Non-Tidal Variability in the Chesapeake Bay and Potomac River: Evidence for Non-Local Forcing

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(Manuscript received 31 March 1977, in final form 22 November 1977)

ABSTRACT

Non-tidal variability in the Chesapeake Bay and Potomac River, and its relation to atmospheric forcing, is examined from two-month sea level and bottom current measurements. The dominant sea level fluctuations in the Bay had a period of 20 days, and were the result of up-Bay propagation of coastal sea level fluctuations generated by the alongshore winds. Consequently, water was driven out of the Bay by the northward/up-Bay wind and driven into the Bay by the southward/down-Bay wind, through the coastal Ekman flux.

There were also large sea level fluctuations at periods of 5 and 2.5 days. The 5-day fluctuations were driven by both the coastal sea level changes and the local lateral winds (Ekman effect). The 2.5-day fluctuations were seiche oscillations driven by the local longitudinal winds.

In the Potomac River, the sea level fluctuations were induced non-locally by motions in the Bay; the associated volume fluxes appeared to have been confined to the upper layer. The near-bottom currents were mainly driven by the surface slopes which were also set up non-locally, by the longitudinal wind over the Bay. In general, the near-bottom current and sea level/volume flux fluctuations were not coherent. A notable exception, however, was found for the 2.5-day fluctuations which were vertically coherent and showed significant upward phase propagation.

Because of the significance of non-local forcing, an adequate model for the non-tidal estuarine circulation would need to include the effects of interaction with the adjacent larger estuary or the coastal ocean. Also, site-specific experiments should be complemented by far-field measurements to determine non-local conditions.

1. Introduction

The nontidal ("residual") motion in a partially mixed estuary can be induced locally by horizontal salinity gradients, wind forcing and river runoff (Hansen and Rattray, 1965). During the past two decades, the gravitational circulation was thought to be the dominant component, and this process was studied rather extensively (e.g., Pritchard, 1956).

The significance of the local wind forcing was examined only recently based on continuous current measurements over several-month periods (Weisberg, 1976; Elliott, 1978). These studies found that the wind-driven flow can be at times much larger than the gravitational circulation. Therefore, the effects of atmospheric forcing cannot be neglected.

Motions in an estuary can also be induced non-locally through coupling with a neighboring larger estuary or coastal ocean. High-frequency "surges" in an estuary may originate from disturbances generated earlier at the ocean coast (Bretschneider, 1966), and tides in an estuary are forced by ocean tides at the mouth. In both cases, the disturbances propagate into the estuary as gravity and/or Kelvin waves. Since these waves exist for low frequencies, coupling between an estuary and its coastal ocean (or two adjacent estuaries) may also occur at low frequencies. Thus, the effects of non-local forcing cannot be neglected.

In this study, non-tidal variability in the Chesapeake Bay and Potomac River, and its relation to local and non-local forcing, is examined from sea level and meteorological records over a two-month period (mid-July to mid-September, 1974). Near-bottom current measurements in the Potomac River for the same period, and 3-day profiling current measurements during a strong wind event (4–7 September 1974) are also included in the analysis.

The main objective of this study is to examine the effects of local and non-local forcing on circulations in the Chesapeake Bay and Potomac River.

0022-3670/78/0225-0232$05.00

2. Sea level fluctuations in the Chesapeake Bay and Potomac River

Sea level fluctuations in the Chesapeake Bay and Potomac River were examined at seven locations: Annapolis, Solomons Island, Grey Point and Kiptopeake Beach in the Bay proper, and Lewisetta, Colonial Beach and Washington D. C. in the River (Fig. 1). The sea level records were low-pass filtered to remove the diurnal, semidiurnal and high-frequency fluctuations. (The half-amplitude point of the low-pass filter is 34 h.)

The non-tidal (low-passed) sea level fluctuations had spectrum peaks at periods of 20, 5 and 2.5 days

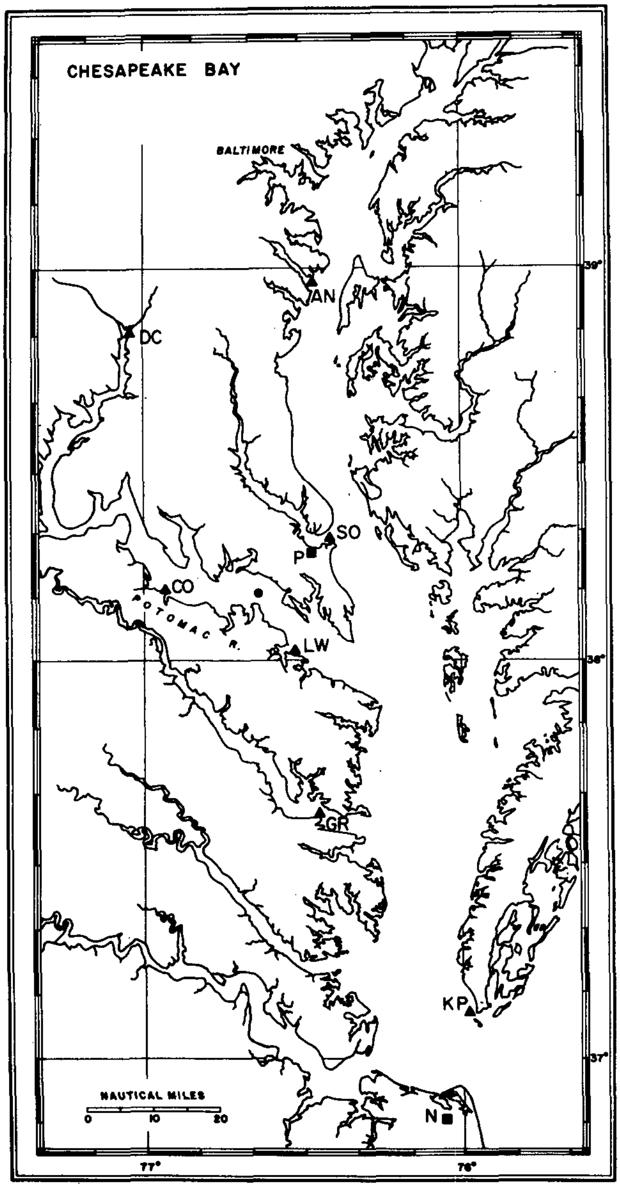

FIG. 1. The Chesapeake Bay and its tributaries (▲, sea level station; ■, weather station; ⊗, current meter mooring).

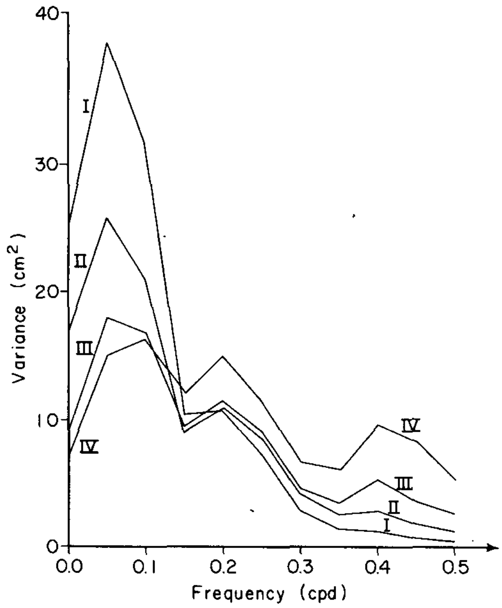

FIG. 2. The power spectra for sea level, at (I) Kiptopeake Beach, (II) Lewisetta, (III) Solomons Island and (IV) Annapolis.

(Fig. 2). (The frequency bandwidth is 0.05 cpd, and the number of degrees of freedom is 13.) In the Bay, the longitudinal distribution of the amplitude of sea level fluctuations changed quite dramatically with frequency. For example, the amplitude of the 20-day fluctuations decreased rapidly away from the mouth of the Bay, while an opposite trend was associated with the 2.5-day fluctuations. In the River, the amplitude of the 20-day fluctuations was nearly uniform, while there was a significant amplitude increase toward the head at the 2.5-day period.

The spatial distribution of non-tidal sea level fluctuations in the Bay and River was determined from an empirical orthogonal function analysis in the frequency domain (Wallace and Dickinson, 1972; Wang and Mooers, 1977). The application of empirical orthogonal function analysis tends to isolate, from the original records, the spatially coherent disturbances as empirical modes. For all frequencies, the first mode accounted for more than 90% of the total variance, indicating that most of the sea level fluctuations were coherent over the Bay. The modal structures in the River were similar to those in the upper Bay, suggesting that sea level fluctuations in the River were due to co-oscillations with the Bay. (As an example, the structure of the first mode of the 2.5-day fluctuations is listed in Table 1.) Thus, for brevity, only the amplitude and phase distribution for the first mode in the Bay are shown (Fig. 3).

Large sea level fluctuations occurred at a period of 20 days. The amplitude of fluctuations decreased toward the head of the Bay. Their phase increased

TABLE 1. The rms amplitude, phase and coherence-squared distributions for the first empirical mode at a 2.5-day period.

	Station	Amplitude (cm)	Phase (deg)	Coherence squared*
Chesapeake Bay	Kiptopeake Beach	0.62	−133	0.33
	Grey Point	0.77	7	0.56
	Solomons Island	2.14	−10	1.00
	Annapolis	3.09	−14	0.99
Potomac River	Lewisetta	1.62	0	0.95
	Colonial Beach	2.22	0	0.94
	Washington, D. C.	2.56	−4	0.99

* The 95% significance level for coherence squared is 0.37.

up-Bay with a time lag of about 2 days between Kiptopeake Beach and Annapolis. Thus, the 20-day sea level fluctuations were generated near the mouth of the Bay, and they propagated up-Bay.

The amplitude of the 5-day fluctuations was nearly uniform in the Bay. These fluctuations also moved up-Bay with a time lag of about 15 h between Kiptopeake Beach and Annapolis. Because of their up-Bay phase propagation, the 5-day sea level fluctuations also appear to have been generated near the mouth of the Bay.

The amplitude of the 2.5-day fluctuations was large near the head of the Bay, and diminished toward the mouth. These fluctuations had an almost constant phase within the Bay, and were not coherent with fluctuations at the mouth, which suggests that they were seiche oscillations with a node at the mouth and an antinode at the head of the Bay. Indeed, an estimate of long-wave phase speed in the Bay suggets that its longest seiche period is about 2 days.

3. Relation of the sea level fluctuations to atmospheric forcing

The non-tidal sea level fluctuations can be simply the result of barometric adjustment to surface atmospheric pressure fluctuations. However, this was not the case, as the coherence between sea level and atmospheric pressure fluctuations was poor. Thus, only the wind forcing appears to be important.

The low-passed wind fluctuations had spectrum peaks at periods of 20, 5 and 2.5 days at both Patuxent River and Norfolk (Fig. 4). The (principal) axis of wind fluctuations was from northeast to southwest at Patuxent River. Near the coast at Norfolk, winds were more or less in the north-south direction, and were stronger. The coherence of wind fluctuations between Patuxent River and Norfolk was significant for periods >5 days.

The similarity between wind and sea level spectra suggests that the non-tidal sea level fluctuations in the Bay were driven by the winds. Relations between sea level and wind fluctuations were examined from cross spectrum analysis; the coherence squared between Norfolk wind and Kiptopeake Beach sea level, and Patuxent wind and Annapolis sea level, are shown in Fig. 5.

The 20-day sea level fluctuations at Kiptopeake

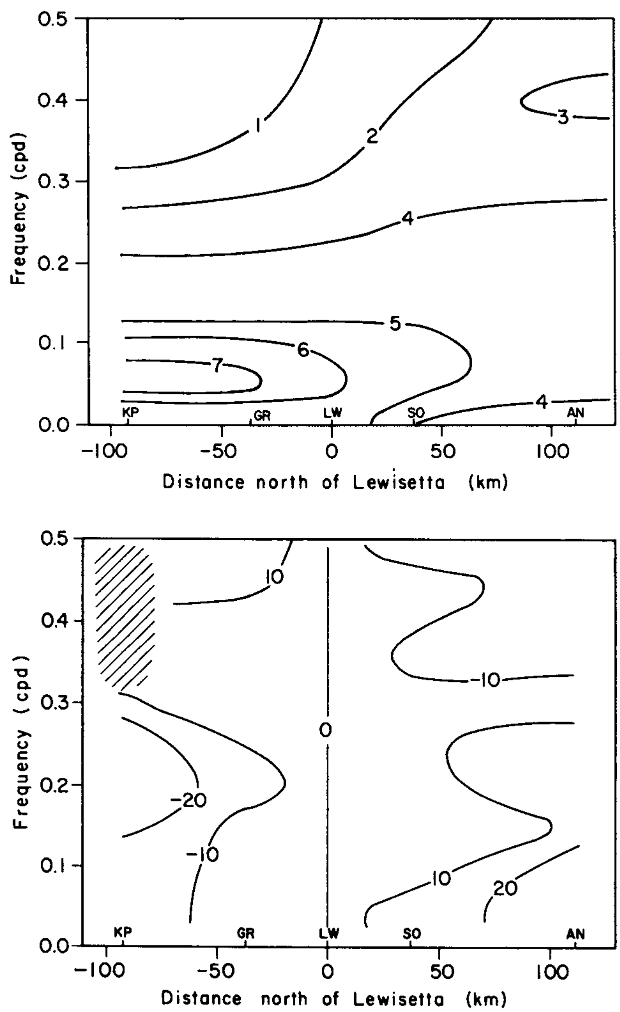

FIG. 3. The first empirical mode of sea level fluctuations as a function of frequency and longitudinal distance in Chesapeake Bay (hatched area, the coherence below the 95% significance level): (a) rms amplitude (cm), (b) phase (reference to Lewisetta) in degrees.

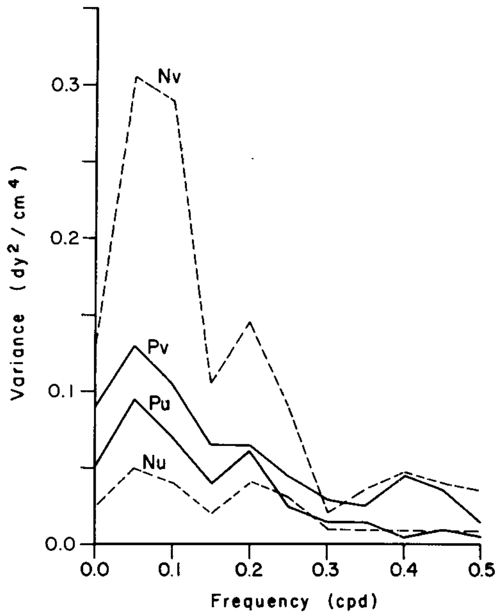

FIG. 4. The power spectra for northward (v) and eastward (u) wind stress, at Norfolk (N) and Patuxent River (P).

Beach were coherent with north-south winds at Norfolk. The rise (fall) of the sea level was associated with the southward (northward) wind, which is consistent with the result of a coastal Ekman flux. In other words, the 20-day sea level fluctuations near the mouth of the Bay were driven by alongshore winds. In the Bay, a similar phase relation also held between sea level and north-south winds, i.e., water was driven into (out of) the Bay by the southward (northward) wind, which is opposite to the effect of local forcing. Thus, the non-local effect was dominant, or the 20-day fluctuations in the Bay were mainly due to the up-Bay propagation of coastal sea level fluctuations.

The 5-day sea level fluctuations at Kiptopeake Beach were coherent with the Norfolk east-west winds. As they had up-Bay phase propagation, the 5-day fluctuations in the Bay also appeared to have been forced non-locally by the coastal winds. On the other hand, the Annapolis sea level fluctuations were coherent with the Patuxent east-west winds, which is suggestive of local forcing. The rise (fall) of sea level was associated with the westward (eastward) wind, which was likely due to the Ekman flux in the Bay. Thus, the 5-day fluctuations in the Bay were probably part of the coupled estuary-coastal ocean response driven by the east-west winds.

The 2.5-day sea level fluctuations in the Bay were coherent with the local north-south winds (Fig. 5b). The rise (fall) of sea level was associated with the northward (southward) wind, which is consistent with the effect of local forcing. In contrast, the sea level fluctuations near the Bay mouth were driven by alongshore winds through the Ekman effect (Fig. 5a). As the coherence between the coastal and Bay-wide fluctuations was poor, the 2.5-day sea level fluctuations in the Bay were mainly forced by the local, longitudinal winds.

The coherence between the surface slope in the Bay (sea level difference between Annapolis and Kiptopeake Beach) and the north-south wind was high over the entire low frequencies (Fig. 6), suggesting that the surface slopes were induced by the local, longitudinal winds. They were set up by the northward wind, and set down by the southward wind, with a time lag of only a few hours. In contrast, the surface slopes in the River were not coherent with the local, longitudinal (southeast-northwest) wind. Instead, they were coherent with the surface slopes in the Bay (Fig. 6), which suggests that the surface slopes in the River were part

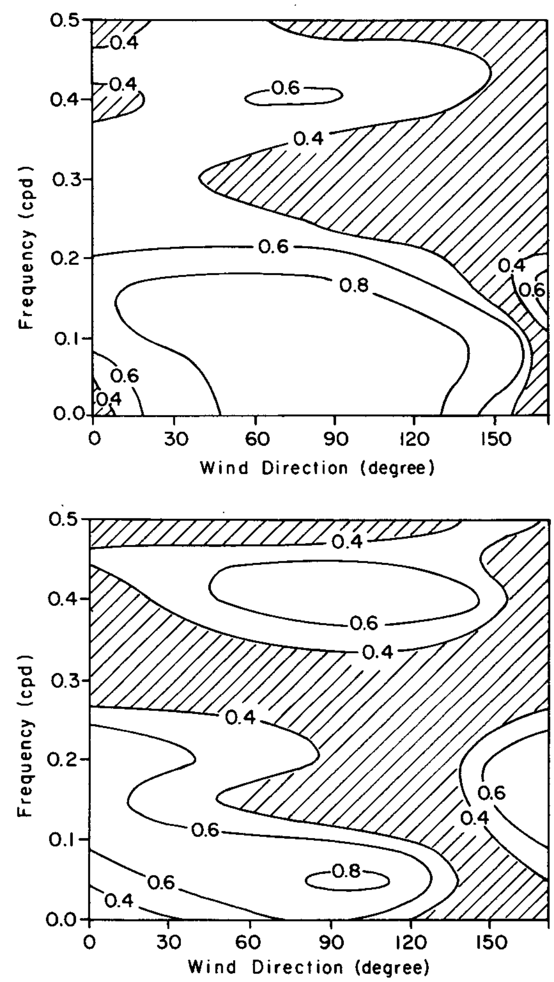

FIG. 5. The coherence-squared between wind stress and sea level (the 90° direction is along the north-south axis) between (a) the Norfolk wind and Kiptopeake Beach sea level and (b) the Patuxent River wind and Annapolis sea level.

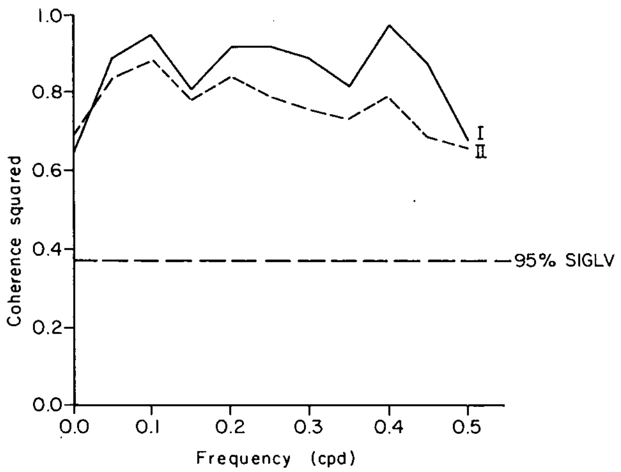

FIG. 6. The coherence-squared between (I) the north-south wind and the surface slope in the Bay and (II) the surface slope in the River and the surface slope in the Bay. (The 95% significance level is marked.)

of the coupled Bay-River response induced by the north-south wind.

4. The near-bottom current fluctuations in the Potomac River

Current measurements in the Potomac River were made 3 m above the bottom with an Endeco 105 meter during the period of 17 July to 23 September 1974. The mooring was located 30 km from the River mouth, and in 15 m water depth. The directions of flow were mainly along the axis of the River, i.e., from northwest to southeast. Since the small lateral currents were subject to large uncertainties as a result of compass error, only the longitudinal currents were included in the analysis. (The longitudinal current and local wind are shown in Fig. 7.)

The two-month averaged near-bottom current was 0.6 cm s^{-1} seaward, which was in the opposite direction to that usually associated with the near-bottom flow in a partially mixed estuary. It was also smaller than the rms non-tidal velocity of 4.0 cm s^{-1}. Thus, the mean near-bottom current during this period was a minor component of the non-tidal flow.

The near-bottom current fluctuations had spectrum peaks at periods of 20, 5 and 2.5 days, which was similar to the wind fluctuations. Relations between near-bottom current and wind fluctuations were examined from cross spectrum analysis; their coherence squared is shown in Fig. 8.

For time scales longer than 10 days, the near-bottom current fluctuations were coherent with the lateral (northeast-southwest) winds over the River. A northeastward wind drove bottom water into the River, and an outflow was induced by the southwestward wind. This is probably the result of a bottom compensating flow to an Ekman flux into the River, or, it may be the result of non-local forcing.

For time scales <10 days, the near-bottom currents were coherent with north-south winds, which is suggestive of non-local forcing due to the longitudinal wind over the Bay. Examination of the relations between near-bottom current and surface slope (sea level difference between Washington D. C., and Lewisetta) indicated that the near-bottom currents were coherent with surface slopes for time scales <10 days (Fig. 9). The bottom outflow was driven by the downstream surface slope (larger sea level at the head) with a small phase difference, and a reverse circulation was induced by the upstream surface slope. Since the surface slopes in the River were set up by the longitudinal wind over the Bay, the near-bottom current fluctuations in the River, for time scales <10 days, were due to non-local forcing.

The volume flux in the River is determined from the rate of sea level change, through the continuity requirement. As the sea level fluctuations were coherent and almost in phase in the River, the volume flux was coherent with the sea level, with a 90° phase lag. (The flow is positive when it is down the River.) On the other hand, the near-bottom current was not coherent with the sea level/volume flux for time scales longer than 3 days (Fig. 9), which suggests that the volume flux was mainly confined to the upper part of the water column.

At the 2.5-day period, the sea level and surface slope fluctuations were coherent, and consequently, the near-bottom current which was driven by the surface slope was coherent with the sea level/volume

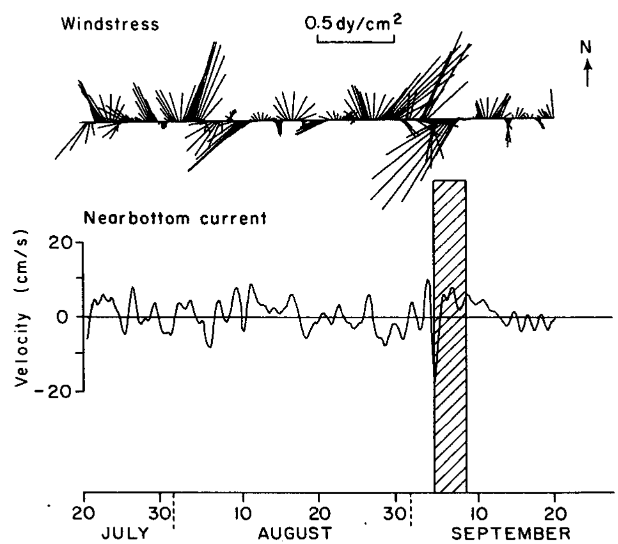

FIG. 7. Time series of near-bottom current in the Potomac River (the flow is positive when it is down the River) and the wind stress at Patuxent River. (The hatched area is the period of profiling current measurements.)

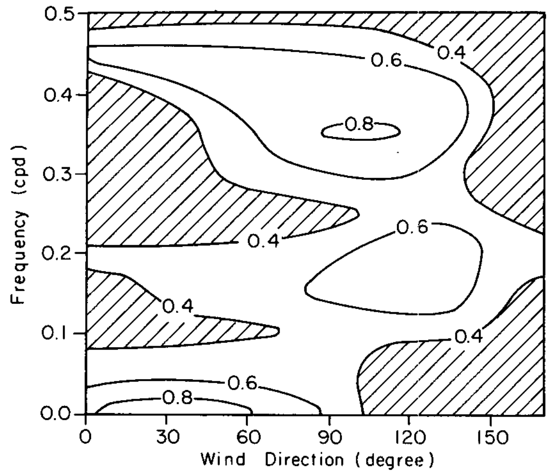

FIG. 8. The coherence-squared between near-bottom current in the Potomac River and the wind stress at Patuxent River (the 90° direction is along the north-south axis).

flux (Fig. 9). Since the near-bottom current was in phase with the sea level fluctuation, it also led the volume flux by 90°. Thus, the near-bottom current would appear to lead the near-surface current, as the volume flux was most likely confined to the near-surface. Further evidence for the upward phase propagation of the 2.5-day velocity fluctuations is obtained from the profiling current measurements.

5. The vertical structure of the 2.5-day current fluctuations

The maximum bottom current fluctuations with a period of 2–3 days occurred in early September (Fig. 7). During this period (4–7 September),

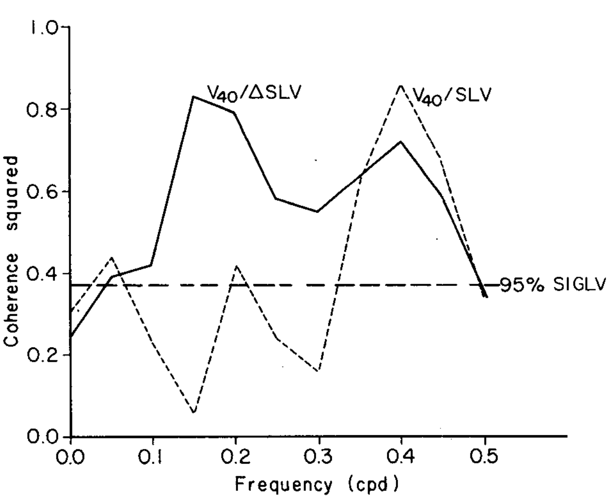

FIG. 9. The coherence-squared for near-bottom current (V_{40}), sea level (SLV) and surface slope (ΔSLV) in the Potomac River. The 95% significance level is marked.

vertical profiles of the horizontal velocity were measured with a direct reading Endeco 110 current meter at two locations 18 km (P10) and 35 km (P19) from the mouth of the River. In addition, there were 11 current meters moored across these two transects (Elliott and Hendrix, 1976).

Even though the two stations were separated by 17 km and were in different water depths (11 m for P19 and 17 m for P10), similar flow patterns were observed. Hence only the measurements from station P19 which had more complete data, are discussed. The low-passed (25 h running averaged), profiling currents are shown in Fig. 10, and the fixed-level measurements from three moorings separated laterally at a 2 km interval are shown in Fig. 11.

Current fluctuations with a period of 2–3 days can be seen clearly in the fixed-level and profiling current records. At the beginning of 4 September currents started flowing landward at the 7.5 m (25 ft) level (Fig. 11), while the seaward flow at the 4.5 m (15 ft) level reached its maximum. About 18 h later, the landward flow extended to the upper level. And, at the beginning of 5 September the seaward flow was found only in the top few meters (Fig. 10).

The upward phase propagation of current oscillations was found throughout the entire water column. While the landward flow gradually extended to the surface, a seaward flow reappeared near the bottom. And, at the beginning of 6 September, water at all the lower levels flowed seaward.

A reverse cycle (i.e., an upward extension of the seaward flow) was found everywhere, except at the central mooring, where the upward phase propagation was slightly masked by the longer period oscillations. Finally, at the beginning of 7 September water at all mid-depths flowed seaward. The period of current oscillations, as estimated from the time interval between two successive maxima of seaward flow at 4.5 m (15 ft), was about 2.5 days. Thus, the profiling measurement supports the conclusion that an upward phase propagation was associated with the 2.5-day motion, deduced from the cross-spectrum analysis of the two-month sea level and near-bottom current records.

6. Discussion

Wind generation of non-tidal current fluctuations in a partially mixed estuary was noted in Weisberg (1976), who found in Narragansett Bay that bottom current and local wind fluctuations were highly coherent over a two-month period. Sea level fluctuations, however, were not coherent with wind/bottom current fluctuations. Thus, the response of the circulation to wind forcing was mainly baroclinic with small volume flux.

On the other hand, significant sea level variations have been observed in the Chesapeake Bay and

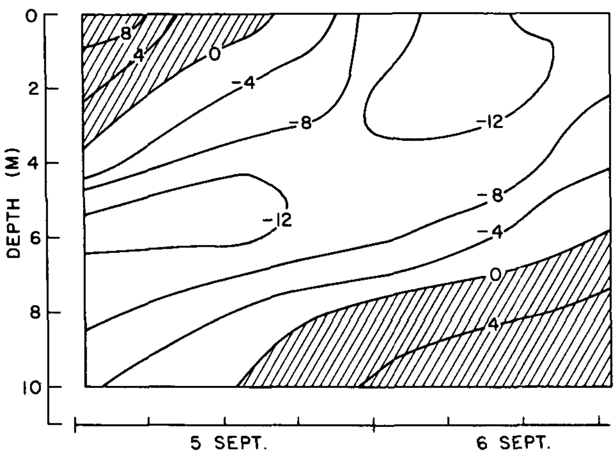

FIG. 10. The time-depth contour of the longitudinal velocity (cm s^{-1}) in the Potomac River from profiling current measurements (the flow is positive when it is down the River).

Potomac River. Based on one-year current measurements in the River, Elliott (1978) noted that about half of the surface and mid-depth current fluctuations and most of the bottom current fluctuations were generated locally by the winds. The other half of the surface and mid-depth current fluctuations were directly related to the sea level fluctuations, suggesting that they were due to the exchange with the Bay. Thus, a significant portion of the sea level and current fluctuations in the River were induced by non-local effects.

In this study, evidence for non-local forcing in the Chesapeake Bay due to the interaction with the coastal ocean is obtained. For example, the 20-day fluctuations in the Bay originated from changes of coastal sea level which had been generated earlier by alongshore winds through the Ekman flux. Consequently, water was driven out of the Bay by the up-Bay wind, which is in apparent contradiction to the local forcing.

In contrast, the 2.5-day sea level fluctuations in the Bay were seiche oscillations forced by the local, longitudinal winds. The seiche oscillations did not respond to sea level changes at the coast, which is probably due to the fact that the mouth of the Bay is in the proximity of the seiche's node. Consequently, the effect of non-local forcing was negligible.

Evidence for non-local forcing in the Potomac River due to the interaction with the Chesapeake Bay is also obtained. Sea level fluctuations in the River originated from sea level changes in the Bay; the associated volume flux was confined to the near-surface and mid-depths, which agrees with Elliott (1978). As the longitudinal wind over the River was small during this period, surface slopes in the River were induced by the longitudinal wind over the Bay. Consequently, the near-bottom currents which were driven by surface slopes, were also due to non-local forcing.

An upward phase propagation of velocity fluctuations was associated with the 2.5-day seiche motion in the River. The phase change appears to be mainly induced by bottom friction. There is also tentative

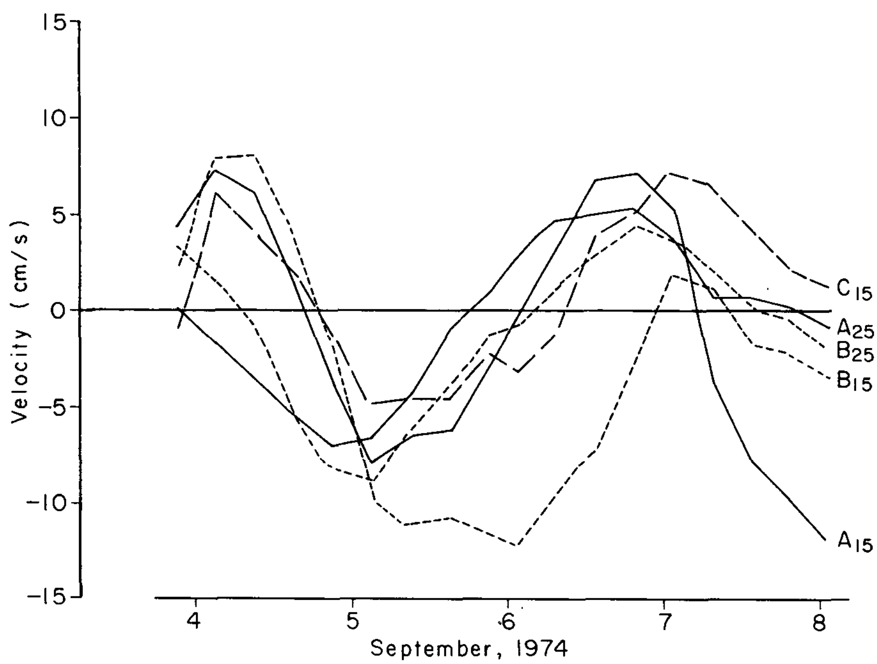

FIG. 11. Time series of intensive current measurements in the Potomac River during the period of profiling measurement (A, west mooring; B, central mooring; C, east mooring). The subscripts are the current meter depths in feet.

evidence that reversals of the horizontal density gradient may also play a role (Elliott and Hendrix, 1976).

Finally, several comments can be made on the study of non-tidal estuarine circulation:

1) The major fluctuations occur at the seasonal and storm time scales. Long-term (several months to several years) monitoring of the wind, sea level, density and current is essential to the complete understanding of estuarine circulation.

2) Non-local wind forcing, at times, can dominate the effects due to local wind forcing. Intensive, site-specific experiments should be complemented by far-field (estuary-wide) measurements in order to document the non-local conditions.

3) Modeling of estuarine circulation should incorporate both the local wind and non-local forcing. The "open ocean" boundary conditions should be formulated to include the interaction with the adjacent coastal ocean.

Acknowledgments. We thank Dr. C. N. K. Mooers for his many helpful comments on the manuscript and Dr. D. W. Pritchard for his continued interest in this study. This work was supported by the National Science Foundation under Grant OCE74-08463.

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