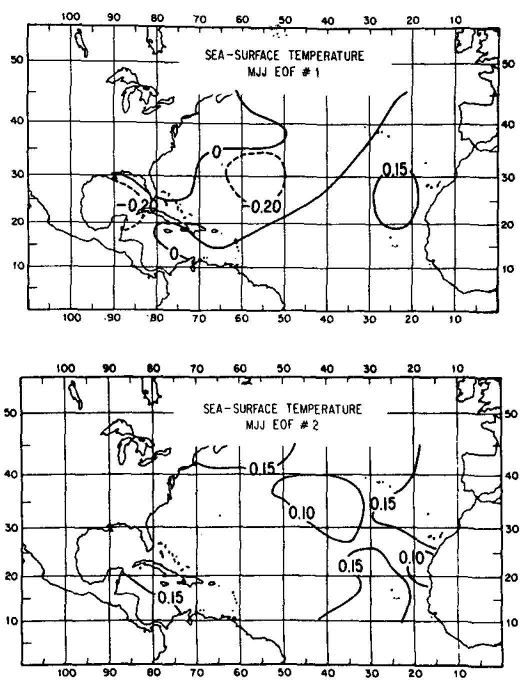

FIG. 10. MJJ SST eigenmodes $n = 1$ and $n = 2$.

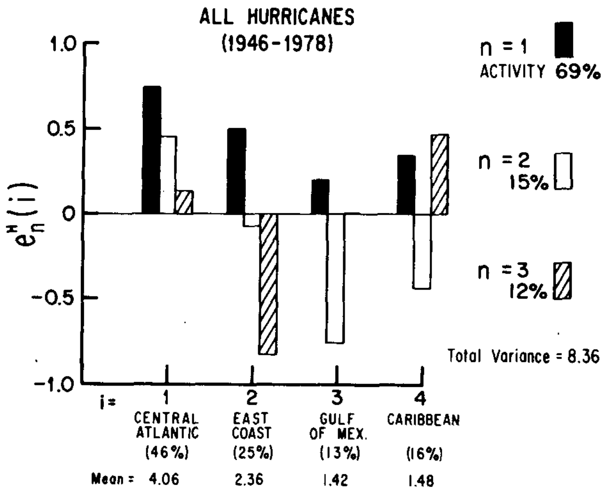

FIG. 11. Eigenmodes corresponding to dominant EOF modes of hurricane incidence for 1946–1978. Percentages are contributions to total variance in hurricane incidence.

anomalies in the mid-Atlantic and Gulf of Mexico. The second mode is more uniform, but shows largest amplitude just off Africa. Both modes show a positive correlation between hurricane activity and SST just west of Africa. This area is near the development region for systems that come off the west coast of Africa. It is an area of relatively cold water, associated with upwelling off the African coast. The maintenance of intense tropical systems would be expected to be sensitive to changes in this region, where SSTs are on the average below the development "threshold" of about 26.5°C.

An analysis was also made with ASO SST. Similar eigenmodes to those for MJJ are correlated with hurricane activity (not shown). In that case $S_H = 0.10$, which is not significant at the 10% level. S_H does, however, pass the chi-squared test at the less stringent 20% level.

Individually, MJJ SLP EOF $n = 1$ and SST EOF $n = 1$ and 2 hindcast, respectively. 19, 9 and 7% of the variance in hurricane activity. The SLP and SST modes are not independent, however. $r(a_1^{\mathrm{SLP}}, a_1^{\mathrm{SST}}) = 0.45$; together these two modes have hindcast skill $S_H \equiv R^2 = 0.21$, computed from the multiple correlation coefficient R. $r(a_1^{\mathrm{SLP}}, a_2^{\mathrm{SST}}) = 0.25$, so that together $S_H = 0.22$. In either case the artificial skill, based on the liberal estimate of considering only one SLP EOF and one SST EOF as available predictors, is $\langle S_A \rangle \approx 0.03$. Since each SST mode adds, at most, 0.03 to S_H, the estimate of true skill $S_H - \langle S_A \rangle$ increases by less than 0.02. Thus, SST adds little to true predictive skill over that of SLP. It is not surprising that seasonal SST and SLP are highly correlated and contain redundant predictive information. Changes in SLP are associated with changes in pressure gradients and thus tropical winds; on seasonal time scales, changes in SST are substantially a response to atmospheric changes as well (e.g., Davis, 1976).

4. 500 mb heights (1946–1978), hurricane activity and regions of increased incidence

In the analyses of SLP and SST, results were presented only for hurricane activity a_1^H. Part I, however, also evaluated other dominant modes of hurricane incidence related to regional shifts of incidence—in particular, the shift between the East Coast, and the Gulf and Caribbean. Correlations of these modes with SLP and SST were evaluated and found to be small and statistically insignificant. This is as expected since the steering of the storms should be evident in the middle levels of the atmosphere. Namias (1955) and Ballenzweig (1959) used 700 mb heights (cf., Section 1). Northern Hemisphere 500 mb height ($Z500$) data have been archived by NCAR since 1946. These data will be correlated with dominant modes of variability of ASO hurricane incidence, derived by an EOF analysis as in Part I.

Fig. 11 shows the three dominant eigenmodes of hurricane incidence, e_1^H, e_2^H and e_3^H, for the period 1946–1978. This figure is of the same form as Fig. 2 of Part I but for the shorter record. As in Part I, EOF $n = 1$ represents the activity of the entire Atlantic basin. The eigenmode e_2^H is similar to that of the top panel in Fig. 2 of Part I, representing the variation of Gulf and Caribbean activity. In the present analysis, e_2^H has a greater contribution from Central Atlantic and a lesser contribution from East Coast variability than for the longer record of Part I. e_3^H represents the variation of the East Coast hurricane incidence. The three dominant uncorrelated modes account for 96% of the total variance in hurricane incidence for the 33 years.

Monthly-averaged $Z500$ data have been saved by

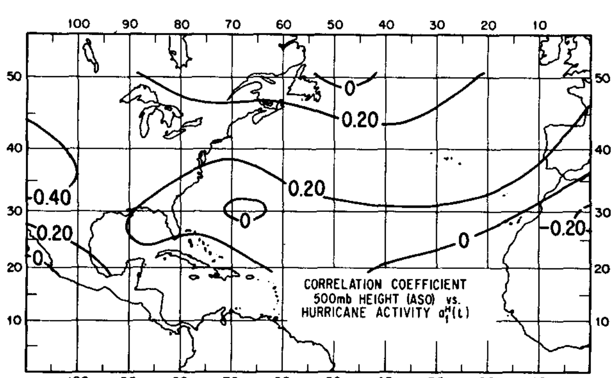

FIG. 12. Correlations between ASO $Z500$ and hurricane activity, 1946–1978.

NCAR on the 47 × 51 National Meteorological Center (NMC) octagonal grid for 1946–1978. These data were derived from twice-daily NMC, U.S. Air Force and Navy grids. For the present analysis the 1200 GMT data were interpolated to a 5° latitude-longitude grid, covering the same areas as for SLP (Section 2). After averaging over adjacent longitudinal grid points, seasonal averages were computed for MJJ and ASO for each of the 33 years. These data will be correlated with the hurricane EOF amplitudes a_1^H, a_2^H and a_3^H for the same period.

The correlation between ASO $Z500$ and hurricane activity is shown in Fig. 12. Consistent with Ballenzweig's (1959) results, greater activity is correlated with a stronger ridge north of about 30°N. Weaker westerlies (or stronger easterlies) are implied south of about 40°N. The weakening of the westerlies during active hurricane seasons may be analyzed more directly. Fig. 13 shows the correlation between hurricane activity and the difference in $Z500$ between two adjacent grid points in the meridional direction. The sign of this height difference, $\Delta Z500$, is chosen so that positive values correspond to westerly geostrophic winds. Negative correlations, which appear in a large zonal band south of 40°N, therefore indicate a correspondence between greater hurricane activity and weaker westerlies.

The statistical significance of the correlations is tested by the method used in Sections 2 and 3. Due to the shorter length of record, the estimates of artificial skill are larger than for SLP or SST. Significance levels were double-checked using the observed distribution of S_H, with lags up to ±10 years. An EOF analysis is made of ASO $Z500$ and $\Delta Z500$. The first 10 EOFs are entered in order as potential estimators of hurricane activity a_1^H. For ASO $Z500$ no significant hindcast skill is found. For ASO $\Delta Z500$ the first three EOF's as estimators together give $S_H = 0.26$, while $\langle S_A \rangle = 0.13$. The $\Delta Z500$ eigenmodes $n = 1$, 2 and 3 are shown in Fig. 14. The hindcast skill for each of these modes is, respectively, $S_H = 0.13$, 0.07, 0.06. Correlations between these modes and activity are positive. Additional EOF's do not contribute to true skill. The estimated artificial skill is one-half of the hindcast skill. By the chi-squared test, S_H is not significant at the 10% level. S_H is significant, however, at the 20% level. Thus, the relationship between the strength of the westerlies and hurricane activity found by Ballenzweig (1959) is statistically confirmed, but the relationship appears weak.

Positive correlations between ASO $Z500$ and a_2^H

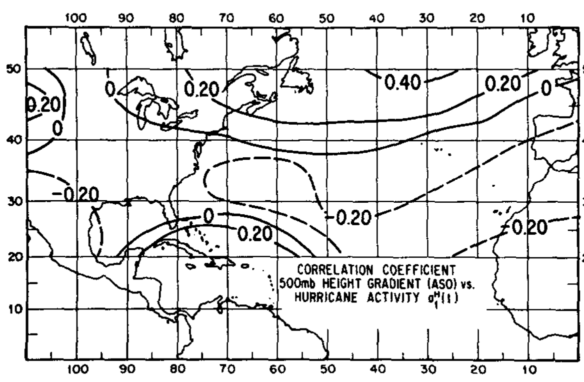

FIG. 13. Correlations between ASO meridional $Z500$ gradient and hurricane activity, 1946–1978. Positive values correspond to stronger westerly anomalies.

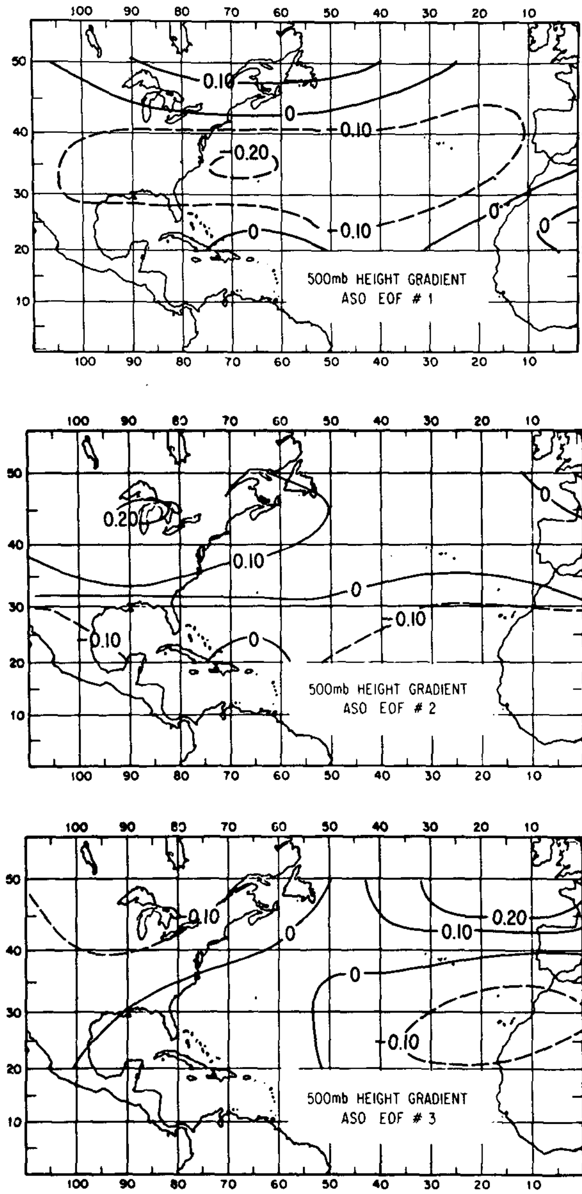

FIG. 14. ASO $\Delta Z500$ eigenmodes $n = 1$, 2 and 3.

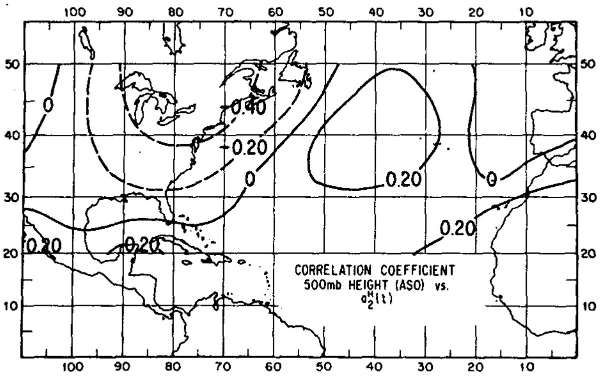

FIG. 15. Correlations between ASO $Z500$ and the amplitude of hurricane EOF $n = 2$.

near 40°N, 40°W in Fig. 15 are consistent with the steering of the storms away from the Gulf and Caribbean by a weakness in the height field over the eastern United States coupled with a stronger subtropical high. From an EOF analysis, a hindcast skill $S_H = 0.24$ significant at the 10% level is found. Correlations with a_3^H (not shown) are consistent with steering of storms away from the East Coast. Thus, the concurrent ASO $Z500$ correlations are consistent with the steering of the hurricanes by the winds near this level, and with the results of Namias and Ballenzweig. No significant correlation is found, however, between ASO $Z500$ and a_3^H.

In order to determine the predictive information present in the 500 mb data, MJJ heights and their meridional gradients are correlated with hurricane activity. No significant correlations are found. Correlations between a_3^H and MJJ $Z500$ are not significant. The hindcast predictive skill for a_2^H from MJJ $Z500$ is $S_H = 0.16$, significant at the 10% level.

5. Conclusion

Large-scale anomalies of seasonal SLP have significant predictive skill for hurricane activity. MJJ SLP predicts about 17% of the variance in ASO activity. This predictive skill is small but significant at the 1.0% level. Lower SLP precedes more active seasons.

Higher SST just west of Africa precedes more active seasons (10% significance level). Due to intercorrelations between SST and SLP, however, SST contributes little to true predictive skill compared to SLP alone.

The results for ASO and MJJ $Z500$ are consistent with steering of the storms by mid-level winds, as well as the results of Namias and Ballenzweig (10% level). Weaker ASO westerlies are associated with greater activity (20% level). Together, the small but significant correlations between ASO heights and Gulf and Caribbean hurricane incidence, and zonal winds and activity, are consistent with the results of Part I. The large-scale circulation modulates both activity and track.

The variance and average number of ASO hurricanes are each about four. MJJ SLP anomalies account for only about one-sixth of the variance. Although very significant, the utility of a regression relation between the amplitude of the dominant SLP and hurricane EOF's for actually predicting the activity of a given season is minimal. The error in a single prediction will be large. Assuming a normal distribution and $T^* = 67$ effective cases, the 80% prediction interval (Kleinbaum and Kupper, 1978, p. 58) for the number of hurricanes in a single season is about $4 - 0.78N_{SD} \pm 3.1$. N_{SD} is the deviation of the area-averaged SLP from the mean, normalized by its standard deviation. The prediction interval includes the average value of four up to $N_{SD} \pm 4$. Thus, unless the MJJ SLP is *exceptionally* high or low, the best prediction of hurricane number is the average.

Deficiencies in the data, as well as the limited number of years available, reduce the apparent significance of real physical correlations. That significant predictive skill was found even in 500 mb heights, with a 33-year record, indicates that a real physical connection probably exists. If the data were better, or the records were longer, other significant relationships might have become evident.

The artificial skill would be reduced if there were more observations or if shorter time-scale variations were more energetic. A natural extension of the present analysis would be to relationships between individual August, September and October hurricane incidence and the monthly-averaged large-scale circulation. This analysis would triple the length of the records, but would increase the number of equivalent degrees of freedom by a smaller amount.

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