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Kinematics and Correlation of the Surface Wind Field in the South Atlantic Bight

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Surface winds observed at Charleston, South Carolina, and at an offshore buoy located some 300 km to the east of Charleston are analyzed to determine operational transformations for estimating the offshore winds from the coastal winds. Both the statistics describing the wind field at each station along with those describing the correlation between stations are found to be seasonally modulated. Ensemble averaged (by season) transfer functions computed by using the first 3 years of available data are applied to a fourth independent data year for assessing their predictive utility. The transfer functions and predictability are both seasonally modulated and the transformation matrix is nondiagonal (each offshore wind velocity component depends upon both coastal components).

1. INTRODUCTION

Adequate representations of the wind field are essential inputs to wind-driven coastal circulation models. Coastal weather station data are abundant, while offshore data are sparse. Therefore, a general problem exists of extrapolating the coastal data seaward.

Over the past several years, the NOAA Data Buoy Office has maintained meteorological data buoys at several locations in the South Atlantic Bight (SAB). The purposes of this report are to describe the wind field variability at the Charleston, South Carolina, coastal station and an offshore Charleston buoy station, analyze the seasonal modulation of the wind field statistics at, and the correlation between, these locations, and to calculate a transfer function matrix capable of estimating the offshore station winds from the coastal winds.

We begin by reviewing literature on the synoptic meteorology of the SAB in section 2. Section 3 presents the data and points out certain discrepancies with section 2. The seasonal modulation of the wind field statistics at the Charleston, South Carolina, coastal station and at an offshore buoy station some 300 km east of Charleston, along with the coherence between these stations, are discussed in section 4. The data are broken into seasons based upon these analyses, and ensemble averaged (by season) transfer functions are calculated in section 5. These transfer functions are then applied to an independent data year in section 6 to assess their hindcast utility. Section 7 discusses and summarizes the results.

2. SAB SYNOPTIC METEOROLOGY

Several recent papers and technical reports including *Jacobsen* [1974], *Ruzecki* [1974], *Saunders* [1977], *Bernard and Bowley* [1979], *Pietrafesa and Weisberg* [1979], and *Weber and Blanton* [1980] provide overviews of the SAB meteorology. They offer descriptions of the seasonal variations in the surface wind field based upon monthly means and synoptic scale variability. Here we will attempt to summarize these descriptions and the systematics from which they derive.

Both the mean wind velocity vectors and their variances change seasonally. Winter and summer are generally seasons of

maximum and minimum in both means and variances, respectively, with fall and spring being seasons of transition. During winter the Icelandic low pressure system, which extends to South Carolina, together with a weaker high pressure system over the North American continent, results in mean northwesterly winds over the SAB. Fronts (cold, warm, and stationary) are present about one third of the time, and extratropical cyclone activity is at its maximum. Storms progress toward the east-northeast, and cyclogenesis occurs over the entire SAB with about six cyclones forming per month. The frequency of cyclogenesis decreases into spring, as does the extent of the cyclogenesis region which shifts northward. Storm tracks remain to the east-northeast with their centroids over the continent and frontal activity increases. As the Bermuda-Azores high intensifies and the Icelandic low and North American high diminish, the mean wind vectors rotate cyclonically becoming southwesterly during the summer. There are no regions of cyclogenesis south of Cape Hatteras from July through September, and, with exception of tropical cyclones that occasionally invade the SAB (a total of 40 occurrences over the 20 year period 1956-1976), August is a month of minimum winds. September and October are transition months. Mean winds turn northerly and intensify as high pressure cells penetrate southward from Canada, and fronts develop over the SAB due to the increasing temperature difference between the coastal and Gulf Stream waters. By December, winter conditions are reestablished.

The seasonal cycle in the mean surface wind field is closely associated with the migration of semi-permanent pressure cells, while the wind variance field also involves more regional air-sea and air-land temperature contrasts. The velocity vector mean and variance fields therefore modulate in phase since they are systematically related to the same seasonal insolation cycle. While the literature cited (most recently *Weber and Blanton* [1980]) often keys upon mean values, it should be recognized that the energy in the variance field generally exceeds that of the mean. Monthly means, though definable quantities, do not represent what an observer instantaneously sees nor what may drive a significant portion of the coastal ocean circulation. With the exception of Cape Hatteras where frequent frontal passages, maximum cyclogenesis, and immediate Gulf Stream proximity result in unique conditions, the bulk of the SAB exhibits a coherent variance field. Similar to the Middle Atlantic Bight findings of *Mooers et al.* [1976], *Pietrafesa and Weis-*

Fig. 1. Coastal and buoy station locations in the SAB.

berg [1979] showed that atmospheric pressure is highly correlated between adjacent SAB coastal station pairs and that the wind velocity components are only slightly less correlated. A degradation in alongshore velocity component coherence observed to be around 0.1 per 150 km demonstrates the large-scale nature of the variance field and the fact that winds recorded at any mid-SAB coastal station are representative of the winds at the other stations (excepting perhaps Cape Hatteras). Alike the energy level of the variance field, its coherence structure should also vary seasonally since, as Bernard and Bowley [1979] point out, the most persistent direction and regularity of extratropical cyclone movement through the SAB is in winter. Thus, wintertime coherence should be maximum while summertime coherence should be minimum because the field is most irregular then. Phase relations among stations should also

vary seasonally as the mean speed of movement decreases from a wintertime maximum of 15 m/s to a summertime minimum of about half that amount.

3. DATA

Wind velocity components from three coastal and four offshore buoy stations shown in Figure 1 were obtained from the National Climatic Center, Asheville, North Carolina. The data were edited for record gaps and vectorially averaged to a uniform sampling interval of three hours. Gaps smaller than 12 hours were filled by linear interpolation, while longer gaps were filled with zeros. The east and north velocity components, u and v , respectively, for the complete data set spanning Aug. 1, 1975 to Dec. 31, 1979, are displayed in Figure 2, after low pass filtering to remove the diurnal sea breeze and higher frequency

Fig. 2a. Low pass filtered ($\sigma = 8$ hr, Gaussian) north and east wind velocity components at the Charleston, S. C., coastal station and at the 41002 and 41004 buoy stations.

oscillations. Coastal data are available over a much longer time, but we are interested in the coastal to offshore coupling. The 41002 station provides the longest time series from the offshore group. Consequently, most of our analyses will be based upon the Charleston, South Carolina, coastal station (CHS) and the 41002 buoy station. Similar analyses were performed on the other station pairs, and these will be mentioned later.

Visual inspection of the time series shows that the wind field is coherent over the SAB with offshore magnitudes being larger than those at the coast (also noted for the Middle Atlantic Bight by *Moore et al.* [1976]). We have made no attempts at boundary layer scaling since one motivation for this study was to obtain an operational transformation from a coastal station

to an offshore buoy station. The buoy winds were measured at a height of 5 m from the sea surface, while the coastal station winds were measured at different levels. For example, the winds at CHS were observed at a height approximately 18 m above sea level (6 m above ground level). If anything, boundary layer scaling would be expected to increase the amplitude disparity between the coastal and the offshore measured winds.

Three characteristic time scales of variability can be delineated in the data. Figure 3 shows the u and v component kinetic energy density spectra at CHS, using approximately 3 years of three hourly sampled data (36,000 hr) beginning 0000 GMT on Aug. 1, 1975. Averaging was performed over a bandwidth of 9.17×10^{-4} cycles per hour for about 22 degrees of freedom. The associated 90% confidence interval for random errors is

Fig. 2b. Low pass filtered ($\sigma = 8$ hr, Gaussian) north and east wind velocity components at the Savannah, Ga., and Jacksonville, Fla., coastal stations and at the 41005 and 41003 buoy stations.

included in the figure (it is reduced at high frequency since the bandwidth was increased). Three regions of the spectrum are addressed: (1) a low frequency rise in energy toward a seasonal time scale, (2) a mid-range plateau defining synoptic time scales, and (3) a sharp peak at the diurnal sea breeze time scale. The relative energy levels of these three time scales (seasonal, synoptic, and sea breeze) averaged over 3 years of data are quantified by integrating the spectra and normalizing by total variance. The resulting kinetic energy distribution function for the horizontal wind velocity vector at CHS is shown in Figure 4. The

synoptic range appears to lie between time scales of 1.5–30 days centered upon 4–6 days. The 3-year averaged energy is partitioned among the seasonal, synoptic, and sea breeze bands in the respective amounts of 5, 58, and 5%. We emphasize that this is an average about which the variations are large.

4. SEASONAL MODULATION

The kinematics and correlation structure of the surface wind field vary seasonally. In this section we analyze the modulation

Fig. 3. North and east wind velocity component kinetic energy density spectra computed using 3 years of Charleston, S.C., coastal station data.

in (1) several kinematical descriptors, (2) the coherence between velocity components at CHS and 41002, and (3) the transfer functions between these two stations. The analyses are performed upon 60-day overlapping segments yielding monthly means as centered averages over two months.

4.1. Time Domain

Both the velocity component means and the variances undergo a fairly regular seasonal cycle at CHS and 41002 as shown in Figures 5 and 6. The mean winds at CHS generally lie in the eastward half plane with the exception of August, September, and October when a small westward component is evident. The period January–July shows a cyclonic rotation of the mean winds from southeastward to northward, while September through December shows a cyclonic rotation from southwestward to southeastward. Averaging over an entire year yields a northeasterly vector. These findings are consistent with the seasonal variation in the semi-permanent pressure cells. Very similar behavior occurs at 41002, with the amplitudes of the mean winds being roughly a factor of 2 larger than those at the coast. This is clearly shown in the vector presentation of Figure 7. A discrepancy exists between Figures 5, 6,

and 7 and the ships' log derived means of *Weber and Blanton* [1980]. With the exception of July, strong northward winds are not indicated in ships' log derived means. Since the CHS and 41002 means are northward over a major portion of the year, the validity of the means derived from ships' log data during months when the fields are weak and variable appear to be suspect.

The standard deviations are generally larger than the monthly means, and, since most of the variability occurs at synoptic scales, these deviations are fundamental inputs to the SAB circulation [e.g., *Pietrafesa and Janowitz*, 1979; *Janowitz and Pietrafesa*, 1980; *Klink et al.*, 1981]. Figure 8 shows the seasonal variation in wind velocity component variance (to which wind stress is roughly proportional) at CHS and 41002. The 41002 variances are strongly peaked in winter, while the CHS variances seem to be more uniform with season. During winter months, the offshore variances (and, consequently, the wind stress) may exceed those at the coast by a factor of 6. Offshore to coastal speed ratios vary from about 1.0 to 1.5 in summer to about 2.0 to 2.5 in winter. These findings suggest that modeling the coastal ocean, using coastal winds alone, would result in significant errors.

Fig. 4. Wind velocity vector kinetic energy distribution function computed using 3 years of Charleston, S.C., coastal station data.

4.2. Frequency Domain

Spectral analyses are presented owing to the nonuniform distribution of variance with frequency. The CHS and 41002 stations are first discussed individually, followed by a presentation of statistics quantifying their inter-relationship. Two-month overlapping segments with an averaging bandwidth of 0.0049 cycles per hour result in roughly 14 degrees of freedom for these calculations.

Anticlockwise and clockwise kinetic energy densities at CHS are plotted as functions of frequency and time in Figure 9. Contours are base 10 logarithms with the 2.00 contour highlighted to show the seasonal modulation. At synoptic scales, significantly more energy resides in the clockwise component and the clockwise energy varies seasonally (maximum from December to March to minimum from June to September), whereas the anticlockwise

Fig. 5. Monthly mean wind velocity components plus and minus one standard deviation at the Charleston, S.C., coastal station from September 1975 through December 1979. Positive $u(v)$ denotes wind blowing toward the east (north).

Fig. 6. Monthly mean wind velocity components plus and minus one standard deviation at the 41002 buoy coastal station from September 1975 through December 1979. Positive $u(v)$ denotes wind blowing toward the east (north).

energy does not. During the winter the wind velocity vector tends to be elliptically polarized in the anticyclonic sense, implying an offshore movement of either cyclonic or anticyclonic disturbances with centroids located to the north of Charleston. The lack of rotational preference during the summer suggests frontal perturbations about the stationary air flow induced by the Bermuda-Azores high. With one exception, these explanations are consistent with section 2. Storm tracks presented by *Bernard and Bowley* [1979] were shown to be centered over the coastal ocean passing south of Charleston in January and February. This would result in cyclonically rotating vectors as opposed to the strong anticyclonic behavior observed.

The diurnal sea breeze energy peak coincides in time with the minimum in synoptic scale energy. This is why the total variance at CHS appears not to be seasonally modulated (Figure 8) when in fact the independent processes comprising the total variance are. The equality between clockwise and anticlockwise energy at the diurnal time scale shows that the sea breeze is rectilinear. Between the synoptic and sea breeze time scales as well as at time scales shorter than diurnal the spectra are much less energetic.

Four statistics further describing the kinematics of the CHS wind velocity fluctuations are given in Figure 10. Minimum and maximum coherencies [*Fofonoff*, 1969] are those between horizontal velocity components measured relative to the prin-

Fig. 7. Monthly mean wind velocity vectors at both the Charleston, S.C., coastal station and the 41002 buoy station.

principal axes of variance and relative to axes rotated 45° to them, respectively. Simultaneously high maximum and minimum coherencies signify coherent (statistically steady) elliptical oscillations, high maximum and low minimum coherencies signify coherent rectilinear oscillations, and equally low maximum and minimum coherencies signify incoherent motions. Coherencies that fail the null hypothesis at the 90% significance level are indicated by stippling. At synoptic frequencies we observe seasonally modulated motions that are coherent and elliptical during winter (especially in the 2–4 day range) while generally being incoherent during summer. At the diurnal time scale, we observe coherent rectilinear motions during spring and summer and incoherent motions during the remainder of the year. Be-

tween the synoptic and the diurnal time scales and at time scales shorter than diurnal, the wind velocity fluctuations are clearly incoherent throughout the year. The orientation of the principal axis of variance [e.g., *Mooers, 1973*] is contoured in tenths of π radians measured anticlockwise from east. Coarsely stippled regions between 0.2π and 0.4π radians correspond to alongshore orientations and finely stippled regions between 0.6π and 0.8π radians correspond to onshore-offshore orientations. Thus the synoptic scale variability aligns alongshore while the diurnal sea breeze aligns onshore-offshore. Stippled areas in the semi-minor to semi-major axis ratio (contours < -0.2) correspond to clockwise polarized elliptical motions. All other areas correspond to rectilinear motions. The sea breeze is

Fig. 8. Wind velocity component variances as a function of time at both the Charleston, S.C., coastal station and the 41002 buoy station.

Fig. 9. Anticlockwise (G_{++}) and clockwise (G_{--}) kinetic energy density spectra as functions of frequency and time for the Charleston, S.C., coastal station wind velocity vector. Contours are base 10 logarithms with 2.0 highlighted to show the seasonal modulation.

rectilinear, while the synoptic scale variability varies from rectilinear during summer to elliptical and clockwise during winter.

Similar analyses were performed for the 41002 buoy station. The synoptic scale goes through a distinct seasonal cycle like at CHS with significantly larger energy in winter months than in summer months, while unlike CHS, the 41002 buoy winds do not exhibit a significant diurnal peak. Maximum and minimum coherencies at 41002 show that coherent elliptical motions are generally the rule during winter, while incoherent motions characterize the summer. Wind velocity fluctuations are generally more coherent with coherence extending over a larger portion of the frequency domain at 41002 than at CHS. This more orderly nature of the wind field at sea probably results from the absence of coastal boundary layer complications. The principal axis of variance orientation at 41002 differs from that

at CHS. While being alongshore in summer the synoptic scale variability aligns onshore-offshore in winter. Since both latent and sensible heat flux from the ocean to the atmosphere is at a maximum over the Gulf Stream during winter, synoptic scale disturbances are modified as they propagate offshore.

The seasonal variations in the wind field over the SAB may now be summarized. Along with the slowly varying monthly mean winds (the seasonal cycle), two portions of the spectrum undergo significant seasonal modulation: (1) synoptic systems with time scales of 1.5–30 days and (2) the diurnal sea breeze. The kinetic energy of the synoptic scale at CHS and 41002 (and over the entire SAB) is maximum in winter and minimum in summer. At CHS, the kinetic energy density of the sea breeze may be as large as that of the synoptic scale; however, the seasonal modulation of these two processes is approximately π

Fig. 10. Maximum and minimum coherencies squared, ellipse orientation, and semi-minor to semi-major axes ratio as functions of frequency and time for the Charleston, S.C., coastal station wind velocity vector. Stippled regions on coherence are those which fail the null hypothesis at the 90% level; stippled axis ratio denotes elliptical clockwise polarization; lightly stippled orientation denotes alongshore alignment; and darkly stippled orientation denotes onshore-offshore alignment.

Fig. 11. Multiple squared coherence as a function of frequency and time between the east (u) and north (v) wind velocity components at the 41002 buoy station and the wind velocity vector at the Charleston, S.C., coastal station. All stippled regions fail the null hypothesis at the 90% level. Darkest stippling indicates the highest coherence.

radians out of phase. Consequently, the total variance at CHS appears to be seasonally uniform when in fact significant modulation exists. The sea breeze at CHS is rectilinear and oriented onshore-offshore. The synoptic systems at CHS are generally oriented alongshore being rectilinear in summer and elliptical with clockwise polarization during the rest of the year. At 41002, the synoptic systems are elliptical and clockwise polarized over most of the year with principal axis of variance orientation changing from alongshore during summer to onshore-offshore during winter. Coherence at both stations is higher in winter than in summer.

4.3. Correlation Between CHS and 41002

The coherence between, and the relative magnitudes of, the velocity components at CHS and 41002 are also seasonally

modulated. Figure 11 shows the multiple squared coherencies [e.g., *Groves and Hannan, 1968; Bendat and Piersol, 1971*] between both the u and the v components at CHS as inputs and each of the u and the v components at 41002 as outputs. Stippled regions fail the null hypothesis at the 90% significance level. Finer stippling further highlights the most coherent regions. Only over the synoptic range does the multiple coherence generally exceed the significance level. During winter, some 80% of either u or v at 41002 may be accounted for by the sum of linear operations upon both u and v at CHS. The multiple coherencies diminish during summer, especially for the v component.

The linear mean square estimation procedure associated with the multiple coherencies involves a 2×2 complex transfer function matrix. Although not shown, these were also season-

ally modulated. The u component at 41002 was primarily associated with the u component at CHS with maximum amplitude ratio in winter. The v component at 41002 was associated with both the u and the v components at CHS, but the seasonal modulation was more complicated. The principal contributor to v at 41002 during fall and early winter was u at CHS, while roles reversed during late winter to spring wherein v at CHS became the principal contributor. Thus, a distinct seasonal modulation exists in the predictability of offshore winds from coastal winds, the transfer functions used in the prediction are themselves seasonally modulated, and the transformation matrix from the coastal wind vector to the offshore wind vector is non-diagonal (i.e., each offshore wind component depends upon both coastal wind components).

5. SEASONALLY AVERAGED TRANSFER FUNCTIONS

Linear mean square estimation is employed to predict the 41002 wind velocity vector from the CHS wind velocity vector. Let the northward wind velocity component at the buoy, v_B , be a linear combination of the northward and eastward wind velocity components at the coast, v_C and u_C , plus a random error ε_{v_B} and similarly for the eastward wind velocity component, u_B , i.e.,

$$v_B = \int_{-\infty}^{\infty} h_{v_C v_B}(\tau) v_C(t - \tau) d\tau + \int_{-\infty}^{\infty} h_{u_C v_B}(\tau) u_C(t - \tau) d\tau + \varepsilon_{v_B} \quad (1)$$

and

$$u_B = \int_{-\infty}^{\infty} h_{v_C u_B}(\tau) v_C(t - \tau) d\tau + \int_{-\infty}^{\infty} h_{u_C u_B}(\tau) u_C(t - \tau) d\tau + \varepsilon_{u_B} \quad (2)$$

The weighting functions h are solved for by minimizing the mean square errors

$$\varepsilon_{u_B}^2 = \overline{(u_B - \hat{u}_B)^2}$$

$$\varepsilon_{v_B}^2 = \overline{(v_B - \hat{v}_B)^2}$$

where the carot denotes the estimate and the overbar denotes the time average. This procedure leads to an orthogonality principle [e.g., Papoulis, 1965] which states that the minimum error is that portion of the observed buoy wind component which is orthogonal to the observed coastal wind components. Thus, only the coherent portion of the spectrum as measured by the multiple coherence squared can be estimated. The computations are most easily performed in the frequency domain upon taking Fourier transforms resulting in a set of complex valued transfer functions that are the Fourier transforms of the weighting functions. These are

$$H_{v_C v_B} = \frac{S_{v_C v_B} S_{u_C u_C} - S_{v_C u_C} S_{u_C v_B}}{A} \quad (3a)$$

$$H_{u_C v_B} = \frac{S_{u_C v_B} S_{v_C v_C} - S_{u_C v_C} S_{v_C v_B}}{A} \quad (3b)$$

$$H_{v_C u_B} = \frac{S_{v_C u_B} S_{u_C u_C} - S_{v_C u_C} S_{u_C u_B}}{A} \quad (3c)$$

$$H_{u_C u_B} = \frac{S_{u_C u_B} S_{v_C v_C} - S_{u_C v_C} S_{v_C u_B}}{A} \quad (3d)$$

where

$$A = S_{v_C v_C} S_{u_C u_C} - |S_{v_C u_C}|^2$$

and the S are cross spectra. Confidence intervals for random errors on transfer function amplitude and phase may be calculated as described in Bendat and Piersol [1972].

The estimations follow from two operations. The first is a complex multiplication and addition in the frequency domain between the transfer functions and the Fourier transforms of the input time series (V_C, U_C) to obtain the Fourier transforms of the estimated time series (V_B, U_B):

$$V_B = H_{v_C v_B} V_C + H_{u_C v_B} U_C \quad (4a)$$

and

$$U_B = H_{v_C u_B} V_C + H_{u_C u_B} U_C \quad (4b)$$

The second step is to take the inverse Fourier transforms of V_B and U_B to obtain the estimated time series v_B and u_B .

In accordance with the seasonal modulation of both the multiple coherence and the transfer functions, it was decided to break the data up into seasons and to ensemble average by season. The seasons chosen are (1) winter, January, February, March (JFM); (2) spring, April, May, June (AMJ); (3) summer, July, August, September (JAS); (4) and fall, October, November, December (OND). Cross spectra were computed for each available seasonal grouping. These cross spectra were then ensemble averaged by season over the years 1975–1978 and frequency averaged over an appropriate bandwidth to produce averaged cross spectra for the transfer function computations. The year 1979 was excluded from the averaging in order to have an independent year for checking the predictive utility of the transfer functions. Owing to the various data gaps, the number of years available for ensemble averaging varied between two and three. The fall, winter, spring and summer season averages included, respectively, 1975–1977 (3 years), 1976 and 1978 (2 years), 1976–1978 (2 2/3 years), and 1976 and 1977 (2 years).

Multiple squared coherencies for each ensemble averaged season are shown in Figure 12 for the v and u components at 41002 relative to the velocity vector at CHS. Frequency averaging was performed over a bandwidth of 0.0059 cycles per hour giving a nominal 25 degrees of freedom for each individual season. Ensemble averaging over 2–3 years then resulted in 51–78 degrees of freedom. The fall and winter are the most coherent seasons. The spring season shows coherence at time scales longer than 2–3 days. In contrast to fall, winter, and spring, the summer season v component is incoherent while the summer season u component is coherent at time scales longer than 3 days. Where coherent, some 75% of the 41002 variance appears to be accountable in terms of the CHS winds.

Transfer functions for the winter (solid lines) and summer (dashed lines) seasons are shown in Figure 13. Subscripts on each of the four transfer functions denote the input and output variables. For example, $H_{u_C v_B}$ multiplies the Fourier transform of u at the coast (u_C) in order to estimate its contribution to the Fourier transform of u at the buoy (u_B). Similarly $H_{v_C u_B}$ provides the contribution to the Fourier transform of u_B from v_C . Upon addition and inverse transformation, one then obtains the estimated u_B time series for comparison with the observed u_B time series. The bars on the transfer function amplitudes and phases are the 90% confidence intervals for random errors. These intervals vary across the spectrum depending upon the multiple coherence and the coherence between u_C and v_C . The confidence

Fig. 12. Multiple squared coherence by season between north and east velocity components at the 41002 buoy station and the velocity vector at the Charleston, S.C., coastal station. Averaging was performed over the indicated bandwidth, and dashed lines represent the 90% significance level for the null hypothesis.

intervals given at a 4-day time scale are representative for the synoptic scale.

During winter, u_c and v_c contribute to their buoy counterparts by factors of roughly 2.0 and 1.5, respectively. Positive phases in this convention means that the buoy winds lag the coastal winds, i.e., the atmospheric disturbances progress offshore. We also observe that v_c contributes negligibly to u_b while the u_c contribution to v_b is nearly equal to that of v_c . The negative phases for $H_{v_c u_b}$ and $H_{u_c v_b}$ do not imply onshore propagation. They merely reflect the near quadrature relation between the u and v components and the clockwise polarization of these motions; the sense of propagation is still offshore and the phase lag of the buoy winds from the coastal winds over the

synoptic scale is less than a half day. Both the offshore progression and the speed are consistent with the historical storm tracks. What remains inconsistent, however, is the sense of polarization, which, as stated earlier, would place the storm track center to the north of Charleston, South Carolina, in winter.

During summer, we observe a reduction in amplitude along with statistically indistinguishable phases in all but $H_{u_c u_b}$. This behavior parallels the multiple coherence which, during the summer, is significant for u_b but not for v_b .

Similar calculations were made by using the three additional coastal and offshore buoy station pairs shown in Figures 1 and 2. The transfer function results given in Weisberg and Pietrafesa

Fig. 13. Transfer function amplitudes and phases between the Charleston, S.C., coastal station and the 41002 buoy station during winter (solid line) and summer (dashed line).

[1982] did not differ significantly from those presented here for the CHS and 41002 pair. The 41004, 41005, and 41003 buoys, though much closer to the coast than 41002, are still offshore of the coastal boundary layer. Consequently, the wind variability was very nearly the same among these stations. The limited record lengths for the additional buoy stations rendered their coherencies and transfer functions statistically indistinguishable from those presented for 41002.

6. RESULTS AND DISCUSSION OF ERRORS

The results from operating upon the independent 1979 data set with the transfer functions calculated in section 5 are shown in Figures 14 and 15 for the spring and fall seasons, respectively. Each figure gives three time series for the u (upper) and v (lower) components: (1) the observed component at CHS, (2) the observed component at 41002, and (3) the predicted component at 41002, using the appropriate ensemble and frequency

averaged seasonal sets of transfer functions. Owing to the 10% cosine taper applied to the data before Fourier transformation, the first few and the last few days of the predicted time series taper out to zero. Apart from this analysis artifact, the predicted time series generally agree very well with the observed 41002 buoy time series. Improvements in using these hindcast winds rather than the original coastal winds in specifying the 41002 buoy winds are threefold. First, the amplitudes are much more realistic; second, the phases generally coincide much better; and finally, the incoherent high frequency noise (diurnal sea breeze and other nonsynoptic scale fluctuations) is filtered out.

As anticipated from the seasonal modulation analyses, the winter and summer results (not shown) are, respectively, slightly better and significantly worse than the transition seasons shown. Fortunately, it is when the atmospheric perturbations are the most severe that one needs the most accurate predictions and this is indeed the case here.

Fig. 14. Observed wind velocity components at the Charleston, S.C., coastal and 41002 buoy stations and the predicted velocity components at the 41002 buoy station during the spring 1979 season.

Random errors associated with the predictions (or hindcasts) arise in two ways. The first comes from the multiple coherence determination that calculates the portion of variance accounted for by linear operations to within a certain error bound. For example, Figure 12 shows that the multiple coherence squared between the 41002 v component and the CHS wind vector at a 4 day time scale is estimated to be 0.7 in the fall season with a 95% confidence interval between 0.79 and 0.56. We would, therefore, expect to account for this range of variance in future hindcasts. The second source of random error comes from the transfer functions used to calculate the coherent portion. The transfer functions in the present example have random errors of

plus or minus some 10–20%. These two sources of random errors are implied but not incurred when applying transfer functions to the same data set from which they are calculated. For example, if we applied the ensemble averaged transfer functions for OND to the years 1975–1978, we would indeed account for about 70% of the variance over the synoptic range. In applying these transfer functions to the 1979 data, however, we would expect to either overestimate or underestimate the observed time series to within the multiplicity of the individual random errors in multiple coherencies and transfer functions.

As quantitative examples of the errors involved, we have computed the coherencies squared, transfer function ampli-

Fig. 15. Observed wind velocity components at the Charleston, S.C., coastal and 41002 buoy stations and the predicted velocity components at the 41002 buoy station during the fall 1979 season.

tudes, and phases between the estimated and observed wind velocity components at 41002 over the independent 1979 seasons. The results are shown in Figure 16 for each of the four seasons. Ideally, the coherence and transfer function amplitude would be unity and the phase would be zero. During the fall season, the time series are significantly coherent for time scales longer than 1.5 days; the phases are very nearly zero; and the predicted series are underestimated by as much as 30–40% in amplitude with somewhat better results for u than for v . During the winter season, the time series are most coherent at time scales longer than 2 days, the phases are very nearly zero, and

the amplitudes are either underestimated or overestimated by as much as 30%. Again, u is somewhat better predicted than v . Similar results were obtained during the spring season with amplitudes much more closely matched particularly in the u component. As anticipated, the summer season results for v are the poorest. The u component on the other hand is predicted fairly well. Even though these errors are substantial, the hind-cast time series are still much better than direct application of coastal winds, which seem to underestimate amplitude by 100% or more.

Two points should be emphasized. First, the estimation pro-

Fig. 16. Coherence squared, transfer function amplitude, and phase by season between the predicted and observed wind velocity components at the 41002 buoy station. Averaging was performed over the indicated bandwidth, and the dashed line represents the 90% significance level for the null hypothesis.

cedure followed is optimal in that it minimizes mean squared error. Second, an assessment of the random error only follows when operating upon an independent data set. Random errors do not appear in the data set from which the estimating functions (transfer functions or other weighting functions) are calculated. They are only implied. Additional weighting functions contribute additional random error so it is desirable to minimize the number of input variables. Since CHS winds are coherent with the adjacent SAB coastal station winds, we used it alone for input.

7. SUMMARY AND CONCLUSIONS

The surface wind field over the South Atlantic Bight (SAB) varies on seasonal, synoptic, and diurnal time scales with seasonal and synoptic fluctuations being coherent over the entire region while the sea breeze induced diurnal oscillations are

coherent only over the coastal area. Wind velocity data from three coastal and four offshore buoy stations were analyzed. The Charleston, South Carolina (CHS) station was found to be representative of the coastal stations and the furthest offshore buoy station, 41002, located some 300 km east of Charleston, provided the only long offshore record. These two stations, CHS and 41002, were analyzed in detail to study the kinematics of the wind field variability at both locations, the correlation between locations, and to compute operational transformations for estimating the offshore winds from the coastal winds.

Both the synoptic and the sea breeze oscillations were found to be seasonally modulated. Synoptic scale variability is largest in winter and smallest in summer while the diurnal sea breeze peaks in spring and early summer. The principal axis of variance for the synoptic scale at CHS is oriented alongshore. Fluctuations tend to be rectilinear during the summer and

elliptical with clockwise polarization during the rest of the year. The synoptic scale fluctuations at 41002 are elliptical with clockwise polarization throughout the year, but, unlike CHS, the 41002 synoptic scale principal axis rotates from alongshore in summer to onshore-offshore in winter.

The coherence between stations was also found to be seasonally modulated, with winter time synoptic scale fluctuations being coherent over the entire SAB, while only marginal coherence occurs in the summer. A distinct seasonality therefore exists in both the ability to predict offshore winds from coastal station data and in the matrix of linear operators used for that prediction. Since the structures of the synoptic disturbances change as they progress offshore, the matrix of linear operators is nondiagonal, i.e., each offshore wind velocity component depends upon the vector wind at the coast and not just a single component of that vector.

The data set was broken into four seasons, each 3 months in duration: January, February, March (winter); April, May, June (spring); July, August, September (summer); and October, November, December (fall). Frequency and ensemble averaged (over 2–3 years) transfer functions were computed, using the principle of linear mean square estimation. These transfer functions were then applied to an independent data year (1979) by season to test their ability in estimating the offshore buoy observed winds from the coastal observations. Improvements over the direct application of coastal wind alone for offshore wind specification were obvious. The problem of having a point specific wind as opposed to a wind field still remains. Owing to the high spatial coherence, Weisberg and Pietrafesa [1982] remedied this problem in one way by fitting surfaces to the observed coastal and offshore station grid and P. Hamilton (unpublished manuscript, 1982) has computed empirical orthogonal functions for these stations. However, all of the offshore buoy locations were seaward of the coastal boundary layer so neither technique adequately describes the marked amplitude transition from the coastal stations to the buoys. A field experiment to define the coastal to offshore surface wind boundary layer would be an important further step in understanding the atmospheric forcing functions for the coastal ocean circulation.

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