Observations of Low-Frequency Variability in Great South Bay and Relations to Atmospheric Forcing

KUO-CHUIN WONG

College of Marine Studies, University of Delaware, Newark, DE 19716

ROBERT E. WILSON

Marine Sciences Research Center, State University of New York, Stony Brook, NY 11794

(Manuscript received 20 December 1983, in final form 6 September 1984)

ABSTRACT

Sea level and current data collected around Great South Bay, New York during December 1979 are examined in conjunction with atmospheric data for evidence of wind-forced, low frequency variability in the Bay and on the adjacent shelf. The subtidal sea level along the coast was found to be highly coherent from Sandy Hook to Montauk Point, with a single empirical mode accounted for more than 97% of the total variance. These coherent fluctuations were forced primarily by longshore winds (along 250–070°T) through the coastal Ekman effect. The sea level within the Bay exhibited large and spatially coherent subtidal fluctuations as a result of a strong coupling with the adjacent shelf. The characteristic volume exchange associated with this Bay-shelf coupling was an active simultaneous inflow or outflow through both ends of the Bay (with fluctuations in excess of 20 cm s^{-1}) in response to the rise or fall of coastal sea level induced by longshore winds.

1. Introduction

In recent years the importance of atmospheric forcing on the low-frequency variability in the coastal and estuarine waters has been widely recognized. A number of studies have been conducted to examine the relationship between atmospheric forcing and fluctuations in sea level and currents at subtidal frequencies within the Mid-Atlantic Bight. Beardsley *et al.* (1976) showed that in the Mid-Atlantic Bight most of the low-frequency variance in near-shore shallow currents was associated with wind driven fluctuations; they also suggested that intense winter lows which produce strong wind stress paralleling the coast from Cape Cod to Cape Hatteras were the most effective wind forcing mechanism. Wang (1979a) found that longshore wind stress was important in producing subtidal sea level fluctuations in the coastal areas from Cape Cod to Cape May. Noble and Butman (1979) reported that during winter a significant portion of the variance in the subtidal sea level fluctuations along the east coast of North America was coherent with longshore winds.

The importance of atmospheric forcing and its effect on subtidal sea level fluctuations and volume exchange for a coupled estuary-shelf system has been documented for the Chesapeake and Potomac estuaries. Elliott and Wang (1978) found that the dominant subtidal sea level fluctuations in the Chesapeake Bay were generated at the mouth of the Bay by alongshore winds. Wang and Elliott (1978) further determined that within the Potomac River, the subtidal sea level fluctuations were induced by motions in the Chesapeake. Based on a one-year study of the subtidal sea level variability in Chesapeake Bay, Wang (1979b) established the existence of volume exchange in the Bay at time scales of 3–5 days with a magnitude much greater than the river runoff; he showed that this exchange was driven primarily by the east–west winds as part of the coupled estuary–shelf response. In a separate study based on direct current measurements, Wang (1979c) found further evidence for large, wind driven barotropic current fluctuations in the lower Chesapeake. In light of these developments, the present study examines some of the details of the response characteristics of Great South Bay to atmospheric forcing.

Great South Bay (Fig. 1) is a long, narrow and very shallow (MLW depth 1.3 m) bar-built estuary on the south shore of Long Island, New York. It is approximately 40 km in length and its width varies from 2.5 to 8 km. The major axis of the Bay is along 250–070°T, which is roughly the same as the longshore direction. Fire Island Inlet is the passage for direct exchange of water between Great South Bay and the Atlantic Ocean. The Bay also communicates with the Atlantic Ocean indirectly through Moriches Bay and Moriches Inlet to the east of the Smith Point

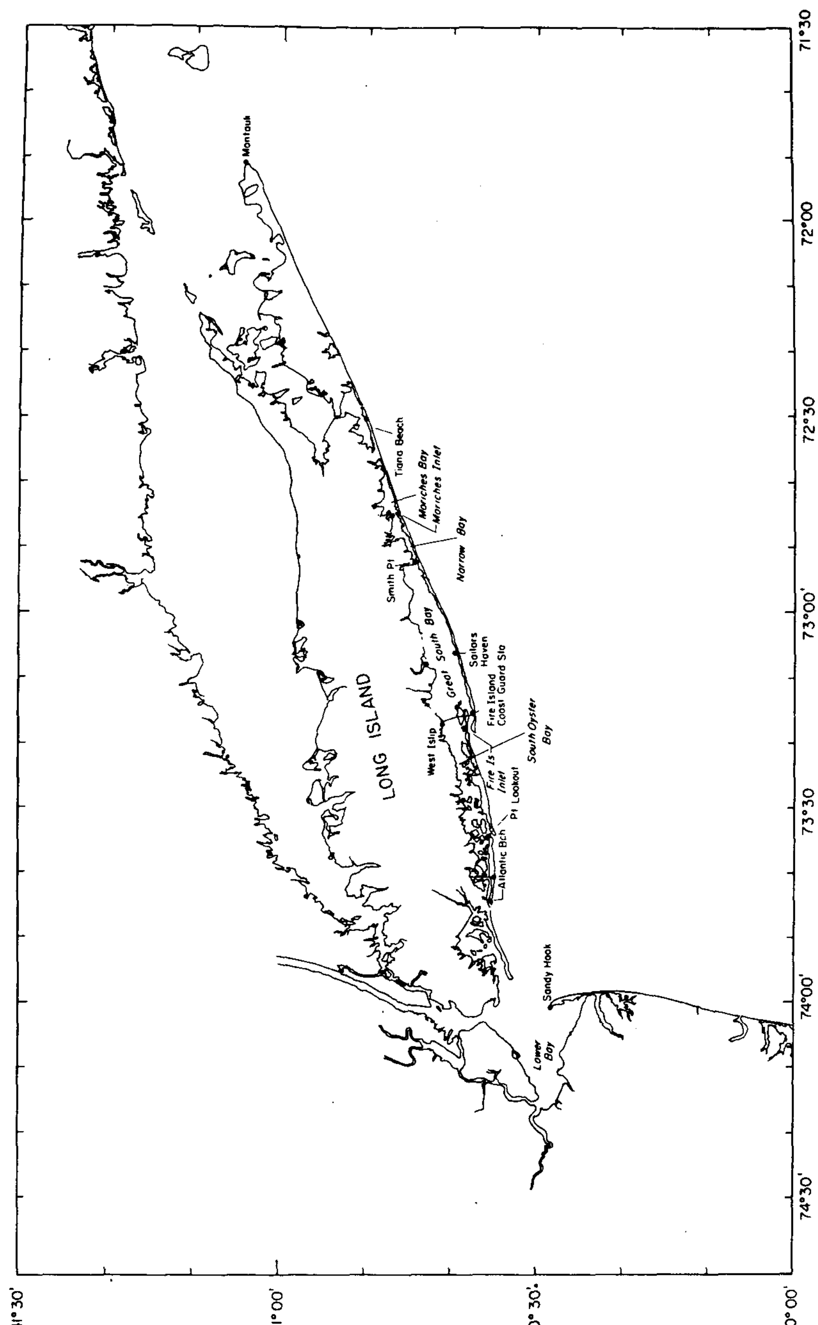

FIG. 1. Great South Bay, New York.

channel. There is also limited indirect exchange between the Bay and the ocean via South Oyster Bay to the west. The predominantly semidiurnal tides (with a mean range of 58 cm at the Fire Island Coast Guard Station) enter the Bay as progressive waves and generate tidal currents with typical amplitudes of 1 m s^{-1} in the Fire Island Inlet. The semidiurnal tides are attenuated rapidly within the Bay due to the narrow inlet and the shallowness of the Bay. For example, the mean tide range at Captree Island just inside the Fire Island Inlet is 45 cm, and that at West Islip is only 30 cm.

Great South Bay has received little attention in the past, and the relationship between atmospheric forcing and subtidal variability there was virtually unknown. By analyzing records of surface winds, sea level and currents measured during December 1979, this study examines

1) the major atmospheric forcing mechanism for producing the subtidal variability within the Bay;
2) the characteristic volume exchange at subtidal frequencies between the Bay and the shelf in response to atmospheric forcing.

2. Data base

During December 1979 current and sea level data within Great South Bay were available from a survey supported by the New York Sea Grant. Current meter observations were made using ENDECO 174 current meters; single instrument moorings were placed in the Fire Island Inlet and the Smith Point channel (located at the eastern end of Great South Bay). Sea level fluctuations within the Bay were measured with Fischer Porter gages at the Fire Island Coast Guard Station, Captree Island (just inside the Fire Island Inlet), West Islip and Sailors Haven. Additional sea level data were also available from permanent town and county gauges at Atlantic Beach, Point Lookout and Smith Point, and from National Ocean Service gauges at Sandy Hook and Montauk Point. Records of near surface winds during the study period were obtained from the Brookhaven National Laboratory weather station at Tiana Beach. Wind stress was estimated from near-surface winds using a drag coefficient $C_d = 1.0 \times 10^{-3}$.

Since our interest here is to examine the atmospherically forced subtidal variability within the Bay, the wind, sea level and current data sets were low-pass filtered using a Lanczos filter with a cutoff period of 34 h to remove fluctuations with diurnal or higher frequencies.

3. Atmospheric forcing

During the study period, sea level along the coast of the south shore of Long Island exhibited large subtidal fluctuations with a maximum range in excess of 60 cm (Fig. 2). These subtidal sea level fluctuations were highly coherent over a distance of 200 km from Sandy Hook to Montauk Point at the eastern end of Long Island. Coherence squared between Sandy Hook and Montauk (Fig. 3), for example, was higher than 0.85 for almost all frequencies lower than 0.5 cpd, and the corresponding phase lag was very small.

To further examine these coherent coastal fluctuations, an empirical orthogonal function (EOF) analysis was conducted. Given time series at M locations, the EOF method separates the time series at any given location into M orthogonal EOF modal series as

$$S_m(t) = \sum_{i=1}^{M} a_i(t)F_{im}. \quad (1)$$

Here $S_m(t)$ represents time series at the mth location, $a_i(t)$ the ith EOF modal series (which is not a function of location), and F_{im} the normalized multiplication factor associated with the ith EOF modal series at the mth location.

The EOF method can provide information such as the fraction of the total variance that can be attributed to the jth mode as well as the fraction of the variance of the mth time series that can be represented by the jth EOF mode. The EOF analysis thus gives both an overall estimate of the strength of each empirical mode and an indication of the relative importance of each mode at each location. Details of the EOF technique can be found in Wallace and Dickinson (1972).

Table 1 shows the result of the EOF analysis conducted on the subtidal sea level fluctuations at five stations along the coast. These stations are, from west to east, Sandy Hook, Atlantic Beach, Point Lookout, Fire Island Coast Guard Station, and Montauk Point. A single EOF mode accounted for more than 97% of the total variance associated with these sea level fluctuations, and at any given location more than 93% of the variance can be represented by this mode. The normalized eigenvectors (the F_{im}) of the first EOF mode are of the same sign at all the stations. The EOF analysis thus indicates that the entire south shore of Long Island exhibited a single mode of coherent in-phase sea level fluctuations during the study period which accounted for almost all the variance.

Relations between wind stress and subtidal sea level fluctuations along the coast were examined using cross-spectrum analysis between different components of the wind stress and sea level at Point Lookout. Point Lookout was used as a representative coastal station since the first EOF mode accounted for almost all the subtidal sea level variance there. We found that the subtidal sea level at Point Lookout responded preferentially to the wind stress component along 250–070°T (the longshore direction). This component of the wind stress is shown in Fig. 2, with

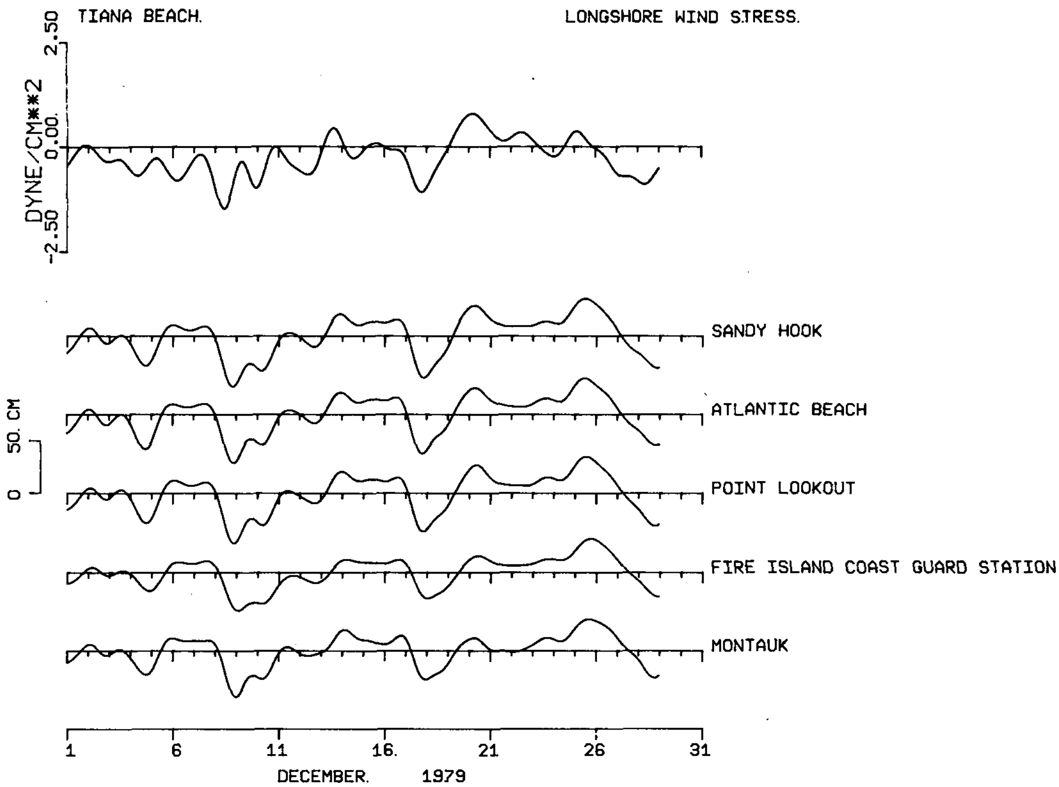

FIG. 2. Longshore component of wind stress (along 250–070°T) and subtidal sea level at Sandy Hook, Atlantic Beach, Point Lookout, Fire Island Coast Guard Station and Montauk Point during the study period.

positive value representing wind stress towards 250°T (alongshore to the west). The coherence squared between subtidal sea level at Point Lookout and this longshore wind stress (Fig. 4) was significant at all frequencies lower than 0.5 cpd, and it was higher than 0.8 at 0.1–0.3 cpd. The corresponding phase lag was almost a linear function of frequency (Fig. 4), implying a constant time lag of about 10 hours. This suggests that coastal Ekman forcing with volume transport to the right of the longshore wind stress was the principal mechanism which was forcing the subtidal sea level fluctuations along the coast. A longshore wind stress fluctuation towards 250°T will produce a rise in sea level along the coast, and stress towards 070°T will produce a drop in coastal sea level.

During the study period, subtidal sea level inside Great South Bay exhibited fluctuations with a maximum range in excess of 50 cm (Fig. 5). By comparing the interior subtidal sea level with that at Fire Island Coast Guard Station (representing the coastal condition), it is clear that the attenuation in the subtidal

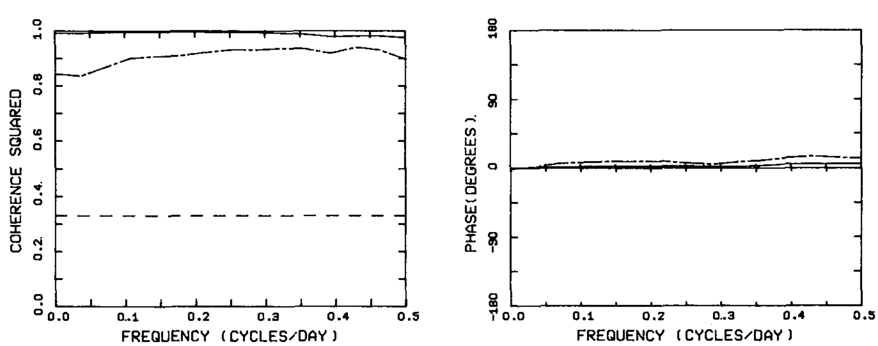

FIG. 3. Coherence squared and phase between subtidal sea level at Sandy Hook and Point Lookout (solid line) and between Sandy Hook and Montauk Point (dash-dot line). The dashed line indicates the 95% significance level.

TABLE 1. Summary of the EOF analysis conducted on the subtidal sea level fluctuations at Sandy Hook (S_S), Atlantic Beach (S_A), Point Lookout (S_P), Fire Island Coast Guard Station (S_F), and Montauk (S_M).

Mode	Eigenvalue	Percent of total variance	S_S	S_A	S_P	S_F	S_M
					Normalized eigenvector		
1	1290.0	97.32	0.498	0.474	0.480	0.375	0.396
2	25.0	1.89	−0.387	−0.388	−0.144	0.642	0.516
3	8.4	0.64	−0.191	0.170	−0.089	−0.623	0.734
4	1.4	0.10	−0.748	0.533	0.330	0.101	−0.193
5	0.7	0.05	−0.081	−0.559	0.795	−0.221	0.016
					Percent of variance explained at each station		
1			98.5	98.4	99.6	93.0	94.7
2			1.2	1.3	0.2	5.3	3.1
3			0.1	0.1	0.0	1.7	2.1
4			0.3	0.1	0.1	0.0	0.1
5			0.0	0.1	0.1	0.0	0.0

sea level fluctuations inside the Bay was slight. Since the semidiurnal tides were substantially attenuated in the interior, the subtidal sea level fluctuations at stations away from the inlet (such as West Islip and Sailors Haven) were even greater than those of the semidiurnal tides.

These subtidal sea level fluctuations in the interior of the Bay were very similar to those at the Fire Island Coast Guard Station (FICGS). Among them the sea level at Captree Island was most similar to the coastal condition due to its proximity to Fire Island Inlet. The subtidal sea level at other interior stations were also highly coherent with that at the FICGS at all frequencies lower than 0.5 cpd (Fig. 6). In the western part of Great South Bay the coherence between the coastal sea level and the interior sea level (at West Islip and Sailors Haven) decreased slightly and the corresponding phase lag increased with distance away from the inlet. The coherence between subtidal sea level at the FICGS and Smith Point (at the eastern end of Great South Bay) was slightly lower but still significant at all frequencies lower than 0.5 cpd, but the corresponding phase lag was not much different from that between the FICGS and Sailors Haven (Fig. 6). This suggests that at subtidal frequencies the sea level fluctuations in the interior of Great South Bay were forced primarily by the coherent coastal sea level fluctuations induced by longshore winds. The interior sea level in the western part of the Bay fluctuated in response to the strong Bay–shelf coupling through Fire Island Inlet. The small relative phase lag between Smith Point and Sailors Haven suggests that the eastern part of the Bay was coupled to the coastal disturbances off Moriches Inlet farther east.

Insight into the characteristics of subtidal volume exchange between the Bay and the shelf in response to atmospheric forcing is provided by current records at Fire Island Inlet and Smith Point channel. Since we are primarily concerned about Bay-shelf exchange, only the principal axes components of the subtidal current fluctuations are considered (Fig. 7). The principal axis direction is approximately 250–070°T, since the orientations of the Fire Island Inlet and Smith Point channel are roughly aligned with the major axis of the Bay. In Fig. 7 positive values of currents indicate flows toward 250°T; so a positive current at Fire Island Inlet indicates flow out of the

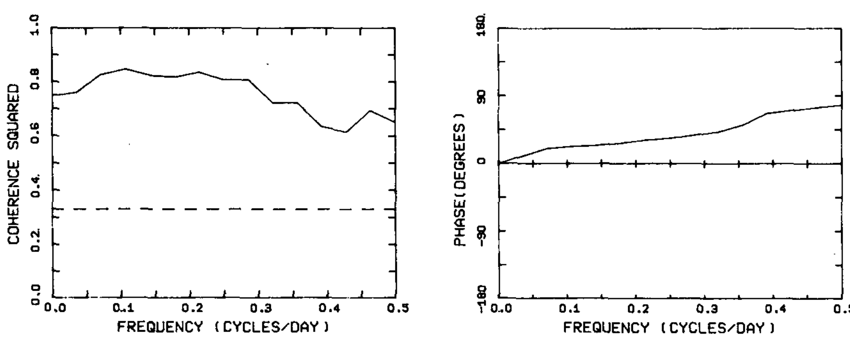

FIG. 4. Coherence squared and phase between longshore wind stress component and subtidal sea level at Point Lookout. The dashed line indicates the 95% significance level.

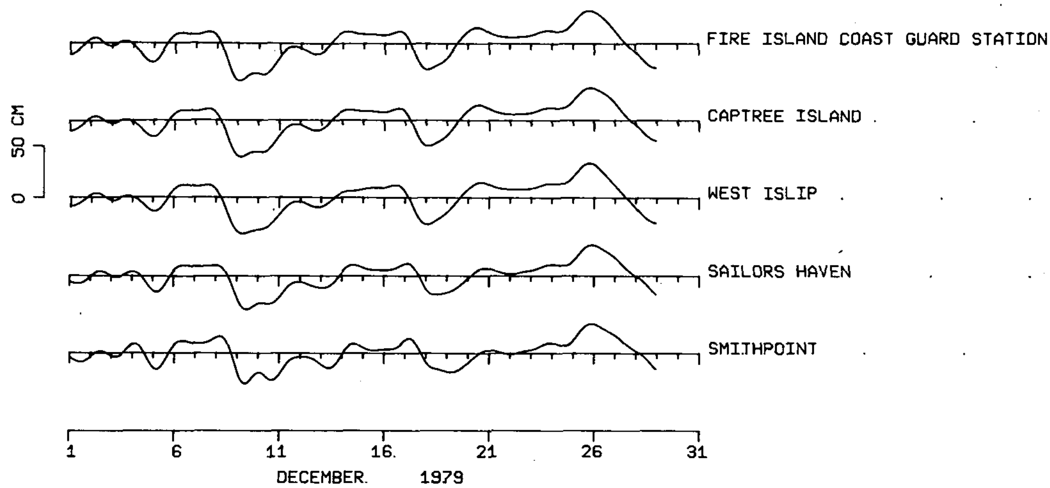

FIG. 5. Subtidal sea level at Fire Island Coast Guard Station, Captree Island, West Islip, Sailors Haven and Smith Point during the study period.

Bay while a positive current at Smith Point channel indicates flow into the eastern end of Great South Bay. During the study period, the subtidal currents at both locations exhibited fluctuations in excess of 20 cm s^{-1}.

As stated above, coherent subtidal sea level fluctuations along the coast were mostly produced by longshore wind stress fluctuations through Ekman forcing. These coastal disturbances then propagated into the Bay relatively unattenuated and subsequently produced coherent fluctuations within the Bay. One would expect the subtidal current fluctuations in the Fire Island Inlet, for example, to be driven by horizontal pressure gradient from free surface slope (estimated from sea level at Sailors Haven less that at FICGS) maintained by this remote wind-forcing mechanism. Figure 7 shows that the subtidal current at Fire Island Inlet followed the surface slope very closely and it was in general in opposite direction to the longshore winds. Water would flow into the western part of the Bay through Fire Island Inlet (negative currents) when the coastal sea level was set up relative to that in the interior by the longshore winds through Ekman forcing. Water would flow out of the Bay when coastal sea level was set down relative to that within the Bay. Even though sea level observations at Moriches Inlet were not available, one would expect the subtidal current at Smith Point channel to behave in a similar way in response to the remote coastal forcing off Moriches Inlet further to the east. Over a 16 day period in which current data were available at both locations (9 December to 24 December), the currents observed at these two open boundaries were very closely correlated and they were nearly 180° out of phase (Fig. 7). This suggests that the characteristic volume exchange between the Bay and the shelf during this late autumn period was an almost simultaneous inflow or outflow of water through both ends of the Bay in response to the remote coastal forcing. Water would converge into or diverge out of the Bay depending on the coherent setup and setdown of coastal sea level by the longshore

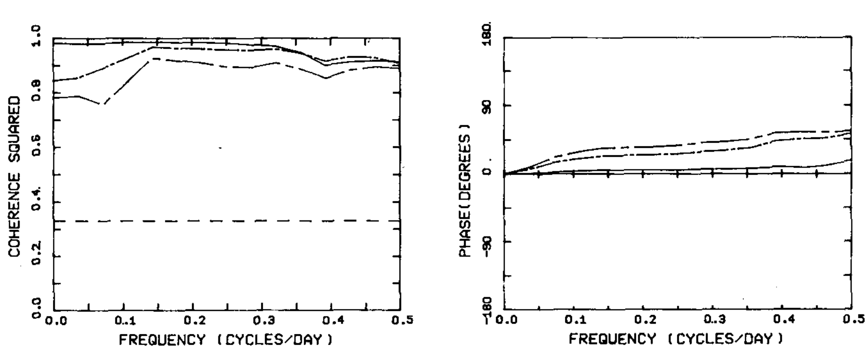

FIG. 6. Coherence squared and phase between subtidal sea level at Fire Island Coast Guard Station and West Islip (solid line), between Fire Island Coast Guard Station and Sailors Haven (short dash-dot line), and between Fire Island Coast Guard Station and Smith Point (long dash-dot line). The dashed line indicates the 95% significance level.

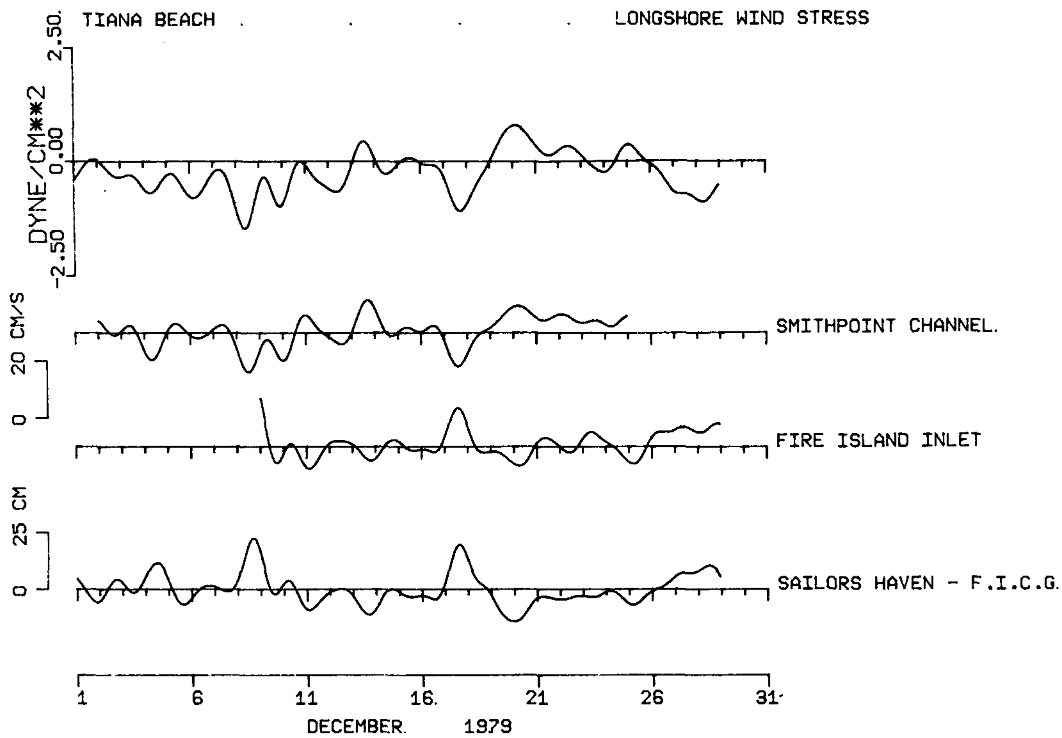

FIG. 7. Longshore component of wind stress, principal axes components of currents at Fire Island Inlet and Smith Point channel, and difference in subtidal sea level between Sailors Haven and Fire Island Coast Guard Station. Positive values of wind stress and currents indicate fluid flowing toward 250°T (see text).

wind through Ekman forcing. The strong coupling between the eastern part of Great South Bay and the shelf off Moriches Inlet is very important to the flushing characteristics of that part of the Bay since the tidal currents have already been heavily attenuated by the time they reach the eastern end of Great South Bay so tidal exchange is extremely weak. Without the active subtidal exchange the eastern part of the Bay would exchange with the shelf very slowly.

The low-frequency variability around Great South Bay does show some variation with season. During summer of 1980, for example, the subtidal sea level fluctuations along the coast were significantly smaller than those during autumn (with maximum range of fluctuations being only about 40 cm) due primarily to the overall reduction in the variance of the wind stress. Wong (1982) reported that even though Bay-shelf coupling was still the major mechanism forcing the interior sea level fluctuations at low frequencies, direct local wind forcing within the Bay was noticeable and caused an overall decrease in the coherence between coastal sea level and those in the interior. The characteristic volume exchange associated with Bay-shelf coupling was still the primary mode of subtidal exchange during the summer but there was also evidence of a secondary mode of exchange with a flow through the entire Bay from one end to the other.

4. Conclusion

Our analyses indicate that during the study period the subtidal sea level fluctuations along the south shore of Long Island were highly coherent. These coherent fluctuations along the coast were forced primarily by longshore winds through the coastal Ekman effect. The subtidal sea level fluctuations within Great South Bay were coherent and lag those along the coast, suggesting a strongly coupled Bay-shelf system. The characteristic volume exchange associated with this Bay-shelf coupling was an active simultaneous inflow or outflow through both ends of the Bay in response to the rise or fall of coastal sea level induced by longshore winds. The evidence strongly suggests that the eastern part of Great South Bay was forced by coastal disturbances off Moriches Inlet to the east while the western part of Great South Bay was coupled to the shelf through Fire Island Inlet. This Bay-shelf coupling was certainly the dominant mechanism in forcing subtidal variability within Great South Bay during this late autumn period.

The importance of volume exchange at subtidal frequencies between the Bay and the shelf can be considered by comparing the time for internal mixing within the Bay to the period of subtidal volume flux. Dye diffusion experiments conducted within the central part of eastern Great South Bay (Carter, 1981;

Becker, 1978) have shown that the horizontal eddy diffusivity K is $O(2.5 \times 10^4 \text{ cm}^2 \text{ s}^{-1})$. The time for an introduced substance to diffuse across the Bay is $O(L^2/\pi^2 K)$ (Saffman, 1962). This time scale is approximately 10 days given the mean width of the Bay L to be about 5 km. Water exchanged at subtidal frequencies thus mixes more completely within the Bay than water exchanged at tidal frequencies, hence producing an enhanced flushing action. In shallow coastal bar-built estuaries the subtidal motions are especially important for the exchange of suspended or dissolved material since the tidal motions are rapidly attenuated in the interior.

Acknowledgment. Support for this study was provided by the New York Sea Grant Institute (Contract 04-7-158-44009).

Professor H. H. Carter was Principal Investigator of this project; he designed and conducted all field experiments and managed the initial processing of the field data. We are grateful to him for providing many helpful comments throughout the course of this project.

Sea level data at Atlantic Beach and Point Lookout were kindly provided by the Town of Hempstead, Department of Conservation and Waterways. Sea level at Smith Point were provided by the Suffolk County Department of Public Works, Division of Waterways. Near surface winds at Tiana Beach were kindly provided by the Department of Meteorology, Brookhaven National Laboratory.

REFERENCES

Beardsley, R. C., W. C. Boicourt and D. V. Hansen, 1976: Physical oceanography of the Middle Atlantic Bight. *Amer. Soc. Limnol. Oceanogr. Special Symp.* Vol. 2, Section 2, 20–34.

Becker, D. S., 1978: Evaluation of a hard clam spawner transplant site using a dye tracer technique. Spec. Rep. 10, Ref. 77-6, Mar. Sci. Res. Cen., State University of New York at Stony Brook, 37 pp.

Carter, H. H., 1981: A dye diffusion study of Great South Bay. Spec. Rep. 43, Ref. 81-3, Mar. Sci. Res. Cen. State University of New York at Stony Brook, 20 pp.

Elliott, A. J., and D.-P. Wang, 1978: The effects of meteorological forcing on Chesapeake Bay: The coupling between an estuarine system and its adjacent waters. *Hydrodynamics of Estuaries and Fjords,* J. C. J. Nihoul, Ed., Elsevier, 546 pp.

Noble, M., and E. Butman, 1979: Low-frequency wind-induced sea level oscillations along the east coast of North America. *J. Geophys. Res.*, **84,** 3227–3236.

Saffman, P. G., 1962: The effects of wind shear on horizontal spread from an instantaneous ground source. *J. Roy. Meteor. Soc.*, **88,** 382–393.

Wallace, J. M., and R. E. Dickinson, 1972: Empirical Orthogonal representation of time series in the frequency domain. Part I: Theoretical considerations. *J. Appl. Meteor.*, **11,** 887–892.

Wang, D.-P., 1979a: Low frequency sea level variability on the Middle Atlantic Bight. *J. Mar. Res.*, **37,** 683–697.

——, 1979b: Subtidal sea level variations in the Chesapeake Bay and relations to atmospheric forcing. *J. Phys. Oceanogr.*, **9,** 413–421.

——, 1979c: Wind driven circulation in the Chesapeake Bay, winter 1975. *J. Phys. Oceanogr.*, **9,** 564–572.

——, and A. J. Elliott, 1978: Non-tidal variability in the Chesapeake Bay and Potomac River: Evidence for non-local forcing. *J. Phys. Oceanogr.*, **8,** 225–232.

Wong, K.-C., 1982: Subtidal volume exchange and the relationship to meteorological forcing in Great South Bay, New York. PhD dissertation, Mar. Sci. Res. Cen., State University of New York at Stony Brook, 230 pp.