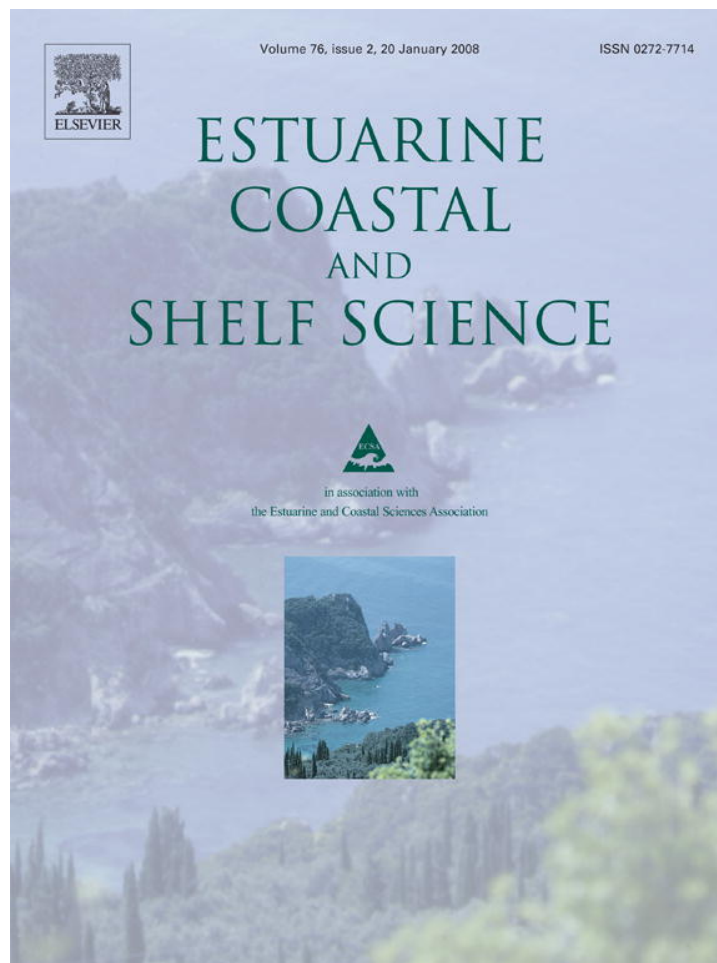


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## Water level variations in the Neuse and Pamlico Estuaries, North Carolina due to local and remote forcing

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### Abstract

Water level time series records from the Neuse and Pamlico River Estuaries were statistically compared to local and distant wind field data, water level records within the Pamlico Sound and also coastal ocean sites to determine the relative contribution of each time series to water levels in the Neuse and Pamlico Estuaries. The objectives of this study were to examine these time series data using various statistical methods (i.e. autoregressive, empirical orthogonal function analysis (EOF), exploratory data analysis (EDA)) to determine short- and long-time-scale variability, and to develop predictive statistical models that can be used to estimate past water level fluctuations in both the Neuse Estuary (NE) and Pamlico Estuary (PE). Short- and long-time-scale similarities were observed in all time series of estuarine, Pamlico Sound and subtidal coastal ocean water level and wind component data, due to events (nor'easters, fronts and tropical systems) and seasonality. Empirical orthogonal function analyses revealed a strong coastal ocean and wind field contribution to water level in the NE and PE. Approximately 95% of the variation was captured in the first two EOF components for water level data from the NE, sound and coastal ocean, and 70% for the PE, sound and coastal ocean. Spectral density plots revealed strong diurnal signals in both wind and water level data, and a strong cross correlation and coherency between the NE water level and the North/South wind component. There was good agreement between data and predictions using autoregressive statistical models for the NE ( $R^2 = 0.92$ ) and PE ( $R^2 = 0.76$ ). These methods also revealed significant autoregressive lags for the NE (days 1 and 3) and for the PE (days 1, 2 and 3). Significant departures from predictions are attributed to local meteorological and hydrological events. The autoregressive techniques showed significant predictive improvement over ordinary least squares methods. The results are considered within the context of providing long time-scale hindcast data for the two estuaries, and the importance of these data for multidisciplinary researchers and managers.

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**Keywords:** water surface elevation; lagoonal estuary; autoregressive; empirical orthogonal function; Neuse Estuary; Pamlico Estuary; Pamlico Sound; North Carolina

### 1. Introduction

Subtidal water level variability in estuaries on time scales longer than a day is induced by winds through a combination of remote winds on the continental shelf adjacent to the estuary, and local effects by winds aligned with the estuary leading

to rapid changes in water level (Weisberg and Sturges, 1976; Marmorino, 1982; Geyer, 1997; Valle-Levinson et al., 2001, 2002; Wong, 2002; Wong and Valle-Levinson, 2002). A recent study of hydrometeorological controls on the Bush River, an upper Chesapeake Bay tributary, revealed a strong coupling of wind and water levels (Pasternack and Hinnov, 2003), and documented higher subtidal water level variations during a La Niña period. Other research has implicated long time-scale climatological forcing in direct effects on estuarine flooding regimes that affect inshore shrimp harvests in coastal

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Louisiana. This non-linear relationship between water level and shrimp catch often corresponds to El Niño Southern Oscillations and La Niña events (Childers et al., 1990).

Wind-driven changes in water level can also be important factors in the wetting and drying of the shallow areas of coastal water bodies (Ji et al., 2001). Studies addressing sea level variations in the San Francisco Bay (Walters, 1982; Walters and Gartner, 1985; Wang et al., 1997) confirmed the importance of the wind field to sea level within the Bay. For example, it was shown that sea-level elevations and slopes respond to the along-shore wind during most of the year, and to cross-shore wind during transition periods in spring and autumn (Wang et al., 1997). Wind-forced sea level variability was also documented along the West Florida Shelf where dominant signals in sea level, alongshore wind stress and atmospheric pressure were coherent and consistent with the movement of cold fronts (Marmorino, 1982). Tropical systems such as tropical storms and hurricanes can provide intense short time-scale wind forcing to coastal regions resulting in increased coastal sea level (Valle-Levinson et al., 2002; Boon, 2004; Peng et al., 2004) and rapid salinity changes and nutrient pulsing into estuaries (Van Dolah and Anderson, 1991; Burkholder et al., 2004).

The watershed of the Pamlico Sound (PS) and two major tributaries, the Neuse and Pamlico River Estuaries (NE and PE, respectively) have undergone rapid agricultural and urban development in the past decade (Burkholder et al., 2006). Bottom-water hypoxia/anoxia (Reynolds-Fleming et al., 2004), noxious and toxic algal blooms and major fish kills (Burkholder et al., 1999; Springer et al., 2005) have occurred frequently, and nitrogen loading and ammonia concentrations have significantly increased in the Neuse Estuary (Burkholder et al., 2006). Seasonal and event driven changes in water level are an important influence on nutrient loading and ecosystem response, due to changes in the residence time and flushing rates associated with these events (Dyer and Taylor, 1973; Brooks et al., 1999; Rasmussen and Josefson, 2002; Ensign et al., 2004). The coastal ocean including bays, sounds and estuaries (Chesapeake Bay, NC Sounds, Texas Estuaries, Florida Bay, etc.) are being impacted by anthropogenic activities directly due to pollutant inputs, and possibly indirectly due to high climatic variability resulting in increased/decreased precipitation related to global warming and associated phenomena such as sea level rise and variability in water level.

These climatic changes affect the long-term health of tidal marshes, and influence overall system responses to increasing and, in some cases, decreasing sea level (Stumpf and Haines, 1998). Monitoring efforts toward predicting system responses to changing water level are of value in discerning difference between normal variability and variability associated with anthropogenic impacts. For example, over the past century human modification of environmental systems has accelerated tidal salt marsh deterioration and shoreline retreat in coastal regions worldwide, leading to the loss of more than 50% of the original salt marsh habitats (Kennish, 2001). The upper reaches of estuaries are significantly affected by changes in water level from winds and sea level fluctuations (Stumpf and Haines,

1998; Ji et al., 2001; Wong, 2002; Pasternack and Hinnov, 2003; Rogers et al., 2006). Accurate assessment of seasonal water level trends and variability are needed for both management and research concerns. It is paramount to monitor and study these coastal areas in a context that addresses both large-scale (regional) and small-scale (local) processes that impact the physical-chemical environment and associated biological activity.

The objectives of this study were to examine long time series wind and water level data from various sources using several statistical approaches (i.e. classical, empirical orthogonal function analysis, exploratory data analysis) to determine the relative contribution of major forcing factors and the short and long time scale variability, and to develop predictive statistical models that can be used to hindcast past water level fluctuations in both the NE and PE. Statistical methods and models can provide both insight and predictive capability to subtidal water level behavior (Bosley and Hess, 2001; Cox et al., 2002). We were motivated by these past research efforts to explore the use of statistical methods to develop predictive water level models for the NE and PE. We examined estuarine water level data sets for patterns similar to water level data from varied coastal stations. It is expected that the hindcast model will be of value in examining historical problems in water quality and biological phenomena (Burkholder et al., 2006), and in the parameterization of hydrodynamic and water quality models for the system (Wool et al., 2003; Peng et al., 2004).

## 2. Study area

The Pamlico Sound is a bar built estuary (Pritchard, 1952; Dyer, 2000). This type of estuary is characterized by shallow depth and reduced tidal action, especially in the upper reaches of sub-estuaries, in this study, the NE and PE. Wind is usually the most significant mixing factor. These systems have high sedimentation rates, which means that wind events and total water column depth are important considerations in sediment transport and nutrient pulsing (Giffin and Corbett, 2003). PS and its tributaries, the NE and PE, are geographically confined by the Outer Banks, through which only a few narrow inlets (i.e. Ocracoke, Hatteras and Oregon Inlets) allow water exchange with the Atlantic Ocean. Its waters are shallow (generally 2–3 m in depth; mean depth 4 m), wind-mixed with little tidal effect (Luettich et al., 2002; Reed et al., 2004), and poorly flushed, with a relatively long residence time in major tributaries (mean over an annual cycle, 50–100 days, Steel, 1991).

An approximately 3-year dataset of hourly wind and water level time series data was acquired in the NE along with water level records from coastal stations and a Pamlico Sound station for the same time period. Hourly winds at local and distant sites, and two hourly time series records of water surface elevation within the Albemarle-Pamlico Sound and outside of the estuary at a coastal station, were examined with these methods to determine the relative contribution of each time series to the NE and PE signal (Fig. 1). The mean

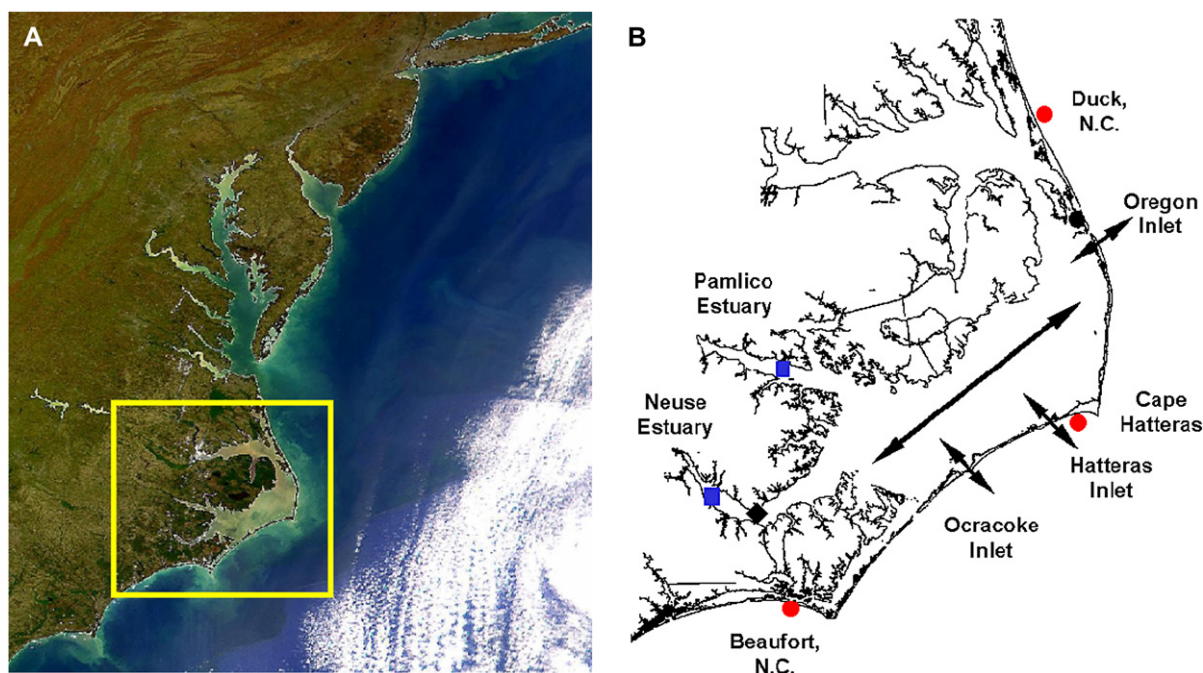


Fig. 1. Study area. (A) Satellite photo of the Albemarle-Pamlico Sound in relation to the east coast of the United States, including the Chesapeake Bay to the north. Study area is enclosed in yellow box. (B) Map of study illustrating the position of the major inlets (Ocracoke, Hatteras, Oregon), coastal sites (red circles), Oregon Inlet Marina (black circle), estuarine water level sites in the Neuse and Pamlico estuaries (blue squares). Wind data was acquired from Cape Hatteras fishing pier (red circle) and NCSU-CAAE site in the Neuse mesohaline estuary (black diamond). Predominant axis of the Pamlico Sound is indicated by the black arrow at approximately  $40^\circ$ .

coastal tidal range recorded at two NOAA/NOS water level stations near the proposed study area is 0.911 m at Hatteras, N.C., located near Ocracoke Inlet, and 0.981 m at Duck, N.C., located near Oregon and Hatteras Inlets. These three inlets are the main channels of Albemarle/Pamlico Sound and coastal ocean communication. However, the astronomical tide is effectively attenuated by the shallow nature of the Albemarle/Pamlico system and especially in the NE (Luettich et al., 2002). This feature is illustrated by the mean tidal range at a site inside the sound near Oregon Inlet ( $\sim 0.271$  m). The lack of a strong tide in the PS system and tributaries means that periodicity in water level rise and fall is not easily predicted due to the chaotic nature of the short-term wind field, which is a prime factor in the study of biological variability in these environments.

### 3. Methods

#### 3.1. Data sources

Hourly wind and water level time series data for the NE were acquired by the NCSU Center for Applied Aquatic Ecology (CAAE) Neuse River Estuary Monitoring and Research Program (NEMReP) at sites in the NE for approximately 3 years (Fig. 1). A vented Global Water Level sensor (WL400) was used to record hourly water levels, and a Met-One wind speed and direction sensor (034B) was used to record hourly wind speed and direction at a height of approximately 5 m. All data were logged to a Campbell Scientific

CR10X datalogger and recovered via remote communication. Hourly water level data for the PE was provided by the U.S. Geological Survey (USGS) for station number 0208455155 located on channel marker Light 3. These data were recorded using a Hydrolab Datasonde 4a (Hach-Hydrolab, Loveland, CO). Hourly water level data for the PS station at Oregon Inlet and coastal Atlantic Ocean sites were obtained from the National Oceanic and Atmospheric Administration – National Ocean Service (NOAA – NOS), for the same time period, along with hourly wind data from Cape Hatteras, NC. Input data sets for the study (Table 1) also included the North/South and East/West components of the NE and Cape Hatteras wind fields. These data were rotated  $40^\circ$  to the east to align the North/South (V) wind component with the long axis of PS and to align the East/West (U) wind component perpendicular to the long axis. The magnitude of wind field rotation was determined by several iterations using a cross correlation procedure (Interactive Data Language, [IDL], *c\_correlate*) to determine the most significant correlation between the NE water level record and the rotated wind field. It was determined that rotating the wind field  $40^\circ$  to the east gave maximum correlation with water level change. Other input data sets consisted of water level series from Oregon Inlet Marina (NOS 8652587), Cape Hatteras Fishing Pier (NOS 8656483), Duck (NOS 8651370) and Beaufort (NOS 8656483). Datum for all NOAA-NOS sites was mean-lower-low-water (mllw). Datum for the NE and PE sites were local relative position and were not benchmarked to any datum. The impact of freshwater input on water level variability was not addressed in this study.

Table 1  
Data sets used in exploratory data analysis, empirical orthogonal function analysis and autoregressive modeling with the assumed water level physical response inherent in the data

Data set	Physical response of water level described
Neuse and Pamlico Estuary Water Level	Local water level response due to short and long term wind effects and long term contributions from Albemarle-Pamlico Sound and coastal Atlantic Ocean. These are the two response variable data sets for autoregressive modeling.
Neuse Estuary Wind Field	East/West (U) and North/South (V) wind components from the Neuse Estuary site, which in theory contribute to short term local water level changes. Rotated 40° to the east to align with the long axis of the Pamlico Sound.
Cape Hatteras Wind Field	East/West (U) and North/South (V) wind components from a coastal ocean site, which in theory contributes to both short term and long term water level changes. Rotated 40° to the east to align with the long axis of the Pamlico Sound.
Oregon Inlet Water Level	Contribution to the long time scale water level fluctuations in the Neuse and Pamlico estuaries due to Albemarle-Pamlico Sound processes.
Cape Hatteras Water Level	Short and long time scale subtidal water level fluctuations due to coastal ocean response.
Residuals from Oregon Inlet water level predictive fit using Cape Hatteras as input data	Captures the difference between Pamlico Sound water level and coastal Atlantic ocean water level due to geographical isolation (Oregon Inlet) and coastal ocean processes. Captures differences due to lags related to coastal ocean communication with the sound through the inlets.

All data was quality controlled and interpolated over missing values to give hourly readings. Missing data from the NE site were replaced by a procedure that involved comparisons with nearby water level records (>3 observations) or by interpolation ( $\leq 3$  observations). Hourly data missing from the PE site were replaced using the SAS PROC EXPAND procedure that replaces data using a cubic spline fit method. The subtidal water level records were recovered from Oregon Inlet, Cape Hatteras, Duck, and Beaufort data using a 40-h low pass filter (MATLAB 5.0, MathWorks, Natick, MA) to remove the presence of a diurnal tide.

### 3.2. Exploratory data and empirical orthogonal function analyses

We employed methods similar to those used in the examination of low frequency variations in sea level in San Francisco Bay (Walters, 1982) and in statistical hindcasts of subtidal water level in Chesapeake Bay (Bosley and Hess, 2001). These included exploratory data analysis techniques (EDA) (Tukey, 1977; NIST, 2005), empirical orthogonal function methods (EOF) (Bjornsson and Venegas, 1997) and autoregressive statistical techniques (SAS Institute, Inc, 1987) in an attempt to determine which types of forcing (i.e. wind, coastal sea level) are dominant and their comparative importance in NE and PE water level.

Exploratory data analysis (EDA) is an approach that uses a variety of techniques to maximize insights into a data set, allowing underlying structures to be revealed. It is also useful in detecting outliers and anomalies and in determining optimal factor settings (Tukey, 1977; NIST, 2005). EDA initially was used to examine the water level and wind field data graphically to determine any obvious patterns with the motivation to help in the choice of which classical statistical methods to utilize (spectral analysis, cross correlation, regression, etc.).

The empirical orthogonal function (EOF) method is useful in analyzing the variability of a single field, in this case, water

level. The method establishes spatial patterns of variability, associated time variation and assigns a value of “importance” of each pattern (Bjornsson and Venegas, 1997). We strictly employed the methods set forth by Bjornsson and Venegas (1997) and adhere to their definition of EOFs and expansion coefficients. Briefly, EOFs refer to the patterns of variability and the expansion coefficients refer to the time series. As outlined in the Bjornsson and Venegas methods, the EOF analyses separate the data into “data modes of variability” which are not necessarily “physical modes of variability” (Bjornsson and Venegas, 1997). Bridging between the data and physical modes is a matter of subjective interpretation, which was accomplished by correlating the EOF signals with results from exploratory data analysis and classical statistical methods (NIST, 2005; SAS PROC CORR).

The motivation for the EOF analyses was to determine the first two EOFs for a variety of scenarios initially starting with coastal stations only and successively adding sites to determine the change in both the percent variation and expansion coefficients of EOF1 and EOF2. The progression was: (1) coastal stations—Hatteras, Duck, and Beaufort; (2) the addition of the Pamlico Sound site at Oregon Inlet; and (3) finally, the addition of one of the two estuarine sites in the NE or PE estuaries. Site abbreviations used in the six EOF analyses that were completed are as follows: Beaufort, NC = BEAU; Cape Hatteras = HATT; Duck, NC = DUCK; Oregon Inlet Marina = OREG; Neuse Estuary = NE; Pamlico Estuary = PE.

### 3.3. Time series and spectral analyses

Various time series and spectral analysis methods were employed to determine any recurrent power signature in the multiple data sets, along with coherence and phase relationships with selected datasets. Also, autoregressive statistical procedures were used in order to develop a statistical hindcast model for water level at both the NE and PE sites. Spectral density plots were constructed using PROC SPECTRA (SAS Institute, Inc, 1987)

on hourly data to determine the power spectrum of the NE and PE water level and wind response, and any periodicities or cyclical patterns in the data. This method is useful in revealing any repetitive short time-scale phenomenon such as a daily sea breeze in the wind data and resulting coupling with water level response. The SPECTRA procedure produces estimates of the spectral densities, cross-spectral densities, and phase and coherence of a multivariate time series, in this case both wind component and water level data. The estimates of the spectral and cross-spectral densities are produced using a finite

Fourier transformation (SAS Institute, Inc, 1987). Frequency band averaging employing a Tukey-Hanning window was used in the smoothing and assignment of confidence intervals for the power density spectra, cross correlation spectra, and phase and coherence graphics (SAS Institute, Inc, 1987 PROC SPECTRA; Emery and Thompson, 1997).

Predictive statistical models using PROC AUTOREG (SAS Institute, Inc, 1987) were constructed using the multiple data sets to estimate the NE and PE water level response. The original hourly data sets were averaged to give daily values, and

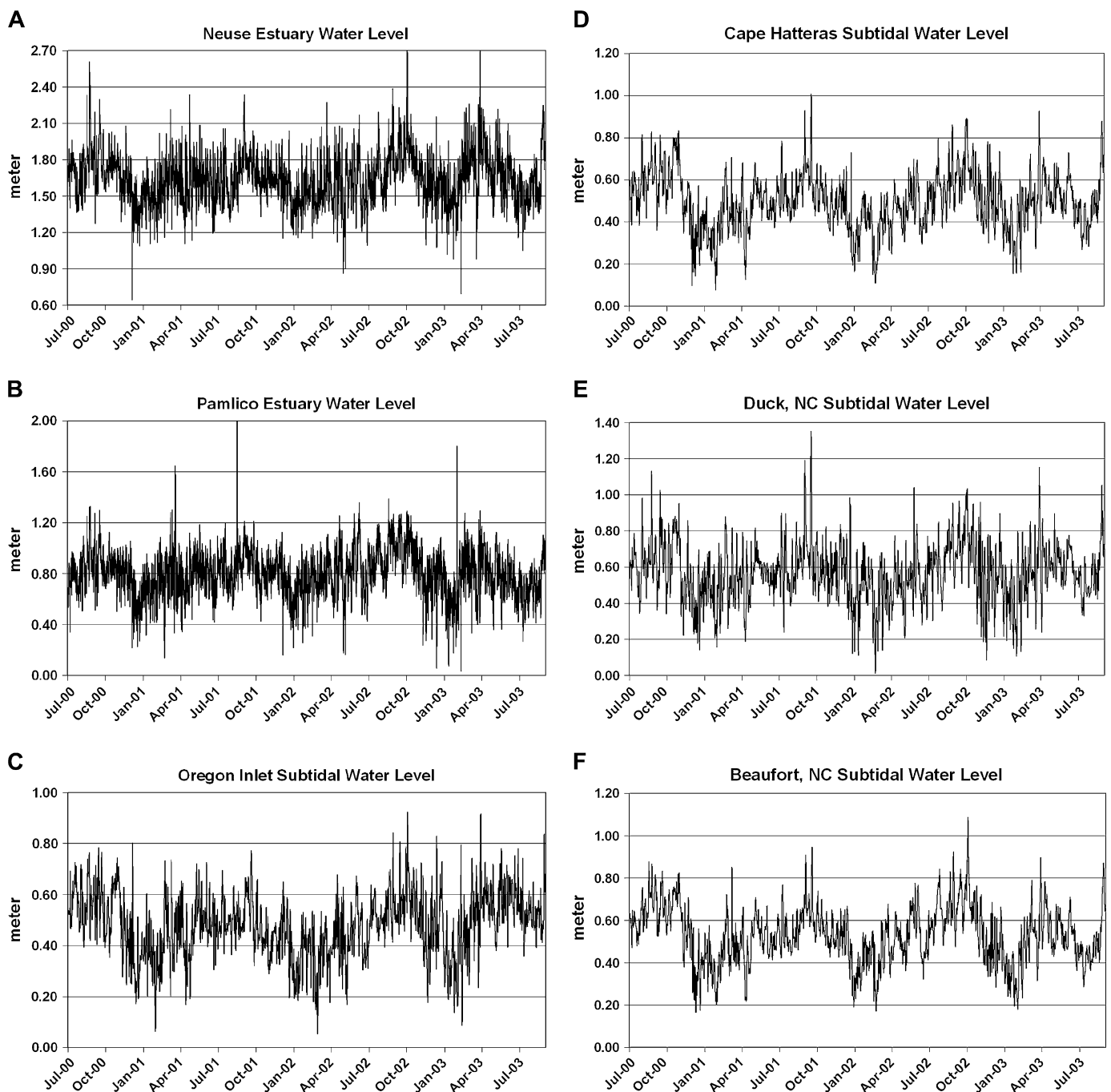


Fig. 2. Water level data time series from the Neuse (A) and Pamlico Estuaries (B), Pamlico Sound near Oregon Inlet (C) and coastal ocean sites—Cape Hatteras (D), Duck, NC (E) and Beaufort, NC (F) used in exploratory data analysis, empirical orthogonal function analysis and autoregressive statistical analyses.

the models were fit to this time scale data. We concluded that daily values of water level were sufficient to hindcast both NE and PE water level. Initially, we explored the use of autoregressive integrated moving average (ARIMA) methods, and from this information, we elected to fit the model in original water levels and allow only autoregressive error structures (Brocklebank and Dickey, 1986; SAS Institute, Inc, 1987). Moving average error structures in ARIMA methods were problematic due to the relationship between wind direction and initial coastal ocean water level. It was determined that the same NE water level would occur under southerly winds and high coastal water level as would occur with high northerly winds and low coastal water level. Programming this interaction between wind and coastal water level in ARIMA methods proved to be unnecessary, and autoregressive methods were sufficient. The AUTOREG procedure forecasts and estimates linear regression models for time series data when errors are autocorrelated (SAS Institute, Inc, 1987). Briefly, autocorrelation occurs when ordinary regression residuals are correlated over time, which is a violation of the ordinary assumptions of linear regression (SAS Institute, Inc, 1987). That is, there is strong association between a residual and a succeeding observation. Autocorrelation results in several problems with statistical tests. For example, the significance of the parameters and the confidence limits for the predicted values are incorrect, and estimates of regression coefficients are inefficient in comparison to estimates derived after accounting for the autocorrelation condition. Most importantly, since the ordinary regression residuals are not independent, they contain information that can be used to improve the prediction of future values. Thus, we used autoregressive techniques to predict the highly positive autocorrelated NE and PE water levels. By utilizing the power of the AUTOREG procedure, great improvement in predictive capability was realized for both the NE and PE.

## 4. Results

### 4.1. Exploratory data analysis—EOF and spectral analysis

Short and long time-scale similarities exist in all time series of estuarine, PS and subtidal coastal ocean water level data (Fig. 2). Short time-scale (hours to days) spikes in water level due to passage of storms (nor'easters and tropical systems) and long time-scale (weeks to months) signals are also evident. Similar short and long time scale variability is also evident in the East/West (U40) and North/South (V40) NE wind field (Fig. 3). Strong seasonality is seen in all time series data. There is an average nine-month periodicity in annual water level off the NC coast (Bohm et al., 2006; Boicourt et al., 1998; Schmeits and Dijkstra, 2000) that results in maximum values being attained in September/October. This is attributed to steric effects from solar heating/cooling, changes in the seasonal wind field, and proximity to the Gulf Stream.

With the manifestation of these strong qualitative patterns, EOF analysis was conducted to establish associated time

variation in the multiple water level time series data, and to determine the importance of the first two EOF components. The stepwise inclusion of time series data sets, starting with the subtidal data from coastal sites and successively including PS and then estuarine sites (either NE or PE sites), revealed a decrease in variation explained by EOF1 and an increase in variation explained by EOF2 (Table 2). Relative proportions of EOF percent variance change due to the inclusion of PS and the estuarine sites. The first two EOF expansion coefficient time series (Fig. 4) were recovered from the analysis and compared to the water level and wind time series data (Table 3). As mentioned, expansion coefficients are the dimensionless time series data recovered for each EOF component, which is the signal that is common to all data sets. Strong Pearson correlation coefficients were found between EOF1 and water level data from the NE Estuary, Duck, and Beaufort. Moderate correlations were also found with the remaining water level sites. Conversely, no significant correlation was determined from a comparison of EOF1 and the Neuse and Cape Hatteras wind components. Pearson correlation determinations for EOF2 and the water level time series data revealed only moderate strength between the NE and Oregon Inlet water level

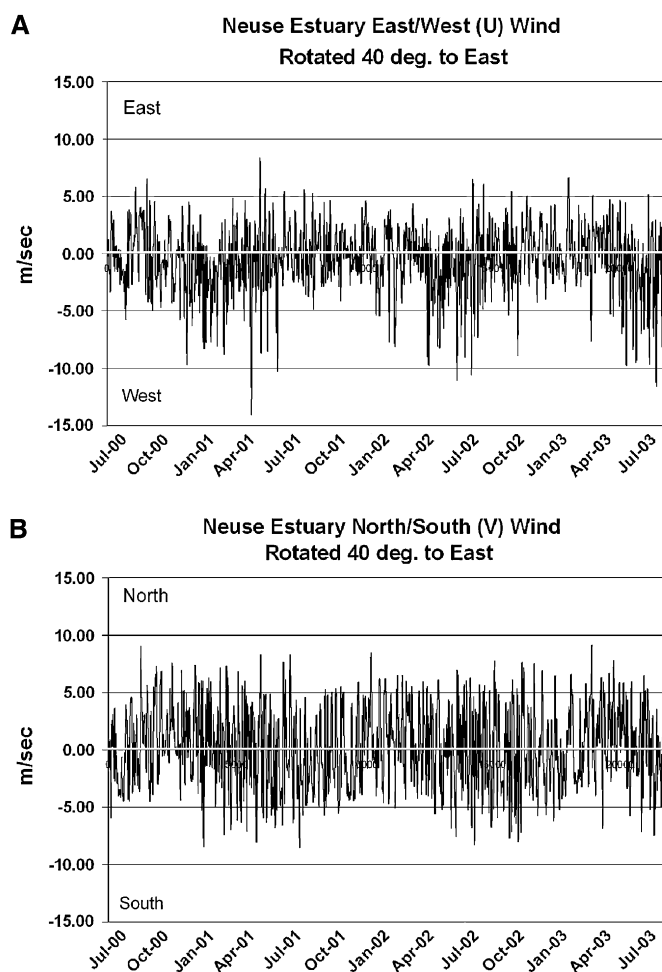


Fig. 3. Time series data of Neuse Estuary (A) East/West (U40) and (B) North/South (V40) wind field rotated 40° to the East.

Table 2

Results from EOF examination of water level stations. Six iterations were conducted, initial analyses were conducted on coastal stations only and then by successively adding the sound station (Oregon Inlet) and then an estuary station (either Neuse or Pamlico) to determine the amount of variability explained by the first two EOF components in coastal stations, coastal and sound stations, and estuarine site, sound and coastal. Eigenvalue =  $\lambda_N$ , Eigenvector =  $F_n$

Examination	EOF mode	$\lambda_N$	% variance	Total explained	$F_n$	Station
I	1	1.489	87.1		0.550	Hatteras
					0.647	Duck
	2	0.178	10.4	97.5	0.528	Beaufort
					0.300	Hatteras
					–0.743	Duck
					0.598	Beaufort
II	1	1.653	77.4		0.345	Oregon Inlet
					0.519	Hatteras
					0.600	Duck
	2	0.279	13.1	90.5	0.502	Beaufort
					0.874	Oregon Inlet
					–0.073	Hatteras
					–0.479	Duck
					0.047	Beaufort
III	1	2.253	70.1		0.584	Neuse
					0.217	Oregon Inlet
					0.429	Hatteras
					0.498	Duck
	2	0.587	18.3	88.4	0.424	Beaufort
					–0.691	Neuse
					0.637	Oregon Inlet
					0.215	Hatteras
					0.200	Duck
					0.174	Beaufort
IV	1	1.933	64.3		0.459	Pamlico
					0.267	Oregon Inlet
					0.468	Hatteras
					0.531	Duck
	2	0.646	21.5	85.8	0.466	Beaufort
					–0.831	Pamlico
					0.453	Oregon Inlet
					0.176	Hatteras
					0.256	Duck
					0.092	Beaufort
V	1	1.370	68.6		0.841	Neuse
					0.205	Oregon Inlet
					0.501	Hatteras
	2	0.515	25.8	94.4	0.434	Neuse
					–0.809	Oregon Inlet
					–0.397	Hatteras
VI	1	1.087	61.0		0.807	Pamlico
					0.262	Oregon Inlet
					0.529	Hatteras
	2	0.553	8.5	69.5	0.526	Pamlico
					–0.727	Oregon Inlet
					–0.441	Hatteras

data. However, in contrast to the lack of correlation between EOF1 and the two wind fields, moderate correlation coefficient values were obtained between EOF2 and the V40 (North/South) wind components from both the NE Estuary and Cape Hatteras sites.

Spectral density plots were used to determine the power spectrum of the Neuse and Cape Hatteras wind fields and the NE and PE water level, and to elucidate any repetitive short time scale phenomenon. Energy spectral density plots of the estuarine water level sites, the U and V rotated wind

components from the estuarine and coastal ocean sites are presented in Fig. 5. A strong diurnal spectral density signal was discerned in both the water level and wind data. There is also a prominent signal at 12.42 h in both estuarine data sets, attributed to a small residual  $M_2$  main lunar semidiurnal tidal component. Cross-spectral density plots between the NE water level and Neuse U40 and V40 wind components are presented in Fig. 6. These comparisons reveal a stronger cross correlation between the water level data and V40 (North/South) components than with the U40 (East/West) component.

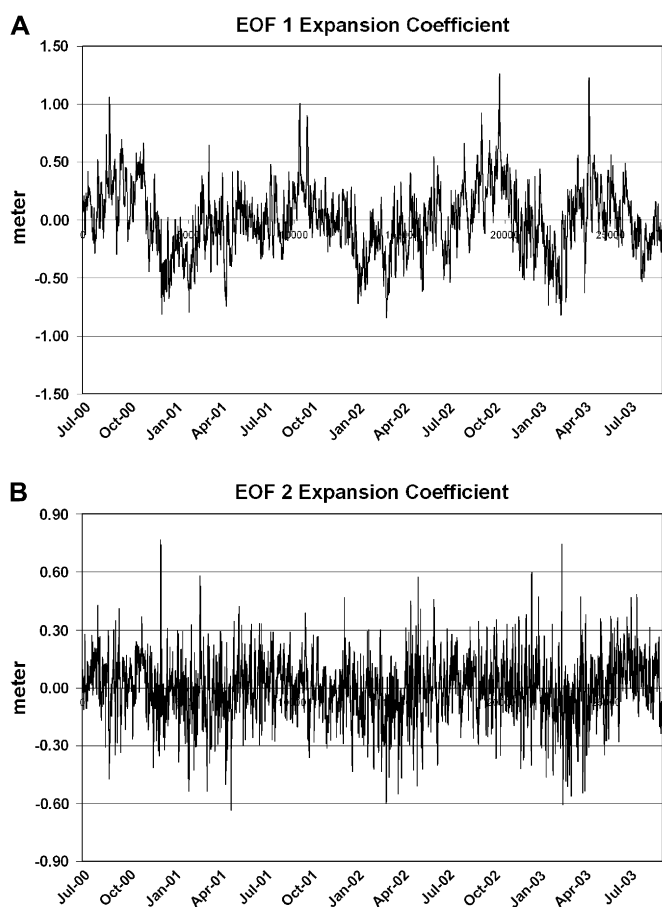


Fig. 4. Empirical orthogonal function (EOF) expansion coefficients for the first two EOF components recovered from the analysis including all stations. Note the resemblance of (A) EOF1 with subtidal water level signal inherent in all stations and the resemblance of (B) EOF2 with the North/South wind field. Pearson correlation coefficients were determined with these data and the various time series of wind and water level.

Coherence and phase plots of NE water level with Neuse U40 and V40 wind components are shown in Fig. 7. The coherency determined between the NE water level and the Neuse V40 wind is high at low frequencies, indicating a strong correlation. However, the coherency determined for the NE water level and the Neuse U40 winds does not show as strong a correlation. Phase determination for the same comparisons indicate that the NE water level and V40 wind are in stronger phase than with the U40 wind.

In our interpretation of these EOF analyses, we have attributed the signal from EOF1 to the change in coastal subtidal water level. The EOF2 signal was attributed to the change in water level due to the wind field unless otherwise noted. The

EOF1 mode examination (Table 2, no. 1) for the coastal stations indicated that the signal for all sites is similar. Eigenvector values are 0.528 (BEAU), 0.550 (HATT), and 0.647 (DUCK). The greater value at DUCK is attributed to the fact that it is located north of the Gulf Stream break at Cape Hatteras and is influenced by the Labrador Current from the north. However, these values are close in magnitude overall. The EOF2 mode for the coastal stations illustrates decreasing eigenvector magnitude, progressing north (i.e. 0.598[BEAU], 0.300[HATT], -0.743[DUCK]) up the coast. This decrease in magnitude of eigenvectors may reflect changes in the wind field over the distance, and/or oceanographic processes such as differences in water masses/currents – for example, Labrador Current at Duck, NC vs. Gulf Stream-influenced coastal waters at Cape Hatteras and below (includes HATT and BEAU sites). Since there are no estuarine or sound stations in this study, a high %variance is attributed to coastal water level vs. wind field/oceanographic factors, and the overall total variation accounted for by EOF1 and EOF2 is also high.

The EOF1 mode examination (Table 2, no. 2) for the coastal stations and the PS station (OREG) shows similar eigenvectors for the coastal stations (i.e. 0.502[BEAU], 0.519 [HATT], 0.600[DUCK]), and a smaller value (0.345) for OREG. This is attributed to a change in the coastal ocean influence on OREG, since the PS site is geographically isolated from coastal ocean. The EOF2 mode examination for the coastal stations and the PS station (OREG) yielded eigenvectors of varying magnitude. The signal attributed to the coastal ocean is similar in magnitude at the two southern coastal sites (BEAU = 0.047 and HATT = -0.073), lower at DUCK (-0.479) and higher at OREG (0.874) inside the Pamlico Sound. We interpret these changes as resulting from the varied effect of wind field on the water level at these sites. OREG is much more influenced by wind than the coastal sites due to its position in PS, whereas the geographically constrained shallow waters are more responsive to changing wind field. With inclusion of the OREG site, the overall variation attributed to EOF1 decreases and the variation attributed to EOF2 increases, likely because of the wind effect on the shallow waters of the PS and its influence on OREG water level.

The EOF1 mode examination (Table 2, no. 3) for the coastal stations, PS and the NE site reveal similar eigenvector values for all coastal sites (i.e. 0.424[BEAU], 0.429[HATT], 0.498[DUCK]). Eigenvector values for OREG (0.217) and NE (0.584) are not as similar, due to their geographical location: OREG is located in the extreme north of PS, whereas the NE is in the extreme south (Fig. 1), and it was concluded that

Table 3  
Pearson correlation coefficient results from a comparison of the first two EOF expansion series coefficients with water level and wind data. All comparisons,  $n = 27,788$  and  $p < 0.0001$ . Strength of correlation is defined as \*\*Strong,  $|r| \geq 0.8$ ; \*Moderate,  $0.5 \leq |r| \leq 0.8$ ; Weak,  $|r| \leq 0.5$

	Neuse water level	Pamlico water level	Oregon Inlet water level	Cape Hatteras water level	Duck water level	Beaufort water level	Neuse U40 wind (E/W)	Neuse V40 wind (N/S)	Cape Hatteras U40 wind	Cape Hatteras V40 wind
EOF1	0.845**	0.635*	0.500*	0.919**	0.878**	0.905**	0.187	0.412	-0.070	0.443
EOF2	-0.510*	-0.425	0.746*	0.235	0.180	0.190	-0.445	-0.561*	0.082	-0.670*

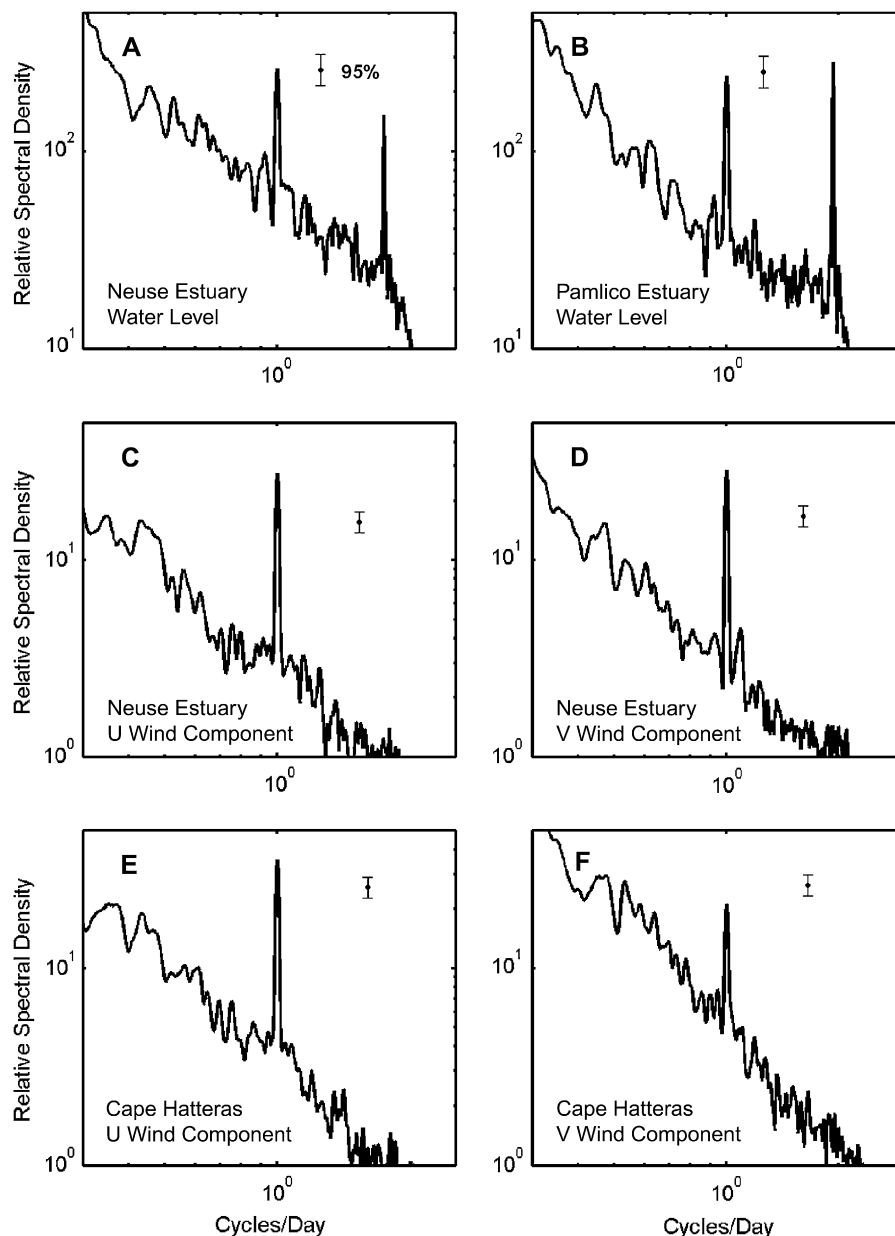


Fig. 5. Spectral density estimates for water level and wind time series. (A, B) Spectral density estimates for Neuse Estuary and Pamlico Estuary water level illustrating signals at approximately 12 and 24-h periods. (C–F) Spectral density estimates for U40 and V40 wind components from the Neuse Estuary and Cape Hatteras wind field illustrating signals in all components at a 24-h period.

distance would account for the difference in these values. The EOF2 mode examination for the coastal stations, PS and the NE site show similar eigenvector values for all coastal sites (i.e. 0.174[BEAU], 0.215[HATT], 0.200[DUCK]), and significantly different values for NE ( $-0.691$ ) and OREG (0.637). The large difference in the NE and OREG values is attributed to the wind effect on water level at these two sites. The site distance indicates that the sites will respond differently to prevailing winds. That is, NE water level would be expected to decrease/increase and OREG water level would increase/decrease under the same wind, depending on the direction. With inclusion of the NE site, the overall variance attributed to EOF1 again decreases and the variation attributed to EOF2 again increases. This is attributed to the wind effect

on the shallow waters of PS and its opposite effect on the OREG and NE water level. Interpretations from the EOF analysis including the PE site is similar to that for case 3 (inclusion of the NE), although autoregressive predictive model results are different in the case of the NE vs. the PE.

The final EOF mode analyses (Table 2: 5, 6) were conducted on only estuarine, PS (OREG) and coastal (HATT) sites to examine any difference that could be attributed to the change in the estuarine sites (NE vs. PE). Eigenvector results are very similar for both cases; therefore, it was concluded that both sites were responding similarly to coastal water level and wind field. However, it should be noted that the total amount of variation that can be explained by EOF1 and EOF2 is much higher in the NE case in comparison to

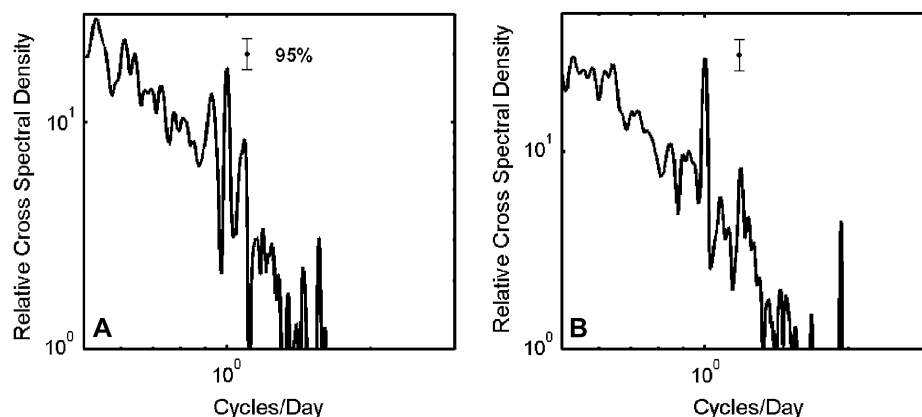


Fig. 6. Cross spectral density estimates of Neuse Estuary water level with Neuse Estuary (A) East/West wind component (U40) and (B) North/South (V40) wind components illustrating a much stronger coupling with the V40 component at a 24 h period.

the PE (94% vs. 69%). We attribute this difference to the geographical location and the alignment of the two estuaries; the alignment of the NE promotes more rapid water level response to prevailing northerly winds due to the longer fetch.

#### 4.2. Autoregressive statistical examination

Using autoregressive model techniques, we conducted three studies using a combination of water level data from the NE and PE and wind field data from the NE and Cape Hatteras. Good agreement was obtained between actual values and predictions with residuals in the 0.05 m range. Significant departures were attributed to local meteorological and hydrological events. Predictive fits of NE water level using NE and Cape Hatteras wind data yielded similar results (Fig. 8; fit using Cape Hatteras wind not presented). In addition, parameter estimates (Table 4) and  $R^2$  values were comparable (Table 5) for these analyses. The total  $R^2$  values for the NE fit using each wind field (0.92 for NE wind; 0.91 for Cape Hatteras wind) are in close agreement, as are the root mean square error and the number of significant lags used in the autoregressive model. Significant predictive improvement was realized over the ordinary least squares  $R^2$  values in comparison to the autoregressive methods (Table 5). Autoregressive predictive results using the PE water level with Cape Hatteras wind field yielded a lower  $R^2$  value (0.76), still with significant improvement over ordinary least squares methods ( $R^2 = 0.52$ ). There were three significant autoregressive lags in the PE model fit (days 1, 2 and 3) in comparison to the NE model fits (days 1 and 3). Autoregression parameter estimates were highly significant for wind field components (U40 and V40), Oregon Inlet residuals and Cape Hatteras subtidal water level in all of the model runs (Table 4).

## 5. Discussion

### 5.1. Implications for estuarine health

Long time series data (>10 years) of water surface elevation are important in both the parameterization of modeling

efforts (Wool et al., 2003) and the descriptive analysis of biological phenomena such as recurrent algal blooms (Springer et al., 2004) and larval fish recruitment (Pietrafesa and Janowitz, 1988). Extensive data sets must also be available to address low frequency phenomena and whether these signals are climatic or anthropogenic driven. Accurate characterization of estuarine/coastal ocean interaction and associated changes in water level can also provide insights for multidisciplinary studies of biophysical processes, nutrient recycling, larval recruitment, fisheries variability, etc. The subtidal water level in the NE and PE is correlated with the coastal water level and wind field along with PS processes described in a residual data set. Therefore, any meteorological or coastal ocean phenomena that could cause increases or decreases in subtidal water levels would change the tidal marsh environment in the study area, resulting in pollutant and pathogen concentration change (e.g. Burkholder et al., 1997; Mallin et al., 2000). This variability in environmentally deleterious constituents would be important to consider in the assessment of human exposure to local waters impacted by fish kills, shellfish contamination with toxins, algal blooms and fecal coliforms or other harmful microorganisms.

The results of this study also have implications for the wetting/drying processes that occur during marsh inundation (Ji et al., 2001). Our findings indicate that the water level in the PS and associated estuaries of the NE and PE is wind dominated in the short term with long-term coastal ocean influences, resulting in highly variable residence times that are not easily predicted as in macrotidal estuaries. Seasonal and event driven changes in water level in shallow estuaries are important to consider when examining life histories of commercially and ecologically important species. A non-linear relationship has been found for water level fluctuations and shrimp catch in Louisiana estuaries that often correspond with ENSO and La Niña events (Childers et al., 1990). It was concluded that climatological events responsible for large fluctuations in water level could negatively impact shrimp catches by blocking access of juveniles to intertidal marsh habitat. Investigation of climatologically driven fluctuations in NE estuarine water level is planned. The key finding of

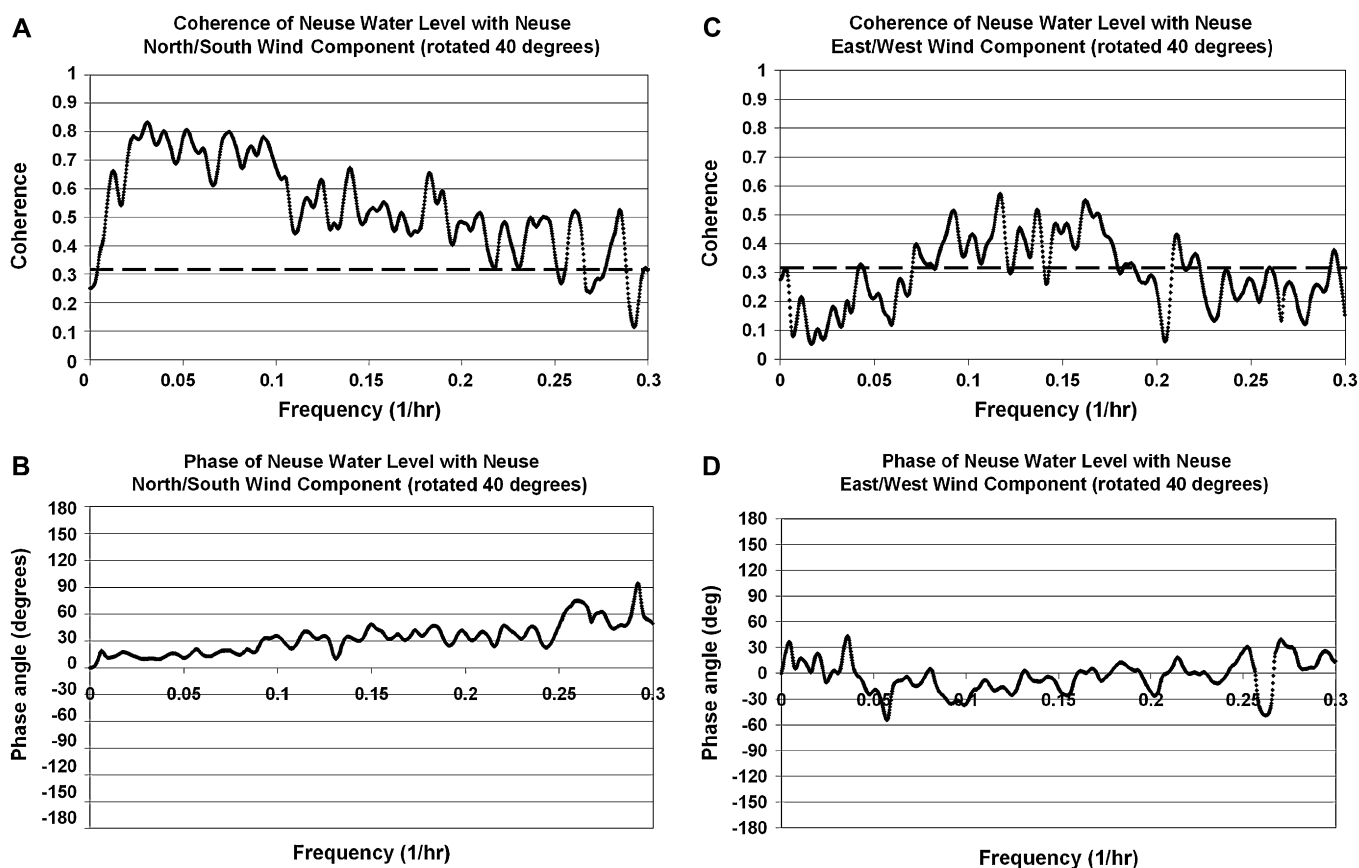


Fig. 7. Coherence and phase plots of Neuse water level with (A, B) Neuse North/South (V40) wind component and (C, D) East/West (U40) wind component illustrating a greater coherence between the North/South (V40) wind component and water level, especially at the longer frequencies. It is also noted that the water level and V40 component is in phase at lower frequencies. Dashed line indicates 95% confidence values.

this study is that water level predictions from a transfer function model constructed with multiple data sets show good agreement with actual values. Future work is also planned to examine the use of this model to construct a proxy data set of the NE water level over past time periods using archived wind and coastal water level data.

The manifestation of severe eutrophic conditions appears to be more pervasive in enclosed or river-dominated estuaries than in more ocean-influenced systems (Bricker et al., 1999). A key factor in eutrophication is increased residence time, which is directly related to estuarine–ocean communication. Poorly flushed systems such as PS and its sub-estuaries are highly susceptible to eutrophication and other water quality problems (Christian et al., 1991; Burkholder et al., 2006). Changes in flushing rates and residence times are directly related to fluctuations in water levels, and the volume of the entire system can be significantly changed by large fluctuations in water level. A water level excursion of  $\pm 1$  m, as was documented in this study, would significantly change the total amount of water in the system, especially in the upper reaches of shallow estuarine creeks. The findings and techniques outlined in this study are useful in addressing important local data gaps that are critical in terms of improving the ability to assess, manage and respond to estuarine eutrophication symptoms. Overall, seasonal and event-driven

water level variability is an important consideration in accurately assessing nutrient loading and biological responses such as in the consideration of the life histories of commercially and ecologically important species (Childers et al., 1990).

### 5.2. Patterns revealed by EOF analysis

The primary results in this work are similar with the findings in studies addressing water level variation in other shallow wind-driven interconnected lagoonal systems, such as Barnegat Bay (Chant, 2001) and Great South Bay, Long Island, New York (Wong and Wilson, 1984). In these investigations it was determined that mode 1 EOF is related to remote forcing through coupling with coastal ocean subtidal motion and that mode 2 EOF is associated with the local wind field. Total variance captured by the first two modes in all three studies was of similar magnitude, that is, 97% for Great South Bay (Wong and Wilson, 1984), 90% for Barnegat Bay-Little Egg Harbor (Chant, 2001) and 95% for the Neuse Estuary (this study). The lower magnitude of total variance captured by the first two EOF components for the PE in this study (70%) may be related to estuary alignment in relation to the main axis of the PS or in equipment measurement error and data interpolation techniques. In lieu of these findings, further

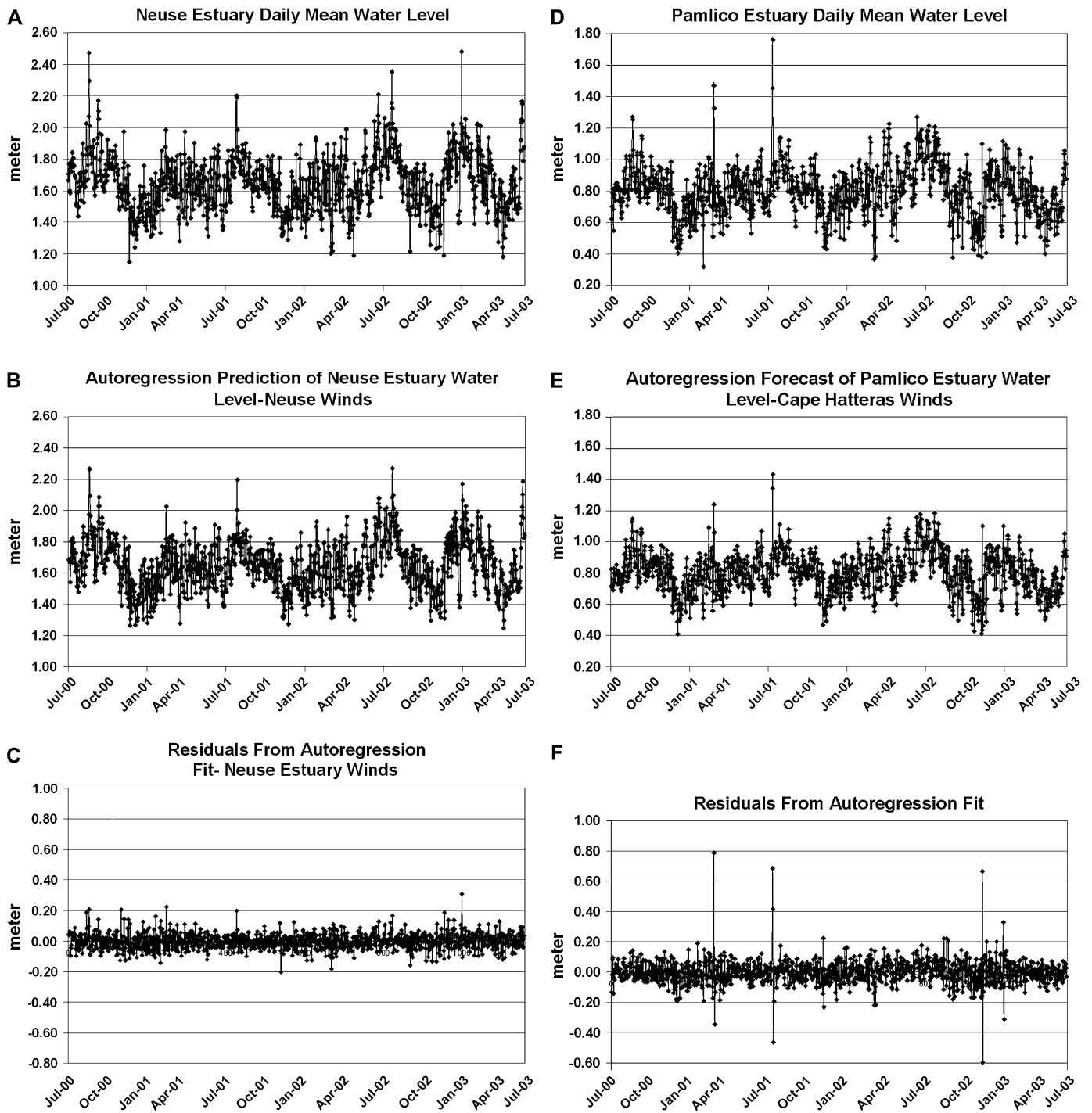


Fig. 8. Autoregression predictive model results for two case studies. (1) Neuse Estuary water level predicted using input data sets of Oregon Inlet residuals, Neuse Estuary wind field (rotated 40°) and Cape Hatteras subtidal water level. Raw data (A), predictive results (B) and residuals (C). (2) Pamlico estuary water level predicted using Oregon Inlet residuals, Cape Hatteras wind field (rotated 40°) and Cape Hatteras subtidal water level. Raw data (D), predictive results (E) and residuals (F).

study is warranted addressing PE wind response and water level variability. Upon comparison, these three systems are similar in many respects. Barnegat Bay-Little Egg Harbor, Great South Bay and PS are systems with a small number of inlets allowing communication with the coastal ocean. The inlets effectively attenuate the coastal ocean tidal signal thereby leaving the major water level forcing factor to the subtidal

regime. The shallow depth and alignment of these lagoonal systems allow for effective wind driven water movement that drives local short time scale water level variation. It was also noted (Chant, 2001) that subtidal motion in Barnegat Bay-Little Egg Harbor varies on both annual and inter-annual time scales resulting in time dependent exchange. This would also be the case for the PS and its sub-estuaries (NE and PE) as

Table 4  
Autoregression parameters for two predictive models using varied wind fields and water level series

Variable	DF	Estimate	Standard error	<i>t</i> value	Approx Pr >   <i>t</i>
a. Autoregression parameters of Neuse Estuary water level prediction using Neuse winds					
Intercept	1	1.4013	0.0177	79.21	<0.0001
East/West (U40 winds)	1	0.0131	0.000788	16.64	<0.0001
North/South (V40 winds)	1	0.0189	0.000842	22.48	<0.0001
Oregon Inlet residuals	1	−0.5270	0.0373	−14.14	<0.0001
Cape Hatteras water level	1	0.5049	0.0256	19.71	<0.0001
Autoregressive lag (AR1)	1	−0.8396	0.0303	−27.72	<0.0001
Autoregressive lag (AR3)	1	−0.1057	0.0294	−3.59	0.0003
b. Autoregression parameters of Pamlico Estuary water level prediction using Cape Hatteras winds					
Intercept	1	0.6930	0.0227	30.55	<0.0001
East/West (U40 winds)	1	0.008319	0.000930	8.94	<0.0001
North/South (V40 winds)	1	0.0126	0.001020	12.33	<0.0001
Oregon Inlet residuals	1	−0.4050	0.0576	−7.03	<0.0001
Cape Hatteras water level	1	0.2341	0.0402	5.82	<0.0001
Autoregressive lag (AR1)	1	−0.8026	0.0295	−27.22	<0.0001
Autoregressive lag (AR2)	1	0.2222	0.0370	6.00	<0.0001
Autoregressive lag (AR3)	1	−0.1913	0.0292	−6.55	<0.0001

shown in the annual variability in PS water level recorded in this study and also seen in NOS data for the three coastal stations. Further study is needed to determine exchange dynamics for the three PS inlets as forced by subtidal water level variability driven by coastal ocean processes and the short time scale water level variability driven by the local wind field. A dedicated water level sensor network would also be valuable in addressing the local and remote forcing factors for the many PS sub-estuaries (e.g. Pungo River, Albemarle Sound, Currituck Sound, etc.)

### 5.3. Autoregression predictive models

Water level predictions from autoregressive statistical models constructed with multiple data sets for the NE showed good agreement with actual values ( $R^2 = 0.92$ ). However, the autoregressive model for the PE did not give as strong a prediction ( $R^2 = 0.76$ ) as for the NE. Possible explanations for this discrepancy could be attributed to the use of different equipment (pressure transducer vs. multi-parameter datasonde), or to differences in the morphometry of the NE and the PE. The lower NE is aligned with the long axis of the Pamlico Sound ( $40^\circ$ ), allowing manifestation of a strong wind effect (Luettich et al., 2002; Reynolds-Fleming and Luettich, 2004). In contrast, the long axis of the PE is oriented in a  $100^\circ$ T direction, not in alignment with the predominant

seasonal winds. The orientation of the PE also results in a limited fetch in comparison to the NE, which may affect water level less during short time scale wind events.

The application of autoregressive techniques in this study shows that it is feasible to develop a statistical model to closely estimate the water level at a specific inland estuarine site, using the closest NOAA coastal water level site as one of the input data sets along with regional wind field data and PS water level data at Ocracoke Inlet. The coastal water level data that were used in the construction of the autoregressive models presented here were acquired at Cape Hatteras because of its close proximity to Ocracoke Inlet, one of the major PS inlets. However, results indicate that water level data acquired at the NOAA-NOS site at Beaufort, NC work equally as well in the construction of these hindcast models (data not presented). Of interest to note, the Beaufort site is not distant from the NE due to the Intercoastal Waterway, which connects both sites via Adams Creek. There are long time scale water level records for the Beaufort site, and the site is also a site in the NOAA-NOS program to assess long-term sea level trends. This long time-scale data record lends itself to the construction of a NE proxy data set, covering the period of 1980 to the present (Fig. 9). The other two input data sets needed for autoregressive model construction, Cape Hatteras wind field data and Oregon Inlet water level, are also available for extended periods. Unfortunately, Hurricane

Table 5

Water level prediction  $R^2$  values using standard regression and autoregressive (AR) statistical methods with wind data from the Neuse Estuary and Cape Hatteras, North Carolina. Note: table shows improvement in predictive capability by using autoregressive methods and lags. \*Wind fields were rotated  $40^\circ$  to the east to align with the long axis of the Pamlico Sound and lower Neuse River. \*\*Maximum Likelihood (ML) methods used in PROC AUTOREG

Water level	Wind field*	Ordinary least squares $R^2$	Regression** $R^2$	Total** $R^2$	Root Mean Square Error (RMS)	No. lags <sup>a</sup>
Neuse Estuary	Neuse Estuary	0.79	0.81	0.92	0.051	2 (1,3)
Neuse Estuary	Cape Hatteras	0.78	0.79	0.91	0.053	2 (1,3)
Pamlico Estuary	Cape Hatteras	0.52	0.47	0.76	0.079	3 (1,2,3)

<sup>a</sup> Number of lags and lag order significant in autoregressive analysis.

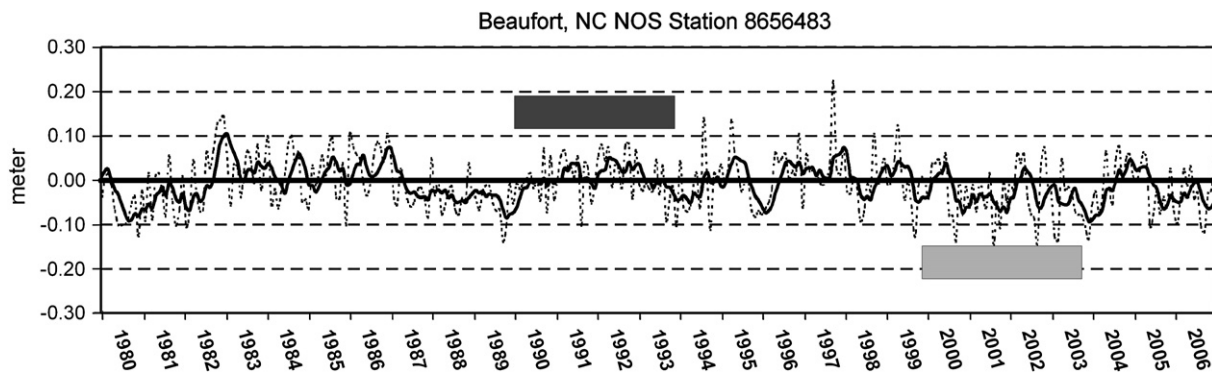


Fig. 9. Time series of long-term water level data (1980–2005) at Beaufort, NC illustrating long time periods of above/below mean subtidal water level. Light gray bar denotes time scale of this study. Dark bar is an example of an extended time period of above mean subtidal water level, other extended time periods can be noted. Figure is modified from NOS-NOAA: Interannual variation of mean sea level from 1980 to the present, station number 8656483 Beaufort, North Carolina. The plot shows the monthly mean sea level with the average seasonal cycle and the linear trend removed (dashed curve) and the 5-month average (solid curve). Located at the following website: [http://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?stnid=8656483](http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8656483).

Isabel destroyed the NOAA-NOS Cape Hatteras Pier site in 2003.

## 6. Conclusions

We examined the water level variation in the NE and PE, part of the PS system, due to local and non-local effects. Local effects were attributed to wind field, in this study the North/South (V40) wind component rotated 40° to align with the long axis of PS accounting for the longest fetch, and PS processes. PS processes were defined as the variability explained by the residuals remaining from a fit of Oregon Inlet water level, using a coastal ocean site as input data. Non-local effects were attributed to the coastal ocean water level, which contains variability due to seasonal processes such as thermal heating/cooling of the water column, large-scale weather patterns (persistent mesoscale systems, La Nina, El Nino, etc.) and changes in the proximity of the Gulf Stream to the NC coast.

EOF analyses indicate that a major portion of the variability in all water level time series can be accounted for by the first two EOF components, which is similar to previous studies in other shallow lagoonal systems. Using Pearson correlation techniques, it was determined that EOF1 is attributed to coastal ocean water level and EOF2 can be attributed to the rotated North/South wind component regardless of where it was acquired, in this case a local site (Neuse Estuary) and a more distant site at Cape Hatteras. Spectral analysis of wind time series data indicates a strong diurnal signal for both U and V components. Diurnal and approximately 12-h period signals were observed in the water level records from the NE and PE. Higher coherency was observed between NE water level and the North/South (V40) wind component in comparison to the East/West (U40) wind component.

Autoregressive statistical methods were used to develop hindcast models for the NE and PE. These methods proved highly accurate for the NE with  $R^2$  values of 0.92 and 0.91 when using different wind field data sets (i.e. Neuse and

Cape Hatteras respectively). The predictive results for the PE were not as accurate ( $R^2 = 0.76$ ) as those for the NE. Factors contributing to this discrepancy are currently under investigation, for example, differences in monitoring equipment and geographical position are being examined. Results from this technique indicate that an accurate hindcast of water level in the NE can be constructed using available long-term data sets. Coastal ocean water level data at Beaufort, NC, wind field data from Cape Hatteras and Pamlico Sound data from Oregon Inlet are all available as input data sets for a long time scale hindcast. These data would be useful in examining biological responses documented over the past 25 years.

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## References

- Bjornsson, H., Venegas, S.A., 1997. A Manual for EOF and SVD Analyses of Climatic Data. Department of Atmospheric and Oceanic Sciences and Centre for Climate and Global Change Research, McGill University, CCGCR Report No. 97–1, Montréal, Québec, 52 pp.
- Bohm, E., Hopkins, T.S., Pietrafesa, L.J., Churchill, J.H., 2006. Continental slope sea level and flow variability induced by lateral movements of the Gulf Stream in the Middle Atlantic Bight. *Progress in Oceanography* 70, 196–212. doi:10.1016/j.pocan.2006.07.005.
- Boicourt, W.C., Wiseman, W.J., Valle-Levinson, A., Atkinson, L.P., 1998. Continental shelf of the southeastern United States and the Gulf of Mexico:

- in the shadow of the western boundary current. In: Robinson, A.R., Brink, K.H. (Eds.), *The Sea. The Global Coastal Ocean – Regional Studies and Syntheses*, vol. 11. Wiley, New York, NY, pp. 135–182.
- Boon, J.D., 2004. *Secrets of the Tide: Tide and Tidal Current Analysis and Predictions. Storm Surges and Sea Level Trends*. Horwood, Chichester, U.K.
- Bosley, K.T., Hess, W.W., 2001. Comparison of statistical and model-based hindcasts of subtidal water levels in Chesapeake Bay. *Journal of Geophysical Research* 106 (C8), 16,869–16,885.
- Bricker, S.B., Clement, C.G., Pirhalla, D.E., Orlando, S.P., Farrow, D.R.G., 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. National Oceanic and Atmospheric Administration – National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science. Silver Spring, MD.
- Brocklebank, J.C., Dickey, D.A., 1986. SAS System for Forecasting Time Series. SAS Institute, Inc, Cary, NC.
- Brooks, D.A., Baca, M.W., Lo, Y.-T., 1999. Tidal circulation and residence time in a macrotidal estuary: Cobscook Bay, Maine. *Estuarine, Coastal and Shelf Science* 49, 647–665.
- Burkholder, J.M., Mallin, M.A., Glasgow, H.B., McIver, M.R., Shank, G.C., Deamer-Melia, N., Briley, D., Springer, J., Touchette, B.W., Hannon, E.K., 1997. Impacts to a coastal river and estuary from rupture of a large swine waste holding lagoon. *Journal of Environmental Quality* 26, 1451–1466.
- Burkholder, J.M., Mallin, M.A., Glasgow, H.B., 1999. Fish kills, bottom-water hypoxia and the toxic *Pfiesteria* complex in the Neuse River and Estuary. *Marine Ecology Progress Series* 170, 301–310.
- Burkholder, J.M., Eggleston, D., Glasgow, H., Brownie, C., Reed, R., Janowitz, G., Posey, M., Melia, G., Kinder, C., Corbett, R., Toms, D., Alphin, T., Deamer, N., Springer, J., 2004. Comparative impacts of two major hurricane seasons on the Neuse River and Western Pamlico Sound Ecosystems. *Proceedings of the National Academy of Sciences* 101, 9291–9296.
- Burkholder, J.M., Dickey, D.A., Kinder, C.A., Reed, R.E., Mallin, M.A., McIver, M.R., Cahoon, L.B., Melia, G., Brownie, C., Smith, J., Deamer, N., Springer, J., Glasgow, H., Toms, D., 2006. Comprehensive trend analysis of nutrients and related variables in a large eutrophic estuary: a decadal study of anthropogenic and climatic influences. *Limnology and Oceanography* 51, 463–487.
- Chant, R.J., 2001. Tidal and subtidal motion in a shallow bar-built multiple inlet/bay system. *Journal of Coastal Research Special Issue* 32, 102–114.
- Childers, D.L., Day Jr., J.W., Muller, R.A., 1990. Relating climatological forcing to coastal water levels in Louisiana estuaries and the potential importance of El Niño-Southern Oscillation events. *Climate Research* 1, 31–42.
- Christian, R.R., Boyer, J.N., Stanley, D.W., 1991. Multi-year distribution patterns of nutrients within the Neuse River Estuary, North Carolina. *Marine Ecology Progress Series* 71, 259–274.
- Cox, D.T., Tissot, P., Michaud, P., 2002. Water level observations and short-term predictions including meteorological events for entrance of Galveston Bay, Texas. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 128 (1), 21–29. doi:10.1061/(ASCE)0733-950X(2002). 128:1(21).
- Dyer, K.R., 2000. *Estuaries: A Physical Introduction*. Wiley, New York, NY.
- Dyer, K.R., Taylor, P.A., 1973. A simple, segmented prism model of tidal mixing in well-mixed estuaries. *Estuarine and Coastal Marine Science* 1, 411–418.
- Emery, W.J., Thompson, R.E., 1997. *Data Analysis Methods in Physical Oceanography*. Pergamon Press, Tunbridge Wells, Kent, Great Britain.
- Ensign, S.H., Halls, J.N., Mallin, M.A., 2004. Application of digital bathymetry data in an analysis of flushing times of two North Carolina estuaries. *Computers and Geosciences* 30, 501–511.
- Geyer, W.R., 1997. Influence of wind on dynamics and flushing of shallow estuaries. *Estuarine, Coastal and Shelf Science* 44, 713–722.
- Giffin, D., Corbett, D.R., 2003. Evaluation of sediment dynamics in coastal systems via short-lived radioisotopes. *Journal of Marine Systems* 42, 83–96.
- Ji, Z.-G., Morton, M.R., Hamrick, J.M., 2001. Wetting and drying simulation of estuarine processes. *Estuarine, Coastal and Shelf Science* 53, 683–700.
- Kennish, J.J., 2001. Coastal salt marsh systems in the U.S.: a review of anthropogenic impacts. *Journal of Coastal Research* 17, 731–748.
- Luettich Jr., R.A., Carr, S.D., Reynolds-Fleming, J.V., Fulcher, C.W., McNinch, J.E., 2002. Semi-diurnal seiching in a shallow, micro-tidal lagoonal estuary. *Continental Shelf Research* 22, 1669–1681.
- Mallin, M.A., Williams, K.E., Esham, E.C., Lowe, R.P., 2000. Effect of human development on bacteriological water quality in coastal watersheds. *Ecological Applications* 10, 1047–1056.
- Marmorino, G.O., 1982. Wind-forced sea level variability along the West Florida Shelf. *Journal of Physical Oceanography* 12, 389–405.
- NIST Engineering Statistics Handbook. 2005. NIST/SEMATECH e-Handbook of Statistical Methods. Available from: <http://www.itl.nist.gov/div898/handbook>.
- Pasternack, G.B., Hinnov, L.A., 2003. Hydrometeorological controls on water level in a vegetated Chesapeake Bay tidal freshwater delta. *Estuarine, Coastal and Shelf Science* 58, 367–387.
- Peng, M., Xie, L., Pietrafesa, L.J., 2004. A numerical study of storm surge and inundation in the Croatan-Albemarle-Pamlico Estuary system. *Estuarine, Coastal and Shelf Science* 59, 121–137.
- Pietrafesa, L.J., Janowitz, G.S., 1988. Physical oceanographic processes affecting larval transport around and through North Carolina inlets. *American Fisheries Society Symposium* 3, 34–50.
- Pritchard, D.W., 1952. Salinity distribution and circulation in the Chesapeake Bay Estuaries system. *Journal of Marine Research* 11, 106–123.
- Rasmussen, B., Josefson, A.B., 2002. Consistent estimates for the residence time of microtidal estuaries. *Estuarine, Coastal and Shelf Science* 54, 65–73.
- Reed, R.E., Glasgow, H.G., Burkholder, J.M., Brownie, C., 2004. Seasonal physical-chemical structure and acoustic Doppler current profiler flow patterns over multiple years in a shallow, stratified estuary, with implications for lateral variability. *Estuarine, Coastal and Shelf Science* 60, 549–566.
- Reynolds-Fleming, J.V., Luettich, R.A., 2004. Wind-driven lateral variability in a partially mixed estuary. *Estuarine, Coastal and Shelf Science* 60, 395–407.
- Rogers, K., Wilton, K.M., Saintilan, N., 2006. Vegetation change and surface elevation dynamics in estuarine wetlands of southeast Australia. *Estuarine, Coastal and Shelf Science* 66, 559–569.
- SAS Institute, Inc, 1987. SAS System for Forecasting Time Series. SAS Institute, Inc, Cary, NC.
- Schmeits, M.J., Dijkstra, H.A., 2000. Physics of the 9-month variability in the Gulf Stream region: combining data and dynamical systems analyses. *Journal of Physical Oceanography* 30, 1967–1987.
- Springer, J.J., Burkholder, J.M., Glibert, P.M., Reed, R.E., 2005. Use of a real-time remote monitoring network and shipborne sampling to characterize a dinoflagellate bloom in the Neuse Estuary, North Carolina, U.S.A. *Harmful Algae* 4, 533–551.
- Steel, J. (Ed.), 1991. *Albemarle-Pamlico Estuarine System, Technical Analysis of Status and Trends*. A/P Estuarine Study Report 90-01, 80 pp.
- Stumpf, R.P., Haines, J.W., 1998. Variations in tidal level in the Gulf of Mexico and implications for tidal wetlands. *Estuarine, Coastal and Shelf Science* 46, 165–173.
- Tukey, J., 1977. *Exploratory Data Analysis*. Addison-Wesley, Boston, MA.
- Valle-Levinson, A., Wong, K., Bosley, K., 2001. Observations of the wind-induced exchange at the entrance to Chesapeake Bay. *Journal of Marine Research* 59, 391–416.
- Valle-Levinson, A., Wong, K., Bosley, K., 2002. Effects of Hurricane Floyd on the exchange at the Chesapeake Bay entrance. *Continental Shelf Research* 22, 1715–1730.
- Van Dolah, R.G., Anderson, G.S., 1991. Effects of Hurricane Hugo on salinity and dissolved oxygen conditions in the Charleston Harbor estuary. *Journal of Coastal Research* 8 (SI), 83–94.
- Walters, R.A., 1982. Low-frequency variations in sea level and currents in south San Francisco Bay. *Journal of Physical Oceanography* 12, 658–668.
- Walters, R.A., Gartner, J.W., 1985. Subtidal sea level and current variations in the northern reach of San Francisco Bay. *Estuarine, Coastal and Shelf Science* 21, 17–32.
- Wang, J., Cheng, R.T., Smith, P.C., 1997. Seasonal sea-level variations in San Francisco Bay in response to atmospheric forcing, 1980. *Estuarine, Coastal and Shelf Science* 45, 39–52.
- Weisberg, R.H., Sturges, W., 1976. Velocity observations in the west passage of Narragansett Bay: a partially mixed estuary. *Journal of Physical Oceanography* 6, 721–734.

- Wong, K.-C., 2002. On the wind-induced exchange between Indian River Bay, Delaware and the adjacent continental shelf. *Continental Shelf Research* 22, 1651–1668.
- Wong, K.-C., Valle-Levinson, A., 2002. On the relative importance of the remote and local wind effects on the subtidal exchange at the entrance to the Chesapeake Bay. *Journal of Marine Research* 60, 477–498.
- Wong, K.-C., Wilson, R.E., 1984. Observations of low-frequency variability in Great South Bay and relations to atmospheric forcing. *Journal of Physical Oceanography* 14 (12), 1893–1900.
- Wool, T.A., Davie, S.R., Rodriguez, H.N., 2003. Development of a three-dimensional hydrodynamic and water quality model to support the TMDL decision process for the Neuse River Estuary, North Carolina. *Journal of Water Resources Planning and Management* 129, 295–306.