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Hydrometeorological controls on water level in a vegetated Chesapeake Bay tidal freshwater delta

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Abstract

Wind vectors, watershed discharge, and subestuarine water levels were monitored in a vegetated delta at the head of the Bush River, an upper Chesapeake Bay tributary in Maryland, during an El Niño/La Niña cycle 1995–1996 to investigate hydrometeorological processes that affect the tidal freshwater ecosystem located there. Time series of these processes were analyzed in both the time and frequency domains using such methods as flood frequency analysis, harmonic analysis, averaged and evolutionary power spectral analysis, and coherency spectral analysis. Wind speed variations with periods of 3–4 and 7 days were found to have both high spectral power and high statistical significance. The frequencies of these variations fluctuated over weeks to months and the amplitudes modulated seasonally, but the variations persisted interannually. Significantly greater subtidal wind speed variations in the prinicipal wind direction occurred during the cold and stormy La Niña winter of 1996 relative to the warm and dry El Niño winter of 1995. Data from five hurricanes occurring in the region during the study provided high-resolution snapshots of the mechanisms revealed by the time series analyses. Water level quickly responded to south–north directed wind speed fluctuations during the aperiodic hurricanes, illustrating the strong coupling between wind and water levels in this system. The magnitude of the response was large enough to determine the extent and duration of flooding over tens of hectares in important intertidal marsh habitats. Subtidal water level variations were greater during the La Niña period. During El Niño conditions, the east–west wind component played a larger role than during the La Niña period. Variations in local watershed discharge as well as Susquehanna River outflow had no measurable impact on water levels in the upper reaches of the Bush River tributary during the study.

Keywords: estuarine circulation; tidal freshwater wetlands; wind drift currents; tidal currents; Chesapeake Bay

1. Introduction

Water flow in the uppermost tidal freshwater reaches of Chesapeake Bay tributaries is hydrodynamically driven by a complex interaction between mainstem-bay processes and watershed discharge. Although field studies and computer models by oceanographers and hydrologists have addressed each end of the spectrum individually, the hydrologic and hydrodynamic regimes in the tidal freshwater tributary boundary zone have been neglected, except in the largest tributaries. The basis for this neglect stems from mass balance considerations, as most tributaries convey relatively small loads of water, sediment, nutrients, and toxins even though concentrations may be high (Schubel & Pritchard, 1986). However, from an ecosystem perspective, the vast expanse of productive riparian and aquatic edge habitats present in small to medium sized bay tributaries and secondary tributaries warrant a thorough consideration of physical processes there.

Watershed discharge into bay tributaries is driven by short-duration rainstorms throughout the year overlying an annual cycle with high flow in spring associated with snowmelt followed by low flow in late summer (Schubel, 1972; Schubel & Pritchard, 1986; Smith, Turcotte, & Isacks, 1998). The spatial distribution of

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rainfall and runoff over the region is governed by seasonally varying paths of primary and secondary storm tracks (Lins, 1997). Infrequent large storms over the Chesapeake Basin can extend the freshwater zone of the estuary over a large area temporarily (Andersen, Davis, Lynch, & Schubel, 1973; Lippson et al., 1979; Schubel & Pritchard, 1986).

Estuarine circulation in Chesapeake Bay is driven by different processes at different time scales. Weekly to seasonal net nontidal estuarine circulation in Chesapeake Bay is due to buoyancy differences between freshwater input from the basin and saltwater input from the sea (Schubel & Prichard, 1986). Hourly to weekly variations in circulation are caused by astronomical tides coupled with subtidal water level variations caused by barometric pressure gradients and local wind forcing in the estuary as well as remote wind forcing out on the coastal ocean (Blumberg, 1977; Boicourt, Kuzmic, & Hopkins, 1999; Garvine, 1985; Paraso & Valle-Levinson, 1996; Wang & Elliot, 1978). Several field monitoring campaigns ranging in duration from 1 to 13 months have revealed that winds blowing along the longitudinal axis (south–north) of the bay generate free oscillations in water level with periods of 2–4 days (Chuang & Boicourt, 1989; Hamilton & Boicourt, 1983; Olson, 1986; Vieira, 1986; Wang, 1979a,b). Boicourt et al. (1999) cite a quarter-wave seiche that causes the oscillations in the 2-day band as the dominant subtidal variation in bay circulation, evident during all times of year. Field data (Wang & Elliot, 1978) and computer models (Garvine, 1985) independently show that the relative impact of local winds on water level increases linearly with distance from the bay mouth. Barometric pressure changes apparently add to the effect of wind stress in causing water level variations (Paraso & Valle-Levinson, 1996), with the effect possibly greater in the upper bay (Spitz & Klinck, 1998). Sanford (1994) found that in upper Chesapeake Bay wave-forced resuspension of bed sediment driven by winds dominated tidal resuspension, confirming the significance of winds and water level variation in broader estuarine processes, especially near the head of the bay. Field monitoring of open water conditions in the large tributaries has determined the spatial limits of the influence of river discharge versus tides, the role of storms in suspended sediment transport, and the entrainment thresholds for fine bed material (Maa, Sanford, & Halka, 1998; Nichols, 1993).

The purpose of this study was to characterize the hydrometeorological processes that impact water levels at the head of a relatively small tributary of upper Chesapeake Bay with significant ecological resources. As dozens of such tributaries (e.g. Bohemia River, Sassafras River, and Bush River) have deltas that can be classified as river-dominated systems based on their geomorphology (Miall, 1979; Pasternack, Brush, & Hilgartner, 2001; Syvitski, Smith, Calabrese, & Boudreau, 1988), one could reasonably hypothesize that local hydrology might be dominated by watershed discharge. Conversely, the presence of tidal marshes as the dominant ecosystem on intertidal delta plains could be seen as indicative of the dominance of main-bay circulation on local hydrology. For the case of the Patapsco River, Schubel and Pritchard (1986) reported that the total watershed discharge into the tributary represents ~1/315 of the tributary's volume, indicating that local hydrology and hydrodynamics are controlled by main-bay circulation, even though tidal currents are weak and would take months to flush the system. In that case, brackish conditions enable a three-layered circulation pattern that is not possible in many tidal freshwater tributaries.

For empirical and theoretical analyses to explain which mechanism affects the hydrology and hydrodynamics of the tidal freshwater zone on which time scales, high quality long-term datasets are required. In contrast to the large amount and increasing availability of such data in the coastal and oceanographic setting, data from the tidal freshwater zone, in particular, remain scant and published research nonexistent. For Chesapeake Bay, published hydrometeorological studies only exist for the main bay and its large tributaries. Even in those cases it may come as a surprise to know that the analyzed datasets have never exceeded 13 months, despite the existence of long-term National Oceanographic and Atmospheric Administration (NOAA) station datasets. Olson (1986) cited a 'limited amount of data' on the spectral content of subtidal fluctuations in Chesapeake Bay for use in his theoretical assessment of Chesapeake Bay circulation. The situation in the estuary's tidal freshwater zone is even more impoverished, with no published scientific analyses of hydrometeorological datasets and a lack of inclusion of this ecologically important zone in the estuary's hydrodynamic models.

In this study, a continuous hourly wind record from Chesapeake Bay twice as long as the longest published in a dissertation or scientific journal to date is analyzed in relation to watershed discharge and tidal freshwater marsh water levels. The long-term water level record from the deltaic tidal freshwater marsh described below is the first ever to be reported for Chesapeake Bay. Furthermore, the data are of special importance because they contain signals from five hurricanes that passed through the region during the study period. To present the most thorough investigation of the data possible, both frequency and time domain analyses were performed. Frequency domain analyses are elementary to oceanographers and thus provide a common understanding of hydrometeorological processes across the freshwater–estuarine–oceanographic spectrum. However, because wetland scientists and resource managers who may have never been exposed to this approach will use the research reported here, it is critical to provide a detailed and basic explanation of the methods.

2. Materials and methods

2.1. Study area

The study area is the Otter Point Creek (OPC) component of Chesapeake Bay (MD) National Estuarine Research Reserve, which is a 138.7-ha river-mouth tidal freshwater delta at the head of Bush River in upper Chesapeake Bay (Fig. 1). OPC consists of a 54.4-ha riparian forest, a 84-ha marsh, a 0.3-ha upland forest island, and an expansive subtidal front. Winters Run drains the 150-km^2 watershed that empties into OPC from the west. Downstream of OPC to the east lies Bush River, which is typical of upper Chesapeake Bay tributaries. Because of its small size, the Bush River tributary has received little attention, except the finding that its mean depth is 1.8 m, its intertidal volume ($13.3 \times 10^6\,m^3$) is 18.1% of the maximum tidal volume, and the tidal range at its mouth averages 0.36 m (Cronin, 1971). Since 1990, OPC has been the focus of an interdisciplinary research program addressing

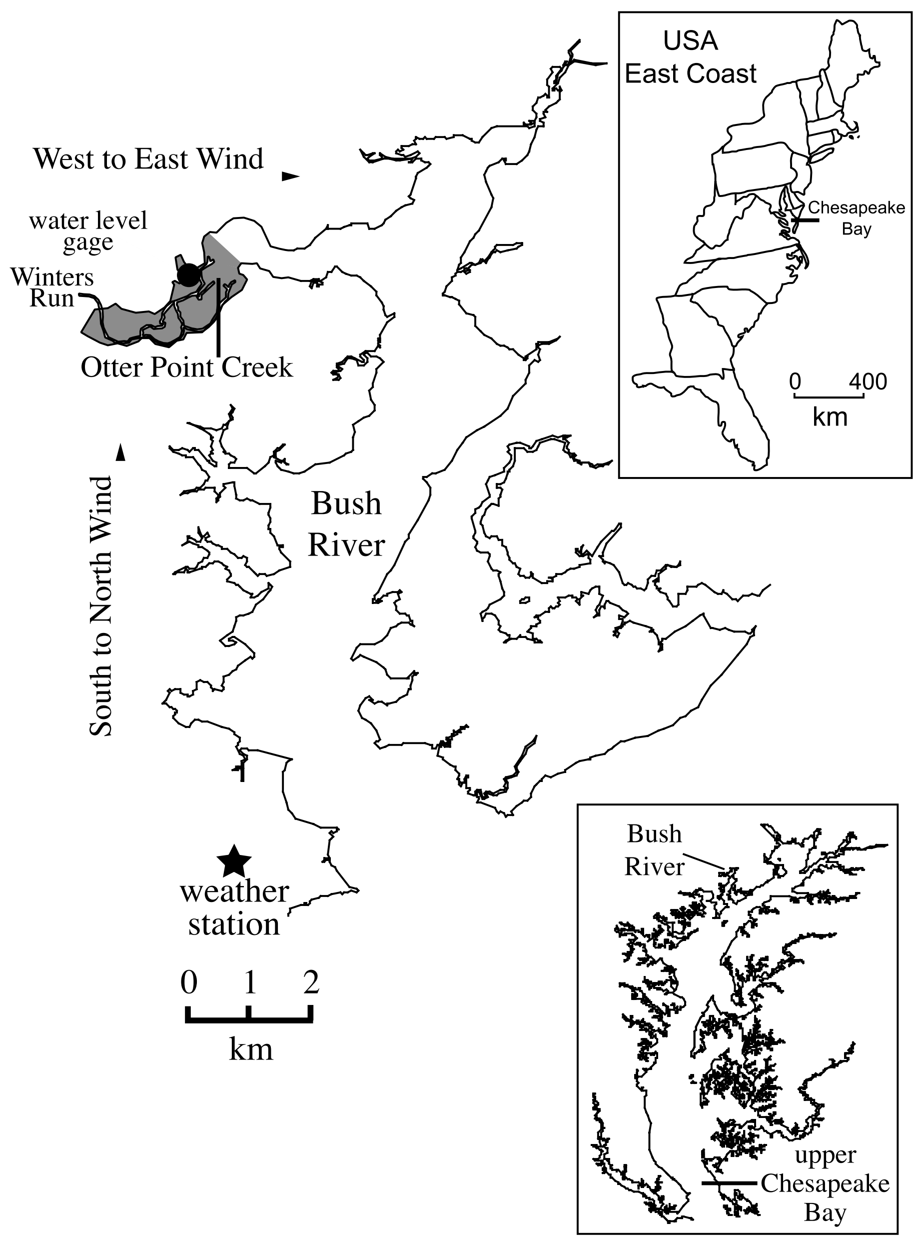

Fig. 1. Map of Bush River in upper Chesapeake Bay showing water level station (circle) and weather station (star) in and around the OPC tidal freshwater delta (shaded area).

ecological, geomorphic, hydrological, and geochemical issues relevant to Chesapeake Bay management (Hilgartner, 1995; Knight & Pasternack, 2000; Pasternack, 1998, 2001; Pasternack & Brush, 1998, 2001, 2002; Pasternack et al., 2001; Pasternack, Hilgartner, & Brush, 2000).

2.2. Climate summary

Because climate conditions drove the hydrometeorological processes observed in this study, the climate status for 1995–1996 is described here based on NOAA climate summaries. The period of this study included two significantly different regimes. During the winter of 1994–1995 an El Niño weather phenomenon was occurring in which the polar jet stream over eastern North America shifted far north of normal. This resulted in weaker weather systems, a significantly warmer than normal condition for the study area, and abnormally low snow cover. This was one of the five warmest periods in the 100-year record for Maryland. Warm conditions continued through the summer in association with a severe drought. Maryland experienced its fourth warmest summer on record and had 25 consecutive days with temperatures above 32 °C. Following this there was a pronounced transition from warm El Niño to cold La Niña conditions. The winter of 1995–1996 saw more than 5 °C below normal conditions along the Atlantic seaboard and well above average snowfall. OPC was completely frozen over by the beginning of December 1995. In January 1996, a blizzard dropped over 508 mm of snow in the region. OPC remained frozen until April. A wet spring and slightly wet summer followed this extreme winter, though temperatures were normal. Autumn 1996 was cold and wet.

2.3. Data

Weather, watershed discharge, and subestuarine water level data from three field monitoring efforts in 1995 and 1996 were used to characterize the hydrometeorological processes impacting water levels in OPC under the different weather conditions represented in this 2-year period. The United States Army Aberdeen Test Center DCP05 station was used as the primary weather record for this study. It is located 6 miles due south of OPC on the peninsula between Gunpowder River, Bush River, and Chesapeake Bay (Fig. 1). The weather dataset includes barometric pressure, air temperature, wind speed, wind direction, peak gust, relative humidity, and precipitation. For this study, only average hourly wind speed ($m\,s^{-1}$) and average hourly wind direction (degrees) were used; these data had no missing values for 1995 or 1996. The 2-year record analyzed in this study is the longest continuous wind record from Chesapeake Bay analyzed and published to date. It testifies to the remarkable effort of the Aberdeen Test Center Meteorological Team and illustrates the availability and quality of this neglected source of data relative to the more commonly recognized NOAA stations. Because Bush River is aligned south–north (S–N) and the western branch of Bush River where OPC is located is aligned west–east (W–E), wind vectors were decomposed into principal components in those directions so that the relative roles of different channel geometries in relation to wind forcing could be assessed. This decomposition has also served as the basis for wind-wave and sediment entrainment modeling reported elsewhere (Pasternack, 1998). North-to-south and east-to-west directed winds were represented by negative signs in S–N and W–E wind speeds, respectively.

Watershed discharges from both the local Winters Run basin and the regional Susquehanna River basin were analyzed for their role in affecting water stage at OPC. Winters Run data were obtained from the United States Geological Survey (USGS) Benson Road gaging station near Bel Air, MD (#01581700). The record dates back to 1967, and it measures mean daily discharge from 60% of the watershed. Although it does not measure the entire flow entering OPC, the Benson Road station captures the majority of it and represents the timing of discharge events in the basin. Historical Susquehanna River data were obtained from the USGS Conowingo Dam gaging station (#01578310) from its inception in 1967. Unlike the other data, streamflow spanned several orders of magnitude and showed a log–normal probability distribution, so it was logarithm-transformed to facilitate frequency domain comparisons against the other variables. For univariate discharge analyses, calculations were made using both log-transformed and raw data, and these were compared to assess any differences.

Water level at OPC was measured using automatic, atmosphere-equilibrated, temperature-corrected pressure transducers (Unidata America Model #6508A, range = 1 m ± 3 mm). Instantaneous readings of water depth were made every 10 min and transmitted to a data logger (Unidata America Model #6003-81). Transducers were mounted into perforated PVC wells anchored in nine different OPC locations, but after water levels were found to be similar between sites, a single, easily accessed well was chosen for long-term monitoring (Fig. 1). Because OPC is intertidal, the low tide minima in the water level record were periodically clipped when the marsh surface was exposed. Because such clipping may cause diversion of spectral power into overtones and intermodulations in frequency domain analyses, these potential effects were checked for. Transducers could not be deployed when the tidal freshwater delta froze, so a continuous 2-year record was not achievable.

Instead, two partial records of 144 days (July 11, 1995–December 2, 1995) and 242 days (April 12, 1996–December 11, 1996) duration were obtained. These records are the first long-term hydrological time series to be published for a tidal freshwater marsh anywhere in Chesapeake Bay, adding further to the importance of this study.

2.4. Characterization of individual time series

Time series analysis, including harmonic line analysis and power spectral analysis, were used to characterize frequency content of wind vectors, watershed discharges, and subestuarine water levels thought to affect the OPC ecosystem. These techniques are elementary to some scientific disciplines, but are infrequently used in wetland science despite their scientific value. For example, they succinctly integrate entire records and are not appreciably biased by individual events. Time series of wind vectors were analyzed for 1995 and 1996 individually as well as using the full 2-year length of each record to characterize wind over the longest time period possible. Winters Run discharge and Otter Point Creek water level data were analyzed individually using time series truncated to match the durations of the water level record for 1995 and 1996. To compare the external driving forces and the subestuarine water level records, all time series were truncated to match the duration of the corresponding water level record for 1995 or 1996.

Harmonic analysis was performed to determine the presence, amplitude, and statistical significance of line components in each time series. A line component in the frequency domain translates into a specific sinusoidal variation in a variable through time. Such variations indicate the characteristic time scales at which individual processes function. The amplitude of a line component is the magnitude of the change in the process about the mean. Statistical significance is reported in terms of probability level estimated from Fisher distributions (Thomson, 1982). High significance ($p < 0.02$) for a line component indicates the presence of a regular, phase-coherent sinusoidal cycle in the record.

Power spectral analysis complements harmonic analysis in that it smooths the magnitude of frequency components over a specified range of frequencies. This accounts for frequency fluctuations that may occur over time as a result of measurement error, component instability (quasi-periodicity), and random noise. Power is reported as spectral power density (data variance/frequency) versus frequency. Units of spectral power are not quantitatively comparable among the time series examined here, but qualitative comparison can be made on the basis of whether the spectral power within frequency bands is high, moderate, or low.

Because the frequency components identified by harmonic and power spectral analyses may not be stable over time, evolutionary spectral analysis was used to detect temporal variations of frequency components. All continuous data available for each time series were used to obtain the longest-term perspective on each physical process. Power spectra were computed over a time window and the window was shifted along the time series in increments. For wind data, a 4-week window was shifted at a 1-week increment, for water level data a 2-week window was shifted at a 3-day increment, and for runoff data, a 913-day window was shifted at a 60-day increment. Output spectra were plotted as a function of position along the time series on a third axis. Spectra calculated incrementally within the spectral window are not independent, but they permit a running, high-resolution view of rapidly developing local frequency instabilities through time.

2.5. Relations between external forces and water level

Fourier-based spectral estimators of Thomson (1982) were used for coherency spectral analysis, which investigates frequency-based correlations between two processes. Coherency is an estimate of the partitioning of the covariance of two time series as a function of frequency, and is reported as magnitude-squared coherency versus frequency. High coherency values indicate a strong relationship between time series. The 99% confidence level for statistically significant coherency was at 0.4 for this study (Carter, Knapp, & Nuttal, 1973; Hinnov, 1994; Priestley, 1981). Coherency analyses were done for the two time frames that water levels were recorded.

Phase differences between two time series provide further insight into the mechanism underlying their coherency. The cross-phase spectrum is the phase difference in degrees over ($-180°$, $+180°$) of the two series as a function of frequency. The interpretation of cross phase is simplified if the response time of the dependent variable to changes in the independent variable is less than half the period of the independent variable. The interpretation also depends on the order of the two records presented to the algorithm, which is manually specified. A positive cross phase can mean that the two variables are positively correlated with the second leading the first or that they are negatively correlated with the first leading the second. The choice of which of these two interpretations is correct is governed by an understanding of the mechanism by which one variable leads and induces the other. For example, changes in subestuarine water level cannot cause changes in wind speed, so a positive cross phase must have wind leading water level, thus pointing to either a negative or positive correlation depending on how wind direction is specified. For two variables that are positively correlated, the time lag between driving force and response is obtained from the absolute value of phase difference by dividing it by 360° and multiplying by the period at which it occurs. For negative correlations, the absolute value of phase difference must be subtracted from 180° before being divided by 360°, and then the result is multiplied by the corresponding period to obtain the time lag. Response times and correlation directions were spot checked by inspecting plots of two series on the same time axis.

All spectral analyses performed in this study used seven 4π prolate multitapers described in Thomson (1982). These provide a maximum of 12 degrees of freedom for the harmonic F-tests and for the placement of the 99% confidence level in the coherency spectra (Carter et al., 1973; Hinnov, 1994; Priestley, 1981).

3. Results

3.1. Wind

The mean wind speed over the 2-year study was $2.12\,\mathrm{m\,s^{-1}}$ ($4.74\,\mathrm{m\,h^{-1}}$), and the mean wind direction was out of the south, which is in alignment with the principal axis of Bush River. The maximum wind speed occurred on January 27, 1996 and was $12.35\,\mathrm{m\,s^{-1}}$ ($27.62\,\mathrm{m\,h^{-1}}$) again out of the south. Wind was less than $5.15\,\mathrm{m\,s^{-1}}$ ($11.51\,\mathrm{m\,h^{-1}}$) ninety percent of the time.

Power spectra of S–N and W–E wind components show the same three general characteristics (Fig. 2). The first two are a low power, low amplitude, and highly significant semi-diurnal periodic variation, and a high power, high amplitude, and highly significant diurnal periodic variation (Table 1). These two wind speed variations only account for 6 and 1% of the total variance, respectively. Highly significant harmonics of the 12- and 24-h variations are present at lower frequencies, but they have very low power. The 12-h variation ranges in amplitude from 0.1 to $0.3\,\mathrm{m\,s^{-1}}$, while the 1-day variation ranges from 0.2 to $0.6\,\mathrm{m\,s^{-1}}$. In 1995, the mean S–N wind speed was $0.35\,\mathrm{m\,s^{-1}}$, so the amplitude of the 1-day variation in that direction represents an 82% deviation. The peak wind speed at this frequency in the records for both years occurred at 9:00 a.m., with the minimum at the same time in the evening.

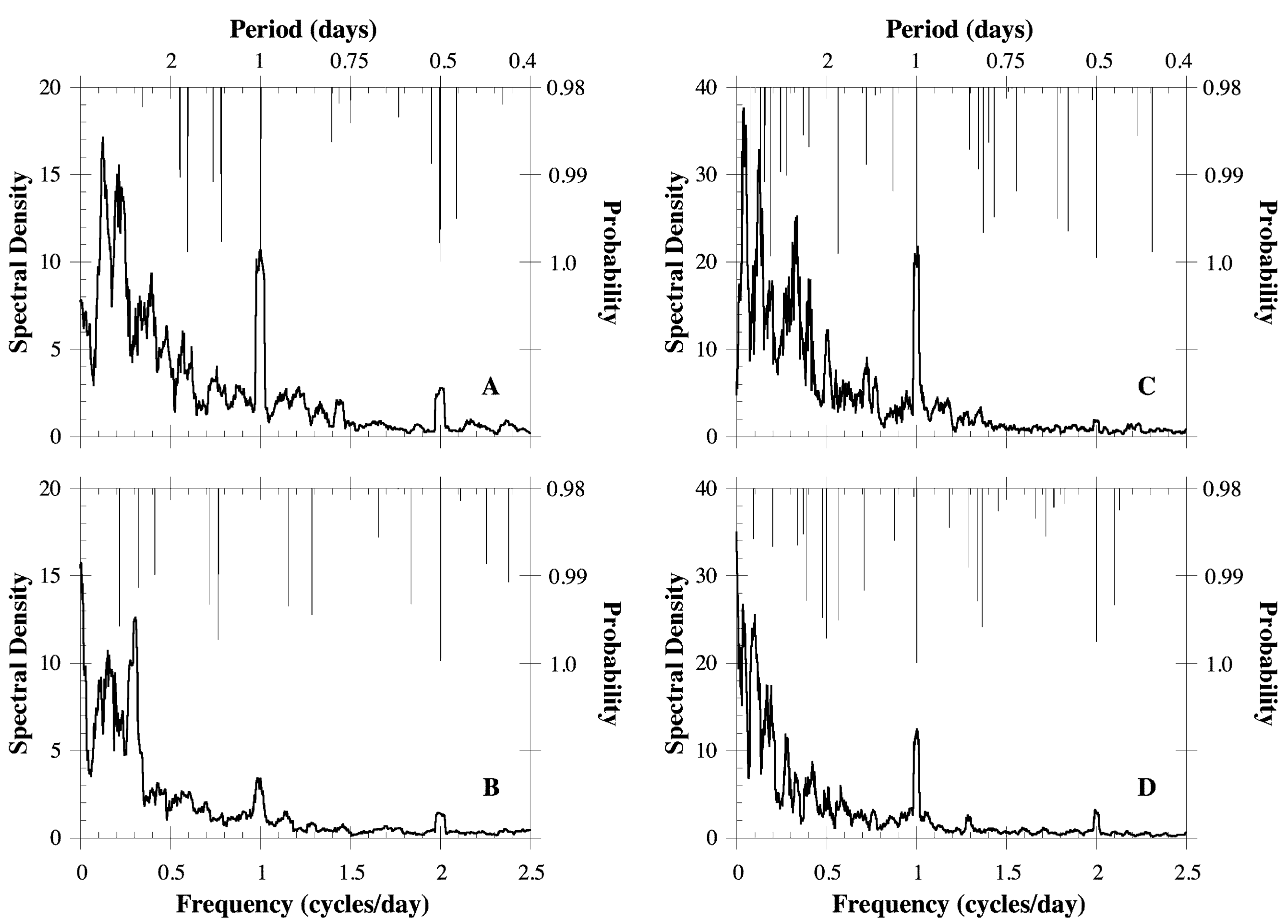

Fig. 2. Power spectra (dark curve) and statistical significance (vertical lines) of (A) 1995 S–N, (B) 1995 W–E, (C) 1996 S–N, and (D) 1996 W–E wind components. Peaks are narrower in the 1996 spectra due to a longer record length.

Table 1
Dominant frequency components in wind records (see Fig. 2)

Frequency (c/d)	Period (days)	Significance	Power	Amplitude (m/s)
1995 S–N				
2.00	0.50	0.999	Low	0.293
1.00	1.00	0.999	High	0.572
0.782	1.28	0.998	Low	0.243
0.595	1.68	0.999	Low	0.292
0.218	4.58	0.938	High	0.436
0.142	7.06	0.949	High	0.462
1995 W–E				
2.00	0.50	0.999	Low	0.198
1.00	1.00	0.885	High	0.196
0.322	3.11	0.991	High	0.359
0.216	4.63	0.996	High	0.371
0.156	6.41	0.940	High	0.350
1996 S–N				
2.00	0.50	0.999	Low	0.129
1.00	1.00	0.999	High	0.432
0.562	1.78	0.999	Low	0.204
0.321	3.12	0.981	High	0.331
0.187	5.34	0.999	High	0.385
0.154	6.48	0.991	High	0.283
0.132	7.59	0.993	High	0.418
0.045	22.0	0.93	High	0.405
1996 W–E				
2.00	0.50	0.998	Low	0.159
1.00	1.00	0.999	High	0.368
0.500	2.00	0.997	Low	0.190
0.200	5.00	0.987	High	0.303
0.100	10.8	0.986	High	0.393
0.050	21.0	0.929	High	0.331

The third general characteristic of all wind power spectra is the presence of <1 cycle per day line frequencies having both high power and high significance, though they are not the same frequencies from year to year. For the 1995 S–N wind component, 1.3- and 1.7-day variations were highly significant, but had low power and relatively low amplitudes (Fig. 2A; Table 1). Wind speed variations on 4.6- and 7.1-day periods had lower statistical significances, but nearly double the amplitude. For the 1995 W–E wind component (Fig. 2B; Table 1), variations with periods of 3.1, 4.6, and 6.4 days were highly significant, had high power, and had an amplitude of ~0.36 m s^{-1}. A very low frequency variation of 0.64 m s^{-1} was present with a periodicity of 139 days, which may indicate a seasonal cycle. For the 1996 S–N wind component, variations with periods of 3.1, 5.3, 6.5, and 7.6 days were highly significant and had high spectral power (Fig. 2C; Table 1). A high spectral power ~22-day periodic variation was evident with a significance of 93%. For the 1996 W–E wind component (Fig. 2D; Table 1), three highly significant low frequency variations were present with high spectral power, and the same ~22-day periodic variation was present. None of the <1 cycle per day line frequencies observed in 1995 recurred in 1996 in the same wind component, though the 3.1-day variation in the 1995 W–E wind was present in the 1996 S–N wind. The total variance of the S–N component was 59% (1995) and 50% (1996) higher than that of the W–E component.

Evolutionary power spectra for both wind components show semi-diurnal and diurnal tidal cycles along with broad bands of power in the 2–3 and 5–7 day period range (Fig. 3). The lower frequency variations were unstable throughout the 2-year period. During winter, the 2–3 and 5–7 day variation bands were well differentiated and had high spectral densities. During summer, the higher of these frequencies were cut off leaving a single high spectral density band with a period of ~3.5–7 days. This strong seasonal modulation of power could significantly impact the temporal distribution of hydrodynamics at OPC.

The coupling between S–N and W–E wind components was studied by coherency spectral analysis in order to assess the presence of winds blowing NE–SW or NW–SE, with cross phase indicating clockwise or counterclockwise wind patterns. In 1995, high coherency was present with 1.6- and 4.3-day periodic variations (Fig. 4A). The corresponding cross phases show a negative correlation between variables, with S–N wind speed changes following W–E changes (Fig. 4B) at time lags of 0 and 18 h, respectively. In 1996, coherency was present for cycles of 1, 1.4, 2.9, and 7.7 days (Fig. 4C). The cross phases for the latter two show a negative correlation with S–N winds following W–E winds, but with substantial lags of 19.7 h and 1.3 days, respectively (Fig. 4D). The time lags between wind components for both years consistently indicate counterclockwise wind patterns at all frequencies.

3.2. Watershed discharge

The log–normal mean Winters Run and Susquehanna River discharges over the 2-year study were 1.42 cm (50 cfs) and 822 cm (29,040 cfs), respectively. Ninety percent of the time daily Winters Run runoff was less than 3.2 cm (114 cfs), while that for Susquehanna River was less than 2775 cm (98,000 cfs). There was no statistically significant correlation between flows for the two river basins during the study period ($R^2 < 0.12$). Some peaks for the two rivers occur at the same time, while others do not (Fig. 5). Susquehanna River was characterized by a gradual increase in discharge on the rising limb of a hydrograph followed by a rapid decrease in discharge on the falling limb, whereas the much smaller Winters Run had a flashy rising limb and a baseflow-dominated falling limb (Fig. 5).

A flood frequency analysis of annual peak daily discharges for Winters Run yielded a statistical bankfull discharge ($Q_{1.5}$) of 12.7 cm (450 cfs), a 5-year return interval magnitude (Q_5) of 33.7 cm (1190 cfs), and a

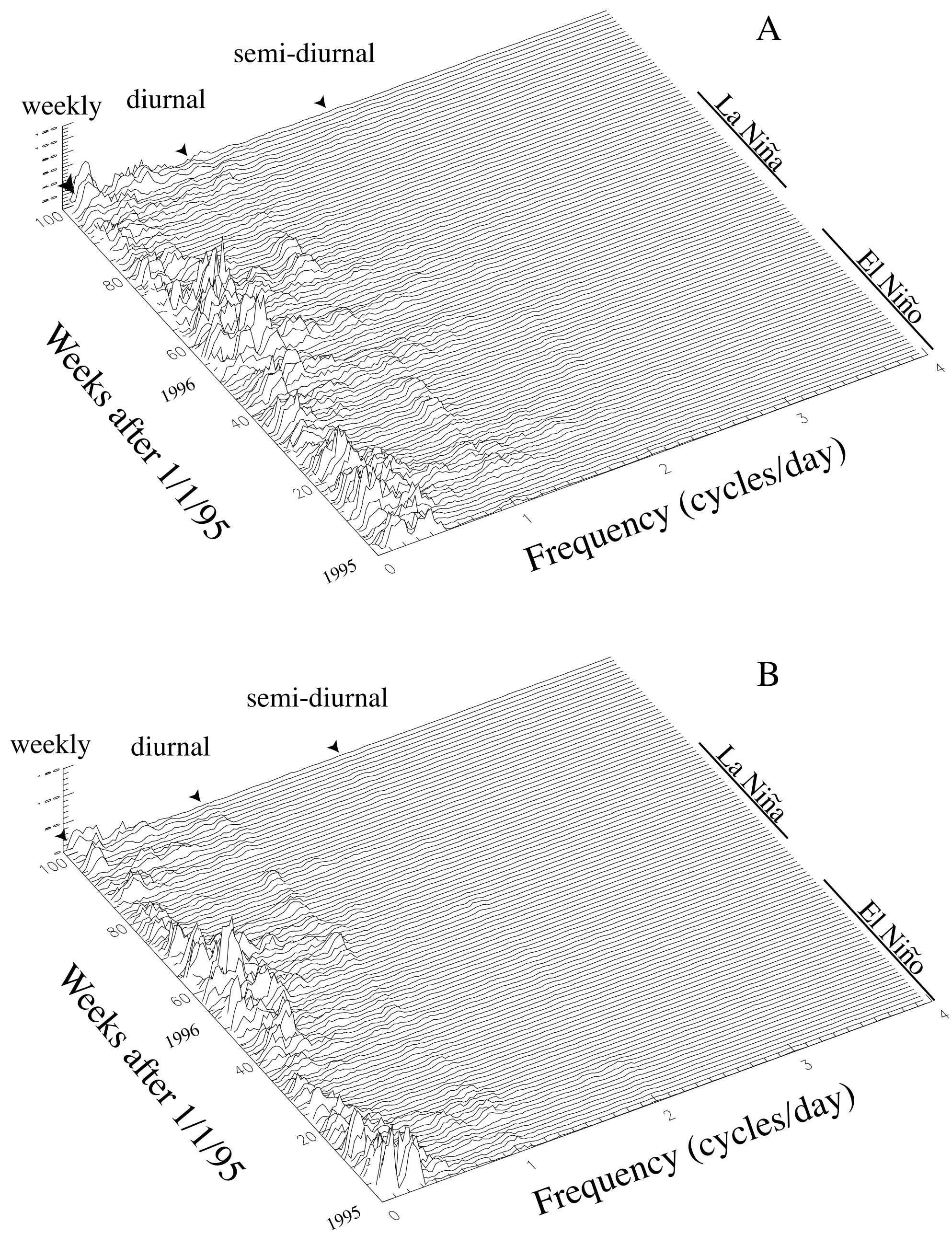

Fig. 3. Evolutionary power spectra of the (A) S–N and (B) W–E wind components in the vicinity of OPC from January 1, 1995 to January 1, 1997. El Niño and La Niña periods are indicated.

100-year magnitude of 103 cm (3650 cfs). $Q_{1.5}$ was exceeded in six events during the study period, while Q_5 was exceeded only once. Four of the six bankfull or greater floods occurred during winter when the delta was frozen, so their impact on the tidal freshwater zone was limited.

The maximum discharge for both basins was the result of snowmelt following the largest blizzard in the region for decades. Winters Run reached 58.3 cm (2060 cfs) on January 19, 1996 and Susquehanna River peaked at 17,613 cm (622,000 cfs) on January 21, 1996. For Winters Run this flood corresponded to an 18-year return interval. Because this event occurred when the delta was frozen under several inches of ice and up to 2 ft of snow, Winters Run flow bypassed the delta plain and injected directly into the subtidal front beyond OPC under ice. Several other small flow peaks occurred for both rivers in 1996, but as will be explained later, most of these showed no relation to OPC water levels (Fig. 5).

Power spectra and harmonic analyses of Winters Run and Susquehanna runoff show low spectral density at frequencies above 0.2 cycles per day (Table 2). For Winters Run, the only significant variation with high power in 1995 had a period and amplitude of 100 days

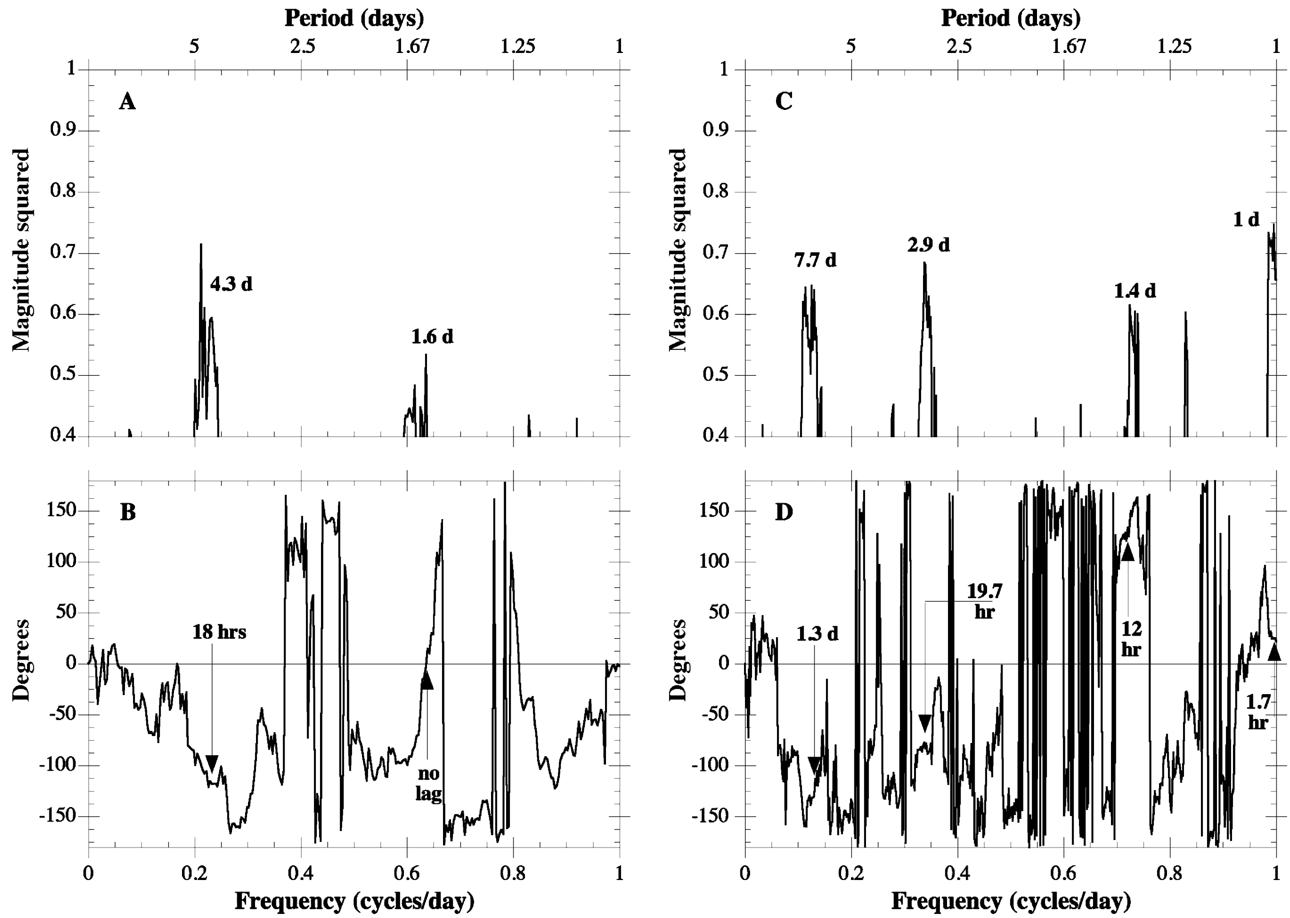

Fig. 4. Coherency and cross phase between S–N wind component and W–E wind component for 1995 (A,B) and 1996 (C,D) in the subtidal frequency band.

and 0.91 cm (32 cfs), respectively. In 1996, Winters Run had many more statistically significant, high power subtidal variations, but in all cases amplitudes were too low to affect delta hydrodynamics (Fig. 6). For Susquehanna River, statistically significant, high power subtidal variations occurred in both 1995 and 1996, with larger amplitudes occurring in 1996 (Fig. 7, note y-axis different scales). The amplitudes of these frequency components increased with increasing period. Overall, Susquehanna River had stronger subtidal cyclicity than Winters Run and the amplitudes of fluctuations were larger relative to the mean annual daily discharge.

Evolutionary power spectra for Winters Run watershed discharge over the entire 28-year record show that virtually no power is present at frequencies above 0.01 cycles per day (Fig. 8). Among the residual subtidal variations, there are no persistent features. The dominant periodic variation in the record is the annual cycle described in Section 1. The amplitude of that variation modulates over a 4–6 year period, which may be reflecting a regional periodic climate variation. Large storms and hurricanes that generate extremely high discharges in Winters Run drive spectral power down. During the years of this study the annual cycle has been near its peak amplitude, so a large magnitude flood may be due.

3.3. Water level

The mean water level observed at the OPC station was 0.2 m (0.66 ft) above the mudflat surface. Water level was less than 0.57 m (1.88 ft) ninety percent of the time. The maximum level of 1.91 m (6.25 ft) occurred on September 6, 1996 when Hurricane Fran passed to the west (discussed below). This peak was not associated with rainfall and streamflow in the basin, but rather with high winds out of the southwest and a storm surge that propagated up the bay ripping boats off their moorings as it went.

Power spectra of OPC water level records show well-defined tidal cycles and subtidal periodic variations (Fig. 9; Table 3). The same tidal constituents caused by astronomical cycles were present in both years, and those were the S_2 (12.00 h), M_2 (12.42 h), N_2 (12.66 h), K_1 (23.93 h), P_1 (24.07 h), and O_1 (25.82 h) cycles. The amplitude of the M_2 cycle (0.143 m) was several times

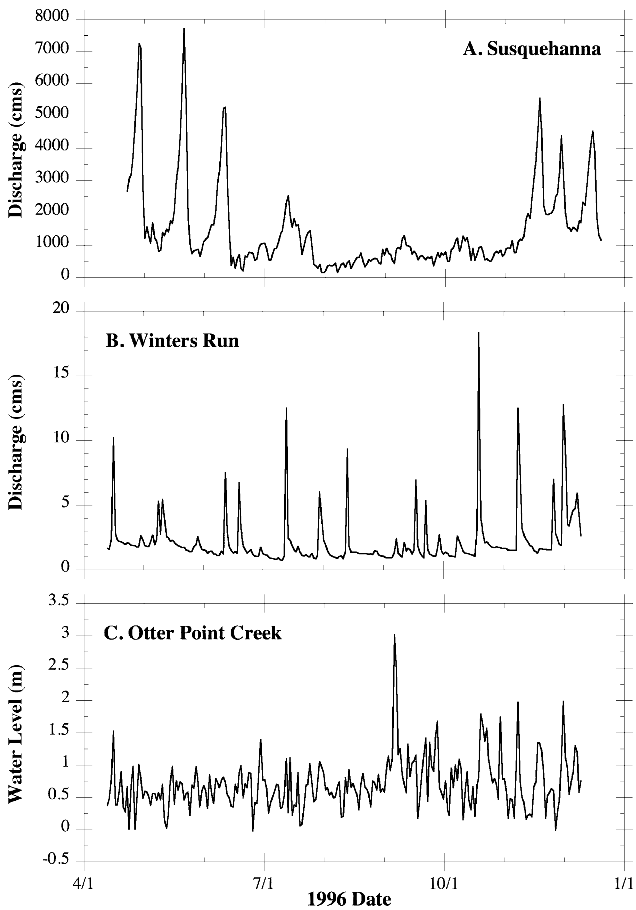

Fig. 5. April to December 1996 mean daily time series of (A) Susquehanna River discharge, (B) Winter's Run discharge, and (C) OPC water level. The highest OPC water level occurred when there was no peak in runoff. The highest Susquehanna River outflow did not affect OPC water levels. Winters Run outflow peaks did not correlate with OPC water levels.

larger than that of any of the others. A neap-spring tidal cycle was not observed in 1995, and barely registered in 1996 (significance = 0.932). The lack of this ~14-day variation in water level may be a result of the geometry of the Bush River basin.

The total power of frequencies <1 cycle per day was five times and 11% greater than that of diurnal and semi-diurnal components, respectively. Of the <1 cycle per day constituents in 1995, 1.7- and 2.2-day periodic variations were statistically significant but had low power. Water level variations with periods of 4.2, 5.2, and 110 days showed high power but were not statistically significant. In 1996, there were many more statistically significant, high power periodic variations in water level with periods of 2–8 days (Table 3), but none were the same as from 1995. Statistically significant longer period variations (11 and 245 days) were present with high power.

Evolutionary power spectra of OPC water level show persistent tidal cycles and unstable subtidal periodic

Table 2
Dominant frequency components in watershed discharge records (see Fig. 6)

Frequency (c/d)	Period (days)	Significance	Power	Amplitude (cm)
1995 Winter's Run				
0.326	3.07	0.882	Low	0.36
0.238	4.20	0.908	Low	0.33
0.131	7.63	0.817	High	0.65
0.080	12.5	0.890	High	0.50
0.050	20.0	0.769	High	0.60
0.010	100	0.940	High	0.91
1996 Winter's Run				
0.450	2.20	0.967	Low	0.23
0.418	2.39	0.965	Low	0.19
0.388	2.58	0.954	Low	0.22
0.287	3.48	0.990	High	0.38
0.255	3.92	0.988	High	0.37
0.226	4.42	0.976	High	0.35
0.195	5.13	0.974	High	0.44
0.147	6.80	0.983	High	0.48
0.126	7.94	0.960	High	0.41
0.099	10.1	0.953	High	0.59
0.091	11.0	0.972	High	0.62
0.06	16.7	0.955	High	0.59
0.032	31.3	0.954	High	0.52
1995 Susquehanna River				
0.377	2.65	0.964	Low	9.6
0.350	2.86	0.996	Low	15
0.134	7.46	0.829	High	119
0.084	11.9	0.875	High	185
0.043	23.3	0.875	High	304
0.009	111	0.918	High	363
0.008	125	0.931	High	363
0.007	143	0.908	High	346
1996 Susquehanna River				
0.499	2.00	0.977	Low	12
0.397	2.52	0.993	Low	24
0.359	2.79	0.981	Low	30
0.286	3.50	0.990	Low	75
0.187	5.35	0.968	High	130
0.145	6.90	0.930	High	191
0.094	10.6	0.904	High	336
0.050	20.0	0.811	High	488
0.017	58.8	0.428	High	524
0.005	200	0.917	High	823

variations (Fig. 10). The subtidal variations show the most power in April and from September through December. Almost no power was present in the subtidal frequencies during July and August. This seasonal variability may be reflecting the same trend in wind (cf. Fig. 3). Unfortunately, freezing winter conditions prevent longer records from being collected on the delta.

3.4. Relations between external controls and water level

The S–N wind component and OPC water level have several bands of highly coherent frequencies. In 1995,

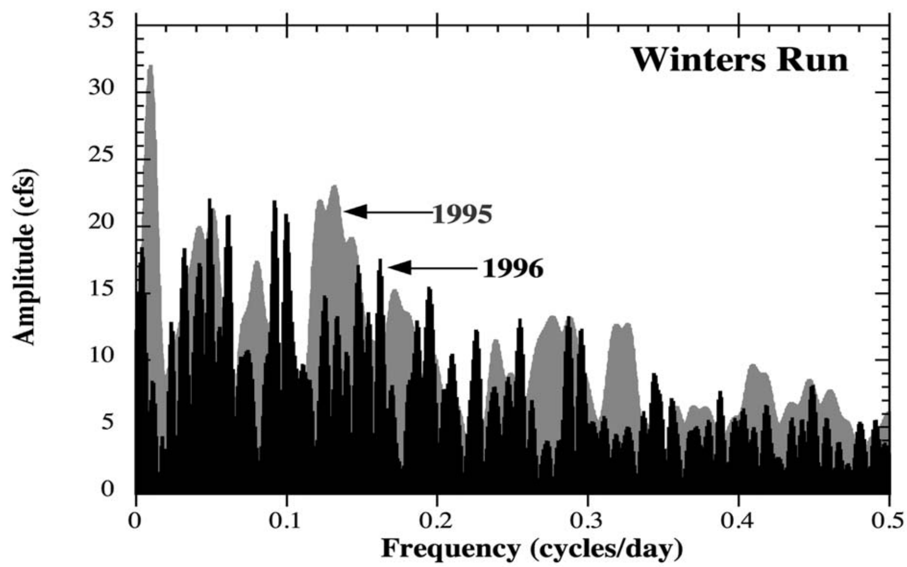

Fig. 6. Harmonic analysis of Winters Run discharge for 1995 (light gray) and 1996 (black).

coherency was strongest at periods of 1.6–1.8, 2.5–2.8, and 3.8–5.6 days (Fig. 11A). The corresponding cross phases show positive correlations for these subtidal frequencies, with water level changes following wind vector changes at time lags of 0–4 h (Fig. 11B). For 1996, coherency was strongest for cycles of 2.4–2.6, 2.8–3.0, and 7 days (Fig. 11C). The corresponding cross phases again show positive correlations for subtidal frequencies, but the time lags in 1996 were 8.8, 5, and 0 h, respectively (Fig. 11D).

As wind blows harder to the north, water in Chesapeake Bay is pushed into Bush River and up into OPC delta. The highest coherency between S–N wind and water level was 0.95, and that was for the 7-day periodic variation in 1996. Harmonic analysis showed that this variation has the largest amplitude of all statistically significant, high power frequencies, except for the diurnal cycle. The negligible time lag between the 7-day wind variation and water level changes means that water level rapidly responds to wind speed changes at that frequency. Higher frequency wind variations have lower amplitudes (Table 1) and their cross phases with water level show the water level response lags by up to 9 h.

The W–E wind component shows some coupling with water level, but to a significantly lesser extent than the S–N component. For 1995, coherency was strongest at periods of 1.6, 3.3, 4.3, and 75 days (Fig. 12A).

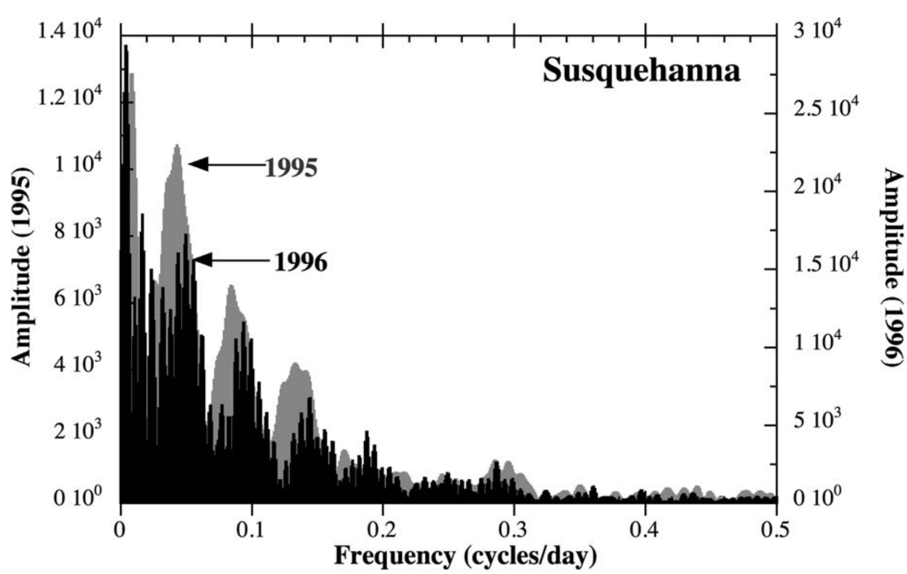

Fig. 7. Harmonic analysis of Susquehanna River discharge for 1995 (light gray, left y-axis) and 1996 (black, right y-axis).

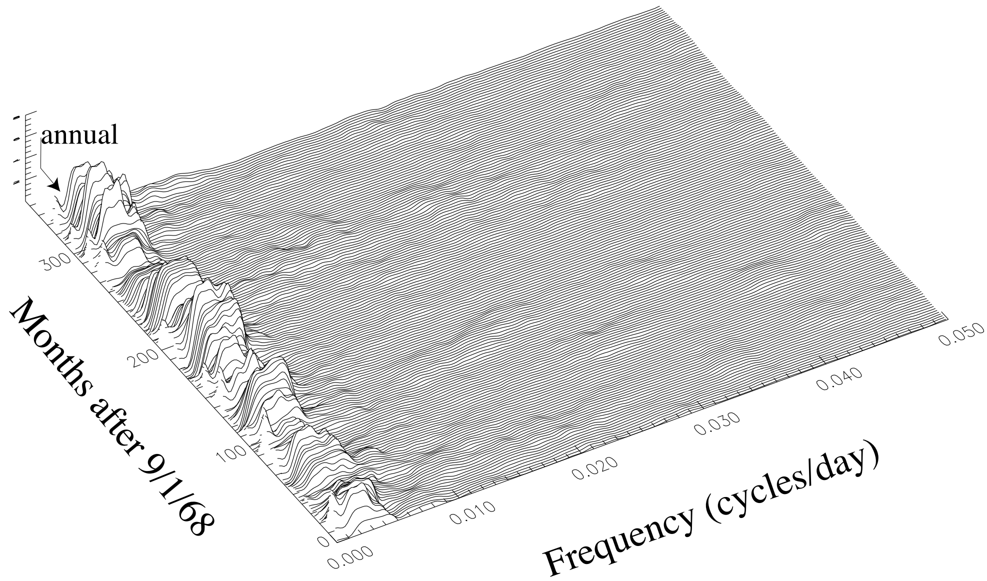

Fig. 8. Evolutionary power spectra of the logarithm of Winters Run watershed discharge from August 1, 1968 to December 31, 1996.

Corresponding cross phases for the subtidal constituents show negative correlations between the two variables, with the drop in water level following an increase in wind speed out of the west at time lags of 0, 19.5 h, and 1 day, respectively (Fig. 12B). In 1996 coherency was significantly lower, but strong coupling existed for 2.9- and 7.7-day periodic variations (Fig. 12C). Corresponding cross phases show the same negative correlations as in 1995, with time lags of 12.7 h and 1.6 days, respectively (Fig. 12D).

To understand the relation between W–E wind and water level it is important to consider the coupling between W–E wind and S–N wind. In 1995, the time lags between W–E wind and S–N wind variations were ~0 and ~18 h for the 1.6- and 4.3-day periodic variations, respectively. Meanwhile, time lags between S–N wind and water level variations were always less than 4 h. Adding these two together results in W–E wind versus water level lags of 0 and ~18–22 h for the 1.6- and 4.3-day cycles, respectively. These corroborate the results of the coherency analysis between W–E wind and water level, which showed that their coupling actually had lags of ~0 and ~24 h for the 1.6- and 4.3-day cycles, respectively. The interpretation is that the 4.3-day variation in W–E wind speed reaches its peak value first and then almost a day later the 4.3-day variations in S–N wind velocity and water level reach their peaks, with S–N wind slightly preceding water level. As a result, water level changes occur in response to S–N wind, and the relation of W–E wind versus water level is an artifact of the coupling between W–E wind and N–S wind. The same results and interpretations are evident for 1996.

All wind versus water level coherency analyses except that for 1995 W–E wind show significant coupling at frequencies just below one cycle per day. For 1995 W–E wind the analysis does not show significant coherency because of the low diurnal spectral power and absence of a significant harmonic line component during that time (Figs. 2B and 3B). The power spectral and harmonic analyses of the other wind records show a highly significant diurnal cycle (Fig. 2A, C, D). For water level, the analyses show the presence of a cycle with a period just under 24 h (K_1 component) and another with a cycle at 25.82 h (O_1 component). The coherency between the two variables falls within the range of these two frequencies. Thus, the coherency results in this frequency range are likely due to averaging across the K_1, P_1, and O_1 tidal constituents. The cross phases in this frequency range (Figs. 11B, D, and 12D) point to increases in water level following decreases in S–N or W–E wind speed by 8–12 h. Since these water level changes are identifiable as tidal driven and not meteorologically driven, the results are interpreted to mean that two distinct cycles—one in water level and one in wind speed—are occurring at nearly the same tidal frequency but without significantly influencing each other.

Watershed discharge and water level have fewer and less significant coherent frequencies than wind versus water level. For 1995, high coherency occurred with 3.4- and 4.4-day variations with respect to Winters Run (Fig. 13A) and only the 3.4-day variation with respect to Susquehanna River (Fig. 14A). Corresponding cross phases show positive relationships with increases in watershed discharge following increases in water level. For Winters Run the time lags were of 11.8 and 11.3 h, respectively (Fig. 13B), while for Susquehanna River the time lag was 1.7 days (Fig. 14B). In 1996 there were more coherent frequencies for both rivers, but in this

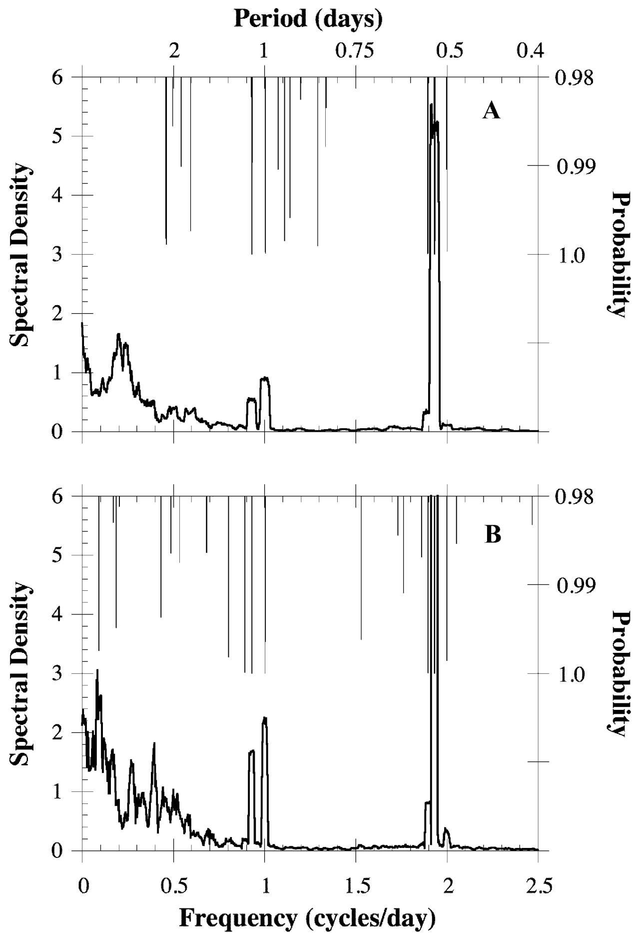

Fig. 9. Power spectra (dark curve) and statistical significance (vertical lines) of OPC subestuarine water level for (A) 1995 and (B) 1996.

Table 3
Dominant frequency components in OPC water level records (see Fig. 9)

Frequency (c/d)	Period (days)	Significance	Power	Amplitude (m)	Darwin code
1995 OPC water level					
2.00	0.500	0.999	Low	0.017	S2
1.93	0.518	0.999	High	0.134	M2
1.89	0.528	0.999	Low	0.032	N2
1.00	1.00	0.999	High	0.050	P1,K1
0.930	1.08	0.999	High	0.044	O1
0.594	1.68	0.997	Low	0.027	
0.462	2.16	0.999	Low	0.023	
0.240	4.17	0.671	High	0.030	
0.192	5.21	0.846	High	0.038	
1996 OPC water level					
2.00	0.500	0.999	Low	0.017	S2
1.932	0.518	0.999	High	0.143	M2
1.893	0.528	0.999	High	0.031	N2
1.00	1.00	0.999	High	0.053	P1,K1
0.930	1.08	0.999	High	0.047	O1
0.432	2.32	0.994	Low	0.022	
0.392	2.55	0.285	High	0.012	
0.338	2.96	0.968	Low	0.022	
0.265	3.76	0.81	High	0.022	
0.187	5.36	0.995	Low	0.026	
0.170	5.88	0.983	High	0.033	
0.155	6.43	0.964	High	0.029	
0.131	7.65	0.951	High	0.031	
0.091	11.0	0.997	High	0.045	
0.071	14.2	0.932	High	0.029	

instance the two basins do not match. Winters Run discharge and water levels showed coherence at 2.6-, 5.4-, and 12.1-day variations (Fig. 13C), while Susquehanna River discharge and water levels showed coherence at 2.2-, 3.9-, 5.2-, and 10.8-day variations. The cross phases again show a positive correlation, with time lags of 8.4, 10.8 h, and 1.46 days for Winters Run (Fig. 13D) and 1–3 days for Susquehanna River. All but two of the coherent frequencies (12.1 and 86 days) between Winters Run watershed discharge and OPC water level for both years overlap with those between wind and water level. As a result, the interrelationships between watershed discharge and water level are an artifact of those between S–N wind versus water level and S–N wind versus discharge. By the same reasoning used earlier to explain W–E wind conditions, changes in runoff must be coupled to changes in S–N wind. This could be the case if precipitation and S–N wind are coupled, and the time for rainfall to become runoff in the Winters Run basin is ~12 h. Corroborating this is a recent hydrologic study of the rainfall–runoff relationship in Winters Run watershed that found a 'time of concentration' of 11.2 h (NIER, 1996). Because the Susquehanna River basin is so much bigger than the Winters Run basin, localized storm cells that affect the latter often do not affect the former, yielding different coherency patterns between the two when related with subestuarine water levels.

Standard statistical correlations between mean daily records of Winters Run discharge, Susquehanna discharge, and OPC water levels yielded no statistically significant relations. The overall correlations (R^2) between Winters Run and OPC records for 1995 and 1996 were 0.08 and 0.02, respectively. For Susquehanna River and OPC they were 0.00 and 0.01, respectively. When a subset of the Winters Run data containing only runoff peaks greater than 3 cm was isolated (13 days in 1995 and 29 days in 1996), correlations improve slightly—0.07 and 0.14 for 1995 and 1996, respectively—but remain statistically insignificant. For a Winters Run discharge of 3 cm, OPC water levels ranged widely from 0.05 to 0.43 m. For a discharge of 10 cm, OPC levels ranged from 0.17 to 0.46 m. Thus, there was no systematic relation between watershed discharge and subestuarine water level in either the frequency or time domains during the study period. Further time domain inspection and analysis of discharge and water level data were performed for hurricane events.

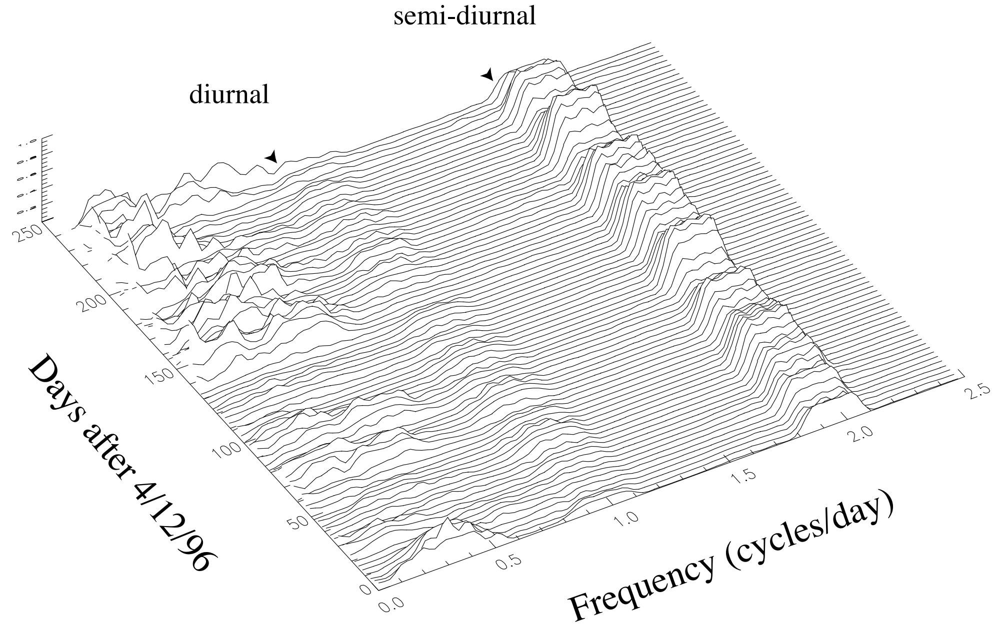

Fig. 10. Evolutionary spectra of OPC subestuarine water level from April 12, 1996 to December 11, 1996.

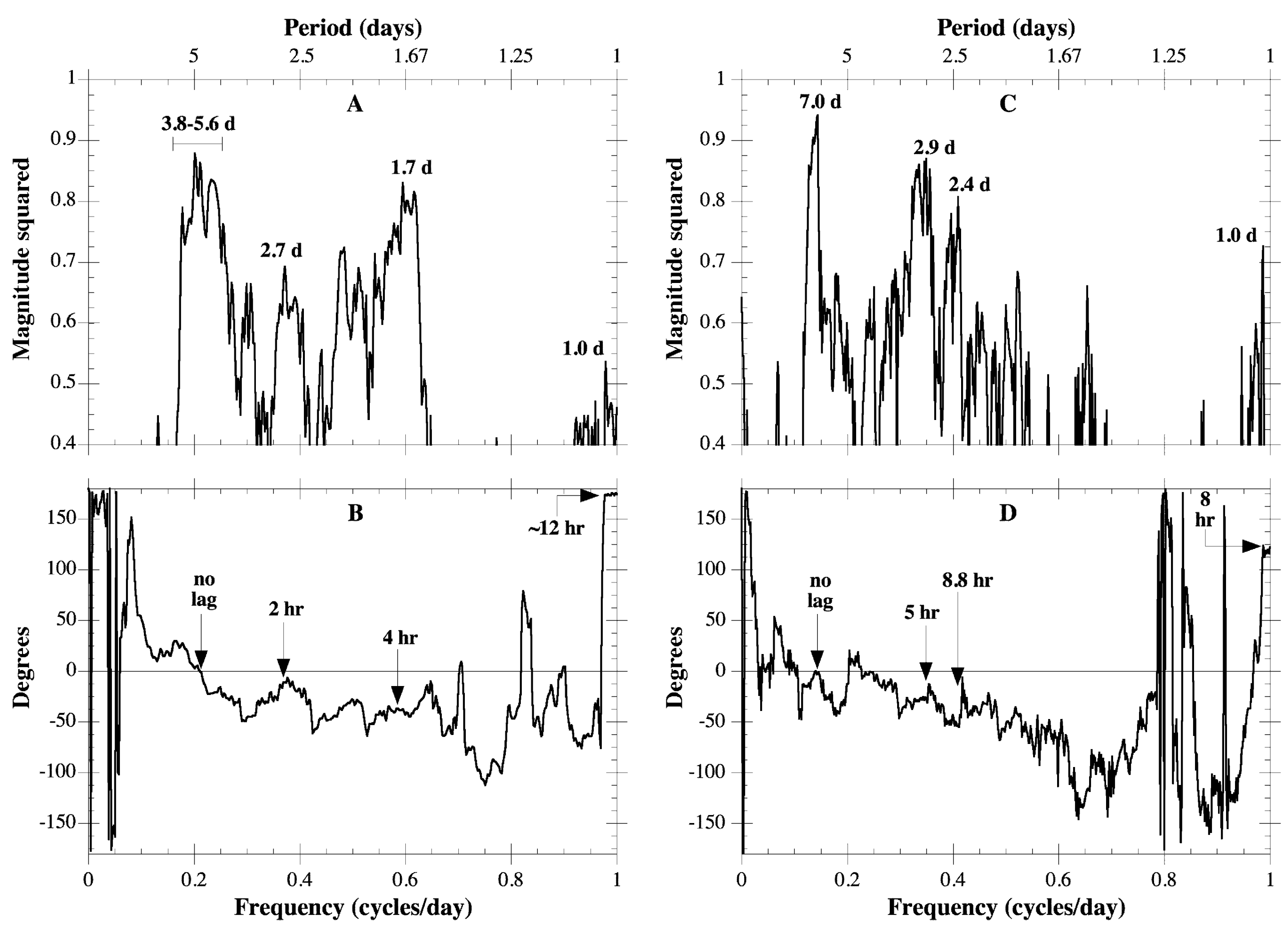

Fig. 11. Coherency and cross phase between the S–N wind component and subestuarine water level for 1995 (A,B) and 1996 (C,D).

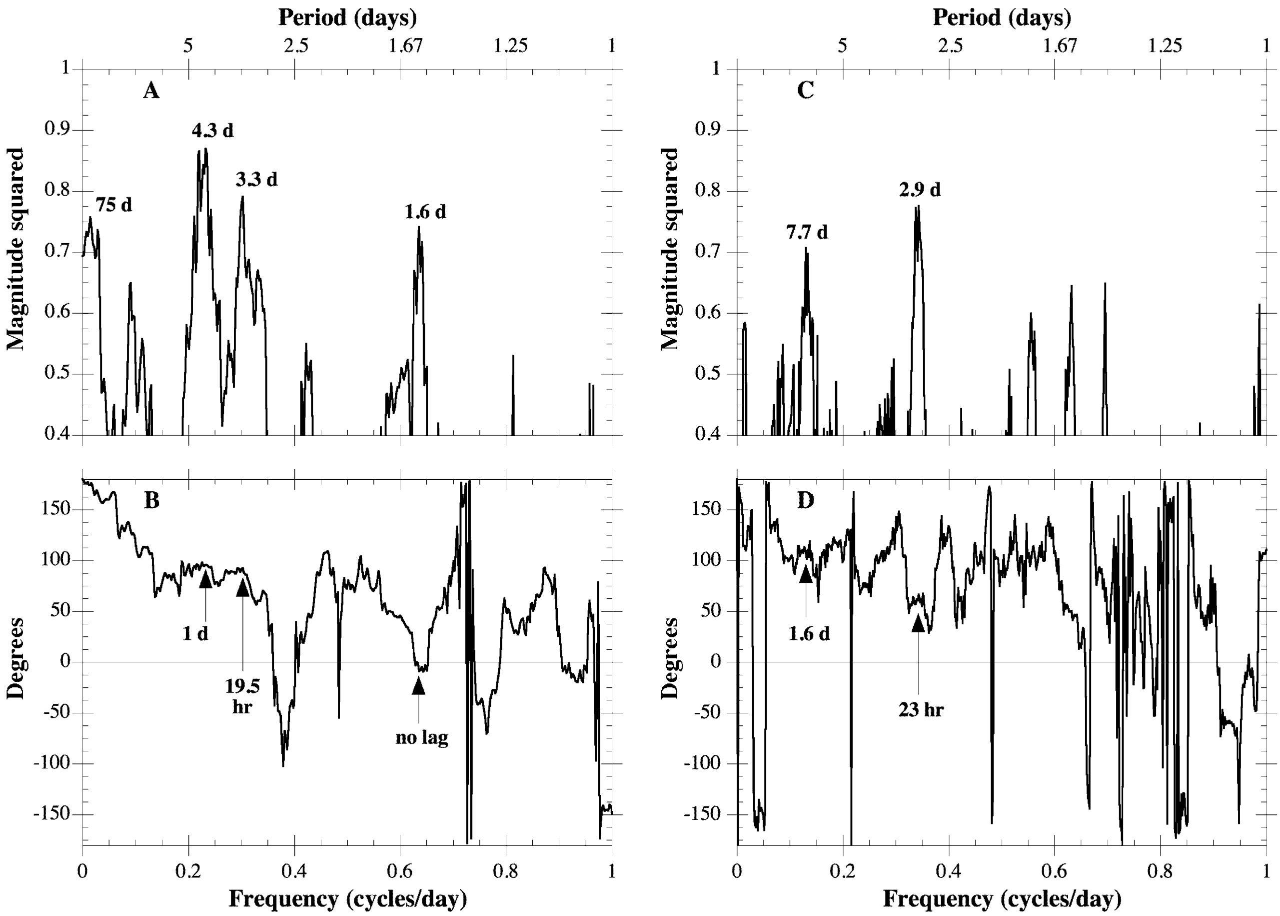

Fig. 12. Coherency and cross phase between the W–E wind component and subestuarine water level for 1995 (A,B) and 1996 (C,D).

3.5. Hurricane hydrometeorology

Hurricanes Felix, Opal, Bertha, Edouard, and Fran passed by OPC during the 1995 and 1996 Atlantic hurricane seasons, though none tracked directly over the site or its watershed (Fig. 15). Each storm had a distinct impact on wind, rain, runoff, and water level in the delta. Plots of the time series of hydrometeorological conditions at OPC during these storms illustrate the dynamics summarized by the above time series analyses.

Tropical storm Felix reached hurricane strength on August 11, 1995 and approached the North Carolina coast on August 16 (Fig. 15). As it approached the coast, the storm stalled and caused a significant storm surge that impacted North Carolina. OPC data from August 15 to 19 showed a normal tidal variation (Fig. 16). During that period, there was a little rain and slowly declining runoff. Winds were predominantly out of the NE, causing a direct conflict between the water level impact of the southerly wind component (which blows water out of OPC) and the westerly wind component (which blows water into OPC). Times of highest NE wind speeds coincided with high tides and caused a decrease in peak water level (Fig. 16). This decrease shows that the S–N wind overcomes the W–E wind at similar wind speeds, presumably due to its larger fetch (12.7 versus 4.2 km). On August 19, the water level in OPC rose substantially and did not return to a normal tidal range until August 22. No rain occurred during this period and runoff was uniformly low. The increased water level was apparently the storm surge from Hurricane Felix that propagated up Chesapeake Bay. The storm surge may have been aided by strong afternoon winds out of the south each day August 20–22. Late on August 22, a strong wind out of the NNW produced a combined S–N and W–E wind effect that blocked the normal semi-diurnal tide from approaching OPC. Even though Hurricane Felix did not enter Chesapeake Bay, its impact on coastal ocean conditions ultimately changed upper bay tributary water levels. According to the data of Pasternack and Brush (1998) it also resulted in a spike of sedimentation throughout the marshes in OPC.

The due north track of Hurricane Opal from the Gulf of Mexico to Lake Superior made that storm unique among the ones reported here (Fig. 15). Hurricane Opal peaked at category 4 on the Saffir/Simpson Hurricane

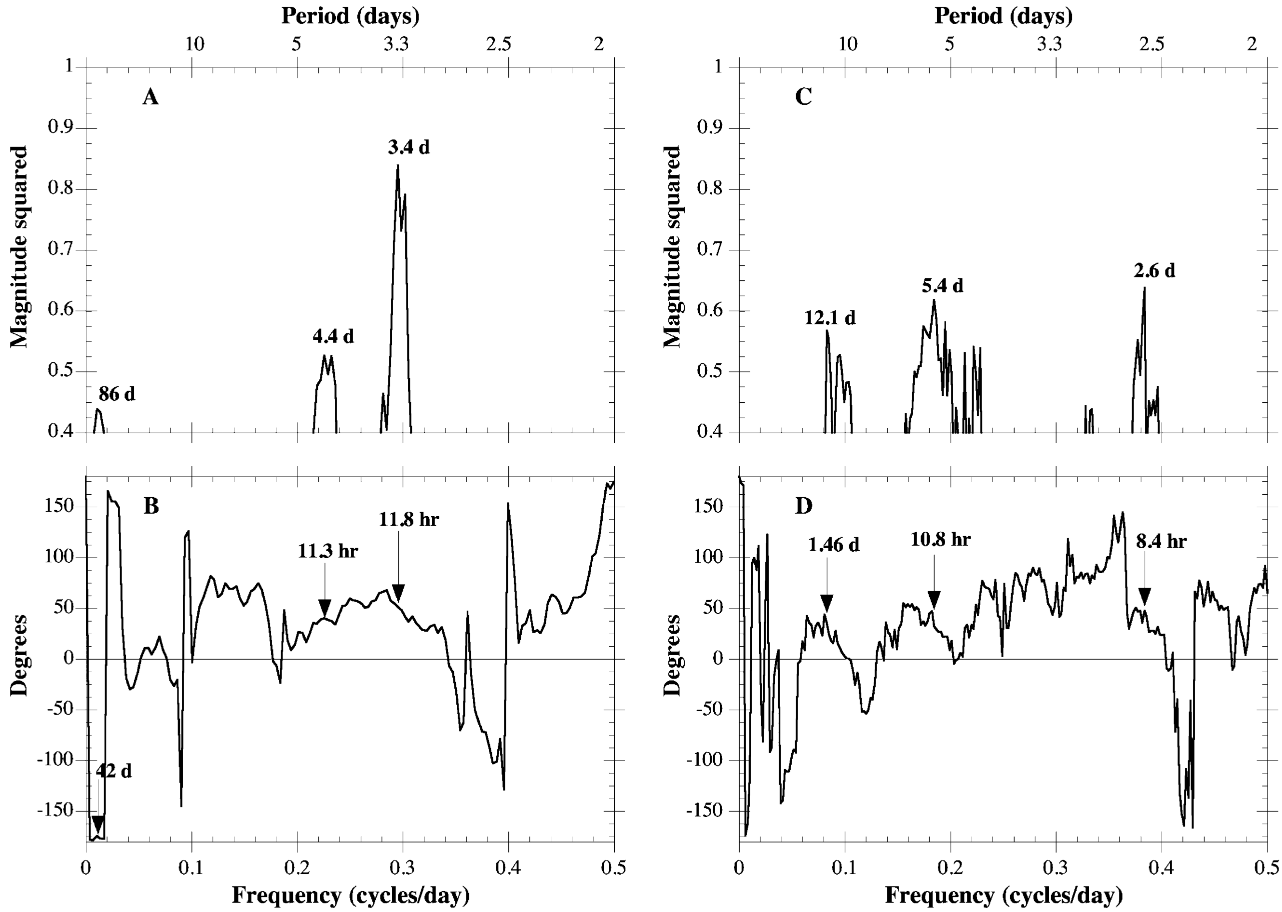

Fig. 13. Coherency and cross phase between Winters Run discharge and subestuarine water level for 1995 (A,B) and 1996 (C,D).

Scale early on October 4, but when it crossed over land it rapidly weakened. By the time it was due west of OPC on October 5, the storm was downgraded to extratropical. Two bursts of precipitation were recorded on October 5, as the storm passed, with peaks of 3.56 and 8.89 mm h^{-1}, respectively (Fig. 17). Winters Run runoff averaged 4 cm that day, which is above the mean daily flow, but only 33% of the statistical bankfull discharge ($Q_{1.5}$) for that stream, indicating that it had little hydrologic or geomorphic effectiveness. OPC water levels did not rise as Winters Run runoff rose. Measurement of discharge (using the velocity–area method) in HaHa Branch, the small tributary entering OPC from the north, showed a negligible flow of 0.03 cm at 10:00 a.m. on October 5. S–N and W–E wind velocities on October 3–5 were opposing, but the former were as much as four times as high as the latter (Fig. 17). The second low tide on October 3, the first high tide on October 4, and the first low tide on October 4 all show higher than normal water levels in response to the high S–N wind speed. When S–N wind speed subsequently dropped, the peak high and low tides correspondingly dropped. Midday on October 5 S–N wind speed reached a maximum (7.1 m s^{-1}) at the same time that rainfall was most intense. Even though the peak astronomical high tide had already passed by then, a second water level spike occurred 1 h after the S–N wind spike. The subsequent low tide level was higher than mean high tide, and it was followed by an extremely high high tide. The primary impact of extratropical storm Opal on OPC was to sustain high wind speeds out of the south causing a large rise in OPC water level. This rise occurred despite an opposing W–E wind, again illustrating the predominance of the S–N wind component.

Hurricane Bertha was the storm with the greatest potential of directly hitting OPC, but it weakened over North Carolina and passed to the south of the site (Fig. 15). A peak rainfall intensity of 146 mm h^{-1} occurred early on July 13, 1996 (Fig. 18). Winters Run streamflow averaged 12.5 cm that day, which was very close to the statistical bankfull discharge, indicating the potential for significant sediment transport into OPC. At that time wind components were opposing each other, with the upriver E–W wind speed exceeding the downriver N–S wind speed by 2 m s^{-1}. Initially, OPC water level rose higher than normal, likely in response to both the wind

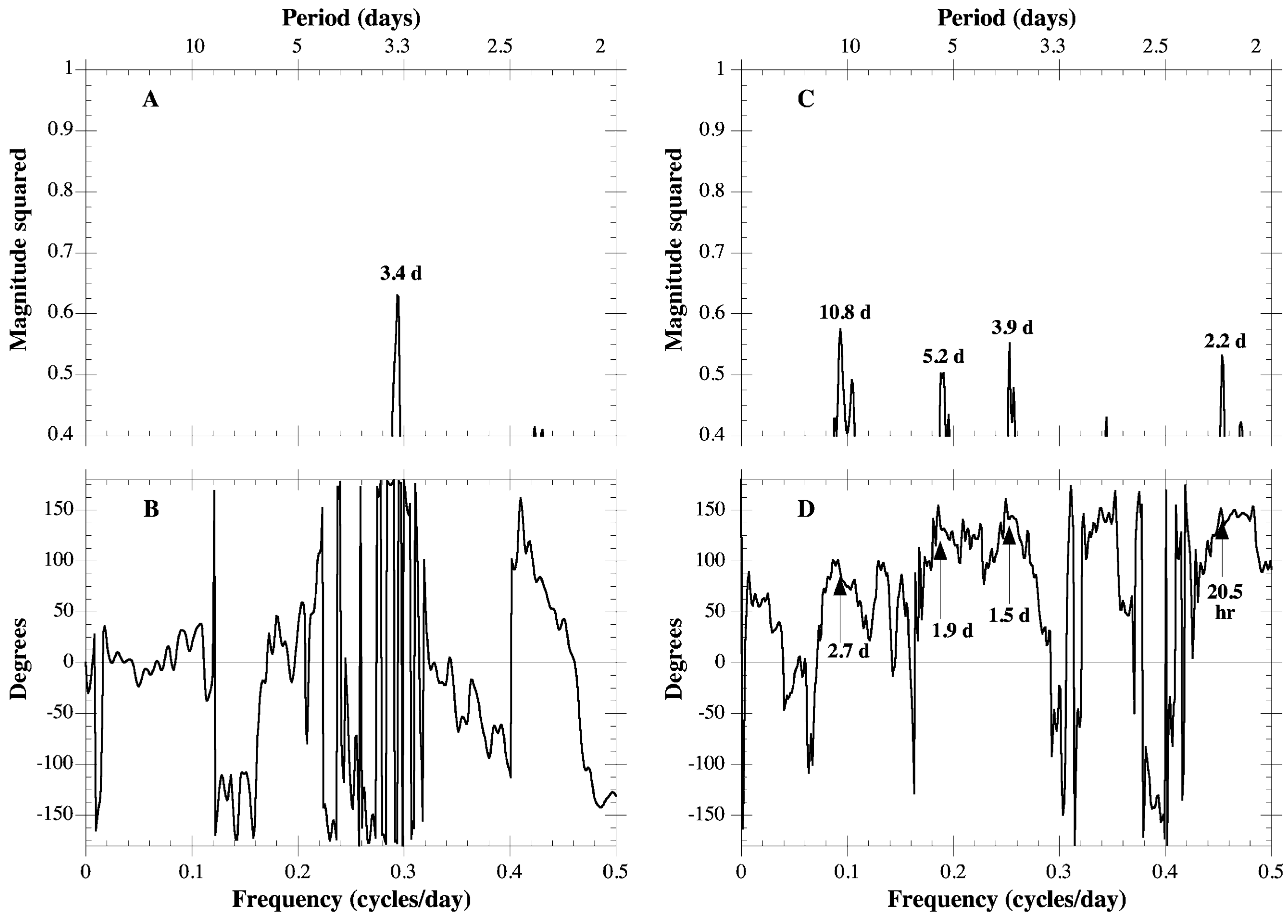

Fig. 14. Coherency and cross phase between Susquehanna River discharge and subestuarine water level for 1995 (A,B) and 1996 (C,D).

speed and runoff, but then the wind shifted to out of the NW and increased in speed to 5.4 m s^{-1} at 10:00 a.m. This wind direction enabled the two components to work together in pushing water out of OPC. The result

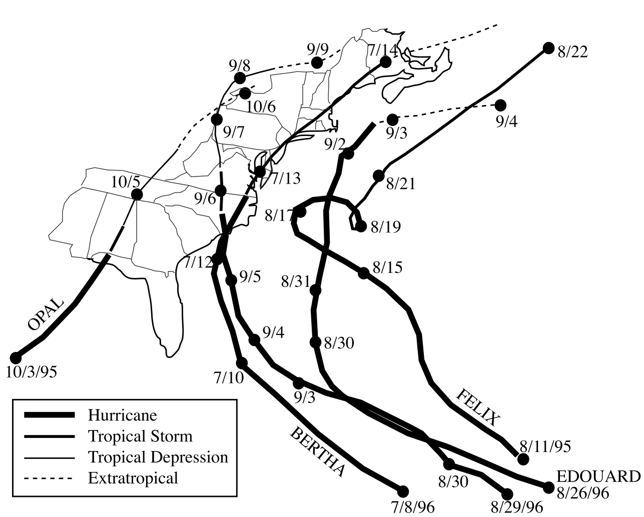

Fig. 15. Map of hurricane tracks showing the change in strength and position of each storm over time.

was an unusual triple peak high tide midday on July 13 (Fig. 18). After the storm passed, the wind components switched to opposition again (out of the SSW). On July 15 the S–N wind speed increased substantially, and that induced the highest water level of the period, even when watershed runoff was greatly reduced. When S–N wind speed dropped and W–E wind speed rose following that period, the next high tide was lower in response.

Hurricanes Edouard and Fran approached the Atlantic seaboard within 3 days of each other in late August–early September, 1996, but they did not follow the same path. Edouard took an oceanic track similar to Hurricane Felix the year before, while Fran passed over the mid-Atlantic states west of Chesapeake Bay (Fig. 15). Only a small amount of precipitation (2.5 mm) was recorded at Aberdeen Proving Ground during the time the storms passed, and that rain coincided with the passage of Fran (Fig. 19). A bigger, unrelated rain event occurred after Fran. No significant deviation form normal conditions were evident August 31–September 3 as Hurrican Edouard passed. Unlike Felix, Edouard did not stall, and its quick passage did not cause a storm surge in Chesapeake Bay. In contrast to Edouard, Fran brought strong winds (up to 6.3 m s^{-1}) out of the

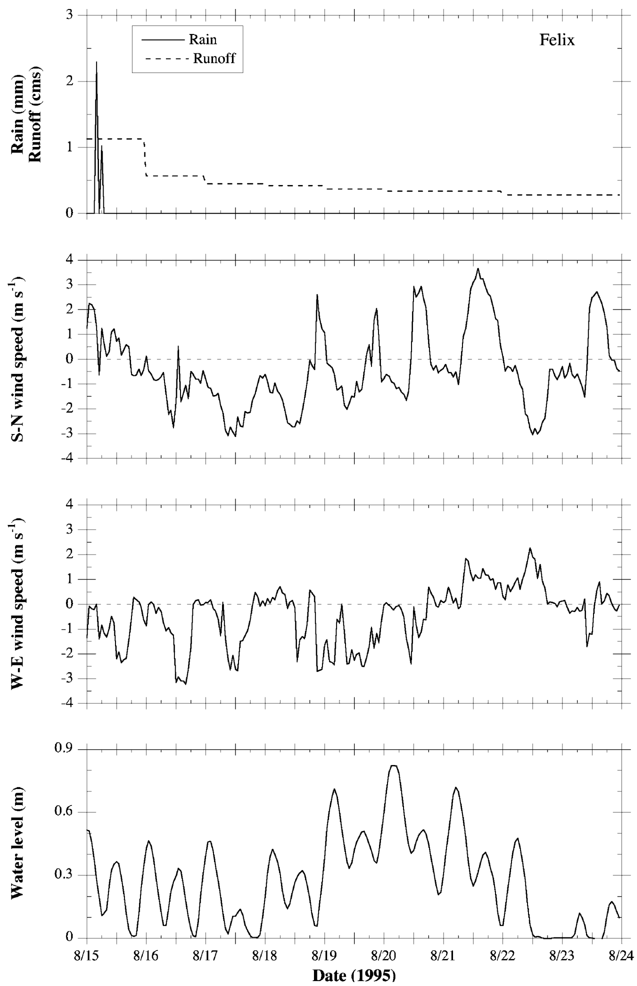

Fig. 16. OPC hydrometeorological conditions and Winters Run discharge when Hurricane Felix passed by the Atlantic coast of United States.

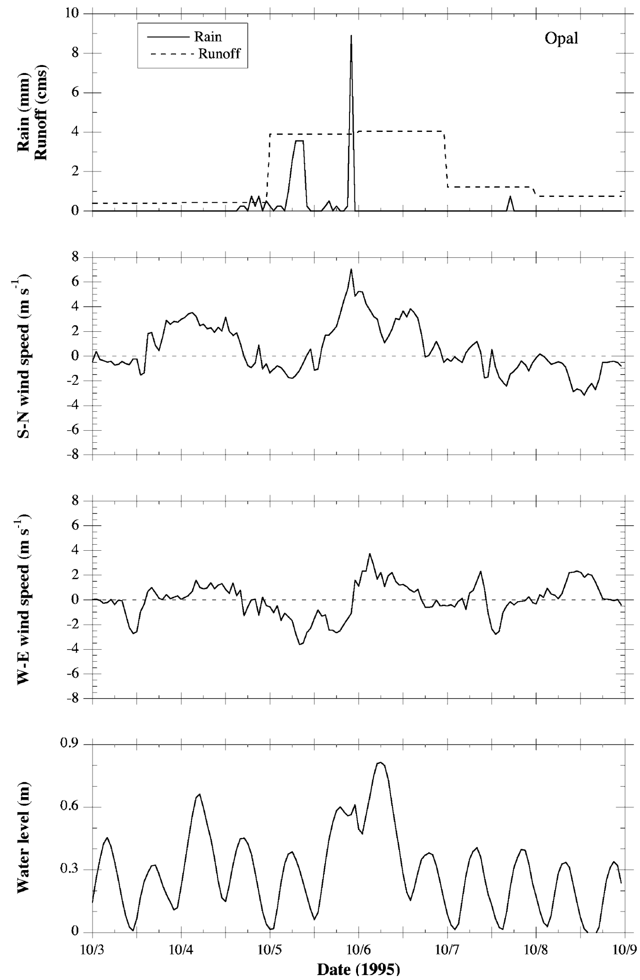

Fig. 17. OPC hydrometeorological conditions and Winters Run discharge when Hurricane Opal passed over eastern United States.

southeast late on September 6. A storm-enhanced high tide propagated up the bay at the same time (Fig. 20). These two conditions combined to produce the highest water levels recorded at OPC during this study. Lower Chesapeake Bay water levels quickly returned to normal, but north of Point Lookout, MD high water levels were sustained over a 24 h period until the S–N wind finally diminished midday on September 7 (Fig. 19). Once again, significant changes to OPC water levels occurred with no significant Winters Run runoff.

4. Discussion

Time series analysis of 2 years of data from the head of the Bush River tributary to upper Chesapeake Bay shows that astronomical tides and nontidal wind forcing are responsible for water level variations at time scales less than 20 days. Wind operates at multiple significant frequencies that fluctuate over weeks to months, but persist interannually. The amplitudes of these frequencies modulate through time, with the highest values in winter and the lowest in summer. The amplitude of water level changed significantly in response to winds at the various frequencies at which forcing was applied. The short time lag (~2–8 h) between wind speed changes and water level changes for 2–5 day quasi-periodic variations is a small percentage of the duration of wind forcing (2–5 days), indicating that water level is responding to wind forcing and not just showing a spurious correlation. The S–N wind component was stronger than the W–E component on average, and it blows over a fetch that is 3.8 times as long. Also, this wind component lines up with the geometry Chesapeake Bay and is known to drive a quarter-wave seiche (Boicourt et al., 1999). Thus, the combination of local and bay-wide responses to S–N wind forcing is the primary cause of subtidal water level variations at OPC.

The 7-day wind speed variation observed in Aberdeen Proving Ground data has been reported elsewhere around Chesapeake Bay (Wang, 1979a), so it is likely part of a regional phenomenon affecting the whole

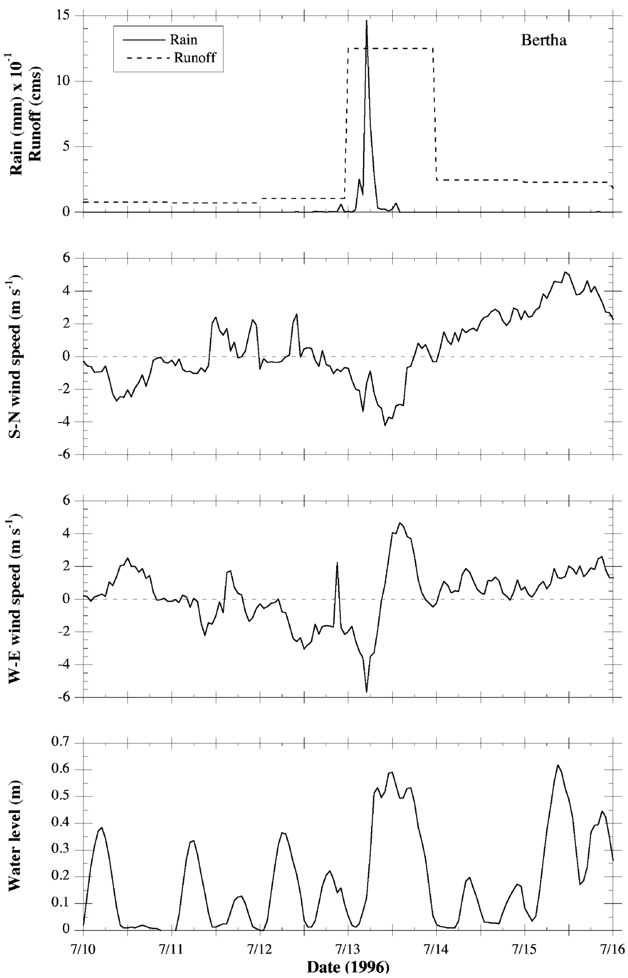

Fig. 18. OPC hydrometeorological conditions and Winters Run discharge when Hurricane Bertha tracked along the Atlantic coast of United States. This storm went over lower Chesapeake Bay on July 13, 1996.

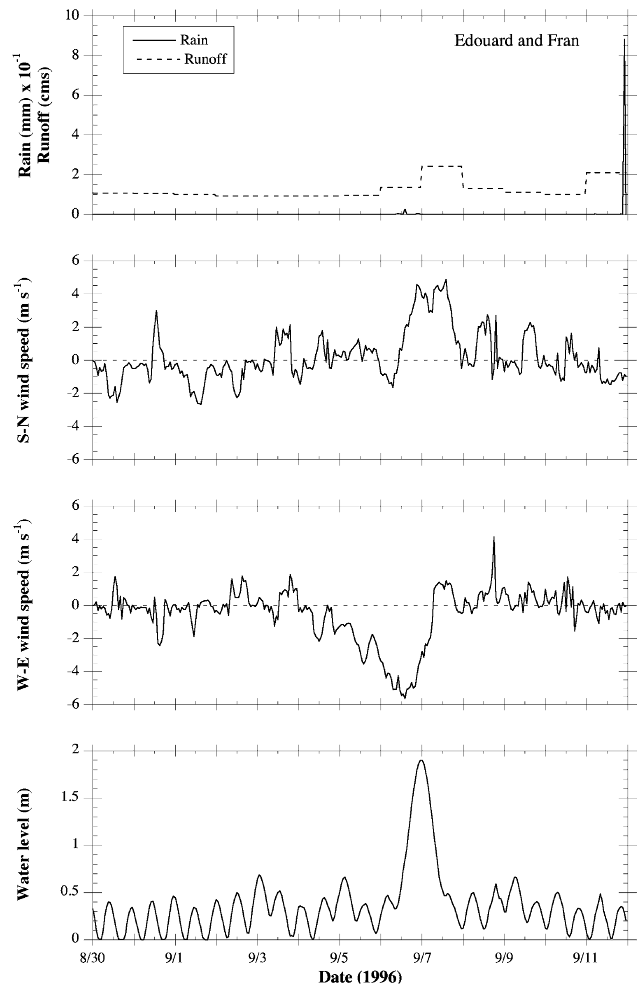

Fig. 19. OPC hydrometeorological conditions and Winters Run discharge when Hurricane Edouard passed by the U.S. Atlantic coast and Hurricane Fran passed over eastern United States.

estuary. In terms of water level impacts, Bush River is aligned with the S–N longitudinal axis of Chesapeake Bay, so the S–N 7-day wind variation occurs over an enormous fetch leading into OPC. The relation between wind and water level at this frequency was very strong in 1996, but according to harmonic analysis, the amplitude of water level response was just 3 cm. In the main bay, such a small change in water level may be insignificant. However, on the OPC delta a 3-cm increase in water level has a significant impact on marsh ecology. For example, the bed surface in the intertidal zone dominated by Spatterdock, a floating leaf plant species, has a slope of 1 cm vertical per 36-cm horizontal. In this zone, a 3-cm increase in water level floods an additional 14 ha of vegetation.

A comparison of hydrometeorological conditions between 1995 and 1996 shows that while the overall hydrometeorology of OPC was very similar between the two years, 1996 experienced more statistically significant subtidal variations in all processes due to La Niña. In terms of wind, the mean and standard deviation of wind speed for the two years were nearly identical and both years experienced multiple subtidal variations in wind that were statistically significant, high power, and high amplitude (Table 1). However, the total amplitude of statistically significant subtidal wind variations was 41% greater in 1996 than in 1995 and two additional periodic components occurred in 1996. The temporal variation in spectral density for wind (Fig. 3) showed the same overall pattern in both years, but there was a maximum during spring 1996 when there were frequent rain events. In contrast to wind, watershed discharge from Winters Run showed many statistically significant subtidal variations in 1996 but few in 1995 (Table 2), though this is partly attributable to differences in record length. The 1996 components were likely a direct response to the wetter conditions and quasi-periodic storm fronts associated with the La Niña condition. Susquehanna River did not show the differences observed for Winters Run. Water levels at OPC showed the most differences in subtidal variations between the two years, but again

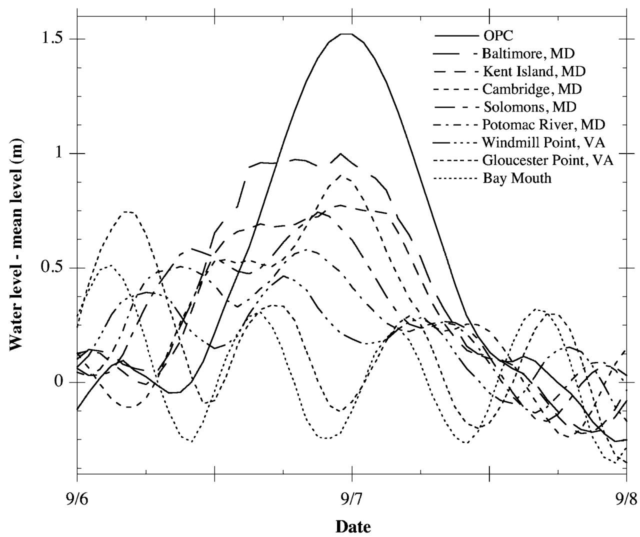

Fig. 20. Deviation from mean August 31–September 11, 1996 water level during Hurricane Fran in Chesapeake Bay according to data from the NOAA NOS coastal water level database.

caution is required because the record was longer in 1996 than 1995, and for the water level response this difference notably included much of the volatile spring conditions when wind was strong and highly variable. In 1995, statistically significant subtidal variations accounted for 16 cm of water level change whereas in 1996 they accounted for 32 cm (Table 3). The greater number of subtidal variations in 1996 yielded a greater range of statistically significant coherent frequencies between wind and water level variations in the principal wind direction of S–N (Fig. 11A, B). During the milder weather conditions of 1995 W–E wind played a greater role in modifying water level than it did in 1996.

Hydrometeorological conditions in OPC during the passage of hurricanes illustrate the predominant role of the S–N wind component in determining the water level on an event basis. Even when opposed by W–E winds of equal magnitude, S–N winds can significantly change water level. When wind blows out of the SE or NW, the two components work together and are able to completely offset either a low or high tide, respectively. The only other process observed to impact OPC water levels as much as this on an event basis was remotely induced storm surge.

Watershed discharge—both local as well as from Susquehanna River—has virtually no impact on water level at OPC under the observed conditions. Whereas runoff volume entering large tributaries such as Potomac River constitutes a large proportion of tributary storage, the volume into small tributaries such as Bush River is hydrologically and hydrodynamically insignificant under most conditions. For the 2 years studied, the mean 12-h inflow volume is equal to just 0.6% of the intertidal volume. One potential source of watershed influence on tributary hydrodynamics could be rain-on-snow events, but during such times mudflats at the heads of these tributaries are usually frozen. Watershed discharge could have the greatest impact during hurricanes, but at those times remote coastal forcing drives extreme water level fluctuations in the estuary, which swamps out the riverine signal, especially at the heads of the small tributaries where the surge is enhanced by geometric funneling. Thus, while watershed processes control sediment delivery to the tidal freshwater zone (Pasternack et al., 2001), estuarine processes control tidal freshwater hydrodynamics.

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