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Coastal Water Level Measurements, Northeast Gulf of Mexico

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ABSTRACT

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Eight months (April-November) of National Ocean Survey water level data from an unprotected open coast site (Gulf Shores, AL) and a protected coastal embayment site (Dauphin Island, AL), have been compared with each other and with the local winds (Dauphin Island, AL). The subtidal records have similar shape and show no statistical difference in sample variance or spectrum levels between sites. Although not statistically different, the subtidal spectrum levels are higher in the fall and spring and lower in the summer at the protected site. Cross-spectral analysis between the subtidal records and the wind stress components indicate similar response at both sites. In general, subtidal water level records are coherent over broader frequency bands with the alongshore wind stress than with the across-shore wind stress. The protected site water level is coherent with alongshore wind stress at higher subtidal frequencies in the spring and fall and lower subtidal frequencies in the summer, than the open coast water level. Neither water level is coherent with the across-shore wind stress in the spring or summer, and only in a narrow band in the fall.

ADDITIONAL INDEX WORDS: *Coastal embayment, coastal water level data, estuarine-shelf water exchange, National Ocean Survey (NOS), subtidal water level records, tide gauge, wind stress.*

INTRODUCTION

Estuarine-shelf exchange, continental shelf circulation and coastal ocean studies use coastal water level data (SMITH, 1978; BLAHA and STURGES, 1981; MARMARINO, 1982; CHUANG and WISEMAN, 1983; SCHROEDER and WISEMAN, 1986). The National Ocean Survey (NOS) maintains hundreds of water level gauges in and around the coastal regions of the United States. Many of the permanent, long term gauges are located near major connections with the open ocean. In order to afford these gauges some measure of protection from storms they are most often situated inside tidal inlets or coastal embayments, rather than along exposed coastlines. An important question relative to the records obtained from these gauges is how representative of the adjacent open ocean water level are these "protected" sites.

In this paper we compare the water level records from two sites in the northeast Gulf of Mexico: one record is from a permanent, long term NOS gauge at Dauphin Island, Alabama (Station 8735180, U.S. DEPT. COMM., 1984) and the other is from a temporary NOS gauge which was located at Gulf Shores, Alabama (Station 8731269, U.S. DEPT. COMM., 1984). The Dauphin Island gauge is located just inside Main Pass, Mobile Bay, and represents a "protected" site while the Gulf Shores gauge was located 35 kilometers (km) east of Main Pass, along the open coast line of Alabama, and represents an "unprotected" site (Figure 1).

Previous studies in the northern Gulf of Mexico have found coherence of coastal water level fluctuations with the local winds at frequencies from 0.4 to 0.05 days (d) (SMITH, 1978; CHUANG and WISEMAN, 1983; SCHROEDER and WISEMAN, 1986), specifically cold fronts, which move through the area with a frequency of five to seven per month in the fall, winter and spring, and as few as one to two per month in the summer (FERNANDEZ-PARTAGAS and

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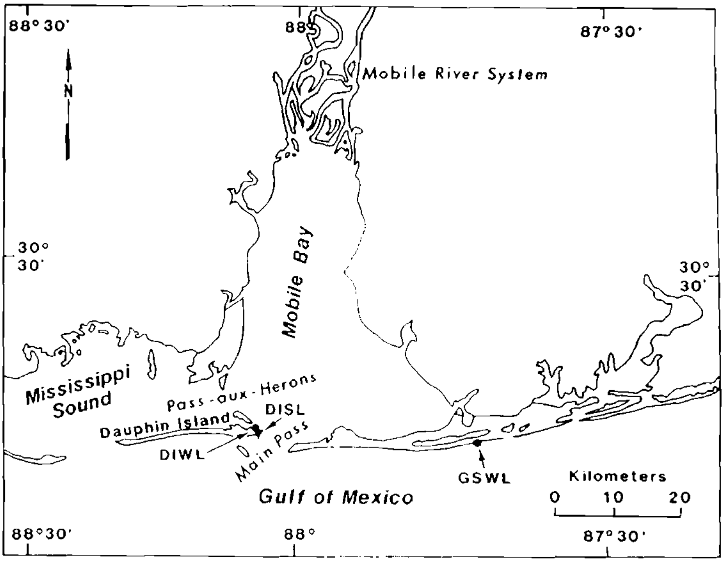

Figure 1. Location map for National Ocean Survey water level gauges at Dauphin Island (DIWL) and Gulf Shores (GSWL), and location of wind station at Dauphin Island Sea Lab (DISL) in coastal Alabama, USA.

MOOERS, 1975; DIMEGO *et al.*, 1976; CHUANG AND WISEMAN, 1983; SCHROEDER AND WISEMAN, 1986). Sea level is set up along the coast by prefrontal southerly winds and falling atmospheric pressure, and set down by strong northerly winds and rising pressure after the passage of the front (HUH *et al.*, 1984). The wind spectrum associated with these aperiodic fronts is usually in the 0.4 to 0.1 cycles per day (cpd) band. The importance of the coastal winds to water level fluctuations warrants the additional comparison of the local winds recorded at Dauphin Island, Alabama, to the water levels from both sites.

DATA

Hourly observations of water level at Gulf Shores (GSWL), from 1800 CST 28 March to 1700 CST 23 November 1980, were matched with water level at Dauphin Island (DIWL) and local winds recorded at the Dauphin Island Sea Lab (DISL) (Figure 1). The water level records were demeaned and detrended. Wind velocity, U, was converted to a quantity proportional to stress, $\tau = U|U|$, and resolved into alongshore (east-west) and across-shore (north-south) components.

All data sets were filtered in the frequency domain with a cut off at 0.25 d, then resampled at 0.125 d, thus removing any high frequency noise. The water levels were further filtered, generating two additional records: a subtidal band record of frequencies greater than 0.6 cpd and a "tidal" band record containing frequencies between 0.6 and 2.4 cpd. Wind stress components were filtered to generate corresponding subtidal band records. The subtidal and "tidal" water level records, along with the subtidal wind stress, were divided into three equal length segments of 81 days. These segments, 28 March to 16 June, 16 June to 4 September, and 4 September to 23 November, approximately encompass the spring, summer and fall seasons. Total variance for all records was computed. Sample variance was computed for the subtidal records. The sample variance is the total variance divided by the number of independent samples within that record. The number of independent samples, i.e. degrees of freedom, within each subtidal record was taken as the period of each record divided by the correlation time scale for each record (BEARDSLEY and BOICOURT, 1981). Correlation time scales, from two to four days, were estimated as the area under the normalized autocorrelation function from zero lag to the lag where the function first crossed zero. The autocorrelation function was determined as the inverse Fast Fourier Transform (FFT) of the autospectrum (BENDAT and PIERSOL, 1986).

Spectral estimates were computed, using an FFT, for the entire water level and wind stress records and for the seasonal segments. Using cross-spectral estimates obtained from the FFT analysis, coherence squared and phase were computed between the entire water level records at both stations, and also between the wind stress components and each water level record for the entire record and for the subtidal records for each seasonal segment. Statistical reliability was enhanced by averaging a constant number of estimates in the frequency domain. Spectrum confidence limits were determined by assuming a chi-squared sampling distribution for each spectral estimate (BENDAT and PIERSOL, 1986). Statistical significance was set at the 95% level.

RESULTS

Demeaned and detrended subtidal water level records are visually similar between the two sites (Figure 2). GSWL has a larger range than DIWL over the entire record, which manifests itself as lower stands in the spring and fall and higher stands in the summer. Although the entire records are detrended, the seasonal segments may contain residual trends. DIWL has negative trends over the spring and fall seasons, and a large positive trend over the summer. GSWL has little trend over the spring or fall records, but, as DIWL did, a large positive trend over the summer record.

Table 1 lists the total variances for each record and the sample variance for the subtidal water level records. Most of the total variance within each water level record is contained in the "tidal" band. The total variance in the across-shore wind stress record is higher than in the alongshore wind stress record and most of the wind stress total variance is in the subtidal records. A Fisher's F test was used to compare the sample variances between the two sites for the entire subtidal water level records and corresponding seasonal subtidal records, and also between different seasonal subtidal water level records at the same site. No statistical differences between sites were found for either the entire subtidal or any of the seasonal subtidal records. There is a statistical difference between the spring and fall sample variances at GSWL, with the fall record having twice the variance that the spring exhibited.

Spectra for the entire records of GSWL and DIWL are very similar in shape, with small differences in subtidal spectral estimates (Figure 3a). Each spectrum is dominated by the diurnal tide and to a lesser extent by the semidiurnal tide. Both spectra have subtidal peaks near 0.05, 0.2, 0.3 and 0.5 cpd, yet only the tidal peaks are statistically significant in either of

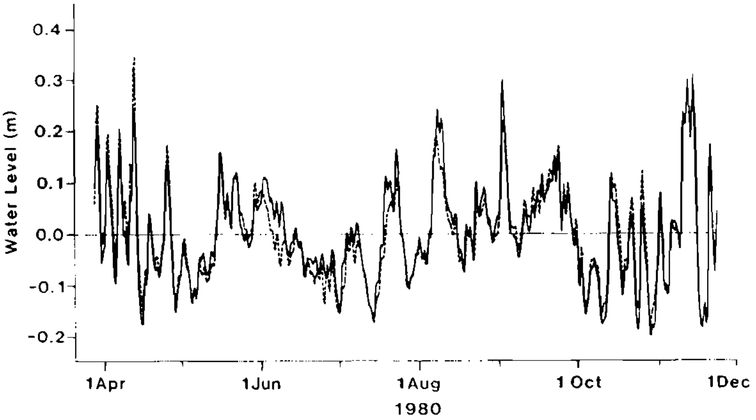

Figure 2. Demeaned and detrended subtidal records for GSWL (solid) and DIWL (dashed) from 28 March to 23 November 1980.

Table 1. *Total variance of water level and wind stress for the entire and seasonal records over the subtidal band record (< 0.6 cpd), and the "tidal" band record (0.6 – 2.4 cpd). Subtidal water level sample variance is denoted by parentheses. Wind stress variance has units of* m^4/s^4, *water level variance has units of* $m^2 \times 10^{-4}$.

	SPRING	SUMMER	FALL	TOTAL
	ENTIRE RECORD			
GSWL	259.24	278.72	279.42	272.80
DIWL	223.73	223.13	252.02	234.89
ACROSS-SHORE WIND STRESS				267.71
ALONGSHORE WIND STRESS				188.69
	SUBTIDAL RECORD			
GSWL	69.42 (1.83)	82.20 (2.50)	122.09 (3.53)	91.55 (0.88)
DIWL	80.91 (2.29)	68.18 (2.36)	112.78 (2.89)	89.20 (0.95)
ACROSS-SHORE WIND STRESS	100.78	44.77	239.36	174.94
ALONGSHORE WIND STRESS	101.40	139.35	157.16	132.83
	"TIDAL" RECORD			
GSWL	187.95	194.14	155.40	179.15
DIWL	142.06	153.73	139.09	144.94

the records. That is, the 95% confidence limits around each spectral estimate do not overlap with those of adjacent estimates.

The spectra of the seasonal water level records, although similar between sites, are different between seasons (Figure 3b-d). In general, for both sites, all three seasons have nearly identical spectral shapes in the "tidal" band. However, differences are observed in the subtidal band. In the spring season the DIWL spectrum levels were slightly greater than GSWL over the entire subtidal band (Figure 3b); both spectra have a plateau from 0.1 to 0.2 cpd. In the summer record (Figure 3c), the GSWL spectrum levels were greater than those at DIWL over most of the subtidal band. Summer record spectrum levels at both stations were less at frequencies higher than 0.15 cpd and greater at frequencies lower than 0.15 cpd than in the spring record. In the fall record (Figure 3d), both water level spectrum levels are approximately equal over most of the subtidal frequencies. Subtidal spectrum levels in the fall record were greater than in the summer record for both sites. At the lowest frequencies and at those greater than 0.3 cpd, the fall records had higher spectrum levels than the spring records, yet in the 0.15 to 0.3 cpd band the spring records had higher spectrum levels. None of the spectrum level differences, between either sites or seasons, are statistically significant. The 95% confidence band around the spectral estimates overlapped with those of adjacent spectral estimates.

Coherence squared between the entire GSWL and DIWL records indicate significant coherence over all subtidal frequencies (Figure 4). The phase is statistically different from zero, at the 95% level, over frequencies 0.1 to 0.14 and 0.2 to 0.35 cpd, with DIWL generally lagging GSWL. Coherence squared and phase between water levels at each site were computed for each season, but are not shown. Briefly, there was significant coherence at all subtidal frequencies in the spring and fall seasons, and in the summer season at frequencies less than 0.3 cpd. At the higher subtidal frequencies there was marginal coherence between sites during the summer record, when most of the water level variance occurs at the lower frequencies. Phase indicates DIWL lagged GSWL at all coherent subtidal frequencies except near 0.4 cpd in the summer season, when GSWL lagged DIWL.

Wind stress spectra are red; most of the variance occurs in the subtidal frequencies (Figure 5). Coherence squared computed between wind stress components indicates significance at 0.2, 0.3 and 0.5 cpd. Wind stress spectra for each seasonal segment (not shown) are complex. Spring wind stress component energies are nearly equal with alongshore and across-shore peaks near 0.18 and 0.3 cpd, respectively. The alongshore stress dominates the across-shore stress at frequencies below 0.3 cpd in the summer. The fall had the highest seasonal spectrum levels of either component and the fall across-shore wind stress subtidal variance is almost three times the spring and six times the summer variance (Table 1). Coherence squared computed between seasonal wind stress components indicates marginal significance in summer near 0.6 cpd, and higher coherence squared values in the fall near 0.35 cpd.

Coherence squared between the wind stress components and both the entire subtidal water level records are very similar (Figure 6a-6d). Both water levels are coherent with and lag the across-shore wind stress at frequencies near 0.033, 0.2, and 0.4 cpd. Both water levels are coherent with the alongshore wind stress at

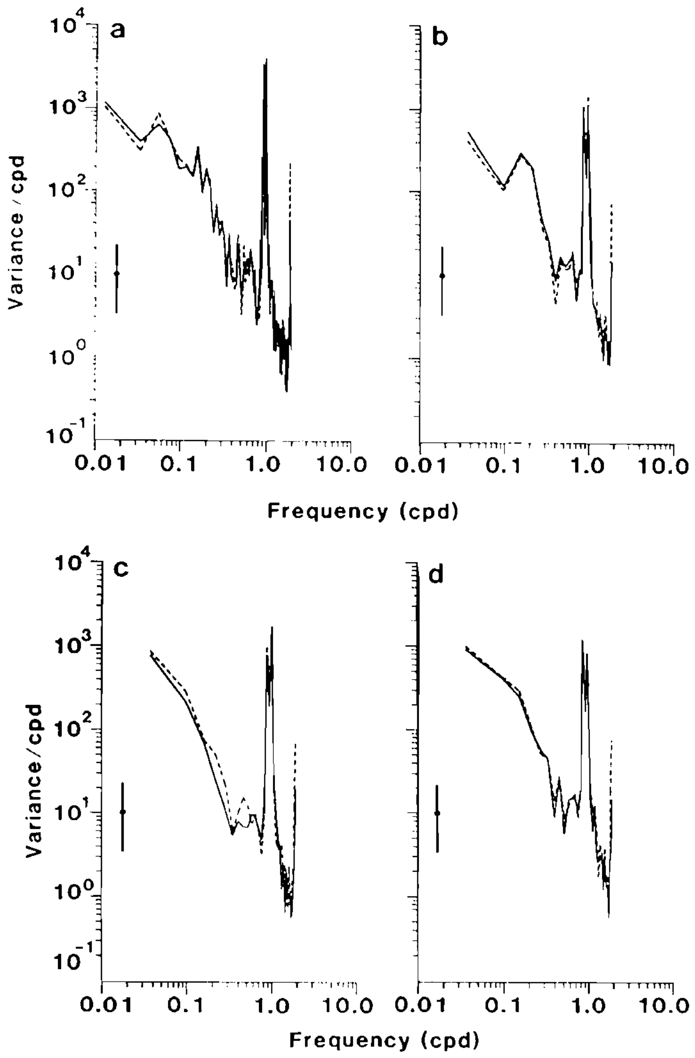

Figure 3. Water level spectra for GSWL (dashed) and DIWL (solid): (a) the entire record, (b) spring, (c) summer, (d) fall. Degrees of freedom are 10 and the confidence interval is at the 95% level.

most frequencies less than 0.36 cpd. At the coherent frequencies, wind stress lags water levels by approximately 120°. Seasonal coherence of water levels with wind stress components, not shown, are very similar to the entire record coherence. DIWL is coherent at higher frequencies than GSWL with the alongshore wind stress in the spring and fall, and GSWL is coherent at higher frequencies than DIWL in the summer. Water levels lead the alongshore wind stress at statistically coherent subtidal frequencies in all seasonal records.

DISCUSSION

Water levels at Gulf Shores and Dauphin Island are very similar; this is not unexpected considering the short geographical distance between the sites, but they are not identical. Statistically, subtidal water levels between the

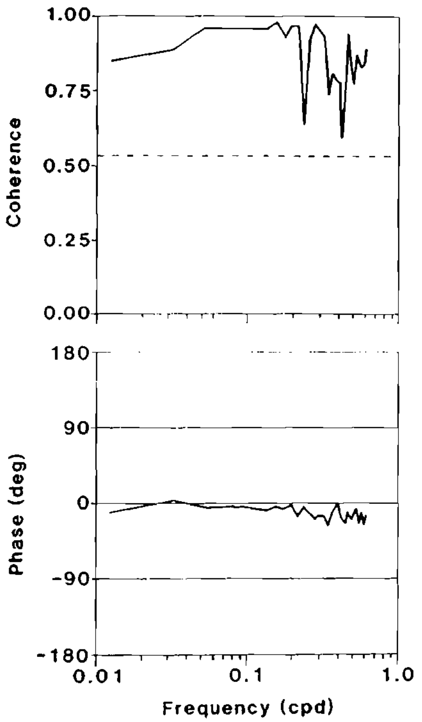

Figure 4. Coherence squared and phase between DIWL and GSWL for the entire record. Degrees of freedom are 10. Positive phase indicates GSWL lags DIWL.

sites are not different from each other, indicated by the sample variance comparison or by comparison of the spectra of the entire records or the seasonal segments. Although not statistically significant, DIWL had higher subtidal spectral levels than did GSWL in the spring, lower levels in the summer and approximately the same in the fall.

Increasing water level trends, observed in the summer record at both Gulf Shores and Dauphin Island, agree with seasonal changes expected over the entire northern Gulf of Mexico (McPHEARSON, 1970; BLAHA and STURGES, 1981). McPHEARSON (1970) observed, in two years of monthly mean low water (MLW) levels from an unprotected site on the south shore of Dauphin Island, an annual high MLW in September, then a rapid decrease through the fall season to the annual low MLW in January. A negative trend over the fall was not observed in either of the two water level records. Although detrending the original water level records would influence the actual values of seasonal segment trends, we expected to observe some negative trend in the fall. If Gulf of Mexico seasonal sea level variation is contributed to by the wind stress, as BLAHA and STURGES (1981) suggest, then the interannual variability in DISL winds observed by SCHROEDER and WISEMAN (1985) could account for this difference from the expected annual signal.

Based on expected cold front occurrences of five to seven per month (FERNANDEZ-PARTAGAS and MOOERS, 1975; DIMEGO *et al.*, 1976), the fall of 1980 was not anomalous; however, the percentage of southerly winds was less than in other years (SCHROEDER and WISEMAN, 1985). Large northerly across-shore winds associated with the frontal passages produced more water level response at DIWL than at GSWL.

Water level and wind stress cross-spectral analysis indicates that DIWL, in its coastal embayment location, was more responsive than GSWL in the spring and fall records when the across-shore winds were more energetic. At the higher subtidal frequencies, DIWL was more responsive than GSWL to the alongshore winds in the spring and fall records, and less responsive in the summer record. The water levels seem to respond primarily to the alongshore winds in the 0.04 and 0.3 cpd frequency bands, which are associated with cold fronts. Both water levels lead the alongshore wind at subtidal frequencies. These results generally support SCHROEDER and WISEMAN (1986), who noted that northern Gulf of Mexico estuary-shelf exchange was driven by along estuary winds at frequencies from 0.5 to 0.2 cpd, and alongshore winds at lower frequencies.

Cold fronts generally move west to east or are oblique to the east-west coastline; the inner shelf and back barrier sounds west of Mobile Bay are affected earlier by the frontal wind shifts. Prefrontal winds from the south set up the water level in the region. As the front passes, the winds rotate clockwise to strong northerlies. This wind shift precedes that at Mobile Bay by approximately 0.5 d over the coastal waters farther west. Winds from the north blow inner shelf and estuarine waters seaward, toward the south. This creates a barotropic pressure gradient along the coast positive toward the east (SCHROEDER *et al.*, 1985).

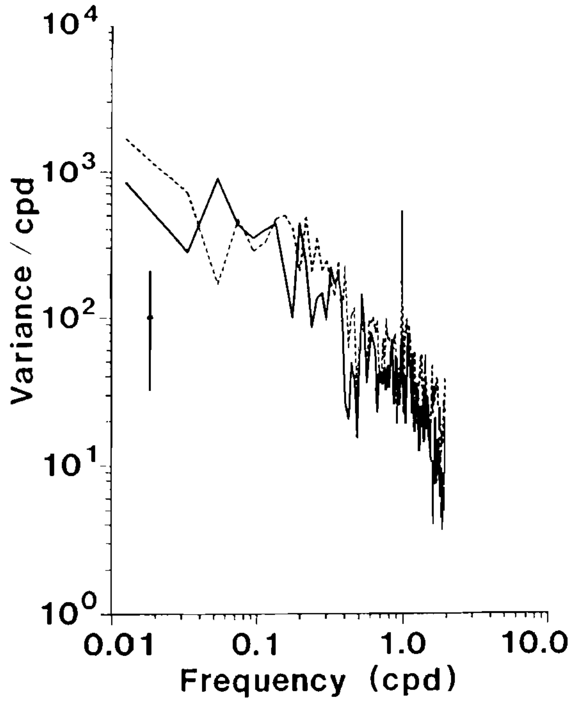

Figure 5. Wind stress spectra for the entire record. The alongshore component (east-west) is solid, the across-shore component (north-south) is dashed. Degrees of freedom are 10 and the confidence interval is at the 95% level.

In order to account for the observed 0.5 day alongshore wind stress lag at GSWL and DIWL, we speculate that this barotropic pressure gradient, created by the frontal wind shift, extends eastward faster than the actual frontal wind shift, so that the water level fluctuations at DIWL and GSWL precede the alongshore wind stress directional shift at frequencies associated with cold front winds.

CONCLUSIONS

Analysis of eight months of northeastern Gulf of Mexico subtidal water level data from an unprotected, open coast site and a protected, coastal embayment site indicates no statistical difference between these sites. Spectral shape and sample variance are not statistically different between the two subtidal data sets. Cross-spectral analysis between the subtidal record and the wind stress components indicate similar response at both sites.

Although we suggest that water level measurements obtained from the permanent site at Dauphin Island are not greatly biased by its protected location and can generally be considered representative of the coastal water level from the adjacent region of the Gulf of Mexico, we also note seasonal differences and differences between sites. Albeit not statistically different, DIWL spectrum levels are higher over the subtidal frequencies in the spring and fall, while GSWL spectrum levels are greater during the summer. Spring and fall segments show broader coherent bands with both the across-shore and alongshore winds at subtidal frequencies at the coastal embayment site. Summer records show no coherence with the across-shore winds but broader coherent bands at GSWL than at DIWL for the alongshore wind stress.

Physical oceanographic studies of very low frequency fluctuations on the continental shelf using long term coastal water level records may not be concerned with seasonal differences. Yet regional analyses focusing on subtidal variability would have to contend with the greater response of Mobile Bay in the spring and fall,

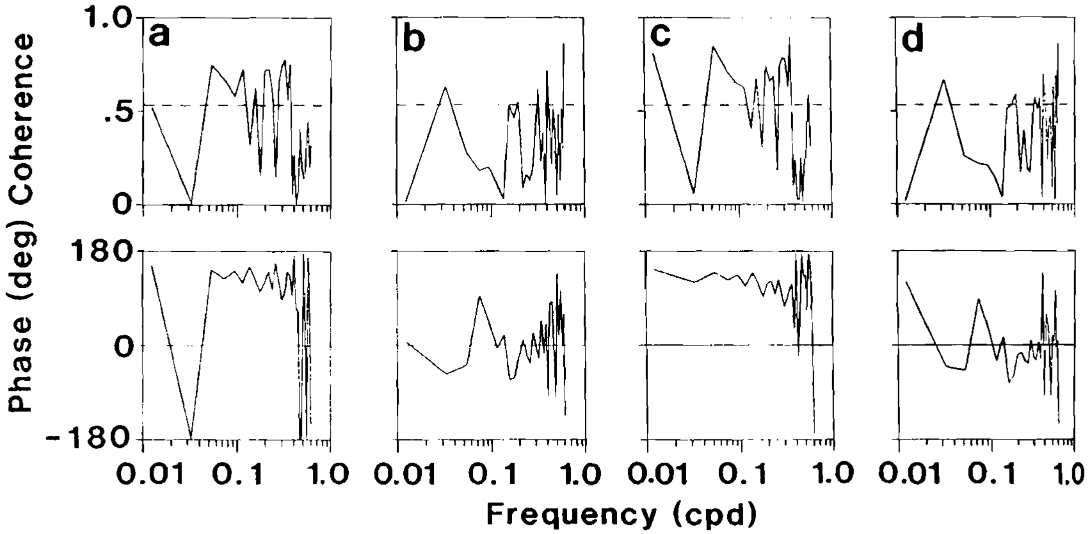

Figure 6. Coherence squared and phase lag between entire DIWL and GSWL records and the wind stress components: (a) Alongshore stress—GSWL, (b) Across-shore stress— GSWL, (c) Alongshore stress— DIWL, (d) Across-shore stress— DIWL. Positive phase indicates wind stress lags water level.

and the lesser response in the summer to local wind forcing. Data quality for this study was reasonably good. However, the period of study was less than one year, covering only three seasons. The winter season water levels, and its energetic meteorological events, were not described or compared. Also, because interannual differences in the wind fields exist, multiple year open coast water level records would have to be made and compared to DIWL in order to obtain a more thorough understanding of coastal water level in this region.

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