Low-Frequency Current Variability on the Southern Mid-Atlantic Bight

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ABSTRACT

Low-frequency current variability on the continental shelf, 84 km off the mouth of the Chesapeake Bay, was examined from 4-month (mid-March to June 1975) current, sea level and meteorological records. Taking into account the seasonal change in wind stress and stratification, the record was divided into two 60-day periods. In both periods, the transient alongshore currents were barotropic and coherent with sea level fluctuations.

During the first period (March and April 1975), winds were in the east–west direction, and the shelf water was homogeneous. At time scales longer than 4 days, sea level was a large-scale feature (coherent over the entire Mid-Atlantic Bight). At shorter time scales, sea level was driven by the local, alongshore wind. In contrast, the cross-shelf current, which was mainly barotropic, was driven by the alongshore wind at all time scales.

During the second period (May and June 1975), winds were in the north-south direction and the shelf water was stratified. Sea level was mainly driven by the local alongshore wind at all time scales. The cross-shelf current, which was baroclinic at time scales longer than 4 days, and barotropic at shorter time scales, was also driven by the alongshore wind.

The difference in response characteristics of the two periods indicate that circulation on the southern Mid-Atlantic Bight is strongly affected by local wind forcing, nonlocal effect, density stratification and the duration of alongshore wind.

1. Introduction

In recent years, through direct current meter measurements, considerable progress has been made in the study of mean circulation and its variability on the Mid-Atlantic Bight. Experiments were carried out in different regions: on the New England shelf (Beardsley and Butman, 1974), off Long Island (Scott and Csanady, 1976), in the New York Bight (Mayer *et al.*, 1979) and between Cape May and Cape Hatteras (Boicourt, 1973; Boicourt and Hacker, 1976). These studies indicated a mean, south-southwestward flow on the order of 5 cm s^{-1}. Beardsley *et al.* (1976) analyzed the discrete data sets over a large portion of the Bight, and they suggested that despite the wind being stronger in winter, there was no significant seasonal variation of mean flow. Since the mean flow moves in opposition to the mean eastward wind, Stommel and Leetmaa (1972) suggested that an alongshore pressure gradient is needed to drive the mean flow. Evidence for the mean westward surface slope was suggested in Scott and Csanady (1976), from examination of the balance between alongshore wind stress and bottom current.

Beardsley and Butman (1974) and Boicourt and Hacker (1976) studied the response of shelf water during strong wind events. Their results indicated that the transient alongshore flow was driven most effectively by the local, alongshore wind. Large wind-driven current fluctuations at several-day time scales were also found in Mayer *et al.* (1979), from examination of 2½ years of records. Evidence for nonlocal forcing was also obtained from examination of 1-year sea level and meteorological data over the entire Bight (Wang, 1979). At time scales longer than 3.3 days, it was noted that south of Cape May, free shelf waves contributed significantly to sea level fluctuations.

There was a clear seasonal variation in the intensity of transient currents; strong currents were usually associated with the winter storms (Mayer *et al.*, 1979). Seasonal variations were also found in the vertical structures of cross-shelf circulation. Boicourt (1973) and Boicourt and Hacker (1976) found that northward winds drove an intrusion of high-salinity slope water near the bottom in winter, but at mid-depths (above the cold water band) in summer, to compensate for the near-surface offshore flow. Scott and Csanady (1976) on the other hand, found a return flow in the lower layer throughout their summer, nearshore experiment. They sug-

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gested that the cross-shelf circulation is due to bottom friction (Csanady, 1976).

In this study, the low-frequency variation on the southern Mid-Atlantic Bight, and its relation to local and nonlocal forcing is examined from current, sea level and meteorological data in water and spring seasons. Sea level data on the Mid-Atlantic Bight from Cape Cod to Cape Hatteras are also included in the analysis.

2. Observations

The current meter mooring was located 84 km off the mouth of the Chesapeake Bay in a water depth of 38 m (Fig. 1). The mooring had three meters at depths of 10, 20 and 30 m. The local isobath is approximately in the north-south direction, which is taken as the alongshore direction. The velocity records were decomposed into the cross-shelf (U) and alongshore (V) component, and low-pass filtered to remove the tidal, inertial and other high-frequency oscillations. [Filter response amplitude was nil at 1 cpd (cycles per day), 50% at 0.7 cpd and 95% at 0.5 cpd.] The low-pass series were decimated to a 6 h interval, covering the period from 8 March to 30 June, 1975.

Wind data were obtained at Norfolk and Chesapeake Light (located $\sim$20 km offshore). The cross-shelf (τ_x) and alongshore (τ_y) wind stress were computed with a constant drag coefficient of 1.4×10^{-3}. In general, the Chesapeake Light wind was stronger, and its direction was 30° counterclockwise from the Norfolk wind. Since the wind fluctuations were coherent between the two stations, only the Chesapeake Light data were used in this study.

Barometrically adjusted sea levels were obtained at seven stations along the Atlantic coast: Nantucket, Montauk, Sandy Hook, Atlantic City, Cape May, Kiptopeake Beach and Avon (Fig. 1). Wind stress and sea level data were low-pass filtered and decimated, similar to current meter records. In the following analysis, sea level at Kiptopeake Beach was taken as the base series for investigation of the local current, wind and sea level relations.

The 4-month data spanned the winter and spring seasons, during which large variations of wind forcing and density structure had occurred. In March and April, the wind was strong (Fig. 2a) and the shelf water was well mixed, with a slight offshore density increase. In May and June, the wind weakened considerably. Reduced wind mixing, together with freshwater runoff and vernal warming, led to a gradual buildup of stratification. In June the thermocline was usually between 10 and 20 m (Boicourt, 1973). Because of the large climatic change in wind forcing and stratification, the record was divided into two 60-day periods, denoted by Phase I (8 March–8 May) and Phase II (1 May–30 June), respectively.

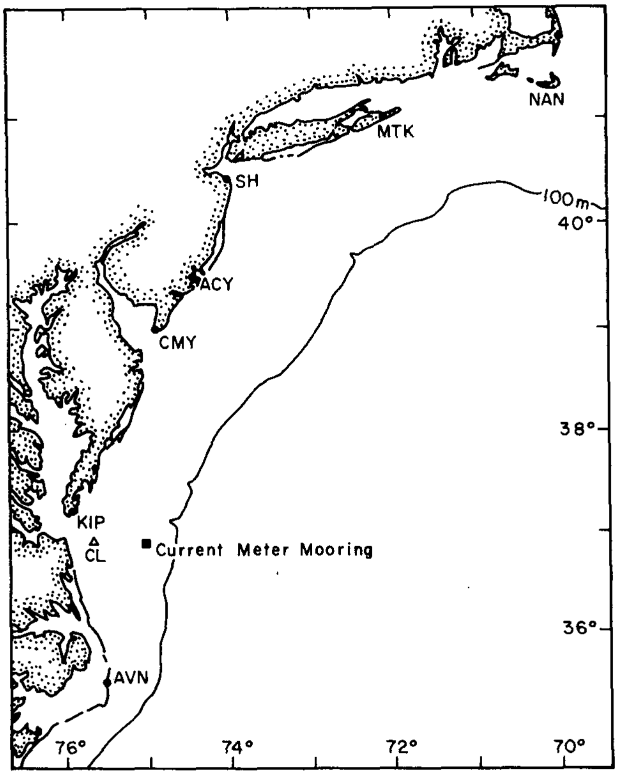

FIG. 1. Map of the Middle Atlantic Bight: sea level station (●), wind station (△), current meter mooring (■).

Table I shows some basic statistics of wind, current and sea level for Phases I and II. The mean alongshore flow was southward at all depths; there was no significant change in the magnitude and vertical structure between the two seasons. In contrast, the mean cross-shelf velocity was onshore at all three depths during Phase I, but it had an offshore component near the bottom and a node at mid-depth during Phase II. In both seasons, the magnitude of the mean flow was about twice as large as the flow in the New York Bight for the same period (Mayer *et al.*, 1979). This is probably due to the continuity of transport on the shelf (Beardsley *et al.*, 1976), which tends to concentrate the mean flow in the smaller cross-sectional area of the southern Bight. The direction of the mean current veered offshore with increasing depth, which is consistent with the bottom Ekman veering. However, this result was different from observations on the northern Bight (Beardsley *et al.*, 1976). The mean alongshore wind and current were in the same direction in both seasons, but their magnitude did not appear to be directly related.

3. Alongshore current and sea level fluctuations

Alongshore current fluctuations were coherent and in-phase at all depths (Fig. 2b); in fact, a single

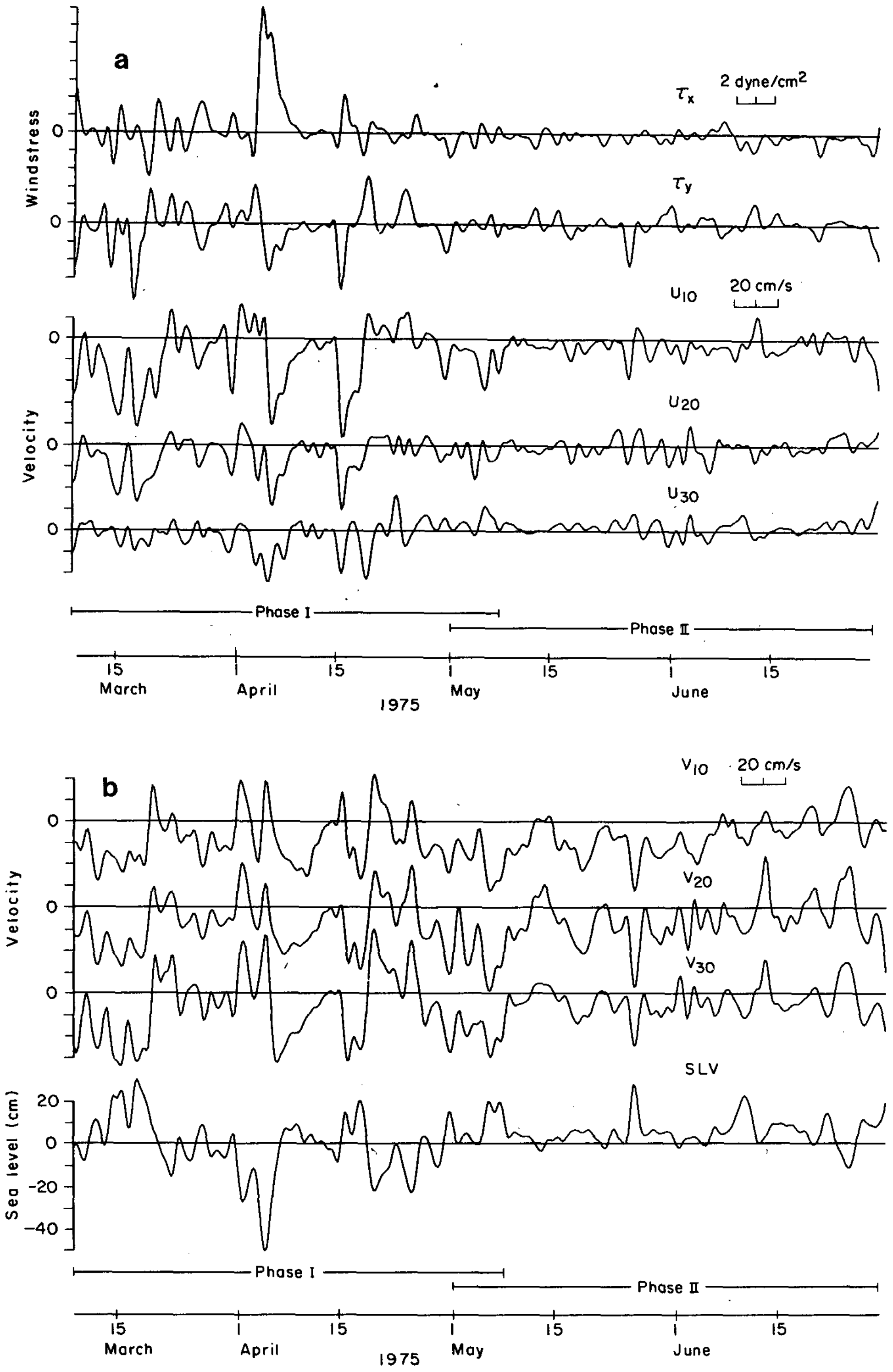

FIG. 2. The lowpass time series of (a) eastward (τ_x) and northward (τ_y) wind stress, and eastward (U) current and (b) northward current (V) and sea level (SLV) at Kiptopeake Beach. (The subscripts are the current meter depths in meters.)

empirical mode (from an empirical orthogonal function analysis) accounted for 91% (Phase I) and 93% (Phase II) of the total variance, respectively. Modal amplitude was 10.7, 11.7 and 14.8 cm s^{-1} at 10, 20 and 30 m in Phase I, 9.5, 12.9 and 8.7 cm s^{-1} in Phase II. The vertical structure was barotropic in both periods; the largest amplitude, however, occurred near bottom during Phase I but at mid-depth

TABLE 1. Statistics of the lowpass data for Phase I and Phase II.

	U (eastward)		*V* (northward)		Vector mean	
	Mean	S.D.	Mean	S.D.	Magnitude	Direction*
			Phase I (from 8 March to 8 May 1975)			
Wind stress (dyn cm^{-2})	0.33	1.36	−0.14	1.08	0.36	−23°
Current (cm s^{-1})						
10 m	−8.3	13.5	−9.5	11.6	12.6	−131°
20 m	−5.1	8.2	−9.8	12.2	11.0	−119°
30 m	−1.8	6.9	−7.7	15.4	7.9	−103°
Sea level (cm)**	−8.1	13.7				
			Phase II (from 2 May to 30 June 1975)			
Wind stress (dyn cm^{-2})	−0.12	0.34	−0.06	0.64	0.13	−157°
Current (cm s^{-1})						
10 m	−4.8	9.0	−8.1	10.2	9.4	−120°
20 m	−0.4	5.2	−8.5	13.0	8.5	−93°
30 m	2.5	4.3	−6.0	9.0	6.5	−67°
Sea level (cm)**	−1.0	9.4				

* Measured counterclockwise from east.
** Relative to the annual mean of 1975.

during Phase II. Alongshore currents also appeared to be 180° out of phase with sea level fluctuations. In other words, sea level decrease was associated with a northward flow at all depths, which suggests a geostrophic balance between the cross-shelf pressure gradient and alongshore current.

The spectra of alongshore current, sea level and wind were computed with a 10-day lag window; the corresponding frequency resolution is 0.05 cpd, and the number of degrees of freedom is 15. The alongshore current spectrum (only the velocity at 20 m depth is shown in Fig. 3) had energy peaks at 20 and 3.3 days in Phase I, and 20, 5 and 2.5 days in Phase II. Similar energy peaks were found in the sea level spectrum (Fig. 4). During Phase I, cross-shelf wind had much greater variance than alongshore wind at time scales >4 days (Fig. 5a). At shorter time scales, the two wind components were comparable, and they had a distinct spectrum peak at the 3-day time scale. During Phase II, cross-shelf wind decreased dramatically (Fig. 5b). Alongshore wind was dominant and it had spectrum peaks at 10, 5 and 2.5 days. The alongshore wind spectrum was similar to the sea level and alongshore current spectra.

Since alongshore currents were mainly baro-

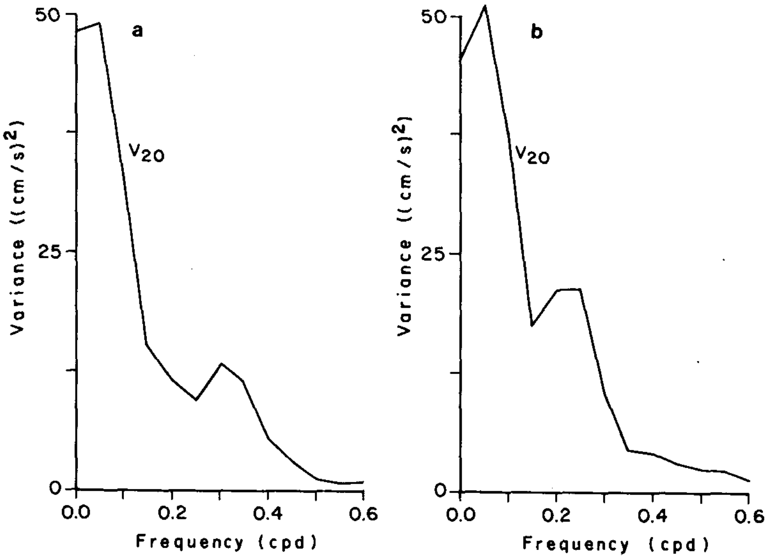

FIG. 3. The power spectrum of alongshore current at 20 m: (a) Phase I, (b) Phase II.

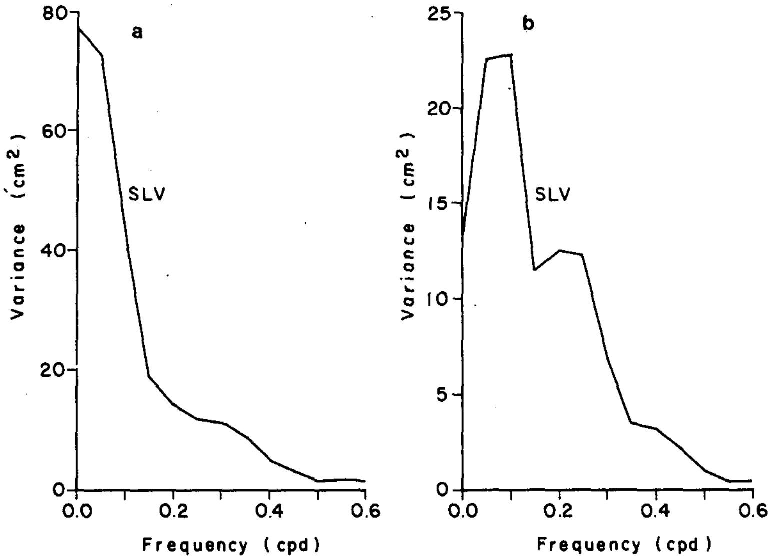

FIG. 4. The power spectrum of sea level: (a) Phase I, (b) Phase II.

tropic, they can best be analyzed through the empirical mode. The correlation between sea level and alongshore current (empirical mode) fluctuations was significant (γ^2 was 0.64 in Phase I, and 0.56 in Phase II; the 95% significant level was 0.48 and 0.20 for Phase I and II, respectively). The cross-spectrum analysis indicates that the coherence between sea level and alongshore current was frequency dependent (Fig. 6). At time scales of the dominant fluctuations, the coherence was high and the geostrophy was valid. However, the coherence dropped considerably near zero frequency. In other words, the long-period (time scales >20 days) sea level change was not related to the alongshore current. This result was consistent with the suggestion of Beardsley and Winant (1979) that the very low-frequency currents on the Mid-Atlantic Bight are induced by the deep ocean circulation; therefore, they may not be related to the coastal sea level change.

The relation between sea level and local wind forcing was examined from cross-spectrum analysis; the coherence squared between sea level and wind components is shown in Fig. 7. During Phase I, sea level and north-south wind were highly coherent at time scales <3 days. The phase relation indicates that the rise (fall) of sea level was associated with a southward (northward) wind, with a time lag of 6–9 h. This result suggests that sea level change at

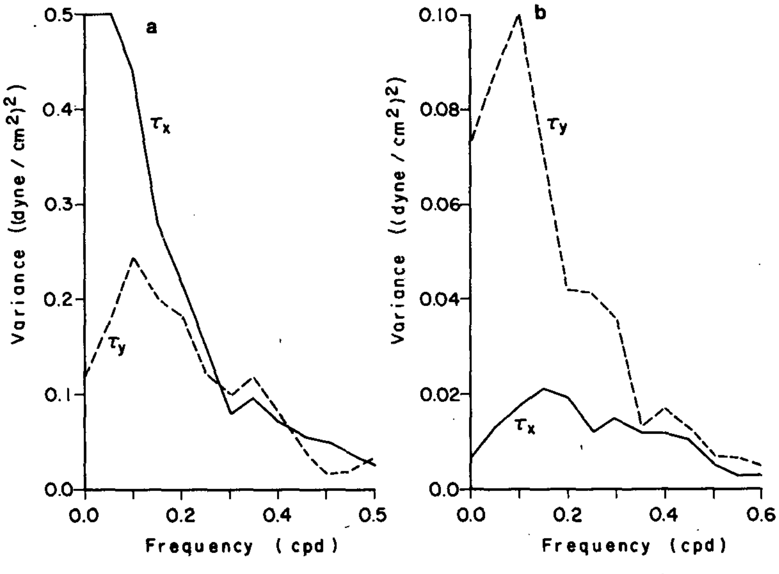

FIG. 5. The power spectrum of eastward (τ_x) and northward (τ_y) wind stress: (a) Phase I, (b) Phase II.

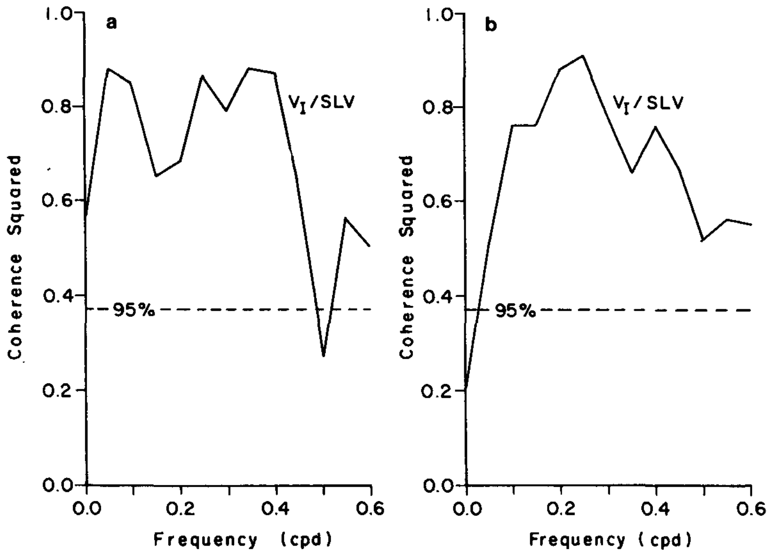

FIG. 6. The coherence squared between the first alongshore velocity mode (V_I) and sea level (SLV): (a) Phase I, (b) Phase II. (The 95% significance level is marked.)

short time scales was induced by the alongshore wind, as a result of Coriolis effect. At time scales >4 days, sea level was coherent with 60°/240° wind (rotating counterclockwise from the east). Coherence was particularly high at time scales >10 days in which the dominant fluctuation occurred. The high coherence suggests local wind forcing. However, the direction of optimum wind was not parallel to the local coastline, contradicting the local Ekman model.

The alongshore coherence of sea level fluctuations was computed between Kiptopeake Beach and all other stations. At time scales <3 days, Kiptopeake Beach was not coherent with stations to the north (Fig. 8a), indicating isolated short period sea level changes in the southern Bight. In contrast, the spatial coherence was high over the entire Bight at time scales >3.3 days. For example, the 10-day fluctuations were significantly coherent between Kiptopeake Beach and Nantucket, over a 700 km alongshore separation. Furthermore, the phase relation indicated a consistent southward propagation (Fig. 9a). Thus, sea level fluctuations at Kiptopeake Beach were part of a large-scale feature at long time scales.

As both local and nonlocal effects were important, a multiple-spectrum analysis (Jenkins and Watts, 1968) was applied between sea level at Kiptopeake Beach, and the Sandy Hook sea level, the cross-shelf and alongshore wind. The multiple coherence was high at all time scales (Fig. 10a); in fact, 95% of the Kiptopeake sea level variations can be accounted for. The local, alongshore wind forcing was dominant at time scales shorter than 3 days. [Similar results for the dominance of local forcing at short periods were found in Wang (1979).] At time scales of 3 to 6.6 days, local wind-forcing and nonlocal contributions were comparable. At time scales longer than 20 days, both the cross-shelf wind and the Sandy Hook sea level were highly coherent

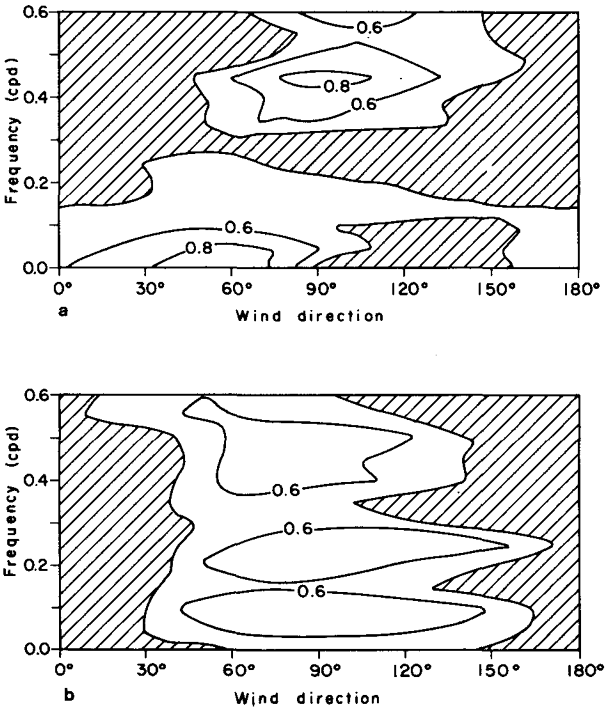

FIG. 7. The coherence squared as a function of wind direction (the 90° direction is along the north-south axis) between sea level and wind stress: (a) Phase I, (b) Phase II. (Shaded areas are below the 95% significance level.)

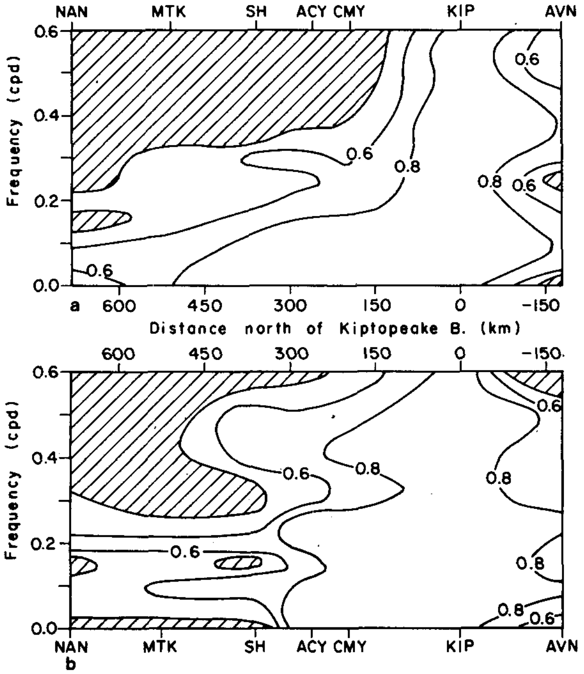

FIG. 8. The alongshore distribution of coherence squared for sea level, relative to Kiptopeake Beach. (a) Phase I, (b) Phase II. (Shaded areas are below the 95% significance level.)

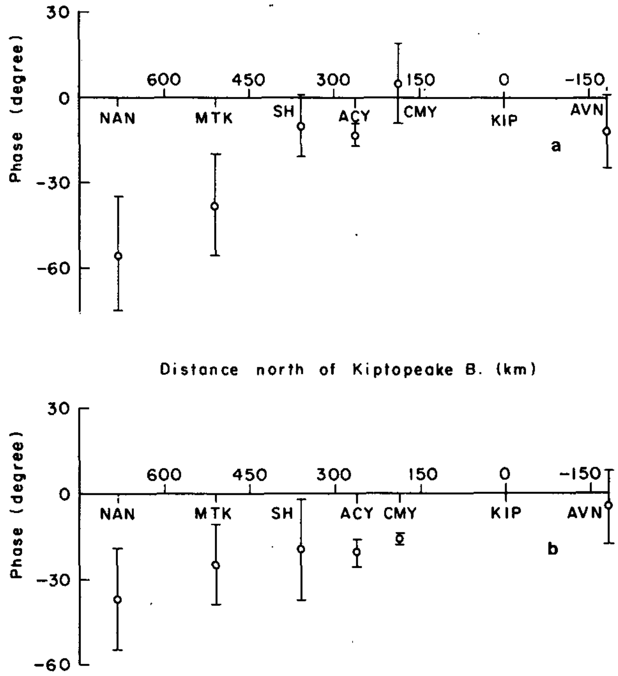

FIG. 9. The phase of sea level relative to Kiptopeake Beach: (a) 10-day fluctuation in Phase I, (b) 5-day fluctuation in Phase II. (The error bar is based on 95% confidence interval.)

with the Kiptopeake Beach sea level, which was due to the fact that the Sandy Hook sea level was driven by the east-west wind (Wang, 1979). Thus, the local and nonlocal effect in the southern Bight could not be fully separated when the cross-shelf (east-west) wind was strong (Fig. 5a).

During Phase II, sea level was coherent with alongshore wind at all time scales (Fig. 7b), with a time lag of 6 h. The coherence was particularly high at time scales of 10, 5 and 2.5 days in which dominant fluctuations of sea level and alongshore wind occurred. As the wind was mainly in the alongshore

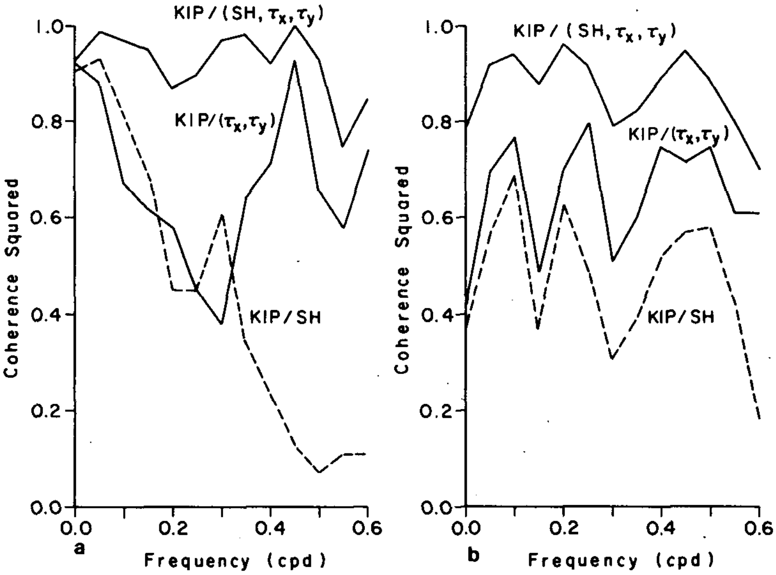

FIG. 10. The multiple-coherence squared between the sea level at Kiptopeake Beach (KIP) and (i) the Sandy Hook sea level (SH), the eastward (τ_x) and northward (τ_y) wind stress, (ii) the eastward and northward wind stress and (iii) the Sandy Hook sea level: (a) Phase I, (b) Phase II.

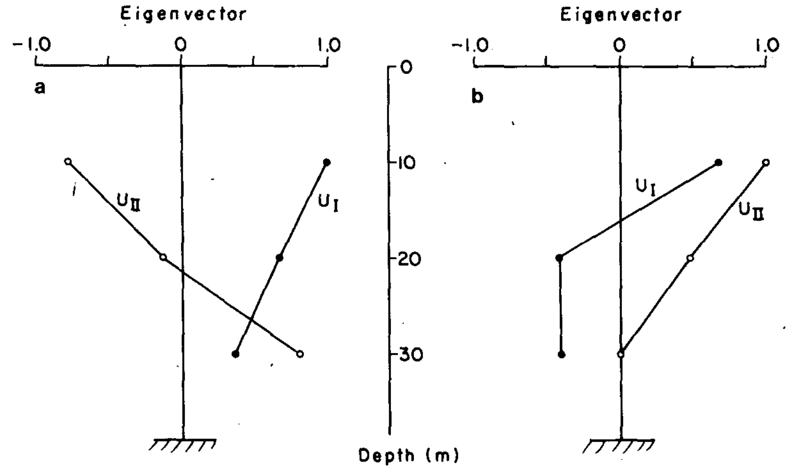

FIG. 11. The normalized vertical structure of the first (U_I) and second (U_{II}) cross-shelf velocity mode: (a) Phase I, (b) Phase II.

direction (Fig. 5b), the sea level response appeared to favor the local wind forcing. On the other hand, the spatial coherence of sea level was also high between Cape May and Avon (Fig. 8b). In particular, high spatial coherence with a southward phase propagation (the phase of the 5-day fluctuations is shown in Fig. 9b), extended over the entire Bight at dominant time scales, suggesting significant nonlocal effect at these time scales.

The multiple coherence between Kiptopeake Beach sea level and the Sandy Hook sea level, the cross-shelf and alongshore wind, indicates that the local wind forcing was dominant at all time scales (Fig. 10b). However, the local wind alone explained 66% of the Kiptopeake Beach sea level variations. When the Sandy Hook sea level was included, total variance explained was ~90%. Therefore, while the nonlocal effect was probably of secondary importance during Phase II, its contribution, nevertheless, cannot be completely neglected.

4. Cross-shelf current fluctuation

Unlike the alongshore currents which were mostly barotropic, cross-shelf currents had a baroclinic component (Fig. 2a). In order to describe their vertical structures, cross-shelf currents were empirically decomposed into barotropic and baroclinic modes. Since the variance of cross-shelf currents decreased considerably with depth (Table 1), the correlation matrix was normalized in computing the empirical modes.

During Phase I, the first mode was barotropic with decreasing amplitude toward the bottom (Fig. 11a). The second mode was baroclinic with a node near mid-depth. The first and second mode accounted for 70 and 27% of the total variance, respectively. However, in the second mode, fluctuations were significant only at 30 m where the amplitude of the first mode was small. The first mode had spectrum peaks at time scales of 10 and 3 days (Fig. 12a), similar to the energy spectrum of the alongshore wind (Fig. 5a). In fact, the first cross-shelf velocity mode and the alongshore wind were in phase and significantly coherent at these two time scales (Fig. 13a); i.e., a northward (southward) wind drove an offshore (onshore) flow. On the other hand, the coherence was poor between the first mode and cross-shelf wind, despite the cross-shelf wind having greater variance than the alongshore wind. These seem to suggest that the dominant cross-shelf current fluctuations were driven by the alongshore wind.

Coherence of the first and second cross-shelf velocity mode with sea level is shown in Fig. 14a. At time scales >4 days, the first mode was not coherent with sea level. As the first mode was clearly associated with the local alongshore wind, this result substantiated the earlier suggestion that the long-period sea level and alongshore current fluctuations were due to nonlocal effect. At time scales of 2.5–4 days, both the first and second mode were coherent with the sea level and alongshore wind. Therefore, short-period cross-shelf currents were mainly driven by the local alongshore wind at all depths. On the other hand, the second mode was in-phase and highly coherent with sea level, suggesting that part of the near-bottom cross-shelf current fluctuations were associated with the large-scale sea level change.

During Phase II, the mean cross-shelf current was baroclinic. The first mode was also baroclinic with a node between 10 and 20 m (Fig. 11b). The second mode was barotropic with negligible amplitude at 30 m. Although the first mode explained 69% of the total variance and the second mode 23%, the spectrum analysis indicated the two modes had comparable amplitude at time scales <4 days (Fig. 12b).

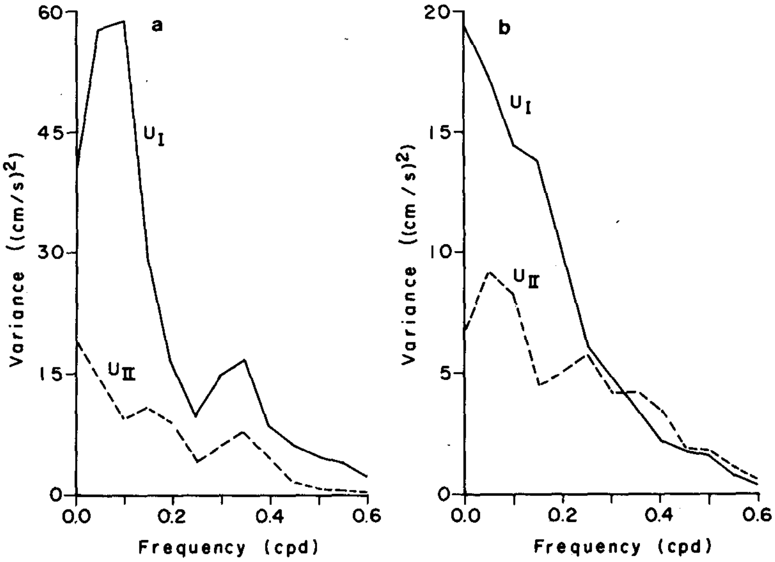

FIG. 12. The power spectrum of the first (U_I) and second (U_{II}) cross-shelf velocity mode: (a) Phase I, (b) Phase II.

In fact, the second mode was larger at time scales of 2–3 days. In other words, the cross-shelf flow was baroclinic at low frequencies, but it had a significant barotropic component at higher frequencies. The first mode was in phase and coherent with alongshore wind at time scales >4 days. On the other hand, the second mode was in phase and coherent with alongshore wind at time scales of 4 and 2.5 days (Fig. 13b). [As sea level was coherent with alongshore wind at all time scales (Fig. 7b), a similar pattern was reflected in the coherence of the first and second mode with sea level fluctuations (Fig. 14b).] In other words, the cross-shelf current was driven by the alongshore wind during Phase II; however, its vertical structures were more barotropic at shorter time scales.

The major difference in the first cross-shelf velocity mode between Phase I and Phase II was that the vertical structure was barotropic in Phase I, but baroclinic in Phase II. As both were driven by the alongshore wind, the difference may be due to the effect of stratification, which was important only during Phase II. In a stratified shelf water, the Ekman flow tends to be confined to the upper layer, above the sharp thermocline. Consequently, a return flow may be induced in the lower layer by the

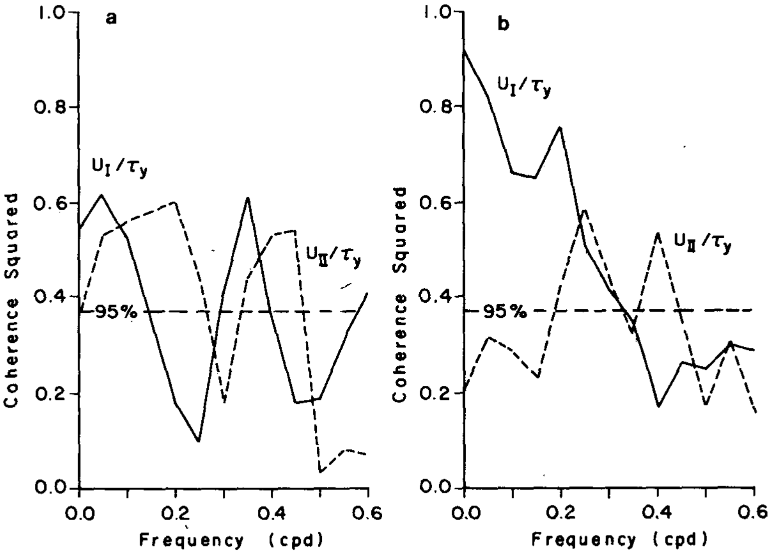

FIG. 13. The coherence squared between the first (U_I) and second (U_{II}) cross-shelf velocity mode and the northward wind stress (τ_y): (a) Phase I, (b) Phase II.

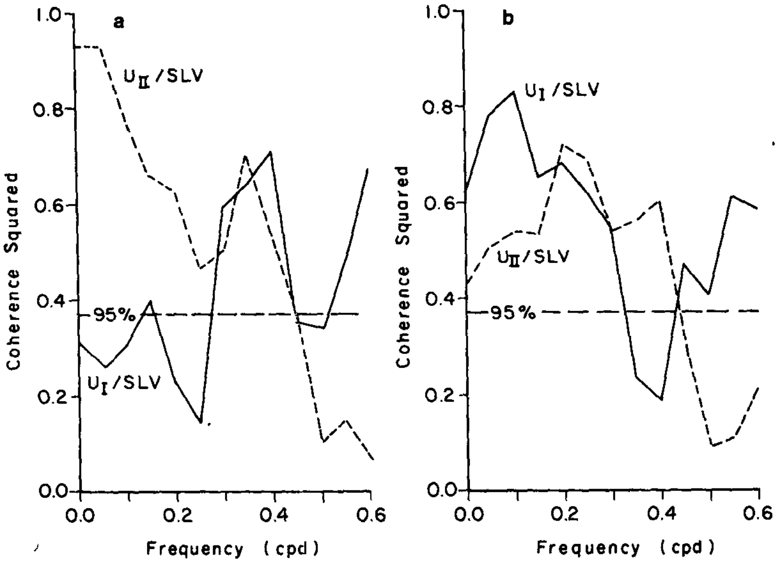

FIG. 14. The coherence squared between the first (U_I) and second (U_{II}) cross-shelf velocity mode and the sea level (SLV): (a) Phase I, (b) Phase II.

cross-shelf pressure gradient. The resulting flow pattern is similar to the baroclinic mode in Phase II. This result was also consistent with Boicourt and Hacker (1976) who found an onshore flow in the upper layer and an offshore flow in the lower layer during a summer, southward wind event. However, if the alongshore wind does not persist long enough to establish a return flow, the response will be confined to the upper layer. This probably explains the increasing contribution of the barotropic component (second mode) at higher frequencies during Phase II.

5. Discussion

In this study, circulation on the southern Mid-Atlantic Bight was examined during two 60-day periods corresponding to the winter (Phase I) and spring (Phase II) season. Although the wind was stronger in Phase I, there was no appreciable difference in mean alongshore flow between the two seasons. This is consistent with the suggestion that seasonal variation in alongshore transport is small (Beardsley *et al.*, 1976). In contrast, the mean cross-shelf flow was quite different between the two seasons. In Phase I, the mean cross-shelf flow was onshore at all three depths. In Phase II, the flow was onshore in the surface layer, but offshore in the bottom layer. The difference in cross-shelf circulation was probably due to the seasonal change in stratification and wind forcing.

The transient alongshore currents were barotropic and geostrophic in both seasons; however, the driving mechanisms were somewhat different between the two seasons. In Phase I, the alongshore currents were due to nonlocal forcing at time scales longer than 4 days, and local alongshore wind forcing at shorter time scales. In Phase II, local alongshore wind forcing was dominant at all time scales, though the nonlocal effect was non-negligible at time scales of dominant fluctuations. The difference between the two seasons appears to be due to the change in wind directions. Winds were mainly in the east-west direction in Phase I, and north-south in Phase II. The east-west wind will favor the large-scale response in the Mid-Atlantic Bight, while the north-south wind tends to generate local response (Wang, 1979).

Cross-shelf currents were mainly driven by the alongshore wind, as a result of Coriolis effect. They were mostly barotropic in Phase I, but were baroclinic at time scales >4 days in Phase II. The difference in vertical structure was probably due to the stratification effect which was important only in Phase II. It was noted that the barotropic response was also important in Phase II, at time scales <4 days. In other words, a return flow can be fully established only during a persistent (over a few days) wind event.

Theoretical studies of current variability on the Mid-Atlantic Bight have been based, for the most part, on the local Ekman model (Stommel and Leetmaa, 1972; Csanady, 1976). Some observational studies seem to indicate that the shelf water response to atmospheric forcing can be described by these theoretical or conceptual models (Beardsley and Butman, 1974; Boicourt and Hacker, 1976; Scott and Csanady, 1976). However, contrary to the common model assumptions of a straight coastline and large-scale atmospheric forcing, there are considerable variations of coastal geometry and meteorological forcing along the Bight. Bennett and Magnell (1979) found discrepancies between the two-dimensional model predictions and observations on the New York Bight. The differences are ascribed to the wind set-up induced by a distant lateral boundary. Wang (1979) also noted that while the northern Bight is dominated by the local wind forcing, the southern Bight is marked by nonlocal influence, as there has been strong evidence of a southward phase propagation in coastal sea levels. The Phase I results seem to support the notion of dominant nonlocal effect in sea level and alongshore current fluctuations. Thus, application of the local Ekman model to the Mid-Atlantic Bight is probably restrictive.

Another common assumption in the modeling of nearshore circulation is a zero net cross-shelf transport (e.g., Csanady, 1976). However, this contradicts the observation that both the mean and transient cross-shelf flow were barotropic in Phase I. Thus, there appears to be substantial three-dimensional effects in this region.

Results of this study indicate that circulation in the southern Bight is affected by local alongshore wind forcing as well as the disturbances propagating from the north. Stratification is essential in determining the cross-shelf circulation. Persistence of alongshore wind seems to be another important factor. Therefore, three-dimensionality, time dependency and density stratification are all essential in modeling the circulation of the Mid-Atlantic Bight.

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