Scales of North Atlantic Wind Stress Curl Determined From the Comprehensive Ocean-Atmosphere Data Set

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Nineteen years of wind data over the North Atlantic are used to calculate a field of wind stress curl. An empirical orthogonal function (EOF) analysis is performed on this field, resulting in spatial patterns of wind stress curl and associated time series. A Monte Carlo technique is used to establish the statistical significance of each spatial pattern. The first four statistically significant EOF modes represent more than 50% of the curl variance. The spatial patterns of curl associated with these modes exhibit the major elements of North Atlantic climatology. The associated time series are spectrally analyzed. Most of the variance is contained in annual and semiannual frequencies. Features observed include the individual annual variation of the subtropical high and the subpolar low, the annual oscillation of intensity between the above pressure centers, the influence of localized strong sea surface temperature gradients and associated cyclogenesis regions, and the constant nature of the trades. The EOF curl patterns are in the form of basin-sized standing waves.

INTRODUCTION

The climatology of the atmosphere over the sea is linked to ocean current and sea surface temperature (SST) through the exchange of momentum and heat. It is therefore critical for the modeling of either medium, ocean or atmosphere, to understand the spatial and temporal scales of motion over the ocean. This work looks at the North Atlantic using empirical orthogonal functions (EOFs).

Other authors have estimated statistically the scales of winds over the ocean. Willebrand [1978] used spectral techniques, particularly autospectra and propagation characteristics deduced from cross spectra. Willebrand recognized the problem of cyclostationarity of his data and resolved it through verification of the similarity of seasonal spectral characteristics. EOF analysis avoids the problem of episodic events. Phenomena in each eigenmode are identified in hierarchical fashion by variance. EOF analysis also eliminates the subjectivity involved in the synoptic approach of selecting and studying dominant sea level pressure (SLP) patterns [e.g., Sorkina, 1965]. Barnier [1986] used the EOF method for investigating seasonal variability of one specific year of wind stress curl data over the North Atlantic. He questioned whether his results were appropriate for extended times. In this study we use 19 years of data and confirm the similarity of his patterns to those calculated in this study.


The data source for the calculations in this work is the Comprehensive Ocean-Atmosphere Data Set (COADS). The parameter provided by COADS is the measured pseudostress parameter, \( \bar{u}\bar{\tau} \), where \( u \) is the velocity vector, centered on 2° latitude by 2° longitude boxes. The curl of the pseudostress is calculated at 466 points in the North Atlantic for 19 years of monthly data. The 466 time series of wind stress curl are combined and statistically resolved into modes representing decreasing amounts of wind stress curl variance. The variance, the spatial distribution of wind stress curl, and a nondimensional time series are associated with each mode. The spatial distributions are examined for similarity to climatology. The curl distributions contain patterns indicative of the oscillation of intensity between the subtropical high and the subpolar low; a second notable pattern can be associated with the region of large sea surface temperature gradient off the coast of North America. The time series are analyzed for annual and interannual variability.

DATA DESCRIPTION

The data are a subset of COADS, which is a global marine data set on a 2° × 2° grid covering the years 1854 to 1979. The number of reports per month for the Atlantic basin ranged from less than 5000 during the first 30 years to about 80,000 in the 1960s and 1970s, the decades herein studied. The collected observations, primarily taken by ships of opportunity, are edited and summarized statistically for each month. The COADS variables used are the two wind stress parameters, defined as wind magnitude times the eastward wind component and times the northward wind component, respectively. This work is not intended to address the diversity involved in the selection of a drag coefficient estimate.
Calculations are performed on the above pseudostresses. COADS has inherent uncertainties due to historical changes in instrumentation, observation techniques, coding methods, data density, and ship tracking. Specifically, wind data consistency suffered in the transition from estimation from sail and sea state (Beaufort scale) to actual measurement.

The geographical area of the North Atlantic covered by this marine climate study extends from 21°N to 53°N and from 79°W to 11°W. Considerations in selecting this area were (1) comparison with the seasonal study of Barnier [1986], (2) reduction of the effect of large variability at high latitude as indicated by Kutzbach [1970], and (3) computer resources. Nineteen years of data, from January 1961 to December 1979, were used. One hundred twenty-nine near-shore grid blocks were removed to eliminate land effect. Gaps in the data were filled using eight-point spatial interpolation. The vertical component of the curl of the wind stress parameters was calculated using a second-order Cartesian central finite difference approximation. The temporal mean was removed from the curl fields. Each of the resulting monthly perturbation wind stress curl sets was subjected to an E-W and a N-S single Hanning filter, i.e., a 1-2-1 running average. At each location the 19-year series of wind stress curl was subjected to a temporal single Hanning filter. These spatial and temporal filters were used to smooth any large jumps between neighboring points that might result from the independent compilation of each of the original data points. The mean and variance fields are shown in Figures 1a and 1b, respectively. The mean field of pseudo wind stress curl compares qualitatively with the actual wind stress curl fields of Willebrand [1978], Hellerman and Rosenstein [1983], and Barnier [1986].

**EOF Analysis**

Lorenz [1956] used the eigenvectors of the covariance matrix associated with a sample data field to calculate the coefficients or predictors for a statistical forecasting technique for SLP. Ten years later, Kutzbach [1967] reawakened interest in this technique. He calculated statistical relations within and between fields of SLP, surface temperature, and precipitation over North America using the same technique as Lorenz. The above technique, called empirical orthogonal function analysis, separates field data sets into eigenmodes. In general, each mode has an associated variance, nondimensional spatial pattern, and dimensioned time series.
To reduce computation time, the EOF analysis procedure is altered for this work as recommended by the response of von Storch and Hannusch (1984) to the work of Legler (1983). Hirose and Kutzbach (1969) show that the traditional EOF method and the method used herein produce the same results. The specific procedure applied to wind stress curl over the North Atlantic is described below. A qualitative approach is used in this application of EOF analysis for deriving temporal and spatial scales from COADS. For a more rigorous approach, see North et al. (1982).

The deviation from the mean of wind stress curl is formed into a 228 x 466 matrix. The 228 corresponds to 19 years of monthly measurements; the 466 corresponds to the number of spatially distributed stations. From this data matrix a 228-square temporal covariance matrix is calculated by multiplying the original array by its transpose. The diagonal elements are the variance at time i, where i is the diagonal index. The off-diagonal elements are the covariance with lag equal to the difference between the row and column indices. The matrix includes all possible temporal covariance. This symmetric matrix is solved for its 228 real eigenvalues, eigenvectors, and associated coefficients. Each eigenvector is a nondimensional 228-element time series. Each set of coefficients is a 466-point distribution of wind stress curl. When normalized, the eigenvalues are equal to the percentage of total wind stress curl variance associated with each EOF wind stress curl distribution and its time series.

Spectra are estimated for the first five time series. The spectral window used has 10.2 degrees of freedom. The frequency spectra are shown in order to accent dominant frequencies. A month-by-month average annual signal is calculated, and its variance compared to the total variance of the given EOF.

In order to determine if the eigenvalues are above noise level, the EOF procedure was applied to 20 random data sets. These results were used in accordance with the selection rules of Overland and Preisendorfer (1982), to distinguish those eigenvalues attributable to North Atlantic wind from those attributable to a spatially and temporally uncorrelated random process.

RESULTS

Figures 2a and 2b show the distribution of the mean eastward wind stress and the component of wind stress curl...
associated with eastward stress, respectively. Similarly, Figures 3a and 3b show mean northward wind stress and the distribution of curl associated with northward stress. Differences between these wind stress fields and those of Willebrand [1978] and Hellerman and Rosenstein [1983] can be attributed to two sources. Using $\Delta \vec{a}$ to represent wind stress corresponds to assuming a linear drag coefficient. For reference to the above authors, note that a pseudostress of 25 m$^2$ s$^{-2}$ in Figure 2a corresponds to an actual stress of 0.45 dyn cm$^{-2}$ for a drag coefficient of $1.4 \times 10^{-3}$. In comparison to the usage of an empirical drag formula such as that suggested by Large and Pond [1981] the $>100$ m$^2$ s$^{-2}$ pseudostress used in this work represents an underestimation. Stress of this magnitude does not appear in the mean stress distributions of Figures 2a and 3a but does appear in some of the individual wind data sets. A second source of difference is the use of a Cartesian del operator rather than a spherical del operator. The mean curl fields resulting from the two del operators are qualitatively the same (and nearly the same quantitatively, owing to dominance of the "dudly terms; see below.) The Cartesian del operator was used because it deemphasizes the variance at high latitude. Note that the error introduced by the Cartesian gradient is of the same order as the error due to the tacit assumption of constant unity area weighting in the EOF procedure (see "metric factor" in the paper by North et al. [1982]).

By comparing magnitudes and patterns it is obvious that the meridional gradient of the eastward wind stress dominates the total mean wind stress curl, as shown in Figure 1. Notable is the thumb of negative curl near Newfoundland, the NE-SW orientation of the pattern near the diagonal and to the east, and the perturbation of this orientation near the North American coast. These characteristics are found also in the results of Willebrand [1978] and Hellerman and Rosenstein [1983]. There is a region of maximum curl gradient directly overlying the region of maximum SST gradient at the western ocean boundary. This region of high gradient, which includes a wind stress curl maximum, is mainly due to the eastward stress distribution. The negative curl in the southeast triangle of the field is due to the combined effect of the eastward and northward wind stress distributions.

The synoptic features observable in the mean wind stress curl field are (1) the western basin curl minimum in the
Fig. 4. Wind stress curl distribution from EOF1, corresponding to 24.6% of the total variance. Dashed lines represent negative deviation of curl from the mean. Units are m s^{-2} \times 10^{-5}. Contour intervals are 20 m s^{-2} \times 10^{-5}.

Fig. 5. Same as Figure 4 but for EOF2, corresponding to 13.3% of the variance of wind stress curl.
eastern and western curl maxima of similar magnitude and separated by a narrow region of slightly negative curl.

EOF5, shown in Figure 8, represents only 4.9% of the variance of wind stress curl. Above 30°N the distribution is clearly divided into four domains with node lines along 30°W and 45°N.

The above EOFs were chosen for discussion because of their distinct spatial patterns and because their variance was well above noise level, as explained in the next paragraph.

The statistical significance of the variance associated with each EOF is verified using the selection rules of Preisendorfer et al. [1981]. We calculate 100 sets of eigenvalues for 100 fields of uncorrelated random numbers, giving a 95% confidence level for each order of eigenvalue. To be significant, the eigenvalues, or variance, of the North Atlantic wind stress curl field must be significantly greater than the eigenvalues of the uncorrelated field. The first eight eigenvalues of the wind stress curl field and the maximum over the random fields are shown in Table 1. This table also shows the cumulative variance and the annual signal percentage of variance of each EOF time series which will be discussed later. Calculation of sampling error, as estimated by North et al. [1982], indicated that the first five eigenmodes are distinct.

The time series associated with the first five EOF spatial distributions are spectrally analyzed. No tapering is applied. The raw spectra of the first four EOF time series are smoothed using four Hanning passes, producing 10.2 degrees of freedom. Sixteen Hanning passes are used on EOF5. The 90% confidence limits are shown with the log-log spectrum. The variance-preserving frequency spectrum is shown to accent the frequencies most responsible for the time series variance. These results are shown in Figures 9-13.

The first EOF time series and its spectra are shown in Figure 9. Superimposed on the time series is the series composite annual signal. The average value for each month is used to form an "expected" year. The composite annual signal is composed of 19 of these expected years. The ratio of the variance of the respective composite annual signal and the variance of all EOF time series is calculated. These values are shown in Table 1. Twenty-five percent of the EOF1 time series is accounted for by the annual signal. The spectrum shows the annual peak as the only peak above the confidence limits. The frequency-spectrum diagram verifies the high level of variance associated with the annual cycle.

The second EOF time series and spectra are shown in Figure 10. The spectrum does not contain any peaks clearly outside the confidence limits. The frequency-spectrum diagram shows the greater part of the variance to be at a nearly semianual frequency. There is also an annual peak. The annual signal accounts for 10% of the variance.

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Fig. 6. Same as Figure 4 but for EOF3, corresponding to 8.9% of the variance of wind stress curl.

Fig. 7. Same as Figure 4 but for EOF4, corresponding to 6.0% of the variance of wind stress curl.
The third EOF time series and spectra are shown in Figure 11. This shows a large annual signal amounting to 24% of the variance. The spectrum contains two significant peaks above the confidence limits corresponding to the annual and semiannual frequencies. The frequency-spectrum diagram shows its largest peak of variance at the annual frequency and a smaller peak at semiannual frequency.

The fourth EOF time series and spectra are shown in Figure 12. The spectrum shows significant peaks at annual and semiannual frequency, with the annual accounting for more of the variance. The annual signal accounts for 15% of the series variance.

The EOF5 time series contains more noise than the previous time series. A spectral estimate with 20 degrees of freedom is used to resolve the variance into dominant frequencies. The fifth EOF time series and spectra are shown in Figure 13. The log-log spectrum shows a significant peak for a period of 1 year. Variance is mainly distributed between the annual frequency and a three cycles per year frequency. The annual part of the EOF5 time series accounts for only 2% of the series variance.

CONCLUSIONS

The EOF spatial patterns and time series are now examined for geophysical significance. This is done by comparison to features of seasonal circulation known to exist over the North Atlantic. A detailed synopsis of climate over the North Atlantic is available from Tucker and Barry [1984]. Elements to consider are the meridional variation of zonal winds with some annual variation of position, the subtropical high with annual oscillation of position and intensity (maximum in summer), the NE-SW orientation of land boundaries, the large SST gradient near the coast of North America producing a year-round region of cyclogenesis (maximum intensity in the winter), and the tropical region of near-constant winds with some semiannual variability. Although the curl of the wind stress parameters involves both a wind curl term and a gradient of wind magnitude term, emphasis is placed upon the vorticity term when making physical interpretations, i.e., cyclonic and anticyclonic motion.

The pattern of the first EOF and the strong annual signal of its associated time series implies that much of the variance over the North Atlantic is due to the annual oscillations of intensity of the subpolar low and the subtropical high. Kutzbach [1970], in his northern hemisphere study, also found these two areas of opposite anomaly in the North Atlantic. Figure 14 shows the annual signal of the first four EOF time series weighted by λi/λ1, where λi is the eigenvalue for the ith EOF. The zeroes of all series are in the temporal proximity of the minimum contrast between the above low and high. The typically negative values of the time series of EOF1 in the winter and the positive values in the summer in conjunction with the EOF1 spatial distribution adhere to the seasonal variation of the subpolar low. The EOF2 spatial distribution and time series imply an increase in anticyclonic motion in the summer in the mid-Atlantic and a decrease in anticyclonic motion in the winter. This corresponds to the greater intensity of the subtropical high in the summer. EOF1 and EOF2 distributions appear as meridional standing waves with wavelength slightly larger than the north-south extent of this study.

The third EOF spatial distribution has a zonal and meridional wavelength equal to basin size. EOF3 is dominated by the region of cyclogenesis in the northeast. The EOF3 annual average (Figure 14) is positive in the winter, corresponding to the greater cyclogenesis in the winter. EOF3 is the first EOF to show the effect of the NE-SW orientation of the land boundaries.

The EOF4 pattern can be interpreted as representing the variance due to blocking highs near Europe. The maximum occurrence of these highs is late spring and autumn, for which the time series agree, having negative values. This EOF may also represent a second geophysical phenomenon. Note that the EOF4 western region of positive curl extends

<table>
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into the mid-Atlantic. The EOF4 monthly annual average is positive in the winter (Figure 14), with a maximum in January. This coincides with the period of maximum extension of large SST gradient into the Atlantic, associated with the increased cyclonic activity.

EOF5 does not exhibit any obvious annual climatological features. Of interest is the proximity of the mid-Atlantic ridge to nodal lines and the diagonally opposed maxima and minima. This latter feature is seen also in a similar analysis of curl over the North Pacific [Rienecker and Ehret, 1988].
The zonal standing wavelength is approximately basin sized. The meridional wavelength is slightly larger.

Fifty-eight percent of the wind stress curl variance is contained in patterns clearly exhibiting basin-sized or greater standing wavelength.

It is seen that time scales associated with the significant EOFs are mostly annual and semiannual; little interannual variability was noted. Thompson et al. (1983) found similar results. The authors found that the anomalous component (or the nonseasonal component) of wind standard deviation was less than one quarter of the seasonal component 95% of the time. Although the seasonal dominance was noted, the above authors also found that their wind stress–induced meridional Sverdrup transport indicated interannual vari-

![Graphs of wind stress curl variance and spectra](image)

**Fig. 11.** Same as Figure 10 but for EOF3.

![Graphs of EOF4](image)

**Fig. 12.** Same as Figure 10 but for EOF4.
ability upon use of a low-pass filter. Although several authors [Busalacchi and O’Brien, 1981; Barnett, 1983; Servain and Legler, 1986] have established the interannual variability of the oceans in the lower latitudes, it will be difficult to realize this temporal scale in any mid-latitude study that includes the influence of the subpolar low.

Since the annual component of the EOFs is dominant, it is appropriate to compare with Barnier’s [1986] 1-year study. The three spatial EOF patterns presented by Barnier are similar to those presented here. The differences are due to the variations of wind in 1979 from the long-term mean and, most notably for EOF1, to the more northerly extent of Barnier’s region to include more of the very active winter storm region near Greenland.

Sorkina’s [1965] analysis divided the SLP over the North Atlantic into six typical patterns. The first four EOF spatial distributions in this study have a correspondent to the geostrophic vorticity fields implied by Sorkina’s six patterns.

It is suggested that the propagation features of North Atlantic wind stress curl be studied using Barnett’s [1983] complex EOF (CEOF) method, which provides both cospectrum and quadrature information, or the Graham et al. [1987] extended EOF (EEOF) procedure, providing anomaly evolution. A second suggestion is an EOF analysis of a data set combining COADS wind stress curl and SST. The EOF patterns of North Atlantic SST as calculated by Weare [1976], have points of similarity with those of wind stress curl.

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