The North Atlantic Subtropical Anticyclone

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ABSTRACT

The semipermanent subtropical anticyclone over the North Atlantic basin (the "Azores high") has a major influence on the weather and climate of much of North America, western Europe, and northwestern Africa. The authors develop a climatology of the Azores high by examining its spatial and temporal changes since 1899. Using gridded surface pressure values, anticyclones are identified when the daily pressure is ≥1020 mb and frequencies are tabulated for each half month from 1899 to 1990. Principal components analysis is applied to analyze the anticyclone's spatial variance structure.

The Azores high is dominated by two spatial modes: a summer pattern, in which high pressure dominates the Atlantic basin, and a winter pattern, in which anticyclones are present over eastern North America and northwestern Africa. Century-long declines in these two modes indicate that there has been a net removal of atmospheric mass over the subtropical Atlantic. Other modes include a meridional versus zonal circulation pattern and omega blocks. Time series of the mean annual principal component scores indicate that meridional flow has been increasing over the Atlantic and that blocking anticyclones have become more prevalent over west-central Europe and less common over the northeastern Atlantic and the British Isles.

1. Introduction

Atmospheric scientists have long recognized the existence of certain quasi-permanent features of the global atmospheric circulation and their influence upon regional weather and climate. These "centers of actions" were first identified by Teissereng de Bort (1883) from maps of average monthly sea level pressure. In the Northern Hemisphere, circulation is closely coupled to daily, seasonal, and interannual changes in four primary centers of action: the Aleutian and Icelandic cyclones, and the subtropical anticyclones over the Atlantic and Pacific Oceans.

The subtropical anticyclone over the North Atlantic Ocean basin, commonly referred to as the "Azores" or the "Bermuda high," has a major influence on weather and climate over the eastern United States, western Europe, and northwestern Africa. Because of its influence, it is important to investigate this and other semipermanent circulation features for changes in their seasonal or yearly strength or position that might indicate longer-term climatic variability or climate change. To date no thorough study has been completed documenting the size, intensity, and variability of the Azores high on both a seasonal and interannual basis.

The primary goal of our research is to develop a climatology of the frequency of high pressure over the subtropical and midlatitude North Atlantic Ocean and the adjacent continents. Specifically, we investigate 1) seasonal variations in half-month anticyclone frequencies by analyzing mean maps and maps of half-month frequency changes, and 2) yearly changes in the frequency of high pressure by analyzing time series of principal component scores. The results provide a complete description of both inter- and intraannual changes in the strength and position of the North Atlantic subtropical high over the last century. This type of study is particularly important since it allows for examination of possible climate changes over a long period of record, in this case almost 100 yr.

2. Background

Anticyclone climatologies are frequently developed by counting the number of occurrences of high pressure (usually defined by a closed isobar) within grid boxes of various sizes. Such studies have been completed using 5° lat × 5° long grid cells by Harman (1987) and Klein (1957) for North America and the Northern Hemisphere, respectively. Zishka and Smith (1980) performed a similar analysis of migratory anticyclones over

[1] The terms Bermuda and Azores high occasionally refer to the western and eastern extensions of the North Atlantic anticyclone, respectively. However, common usage, especially in North America, considers these terms to be interchangeable, however geographically inexact. In this paper we refer to this semipermanent high pressure feature as the North Atlantic subtropical anticyclone or the Azores high.

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North America on a $2° \times 2°$ grid. These analyses proved useful in identifying predominant anticyclone tracks and their seasonality, as well as interannual anticyclone frequency changes. The semipermanent anticyclones have also been studied using mean sea level pressure maps. Lamb (1973) computed mean sea level pressure for 5-day periods for two 20-yr time periods characterized by different circulation types. He noted that certain circulation features (including the Azores high) exhibit a ''pulse'' phenomenon, in which their mean position and intensity change dramatically between consecutive 5-day periods. Makrogiannis (1988) used mean sea level pressure values to calculate the total atmospheric mass over seven $5° \times 5°$ grids over Europe and the eastern Atlantic Ocean.

In the study most closely related to ours, Sahsamanoglou (1990a) focused on spatial and temporal changes of Atlantic centers of action based upon monthly and annual mean sea level pressure values from 1873 to 1980 at a 5° lat $\times$ 10° long resolution. His analysis was primarily concerned with changes in the magnitude and location of the highest central pressure of the North Atlantic subtropical high. His general results showed that the anticyclone migrates in a somewhat elliptical pattern from month to month within an area bounded by 25°–40°N and 20°–50°W. Based upon mean central pressures, he also detected three Azores high epochs: from 1903 to 1930 when the pressure was extremely high, from 1968 to 1980 when it was somewhat above normal, and from 1931 to 1967 when pressures were generally below normal. Angell and Korshover (1974) detected an eastward shift in the mean position of the Azores high from 1899 to 1967, as well as a significant decline in central pressure between 1920 and 1965.

Our work differs from previous research on the Azores high for the following reasons.

1) The data collection method incorporates the entire regional domain occupied by the anticyclone, yet is still responsive to intensity changes. Thus, even though our analysis focuses on changes in the size and position of the system, variations in the anticyclone's strength are implied.
2) This is the first multivariate analysis of the spatial dimensions of the Azores high.
3) The combination of the half-month time interval employed, the long period of record (1899–1990), and the $5° \times 5°$ grid provides the most detailed spatial and temporal analysis of the Azores high yet undertaken.

3. Data collection and analysis

Data were obtained from the National Center for Atmospheric Research (NCAR) gridded sea level pressure dataset. This data source includes daily values of sea level pressure that have been interpolated to a 5° lat $\times$ 5° long grid network. From 1899 to 1939 the data were derived from the U.S. Historical Map Series; after 1939 several sources were used, including both objective and hand-drawn analyses by the navy and the National Meteorological Center (currently known as the National Centers for Environmental Prediction) (Williams and van Loon 1976; Trenberth and Paolino 1980).

In our research, an anticyclone was deemed to be present at a grid node on a given day when the sea level pressure equalled or exceeded 1020 mb. This threshold was selected based upon observations that values above 1020 mb tend to isolate regions of local pressure maxima over subtropical and midlatitude regions of the Atlantic Ocean and adjacent land areas. Sahsamanoglou (1990a) determined that the average central pressure of the Azores high is 1023.5 mb and the standard deviation is 1.2 mb. Thus, 75% of all central pressures fall between 1022 and 1025 mb, and values less than 1021 mb occur less than 4% of the time. For each half month, the number of days in which the pressure exceeded 1020 mb was counted at each grid node. Therefore, our final dataset consists of frequency counts of high pressure occurrence within $5° \times 5°$ cells for 24 half months yr^{-1} over 91 yr.

The NCAR gridded dataset is commonly used in atmospheric research and thus has been carefully scrutinized by several researchers. Williams and van Loon (1976) identified numerous anomalies in which observations deviated by more than three standard deviations from the nodal mean and did not correspond with values at nearby stations. However, they detected almost no outliers over the Atlantic basin—the area used in our study. Trenberth and Paolino (1980) noted a substantial number of errors in the dataset, as well as several discontinuities between 1899 and 1977. The primary discontinuities occurred in the summer of 1939, in December 1945, and during 1956. In comparison to other regions of the globe, particularly Asia, errors and systematic biases are not prevalent over the subtropical Atlantic, where substantial ship traffic has allowed for the compilation of a fairly robust dataset. The apparent bias of primary concern to our research is in elevated pressure in the early part of the record. *T*-tests of mean pressure between two subperiods (1899–1939 and 1956–77) indicate that pressures are significantly higher in the earlier period over the western Atlantic south of 30°–35°N. The question of whether these early readings are real or fictitious is addressed in our conclusions and implications section.

Prior to 1940 data are frequently missing. In our analysis, a grid node is coded as ''missing'' for a half month if any single daily value is missing over that 15-day period. This conservative criterion assures that all of the semimonthly frequency counts are directly comparable.

4. Mean frequencies

Mean frequencies of high pressure are plotted semimonthly at each $5° \times 5°$ grid node and contoured. High

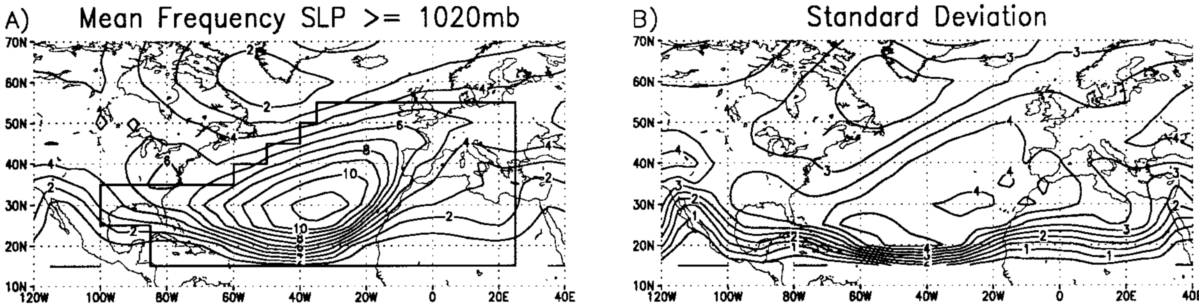

FIG. 1. The (a) overall mean frequency and (b) standard deviation of days per half month with sea level pressure ≥1020 mb at each 5° lat × 5° long grid node, based upon observations from 1899–1990. The outlined region in (a) depicts the spatial domain for the principal component analysis. Note that the steep isoline gradient along the southern boundary on some of the maps arises from the lack of observations at 15°N.

pressure is most common over the subtropical eastern North Atlantic and is centered at 30°N, 35°W (in general agreement with Sahsamanoglou 1990a), where pressures ≥1020 mb occur on more than 11 days per half month (Fig. 1a). Frequencies decline more rapidly to the east of this center toward the African coast than to the west, resulting in a contour pattern similar to mean surface pressure maps of the region. This shape suggests that transient anticyclones exiting the U.S. east coast travel eastward across the western Atlantic and then veer northeastward toward western Europe.

The standard deviation map of high pressure frequencies identifies numerous regions of high variability (Fig. 1b). Standard deviations are highest over the south-central Atlantic at 25°N from 40°W to 65°W and over and west of Morocco and southwest of the Iberian Peninsula. These regions are frequented by anticyclonic incursions seasonally, but are not dominated by anticyclonic control for 12 months. Near the center of the Azores high, the standard deviation is greater than 4, or about one-third of the mean frequency of 11. However, the 4.0 isoline, while generally corresponding with the shape of the mean field, encompasses a large area that approximates the 6.0 mean frequency isoline in Fig. 1a. Thus, the variability in anticyclonic frequency is quite high along the fringes of the Azores high.

The following map sequence shows the seasonal progression of high pressure frequencies over the northern

TABLE 1. Correlations between spatial principal component loading fields computed for the monthly high pressure frequency count dataset and the mean monthly sea level pressure dataset over the domain shown in Fig. 1a.

Frequency count	Mean Monthly Pressure				
	PC1	PC2	PC3	PC4	PC5
PC1	0.93	−0.84	0.07	0.08	−0.08
PC2	−0.51	0.87	−0.46	−0.26	−0.10
PC3	−0.51	0.16	0.91	0.03	0.20
PC4	−0.23	0.10	−0.12	0.92	−0.10
PC5	−0.11	−0.05	−0.23	−0.06	0.87

Atlantic and adjacent land areas for selected half months. Because of space constraints, the complete 24-map sequence is not shown here. The 6 maps included depict the subtropical high at important junctures during its seasonal course. Since frequency counts are mapped rather than sea level pressure, we are not directly observing the intensity of the anticyclone. However, as the central pressure of the anticyclone increases, the dome of high pressure broadens and more grid nodes have pressures that exceed the 1020-mb threshold. To examine the correspondence between anticyclone frequency counts and intensity, a correlation is computed between our frequency count dataset and mean monthly sea level pressure from the NCAR dataset. A principal components analysis (PCA) is run on each dataset over our domain (Fig. 1a), and the resulting loadings maps are correlated (Table 1). Results show that the two fields are very highly correlated; therefore, the Azores high is most intense at the locations of frequency maxima.

Since our counting procedure does not discriminate between quasi-stationary and transient anticyclones, the maps depict both the semipermanent anticyclone and migrating highs that typically move across the Atlantic behind frontal systems. The tracks of these migratory anticyclones can be identified from frequency count mapping, but are not usually captured on monthly mean pressure maps. Therefore, the shape of the contour patterns indicates the direction in which these transient highs are moving.

The following sequence (Figs. 2a–f) shows that the center of the Azores high migrates significantly throughout the year and that its areal extent and intensity vary markedly. Changes in the position and strength of the anticyclone are often rather abrupt, manifesting themselves in half-month periods; therefore, the notion of a gradual seasonal migration of the anticyclone is not always correct. It is apparent that the subtropical high occupies two preferred spatial modes: a single summer maximum with the high centered over the central Atlantic, and a weaker winter dual-maxima pattern with the highest frequencies over the continents.

In early March (first 15 days) the anticyclone occupies

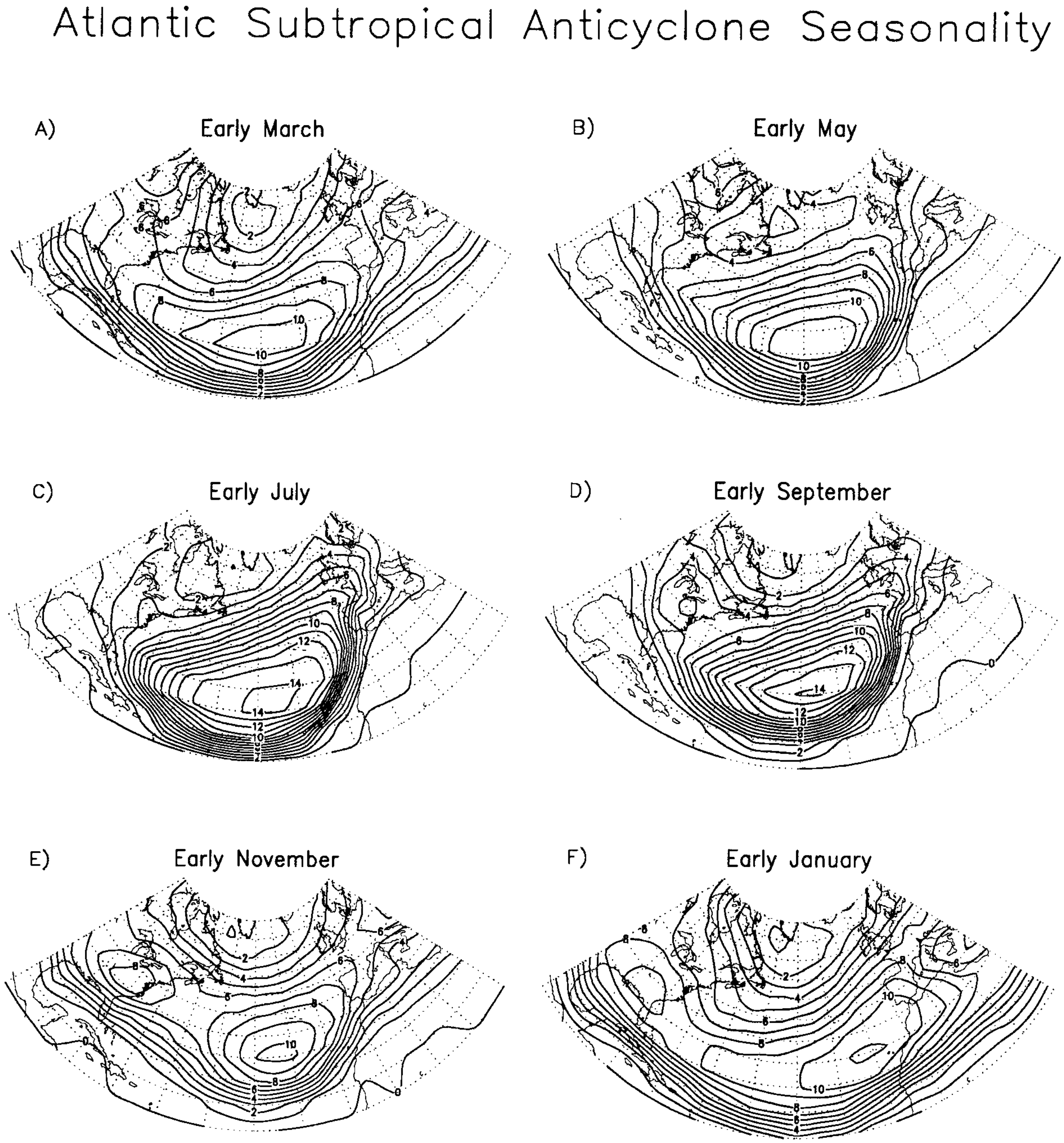

FIG. 2. Average number of days with sea level pressure ≥1020 mb in the first half of (a) March, (b) May, (c) July, (d) September, (e) November, and (f) January.

its southernmost position and is relatively weak (Fig. 2a). Although March marks a winter minimum of anticyclonic intensity, the absolute minimum for the year occurs in October (Sahsamanoglou 1990a). Polar highs that form over northwestern Canada preferentially travel south-southeast through the Ohio River valley and enter the Atlantic between 30° and 35°N (Klein 1957). Throughout the next 2 months, anticyclonic flow strengthens to the eastern side of the high as it expands and migrates toward the Mediterranean region. By early May (Fig. 2b) the pressure at the center of the Azores high has increased slightly, but anticyclones are less common over Europe and North America as the land warms (Klein 1957). The high is now beginning to take on a shape that is characteristic of all semipermanent oceanic anticyclones, with southwest to northeast flow to the north of the high and more southerly flow to its east. This asymmetry allows for the transport of eastward momentum from the Tropics northward into the midlatitudes, thus sustaining the westerlies. However, on the eastern side of the high there is almost no transport of momentum equatorward (Trewartha and Horn 1980). Anticyclones are now much less common over the southern United States and the Iberian Peninsula as the westerlies continue to weaken and the primary storm track shifts poleward (Klein 1957).

Early May marks the beginning of rapid anticyclonic expansion, strengthening, and northward migration that continues through late July. By early July (Fig. 2c) the Azores high has expanded substantially and occupies much of the Atlantic basin. The high is now centered at 30°N, 40°W, where pressures greater than 1020 mb occur almost daily. Over North America, southeasterly winds from the high allow warm, humid air from the Atlantic Ocean and Gulf of Mexico to dominate the weather throughout the eastern half of the continent. The primary North American anticyclone track is over the Great Lakes, where high pressure systems with central pressures $>$1020 mb are nevertheless rare (Klein 1957; Zishka and Smith 1980). The northeastern portion of the Atlantic subtropical high extends well into western Europe at 50°N, where migratory high pressure systems are now more common.

Weakening of the Azores high begins in early August and continues through the winter. In early September over the eastern United States, there is clear evidence of a secondary maximum in the high pressure frequency that intensifies and migrates south through autumn and winter (Fig. 2d). High pressure becomes more dominant over the continents, as is evident over western Europe where the influence over the Azores high extends inland, and over Pennsylvania, where a local maximum is now present, as indicated by the closed contour (Harman 1987). This pattern of oceanic weakening and continental strengthening continues throughout autumn. By early November (Fig. 2e) the pattern is dramatically different from that of midsummer. The secondary maximum over the eastern United States is almost as strong as the oceanic high, which is weaker than it was in early March (Sahsamanoglou 1990a). Additionally, high pressure is more frequent over France and Germany than at any other time in the sequence. The oceanic high is expanding eastward into Iberia and Morocco, and the continental high over the eastern United States is intensifying as it moves southward.

During November and early December, the oceanic high continues migrating toward Morocco and has moved 15° east of its summer position and south of the Azores. In early January (Fig. 2f) the eastern maximum reaches its most eastward position—30°N, 20°W, just off the coast of Morocco and Mali. High pressure is slightly more frequent here than over Georgia, where the western maximum has changed little over the past 3 months. Late January is the time in which the winter spatial mode is strongest, since it is this half month in which anticyclones occupy the greatest area and high pressure is most common throughout the subtropics (continents and ocean) (Lamb 1973; Harman 1987; Sahsamanoglou 1990a).

The seasonal migration of the Azores high for each half month is summarized in Fig. 3. During most of the year, the center of the anticyclone migrates slowly, tracing out a pseudoelliptical path with a major axis at about 29°N (in general agreement with Sahsamanoglous 1990a). The oceanic center of the Azores high is farthest east in early January and farthest west in midsummer (Fig. 3a). However, during certain times of year, the position of highest pressure abruptly changes, such as between late January and early February, and between late February and early March. The anticyclone moves as far west over a 2-month period from early January to early March as it moves east over the 6 months from July to January. The secondary maximum over the eastern United States generally migrates southwestward from its initial appearance as a distinct frequency maximum in late August until it disappears in early February (Fig. 3b). The largest half-month displacement takes place between late October and early November, when the center of the high moves from southwestern Pennsylvania to northern Georgia.

5. Half-month change in mean frequencies

The following map sequence (Figs. 4a–e) depicts the *change* in mean frequencies between consecutive half months. Five maps are selected to illustrate times of year in which the change in the Azores high is most significant. For each 5° lat $\times$ 5° long grid node, the change in frequency (later half month minus earlier half month) is plotted and contoured. Thus, areas with positive values have increasing anticyclone presence, and negative nodes depict declining high pressure frequencies. In the following map series, half-month changes greater than 2.0 are fairly rare, while 1.0 frequency changes are rather common.

Early May marks the beginning of strengthening and westward expansion and of the oceanic anticyclone, and declining frequencies over the continents, as radiation receipt increases throughout the middle and high latitudes of the Northern Hemisphere (Fig. 4a). Thus, April and May are transitional months between the characteristic winter and summer patterns. June is a period of significant expansion and intensification of the oceanic maximum (Fig. 4b). Anticyclone frequencies increase everywhere over the Atlantic and adjacent land areas, and the high occupies the greatest oceanic area in late June, even though it has not yet reached maximum intensity.

August marks the beginning of declining anticyclone frequencies over the Atlantic basin that will continue for the next 3 months. This coincides with increasing anticyclone prevalence south of Hudson Bay and over Scandinavia. By early October, development of the winter dual-maxima pattern is clear (Fig. 4c). The formation of continental anticyclones continues as cold air begins fil-

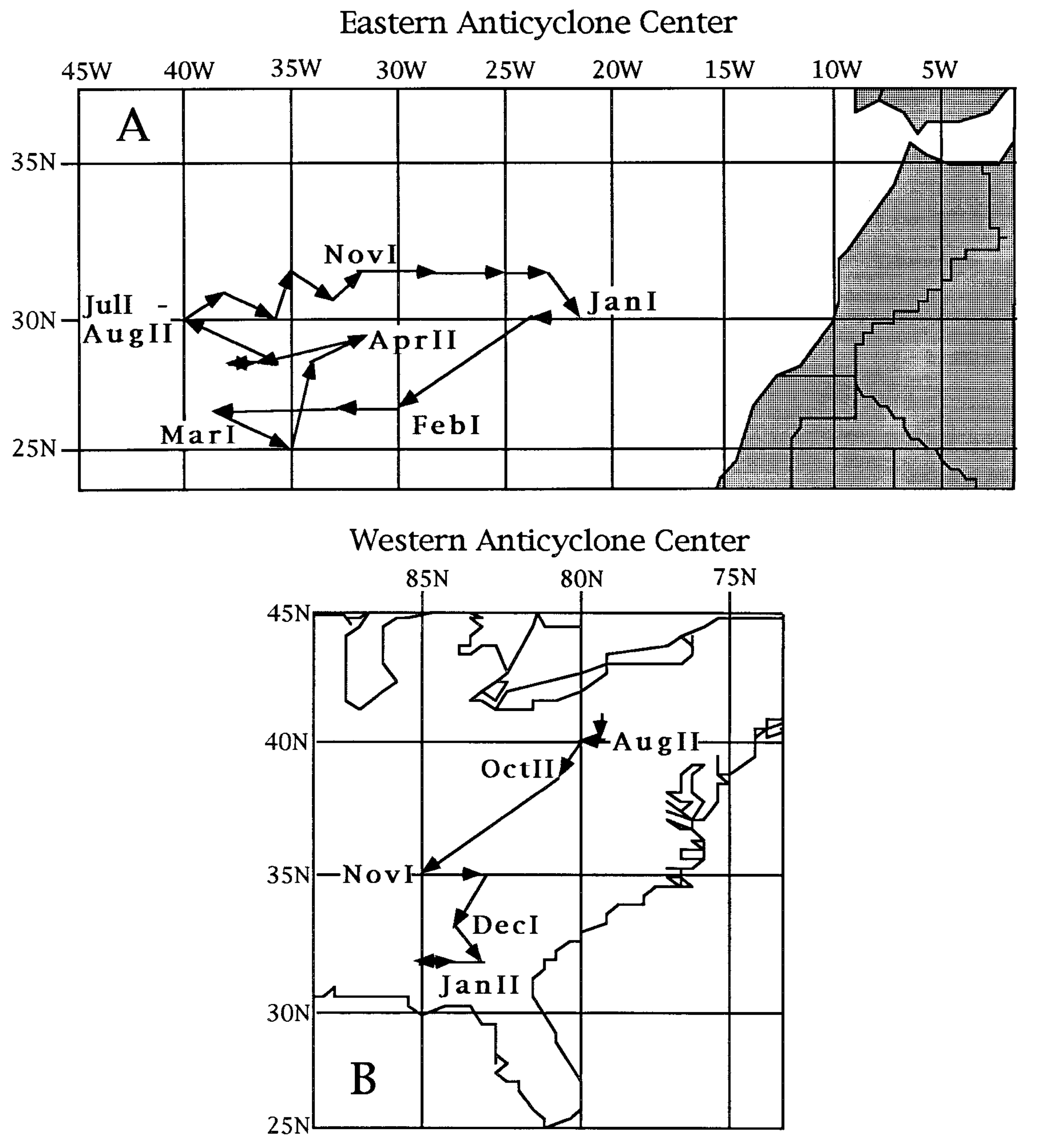

FIG. 3. (a) Intraannual migration of the Azores high (oceanic) center for each half month (I = first half of month and II = second half). Mean half-month positions correspond with arrowheads. (b) Migration of the secondary high pressure center (continental) over the eastern United States between August and the end of January.

tering farther south over eastern Europe and the western United States.

Early to late December is an interesting period because of an overall increase in anticyclonic activity across the entire region, as cold, transient anticyclones are now quite common (Fig. 4d). The greatest increase is at 25°N over the western Atlantic. February exhibits some of the most dramatic changes in anticyclone frequency, with a rather quick transition from dual continental maxima to a single oceanic maximum. By early February, the decline in anticyclones is obvious, as frequencies decrease over almost the entire map (Fig. 4e). Most of this weakening occurs from 20°N to 40°N, where the anticyclones were strongest in January. Since the subsequent change during the February and March is remarkably small, the demise of the winter mode takes place abruptly in a 2-week period at the beginning of February.

6. Principal components analysis

One of the primary goals of our research is to assess decadal-scale climate changes over the subtropical At-

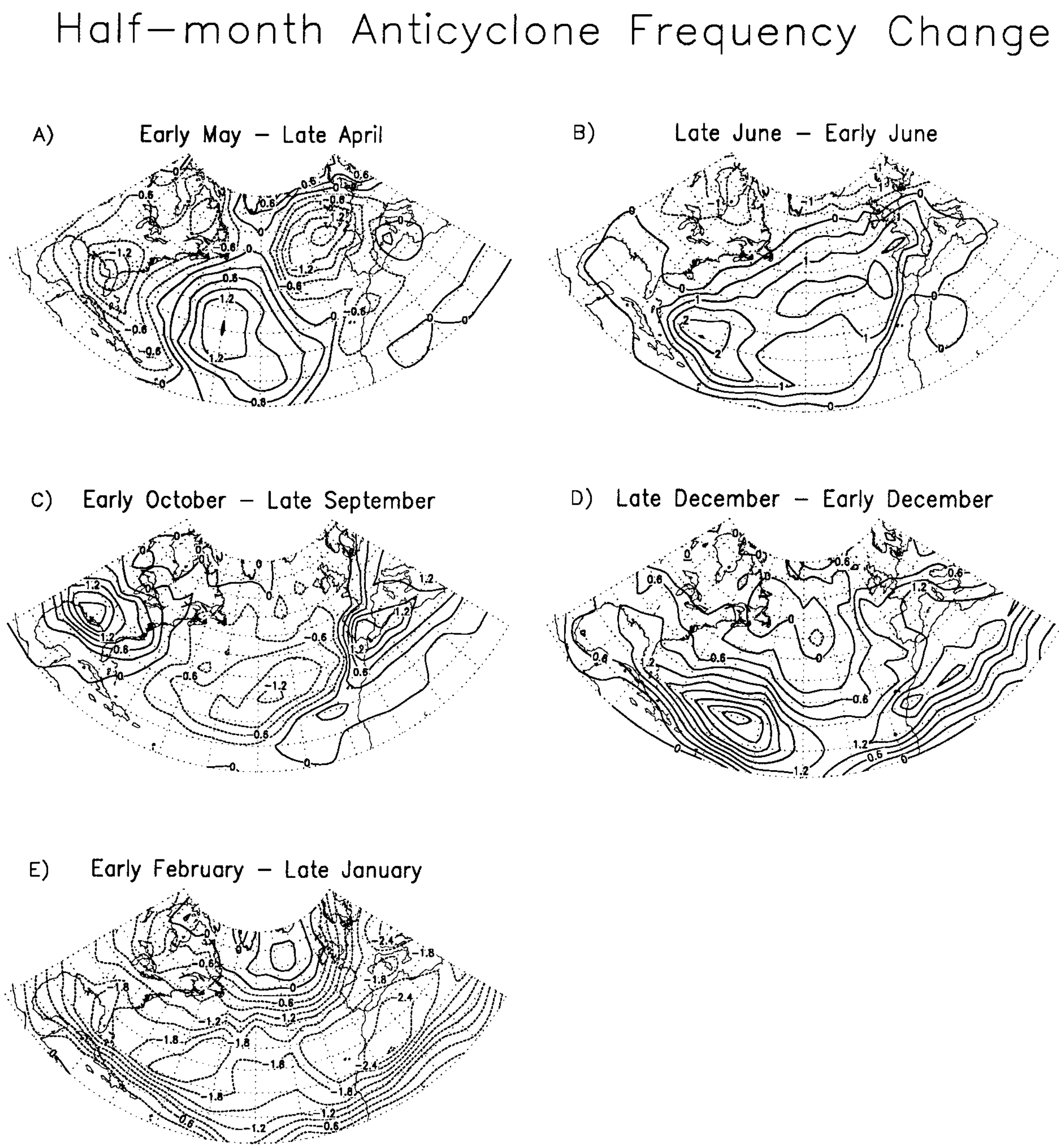

FIG. 4. Average change (in days) in the half-month frequency of sea level pressure readings ≥1020 mb between (a) early May and late April (early May frequency minus late April frequency), (b) late and early June, (c) early October and late September, (d) late and early December, and (e) early February and late January. The contour interval is 0.3 for all maps.

lantic, as identified by changes in the frequency of high pressure. Our analyses indicate that the North Atlantic subtropical high occupies preferential locations at various times of the year. Because the semimonthly frequency of high pressure over this region varies significantly both intra- and interannually, multivariate statistical techniques are useful for identifying the variance and correlation structure of the field.

In this study, PCA is used to partition the spatial variance of anticyclone frequencies. Variables (columns) are the various grid nodes over a subregion extending from the eastern United States through western Europe and northwestern Africa (the outlined area in Fig. 1a), and observations (rows) are frequencies for each half month over 91 yr. If any value is missing from any node during a given half month, that grid node is coded as missing. Entire years are eliminated (i.e., component scores are not calculated) if more than 10% of the grid nodes are missing for that year. This conservative process eliminates 21 yr from the PCA (1899–1901, 1905, 1908, 1922, 1924, 1926–33, 1935–39, and 1945). The final dataset includes 1690 half months (over 70 yr) recorded at 150 grid nodes.

PCA and related methods (common factor analysis, eigenvector analysis, and rotated PCA) are commonly used in the atmospheric sciences for variable reduction, for the analysis of intervariable correlation and/or covariance structure, and for detection of recurring modes of variability. Despite widespread application, considerable disagreement remains regarding which techniques to use and how to apply them. For example, some argue that rotation of principal components (PCs) is necessary for proper interpretation and because of the effects of domain shape (Richman 1986, 1993), while others counter that rotation is only appropriate in common factor analysis and that domain shape has little influence on the PCs (Daultrey 1976; Legates and Willmott 1984; Legates 1991, 1993).

In our analysis, we compared unrotated loading maps to loading maps produced using a varimax rotation. Node-by-node correlations of the unrotated and rotated loading fields indicate that each of the first four unrotated PCs corresponds with one of the rotated PCs (at $r > 0.67$). Both unrotated and rotated fields are presented in Figs. 5–9 for comparison purposes.

Our analysis focuses on the first five PCs that cumulatively account for two-thirds of the total variance in the data. These five components pass the significance test proposed by Overland and Preisendorfer (1982) for the detection of a signal stronger than the background noise component. In addition, truncation at five components does not occur in the middle of an eigenvalue multiplet (Table 2) (North et al. 1982).

A correlation matrix is used as input into the principal components procedure. Loadings maps are presented for the first five unrotated PCs, and the rotated component field that is most highly correlated with that loading map is inset. Mean component scores are calculated on both a half-month and annual basis to evaluate the seasonal and year-to-year changes in each PC.

a. Principal component 1

The first PC depicts the predominant winter position and accounts for 26% of the total variance in the data (Fig. 5). High positive loadings occur over northwestern Africa and the Gulf of Mexico, where large variations in the frequency of high pressure occur. Positive loadings indicate that these two centers tend to covary; thus, when high pressure occurs over northwestern Africa, it is also frequently present over the northern Gulf of Mexico. The central Atlantic basin contours are relatively flat and only slightly negative.

To gain insight into the associated surface circulation, surface weather maps were examined for months with large positive and negative component scores on each PC. For the first PC, the western maximum is dominated by transient high pressure systems associated with continental polar air masses that form the leading edge of cold fronts. The eastern maximum is often related to entrenched, blocking high pressure systems that tend to move or dissipate fairly slowly. When the positive phase of this pattern occurs, few anticyclones are present over the central Atlantic, which is populated by cyclone families extending from the western Atlantic northeastward to the British Isles. The positive mode of this PC predominates in winter (Fig. 5, bottom left), and the yearly average score is highest in late January, when the dual-maximum winter pattern is strongest. The negative phase of PC 1 is associated with a lack of cyclones over the Atlantic basin. During these half months high pressure is permanently established from 25° to 40°N, and most storm systems track well to the north of the anticyclone. The negative mode is most common in August, when the central Atlantic is dominated by high pressure.

The time series of annual component scores indicates that PC 1 has become less prevalent in the last half century (Fig. 5, bottom right). A linear trend line fitted to the mean annual scores has a statistically significant negative slope. Although the decline is fairly steady from 1900 to 1980, there is some evidence of increasing scores on PC 1 through the 1980s. The extreme annual average scores range from over $+3.0$ units for 2 yr in the 1910s to -3.0 units in the 1950s and 1960s. This range of 6.0 units is about 35% of the intraannual range of about 17.0 units (from -6.0 in August to 11.0 in January). One can thus envision climatic changes of the Azores high as the modulation of the seasonal component score signal by interannual variations.

b. Principal component 2

Principal component 2 corresponds to the summer mode of the subtropical anticyclone and explains 18% of the variance (Fig. 6). The loadings are highest in the mid-Atlantic and are centered at 35°N, 40°W, which is just north and west of the overall mean and late July position. Loadings are only slightly negative over the adjacent continents.

During half months with high positive loadings, there is a very strong anticyclone over the Atlantic basin that extends northeastward toward western Europe. This feature is semipermanent, and cyclonic storm systems tend to track well to the north of the high between 45° and 50°N and move toward the British Isles. Half months with negative loadings on PC 2 are characterized by the lack of high pressure over the Atlantic Ocean. In these half months, the Atlantic is dominated either by cyclone families traveling from the southwest toward the northeast or by persistent blocking patterns, in which a strong high pressure system is centered over Greenland and cyclones track to its south.

Component scores are highest in July, when the sub-

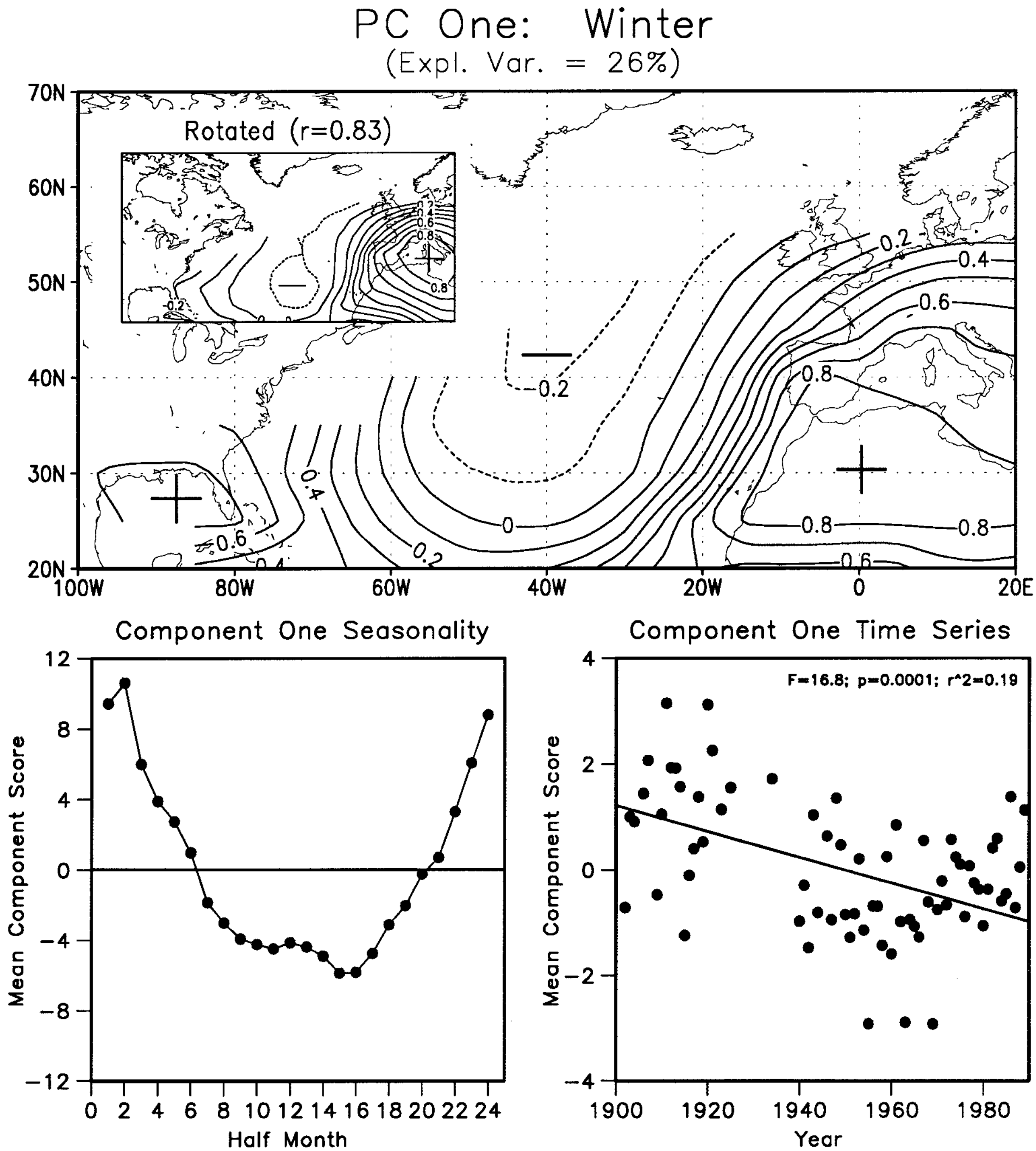

FIG. 5. Component loadings (top) and mean half-month (bottom left) and mean annual (bottom right) component scores for principal component 1. Half month 1 is the first half of January, half month 2 the second half of January, etc. The rotated loading field with which the unrotated PC had the highest correlation is inset to the upper left, along with the correlation coefficient between the two fields. Summary statistics for the statistically significant trend (based on least squares linear regression) in the mean annual scores are included in the bottom right figure and include the ratio of regression sum of squares to residual sum of squares (F), the significance level of the regression line (p), and the variance it explains (r^2).

tropical high reaches its summer frequency maximum, and lowest in October, November, and February (Fig. 6, bottom left). Except for summer, the only half month with a mean positive score is late January. This is probably related to the well-known "January thaw" singularity, a brief period of warming in late January that is present in many station records in the United States (Wahl 1952, 1953; Duquet 1963; Lazante and Harnack 1982). The circulation mechanisms responsible for the January thaw are not well established. Hayden (1976)

TABLE 2. Eigenvalues (λ) and portion of total variance explained by the first five principal components. The change in consecutive eigenvalues ($\Delta\lambda$) and the critical value of a test used to determine principal component separation ($\delta\lambda$) are also included (North et al. 1982).

PC	λ	Explained variance (%)	$\Delta\lambda$	$\delta\lambda$
1	39.64	26.5	13.2	1.3
2	26.43	17.6	10.0	0.8
3	16.40	10.9	6.5	0.5
4	9.87	6.6	1.7	0.3
5	8.12	5.4	0.6	0.3

found evidence of a late January shift in predominant wave direction from the southeast along the U.S. east coast. Hayden hypothesized that this directional shift was related to a temporary reorientation of the Bermuda high to a position similar to its summertime mode. The positive PC 2 scores provide further evidence of the circulation associated with this climatic singularity.

The PC 2 scores time series is very similar to that of component one (Fig. 6, bottom right). A statistically significant decline is evident, indicating that the summer mode of the subtropical high has become consistently less frequent throughout the twentieth century. There is evidence of increasing scores since about 1970, but the overall trend is negative. The variation in mean scores between extreme years (about 9.0 units) is comparable in magnitude to the seasonal variation in PC 2.

c. *Principal component 3*

The third PC (11% explained variance) depicts a dichotomy between meridional versus zonal circulation over the Atlantic basin (Fig. 7). The highest positive loadings occur south of Ireland, and negative loadings (about half as strong) are found southwest of the Azores. Thus, when high pressure is present over the British Isles, anticyclones are rare off the northwest African coast.

During half months with strong positive loadings on PC 3, the circulation is meridional. Blocking highs develop over northwestern Europe and guide low pressure systems either north of the block, toward Scandinavia, or (less frequently) south of the high into Africa. Thus, cyclones in the central Atlantic are forced to track to the north or north-northeast rather than in the typical easterly or northeasterly direction. Conversely, negative scores on PC 3 are related to zonal circulation. During these periods, there is a persistent anticyclone positioned off the coast of Morocco. Cyclones cross the U.S. east coast and track from west to east or northeast (between 35° and 55°N), north of the high, over western Europe or Scandinavia.

The time series of component 3 exhibits a significantly increasing slope since 1900 (Fig. 7, bottom right). This trend indicates that meridional circulation has become more common over the eastern Atlantic Ocean in the last half century. Most of the highly negative (zonal) years occurred between 1900 and 1920, although negative years occurred throughout the record. As with PC 2, the variation between extreme years (about 5 units) has the same magnitude as the intraannual variability, indicating that we have experienced year-to-year variations in circulation in the past century that are comparable to typical seasonal fluctuations.

d. *Principal component 4*

The last two principal components presented here both depict common blocking patterns. Principal component 4 (7% explained variance) is an omega block with pressure varying inversely between the British Isles and the Azores (Fig. 8). This pattern is quite similar to the first PC, but is shifted from a zonal pattern to one oriented along a southwest-to-northeast axis. When anticyclonic blocking occurs over the British Isles, closed low pressure systems tend to occur over the Azores off the Iberian Peninsula. A second positive loading region is present east of the Caribbean and is similar in magnitude to the other two centers.

In half months with high positive scores, an entrenched blocking pattern is present over the British Isles. Migratory anticyclones are common over the western Atlantic after crossing the southeastern U.S. coastline. The central Atlantic is dominated by stalled or slow-moving cyclones traveling toward Spain and Portugal. Half months with large negative scores are typically dominated by a blocking anticyclone off the Iberian coast and cyclones moving north of the block from southwest to northeast toward the British Isles. In some cases a series of migratory highs move zonally across the central Atlantic.

The positive mode of this blocking pattern is most common in February, March, and June, while the negative phase is prevalent in late autumn and early winter (Fig. 8, bottom left). These results are in agreement with Rex (1950), who noted that blocks are common at 10°W from March to June and that most blocking between 45° and 55°N occurs from December to May. In addition, Brezowsky et al. (1951) identified two types of blocking patterns over this region—Atlantic blocks, which occur between 20°W and 10°E, and European blocks, which are found between 10°E and 50°E. They noted that Atlantic blocks are most common from April to June and are rare in summer and winter. Thus, with the exception of positive scores in late winter, the positive mode of PC 4 corresponds with the location and seasonality of the Atlantic blocking pattern.

The annual time series of PC 4 exhibits a statistically significant decline over the period of record (Fig. 8, bottom right), indicating that blocking patterns with anticyclones centered over the Azores have become more frequent than blocking highs over the British Isles. This also suggests that high pressure off the U.S. southeastern

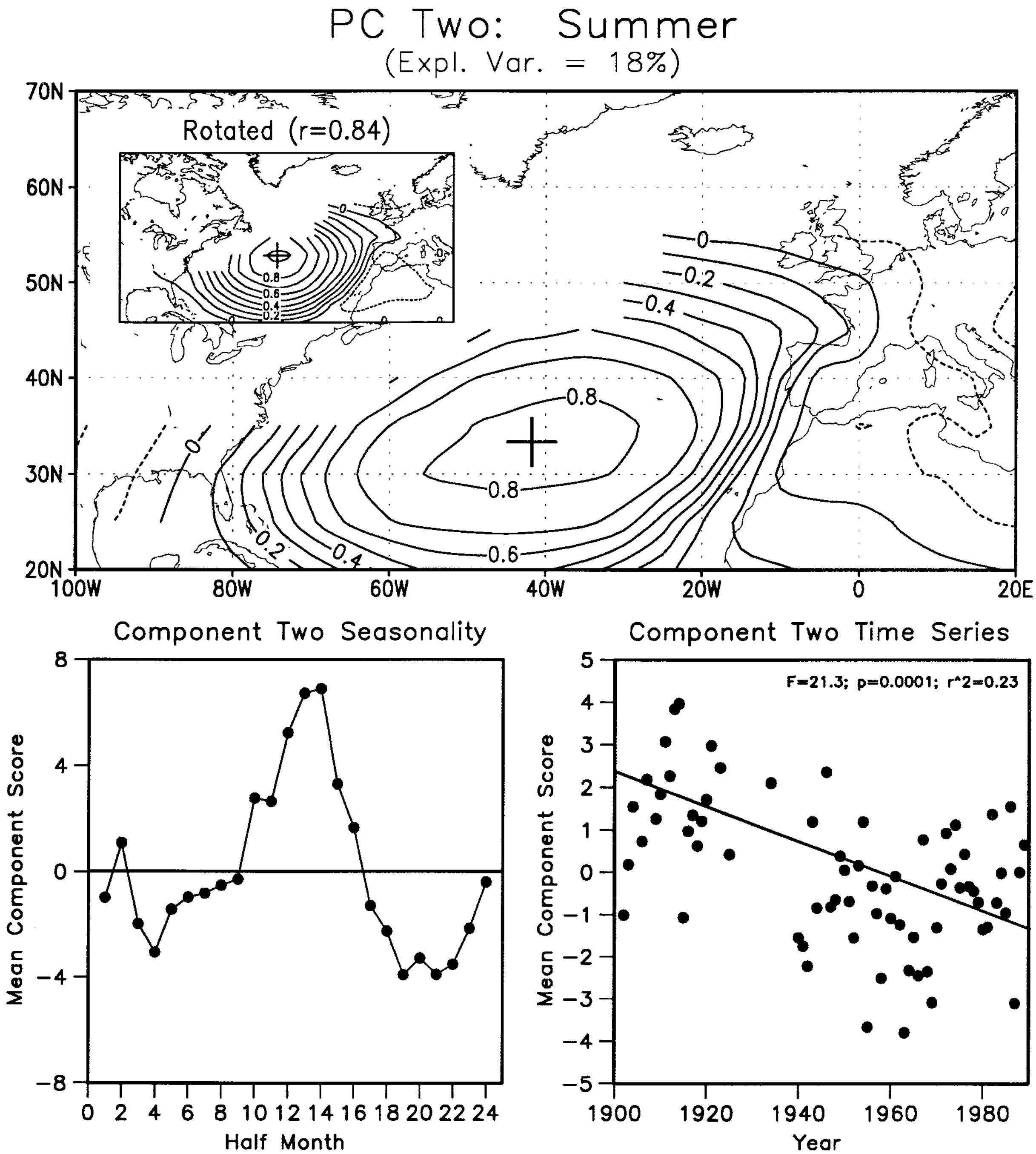

FIG. 6. Same as in Fig. 5 but for principal component 2.

coast, particularly from late February to June, has become less common over the past 50 yr.

e. Principal component 5

Finally, PC 5 (5% explained variance) depicts a blocking pattern with four centers: maxima occur just west of Ireland and over Florida, and minima are found over Italy and the central Atlantic at 30°N (Fig. 9). However, the negative loading area could be considered to be one broad belt extending from the central Atlantic through north-central Europe. The entire pattern is similar to the PC 4 loading map, but is shifted about 20° of longitude to the west.

Half months with high positive scores are primarily dominated by a blocking anticyclone west of the British Isles. With this block in place, cyclones over the Atlantic track almost due north toward Greenland or south of

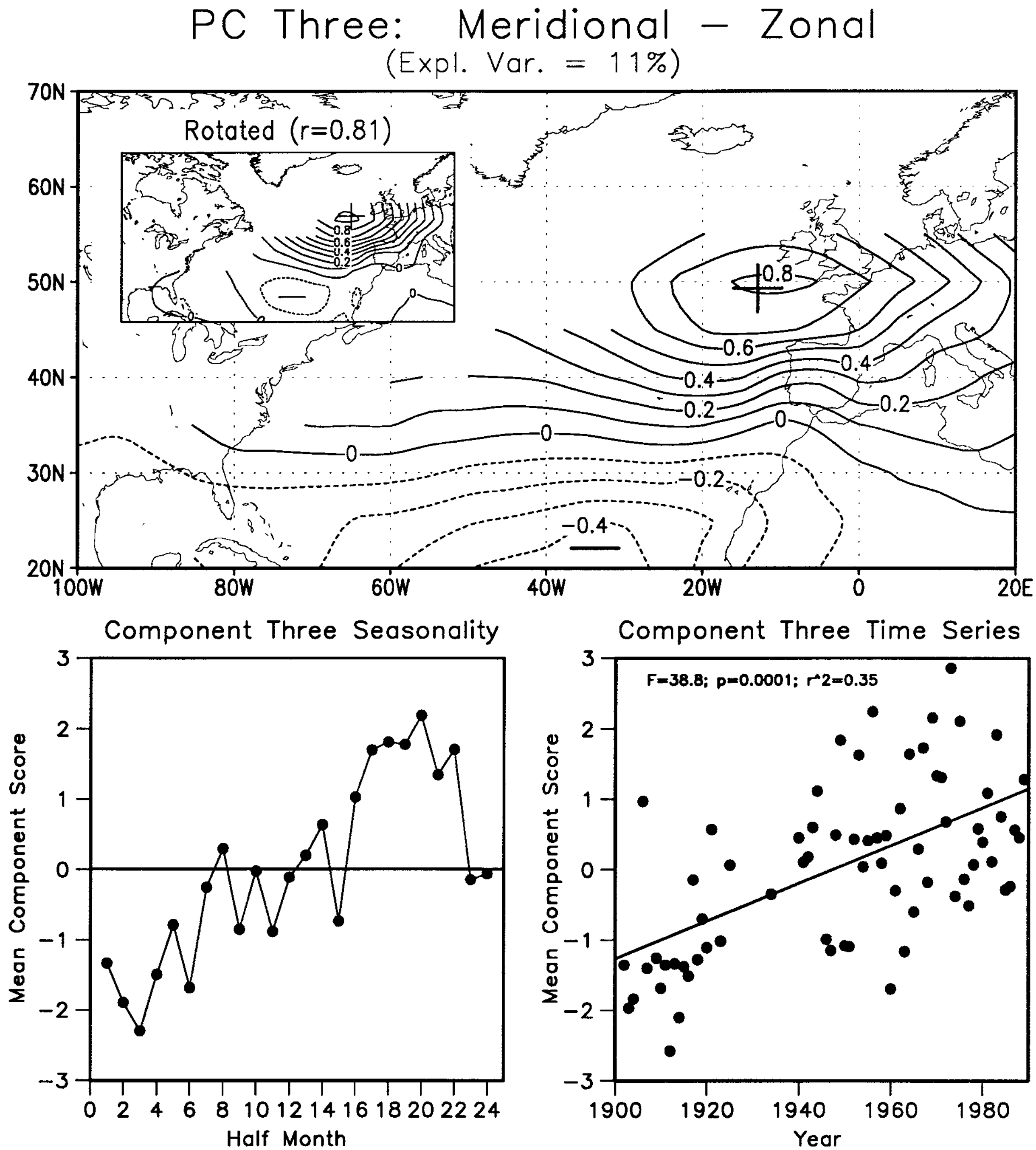

FIG. 7. Same as in Fig. 5 but for principal component 3.

the block eastward toward Portugal. Upstream of the block, high pressure is common over the southeastern United States. In the negative phase, a strong block is present at the surface over western Europe. This block is accompanied by either a distinct anticyclone over the central Atlantic or a broad belt of high pressure extending from the central Atlantic eastward through Spain and Italy into Germany. Low pressure systems moving across the eastern United States tend to track northeastward over the northern Atlantic toward the British Isles.

The positive phase of this pattern (blocking west of the British Isles) corresponds with the Atlantic blocking pattern identified by Brezowsky et al. (1951) and includes the April peak they identified that was missing in PC 4. In addition, the positive mode is most prevalent from December to early April, in agreement with Rex (1950). Conversely, the negative mode of PC 5 bears

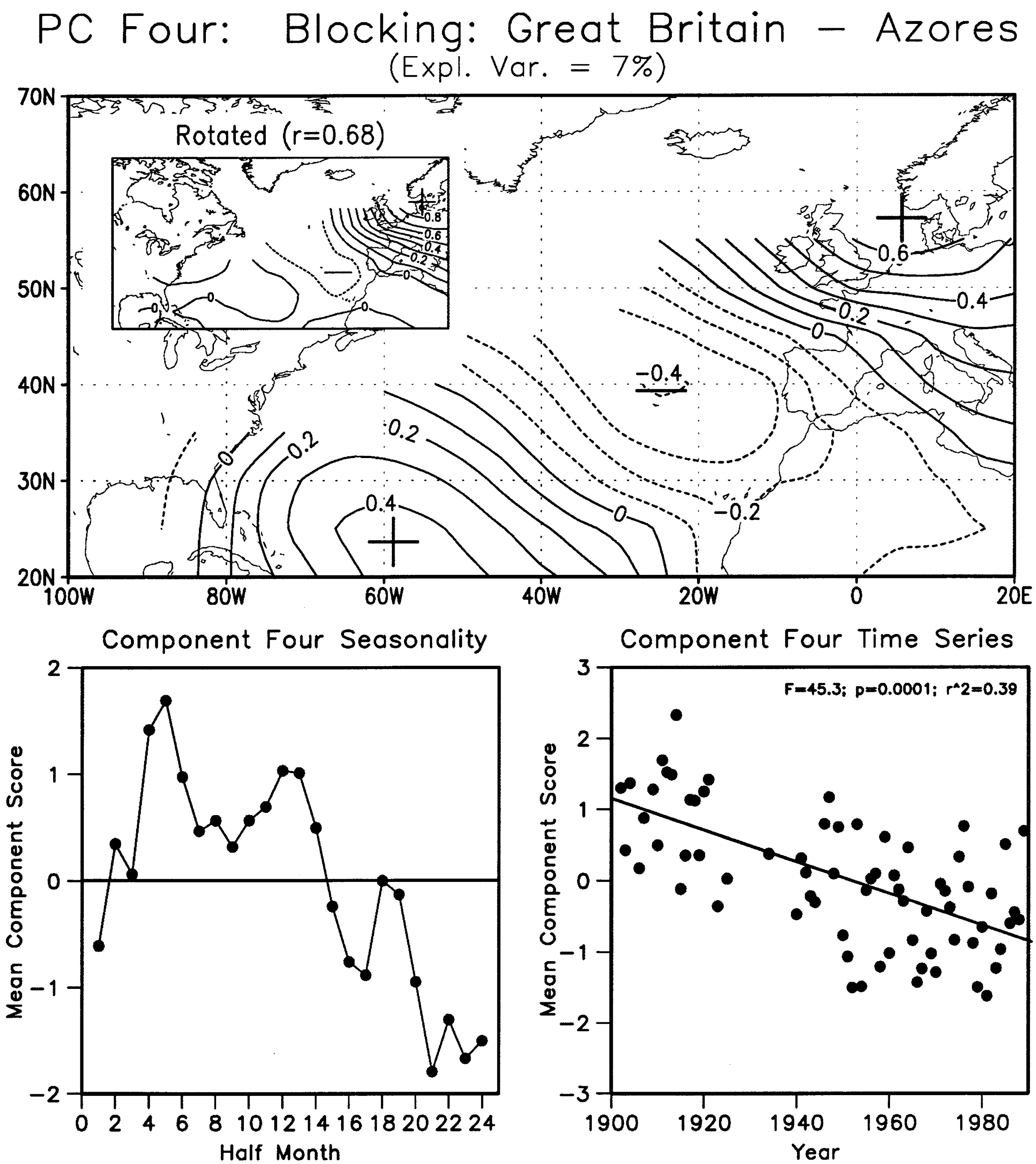

FIG. 8. Same as in Fig. 5 but for principal component 4.

some resemblance to the Brezowsky et al. (1951) European pattern, which has a maximum in October.

Once again, the yearly component scores have a statistically significant trend (Fig. 9, bottom right). Principal component 5 has declined in frequency over the past century, as has the amount of year-to-year variability. Therefore, blocking high pressure systems are more prevalent over north-central Europe, particularly from late summer to autumn.

7. Conclusions and implications

By examining the frequency of high pressure over a threshold value, we have investigated changes in the intensity, size, and spatial characteristics of the North Atlantic subtropical anticyclone both seasonally and interannually. Most of the variability in high pressure over the Atlantic Ocean and adjacent continental regions is dominated by two patterns: a single maximum over the

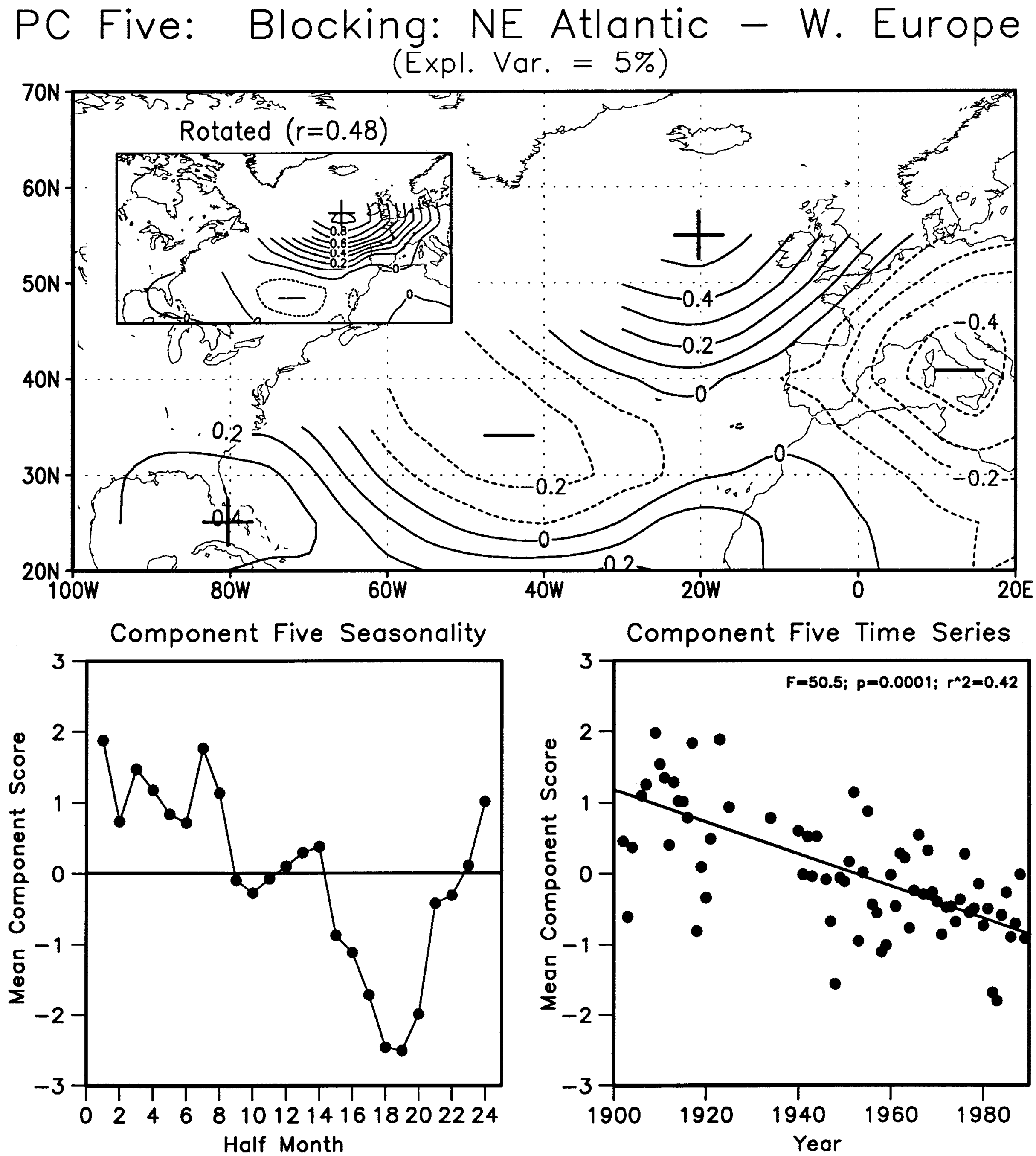

FIG. 9. Same as in Fig. 5 but for principal component 5.

central Atlantic that reaches its peak in July and a dual-maxima pattern with anticyclones over the southeastern United States and west of Morocco that is most intense in January. Throughout the remainder of the year, the Azores or Bermuda high occupies some transitional state between these two common modes. While at some times of the year the area(s) of highest anticyclone frequency (and highest central pressure) tends to migrate slowly (e.g., March through May), at other times the position of the anticyclone changes abruptly over a 15-day period (e.g., late January to early February). Much of the variance not described by these two modes can be accounted for by meridional versus zonal flow configurations and by changes in the locations of blocking patterns. The first five PCs account for over two-thirds of the total variance in the data.

For all but the first component, the interannual variation over the past century is comparable to the average seasonal variation. Thus, we have experienced extreme climatic variability in the recent past that is similar to the extremes commonly found during a typical annual cycle. For example, in years with large negative loadings in the summer on PC 2, the strong, single-maximum Azores high does not establish itself over the central Atlantic because the midlatitude storm track is displaced unusually far to the south.

Finally, trends in the yearly average component scores are statistically significant for all five PCs. These trends indicate that the following climatic changes have taken place over the northern Atlantic.

1) Meridional flow has become more frequent over the eastern Atlantic and western Europe (increasing scores in PC 3). This has been documented by various researchers using different techniques and datasets. Lamb (1968) and Dzerdzeevskii (1962, 1969) detected a shift from zonal to meridional circulation around 1950. Similarly, Makrogiannis et al. (1982) determined that flow over the North Atlantic was predominantly zonal prior to 1939, but that meridional flow and blocking became more common afterward, and Parker and Folland (1988) noted stronger westerlies in the North Atlantic in the early 1900s. Briffa et al. (1990) detected a decrease in zonal circulation in the late 1960s over the British Isles. Based upon PCAs of hemispheric pressure and geopotential height fields, Kutzbach (1970) and Kalnicky (1974) detected a shift from zonal to meridional circulation in the 1950s. Sahsamanoglou (1990b) computed monthly zonal index values over the Atlantic from 1899 to 1980. He found a zonal epoch from 1905 to 1933 and a meridional epoch from 1939 to 1974, and determined that the decline in the zonal index was caused by decreasing intensity of the Azores high. In addition to the prevalence of meridional flow, the positive trend in PC 3 suggests a long-term eastward shift in the position of the subtropical high, a shift that has been identified by other researchers (Perry 1971; Angell and Korshover 1974; Sahsamanoglou and Makrogiannis 1992).

2) Blocking has become less prevalent over the Atlantic and the British Isles, but has increased over west-central Europe. Declining trends in PCs 4 and 5 suggest that the Atlantic blocking pattern has been supplanted by European blocks. Additionally, trends in these two PCs indicate that anticyclones are less common over the southeastern United States and off the western Atlantic, particularly in spring (when average scores are highest). Stahle and Cleaveland (1992) identified a trend of increasing spring rainfall over the southeastern United States during the past century that was related to the lack of ridging off the coast. Their dry periods correspond to years with high positive scores on PCs 4 and 5.

3) The frequency and intensity of the North Atlantic subtropical high has declined significantly over the past 90 yr. Negative trends in the scores of first two PCs, which account for 44% of the total variance, indicate that both the winter and summer modes are less prevalent. Thus, there has been a net removal of mass from the subtropical Atlantic and the adjacent continents. Declines in central pressure in and around the subtropical anticyclone have been detected by numerous researchers (Perry 1971; Wagner 1971; Angell and Korshover 1974; Sahsamanoglou 1990a,b; Deser and Blackmon 1993), as have overall declines in anticyclone frequencies (Zishka and Smith 1980; Harman 1987).

TABLE 3. Correlations between spatial principal component loading fields derived from the uncorrected and corrected sea level pressure datasets (Trenberth and Paolino 1980).

Uncorrected	Corrected PC1	PC2	PC3	PC4	PC5
PC1	−0.30	0.83	−0.09	−0.16	−0.04
PC2	0.62	−0.62	−0.09	−0.16	−0.04
PC3	0.22	−0.15	0.71	−0.12	−0.08
PC4	−0.31	0.02	−0.40	−0.74	−0.11
PC5	−0.02	−0.10	−0.13	−0.07	−0.90

It is possible that this apparent decline in atmospheric mass over the subtropical Atlantic is fictitious, resulting from systematic errors in the gridded dataset. Trenberth and Paolino (1980) noted that the period 1899–1939 had significantly higher pressures over the Atlantic than subsequent years. Although they considered the early data questionable, they did not rule out the possibility that the change in pressure was real. Others believed that the declines in anticyclone frequency and strength (over this and other regions) were real because the change was exhibited as a gradual downward trend rather than a discontinuity and because similar trends were present over continental areas where station networks were denser (Wagner 1971; Zishka and Smith 1980; Harman 1987). Further evidence of an actual decline was presented by Deser and Blackmon (1993), who found pressure falls in the subtropical Atlantic consistent with independent, ship-based, surface wind measurements.

To further examine the possibility of a data bias in the early portion of the record, we analyzed Trenberth and Paolino's (1980) corrected hemispheric mean monthly pressure dataset over our Atlantic domain (Fig. 1a). First, a spatial PCA was run on the monthly mean values of both the corrected and uncorrected pressure data, and the loadings maps were correlated (Table 3). These fields are fairly similar, except that the summer pattern is the first PC in the corrected dataset rather than the second. We then calculated and correlated the monthly component scores time series for both datasets (Table 4). The correlations are greater than 0.84 for all five components, indicating that the trends in the corrected mean monthly pressure dataset are similar to those in the uncorrected data. Thus, there is additional evidence that our trends, which are based upon anticyclone frequency counts rather than mean pressure,

TABLE 4. Correlations between the monthly principal component scores time series calculated from the uncorrected and corrected (Trenberth and Paolino 1980) sea level pressure datasets.

Uncor-rected	Corrected PC1	PC2	PC3	PC4	PC5
PC1	0.48	0.85	0.01	−0.15	0.00
PC2	0.84	−0.48	−0.22	0.12	−0.05
PC3	0.21	−0.13	0.89	−0.25	−0.06
PC4	−0.07	0.02	0.33	0.88	−0.14
PC5	0.04	−0.05	0.12	0.09	0.96

represent a real shift in the general circulation and do not result from anomalous pressure readings early in the record.

If a shift in the general circulation has resulted in a displacement of mass from the subtropical Atlantic, the logical question is, where has the mass gone? Is there a concomitant increase in mass over the semipermanent low pressure centers, or is there interhemispheric transport? Christy and Trenberth (1985) examined the interannual global redistribution of mass and determined that, while the primary mode of transport is within the hemisphere, there is substantial likelihood of net interhemispheric movement. We are currently performing similar analyses for other semipermanent anticyclones in the Northern Hemisphere, the results of which should help to determine whether this movement of atmospheric mass is a regional or hemispheric phenomenon.

Finally, are these trends consistent with general circulation model prognostications of circulation change in an atmosphere with elevated CO_2 and trace gas concentrations? Sea level pressure anomaly maps for 2 times CO_2 or transient model runs are rarely published, and based on limited evidence there are significant differences between models with respect to changes in the North Atlantic subtropical anticyclone. Washington and Meehl (1989) depict 1- to 2-mb declines in winter sea level pressure over the subtropical North Atlantic for both 2 times CO_2 and transient runs, in agreement with our trends in PC 2. Results from the Canadian Climate Centre model for winter depict increasing pressure north of about 35°N and declining pressure to the south, particularly over the southeastern coast of the United States (Houghton et al. 1990). Their summer map exhibits higher pressure over the eastern United States and western Atlantic Ocean, but strong declines (over 2 mb) over northwestern Africa. However, the experiments of Rind et al. (1990), using the Goddard Institute for Space Studies model with an exponential growth of radiative greenhouse forcing (Hansen et al. 1988), indicate that the frequency of summer drought should increase in the southeastern United States because of intensification of the North Atlantic subtropical high. Thus, at this time it is difficult to confirm whether the circulation changes we observed are indicative of general circulation changes related to increased trace gas concentrations. Further comparisons of observed and modeled circulation changes will be provided upon completion of our analyses of other semipermanent anticyclones over the Northern Hemisphere.

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