BNL-25068

CONF-7805132--1

CORRELATION BETWEEN WAVE SLOPES AND NEAR-SURFACE OCEAN CURRENTS

S. SETHURAMAN

Department of Energy and Environment, Brookhaven National Laboratory, Upton, NY, USA.

093 6000

ABSTRACT

SethuRaman, S., 1978. Correlation between wave slopes and near-surface ocean currents.

The development of wind generated currents in the ocean was studied with simultaneous observations of mean wind speed, wind direction, surface wave parameters and near-surface ocean current. The measurements were carried out during February 23 - March 14, 1976 as part of a coastal ocean boundary layer and diffusion study off Long Island, New York in the Atlantic Ocean.

The results show a high correlation between wave slope and near-surface current indicating the possibility of wave age playing a significant role in the generation of current. Wave age is known to cause variations in momentum transfer (Kraus, 1972; SethuRaman, 1978). The wind generated current was found to have a broad spectral peak as compared with tidal currents. This peak was found to occur at approximately the same frequency as wind speed spectral peak. Integral time scales associated with wind and near-surface current were about the same, indicating the dominance of wind forcing near the ocean surface for this period of observations.

INTRODUCTION

As wind blows over water, wind-generated currents are produced in the water due to the transfer of momentum from air to water at the interface and by friction between adjacent layers within the water. The downward, horizontal momentum flux from the atmosphere is partly spent on the generation of waves and the rest on drift currents or wind generated currents. The mechanism of momentum transfer is not yet fully understood, but the magnitude seems to depend on the aerodynamic roughness of the sea surface (SethuRaman and Raynor, 1975) which is a function of sea state conditions (Neumann, 1968; Kitaigorodskii, 1973; SethuRaman, 1977). Variations in wave age caused by the changes in mean wind direction, duration and fetch appear to influence the momentum transfer significantly (SethuRaman, 1978). Partially developed waves have steeper slopes and move at a lower speed than the low-level winds contributing to higher frictional and form drags. On the other hand, fully developed waves have flatter slopes and move at significantly higher speeds relative to near-surface winds. The relationship between wind speed and drift current has been investigated in the past by several investigators in the

field and in the laboratory (Hughes, 1956; Carruthers, 1957; Shemdin, 1972; Wu, 1975). There seems to be a general agreement that the ratio between the surface drift velocity and the surface wind speed assumes an asymptotic value of about 3 per cent at long fetches.

The purpose of this study is to investigate the possible mechanism by which the wind generated currents are produced and maintained. Wave height and wave period measurements and near-surface current and wind observations were used to study the variations in wind-induced drift. Spectral analysis of various parameters were performed to determine the dependence of one on the other. Wave slope, wind speed and surface current were some of the variables considered important to determine as to whether the pattern of variability of atmospheric momentum is followed in the process of current generation.

MEASUREMENTS

The oceanographic measurements consisted of a moored instrument array 5 km off shore in the Atlantic Ocean near Long Island (Fig. 1). Observations of currents, salinity and temperature at different depths were recorded with this spar buoy. A description of the development of this telemetered, moored instrument array is given by Dimmler, et al (1975). Wave heights and wave periods were observed with a "waverider" which is essentially a buoy that follows the movements of the water surface and measures waves by measuring the vertical acceleration of the buoy. The spherical buoy was 0.7 m in diameter and was provided with an antenna for the tranmission of data to the shore. Mean wind speed and direction were measured at a height of 24 m at the coastal meteorological station at Tiana Beach (TB). The analyses reported here are based on measurements made for a period of three weeks from February 23 to March 14, 1976.

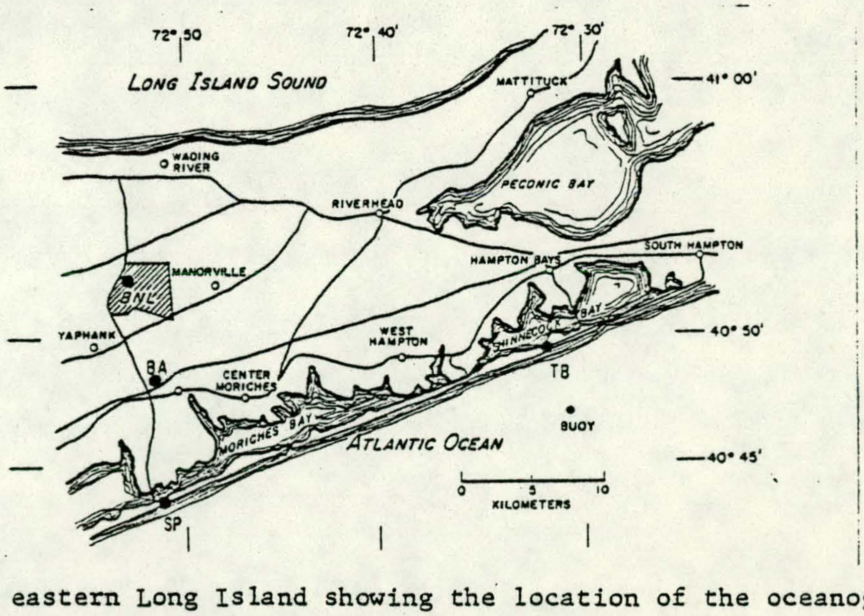

Fig. 1. Map of eastern Long Island showing the location of the oceanographic spar buoy, and the meteorological tower at Tiana Beach (TB). Wave rider was deployed close to the buoy.

ANALYSIS

Passage of synoptic meteorological systems over Long Island and the vicinity causes variations in near-shore wind speeds and wind directions. A typical time period of mean wind speed measured at Tiana Beach (TB in Fig. 1) at a height of 24 m is shown in Fig. 2, for the duration of this study. Wind speeds varied from 1 to 18 m sec^{-1}. Observations at the beach are approximately representative of over-water winds (SethuRaman and Raynor, 1978). Time histories of the wave height and wave periods are given in Fig. 3. Increase in wind speeds and wave heights with the approach of storms can be seen in Figs. 2 and 3, respectively.

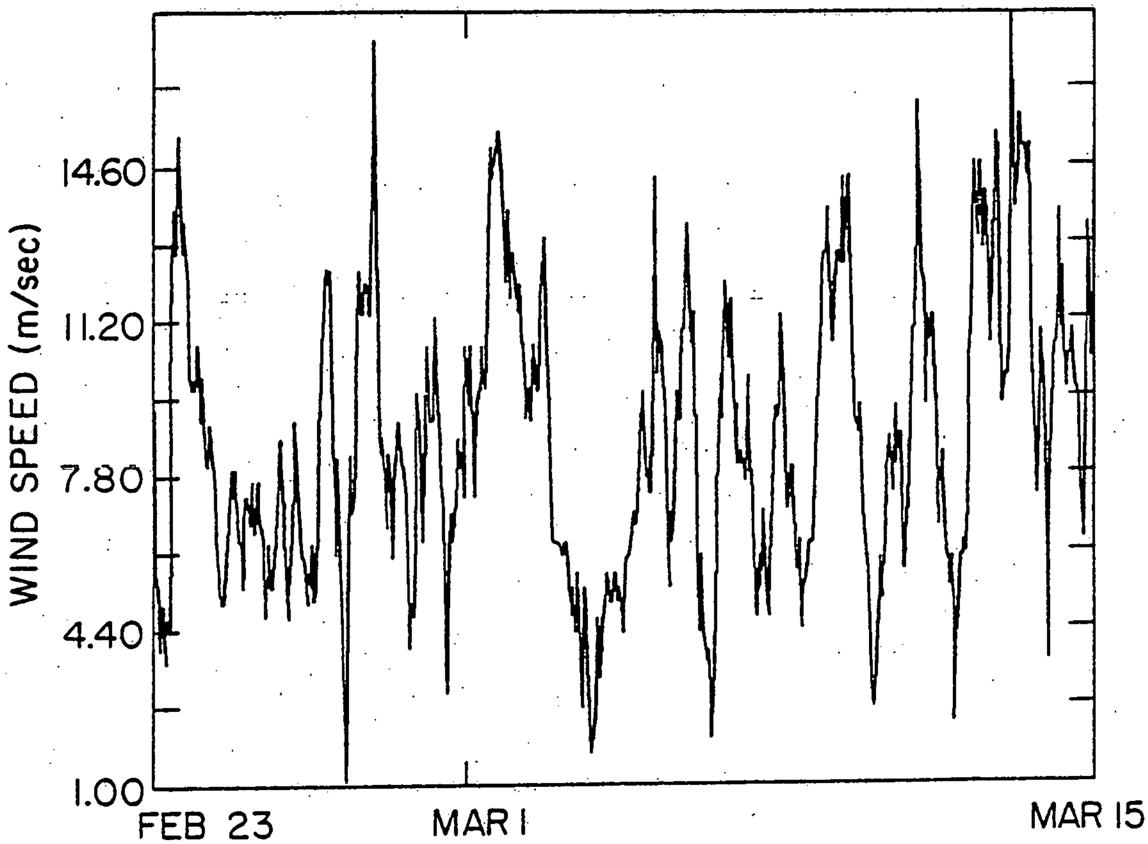

Fig. 2. Time history of one-hour mean wind speeds at Tiana Beach at a height of 24 m for the duration of the experiments.

One of the objectives of the analysis was to separate the wind generated current from the total current and study its variation. Separation of the tidal component is a difficult procedure due to its dependence on several factors. The tidal ellipse seems to have an along-shore component of about 17 cm/sec with the ellipse inclined to the shore (Scott and Csanady, 1976). Analysis of near-surface currents during low wind periods indicated tidal amplitudes of comparable magnitude. A tidal

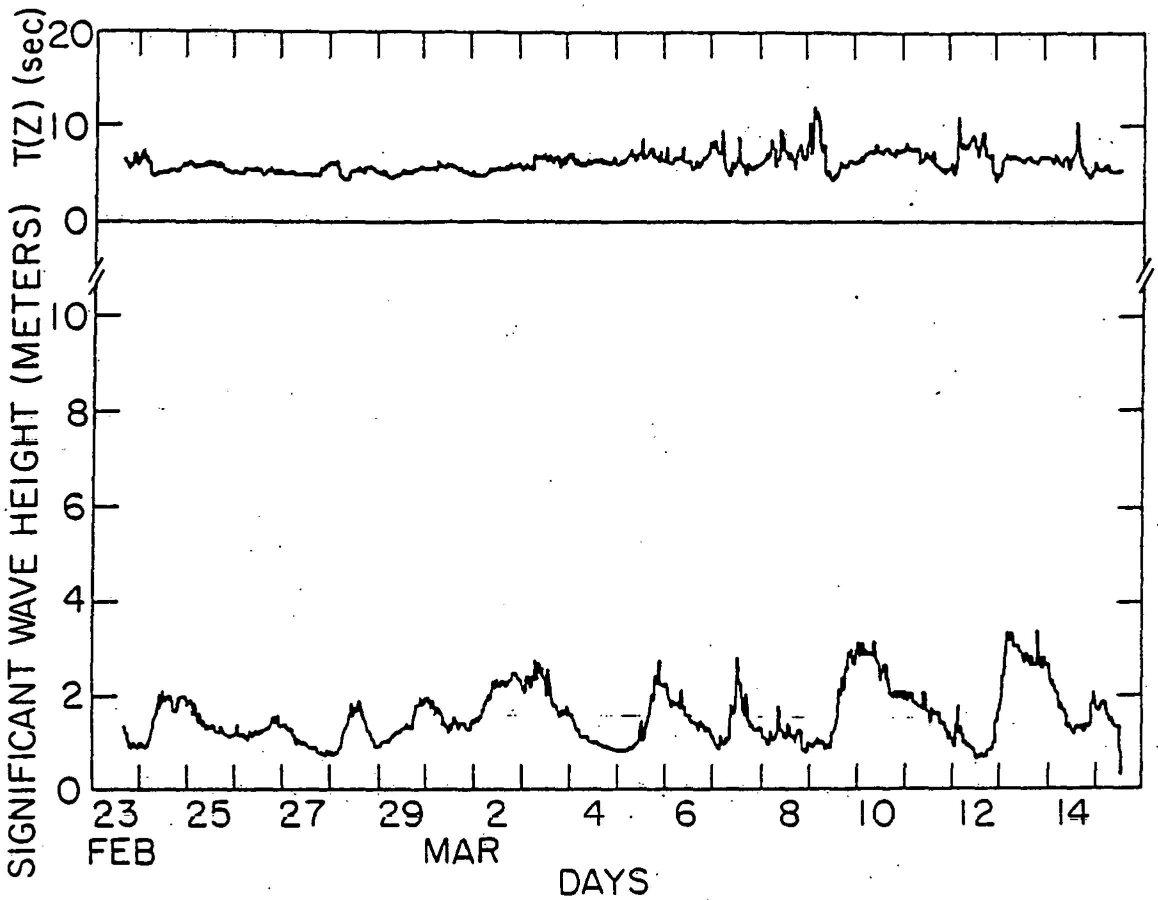

Fig. 3. Time history of 20-minute wave heights and wave periods near the buoy (see Fig. 1).

amplitude of 15 cm sec^{-1} was used to help estimate the wind generated currents from along-shore current observations. Observations of tides at Shinnecock Inlet were used to get tidal cycles. This inlet is in the vicinity of the measurements site. Any possible nonlinear interactions between the tidal and wind generated currents were neglected in the present study. Some of the analyses were also performed without separating the tidal current to provide an alternate interpretation. The measurements used here to study the wind generated current were made at an average depth of 3 m below the water surface.

Wave slopes

The significant wave height, H, obtained from the waverider is the average height of the highest 1/3 of the waves. Time periods, T, of the waves averaged over 20 min. duration are used here. Mean wind speeds also corresponded to the same 20 min. Wave length, L, was obtained from the relationship,

$$L = \frac{g T^2}{2\pi} \qquad (1)$$

where g is the gravitational acceleration. Mean slopes of the waves were then estimated from

$$s = \frac{H}{L/2} \qquad (2)$$

A case study

A typical high wind period has been chosen to study the simultaneous variation of wind direction, wave height, wave slope and wind generated current. High winds with a long fetch over the water occurred on February 24 after a high pressure system moved over the ocean. This caused a change in wind direction from off shore to along shore. Wind speeds increased from about 3 m/sec to 15 m/sec. Maximum wind speeds corresponded with maximum wave height observations shown in Fig. 4. A time history of mean wind directions and mean wave slopes computed from Eq. 2 are given in Fig. 5. The slopes are the steepest immediately after a significant change in wind direction. The wave slope then reaches an asymptotically constant lower value as the wind direction becomes more persistent. This phenomenon is believed to be due to different stages of development of waves or in other words due to wave age. An increase in surface drag was observed immediately following significant changes in wind direction in previous studies (Neumann, 1968; SethuRaman, 1978). Mean wind speeds and the estimated wind generated currents are shown in Fig. 6. The maximum wave slope and the highest current lag maximum wind speed by a few hours. As the wind speed, wind direction and the wave slope reach approximately constant values, wind generated current also tends to approach an asymptotic value. This average equilibrium value can be estimated to be about 13 cm/sec for current and about 6 m/sec for wind for this case. Assuming fully rough conditions, friction velocity u_* for the air can be estimated as 24 cm/sec (SethuRaman and Raynor, 1975) yielding an average ratio of wind generated current, V, to friction velocity u_* as 0.54. Values close to 0.53 have been found by Wu (1973) and Phillips and Banner (1974).

Spectral analysis

Frequencies associated with wind generated currents will be readily apparent in a spectral analysis of the time series data since the tidal frequencies are

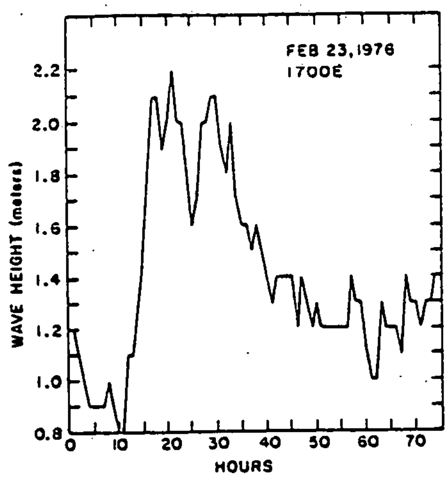

Fig. 4. Wave height variations fot February 23-26. Starting date and time are also indicated. Increase in wave height due to increase in mean wind speed is seen.

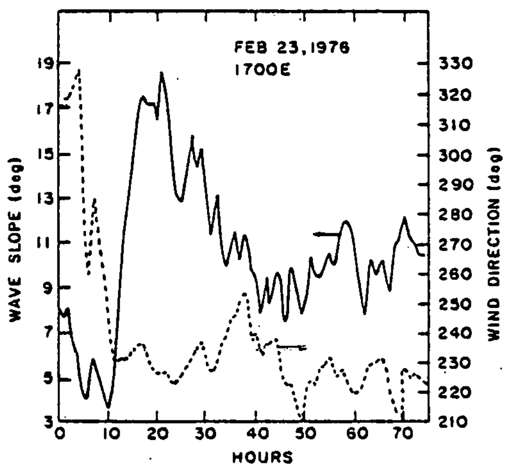

Fig. 5. Variance of wave slopes and mean wind directions for February 23-26. Starting date and time are as indicated. Solid lines represent the wave slope and dashed line the wind direction. Close correlation between wave slope and wind direction seems to exist.

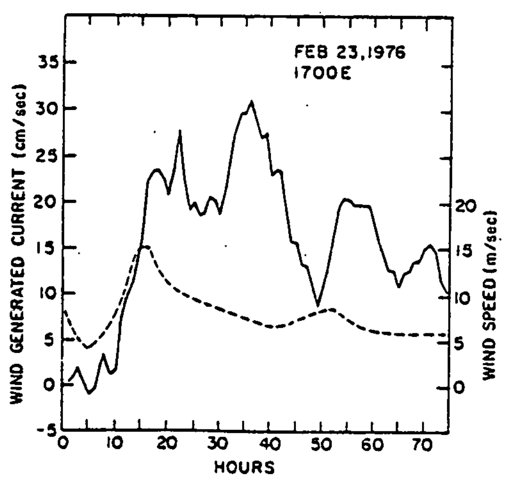

Fig. 6. Wind generated current (estimated) and wind speed for February 23-26.

diurnal and semi-diurnal. One advantage of this analysis is that there is no need to separate the tidal currents. The variance spectrum of the one-hour along-shore mean wind speeds for the duration of the study is shown in Fig. 7. The spectrum has a pronounced peak around .014 cycles per hour which corresponds to a time period of about 3 days. This time period represents the average time elapsed between two successive high wind episodes caused by the movement of synoptic systems and is in agreement with a similar analysis made with observations collected continuously over one year (SethuRaman and Brown, 1977). A small diurnal peak can also be seen in Fig. 7. Variance spectra of along-shore currents at depths of 3.1 m, 14.3 m, and 24.6 m are shown in Fig. 8. A pronounced, but narrow peak for all depths with constant amplitude was found at a frequency corresponding to semi-diurnal tidal period. An estimate of the semi-diurnal along-shore tidal current from Fig. 8 gives about 16 cm/sec. A value of 15 cm/sec was assumed here and a value of 17 cm/sec was reported by Scott andCsanady (1976). Diurnal tidal currents did not produce a pronounced peak but was found to be present at all depths with decreasing amplitudes. Decrease in spectral amplitude between the depths of 14.3 and 24.6 m was more than that between 3.1 and 14.6 m. Bottom friction might be the reason for this difference. Depth of water at the site of the buoy was about 30 m. The frequency associated with wind-generated current is also seen in Fig. 8 which corresponds to the dominant peak of wind speed spectra in Fig. 7. A comparison of the spectral amplitudes at this frequency would yield a ratio of 3 per cent between the wind-generated current and wind speed which has been found to be the equilibrium value by several investigators (Wu, 1973). Spectral densities for wind speed and along-shore current at 3 m have been plotted as a function of frequency in Figs. 9 and 10, respectively. The current spectra (Fig. 10) seems to follow Kolmogorov's inertial subrange relationship at frequencies more than 0.1 cycle per hour. With a mean current of 18 cm sec^{-1} this corresponded to a wave length of about 2 m which was approximately equal to the depth of measurement. Atmospheric turbulence was found to obey Kolmogorov's relation at frequencies above 0.1 Hz (SethuRaman, et al., 1974).

Time scales

Autocorrelation function for wind speed $R_u(t)$ defined as

$$R_u(t) = \frac{\overline{u(t_1)\ u(t_2)}}{\bar{u}^2} \quad (3)$$

where $\overline{u(t_1)\ u(t_2)}$ is the autocovariance of wind speed and $\bar{u}^2$ is the variance, is a function of only the time difference $t_2 - t_1$, and describes the memory of $u(t)$. A similar function, $R_c(t)$ can be defined for the water current. Variation of $R_u(t)$ and $R_c(t)$ with time lags are shown in Figs. 11 and 12, respectively.

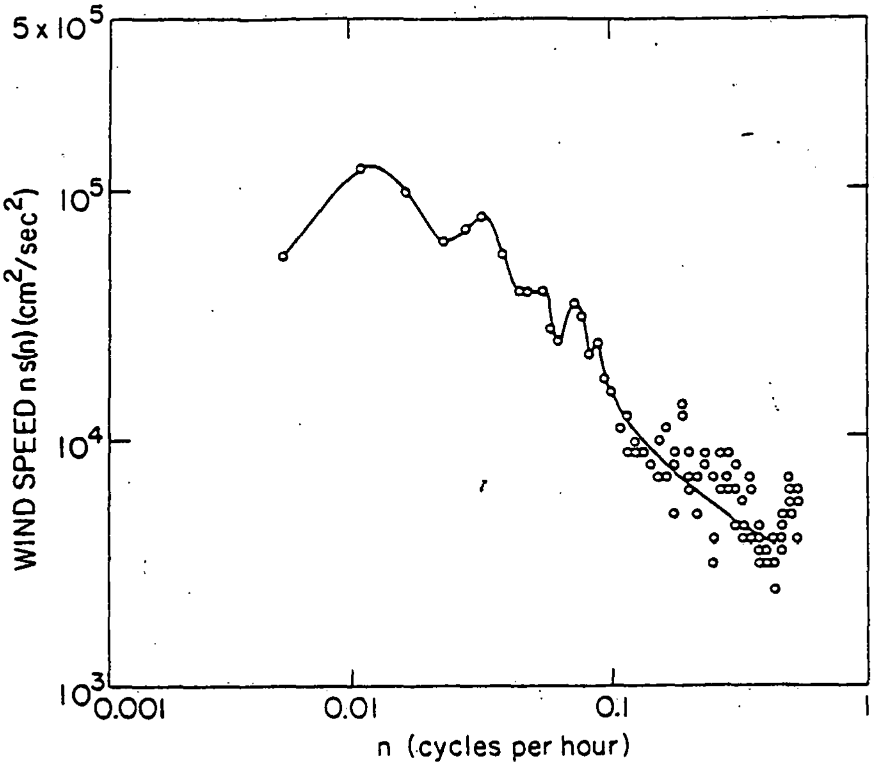

Fig. 7. One-dimensional variance spectrum for one-hour mean wind speeds at Tiana Beach.

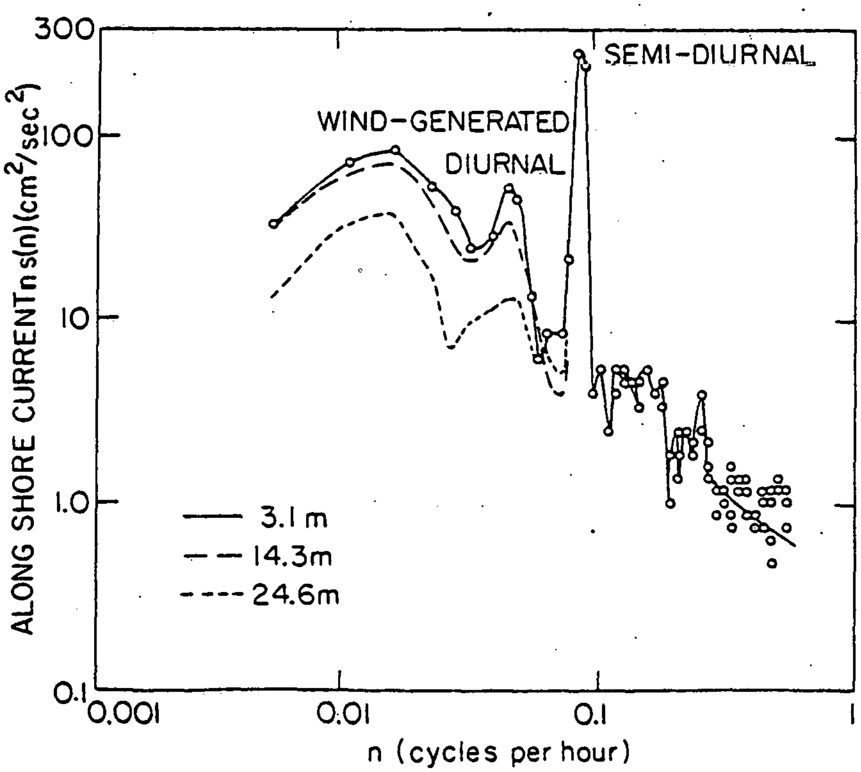

Fig. 8. One-dimensional variance spectrum for one-hour mean along-shore currents at different depths.

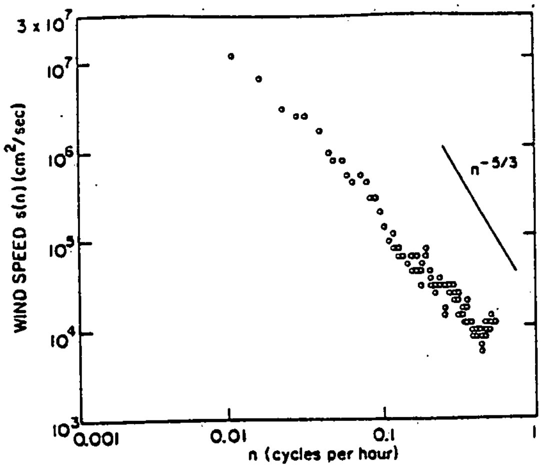

Fig. 9. Variation of spectral densities as a function of frequencies for mean wind speeds at Tiana Beach.

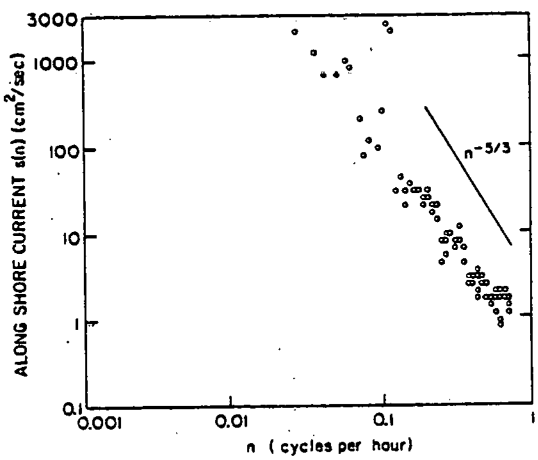

Fig. 10. Variation of spectral densities as a function of frequencies for one-hour mean along-shore near-surface currents (depth $\simeq$ 3 m).

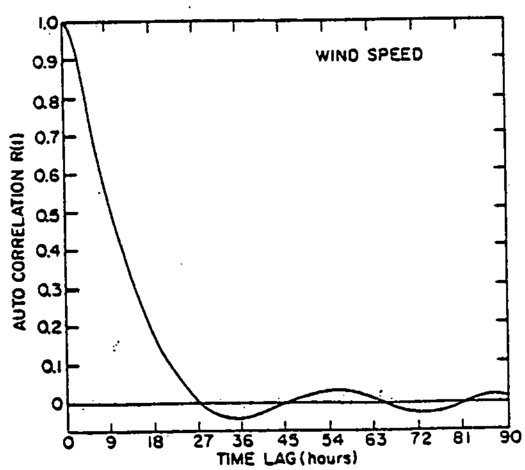

Fig. 11. Autocorrelogram for wind at Tiana Beach.

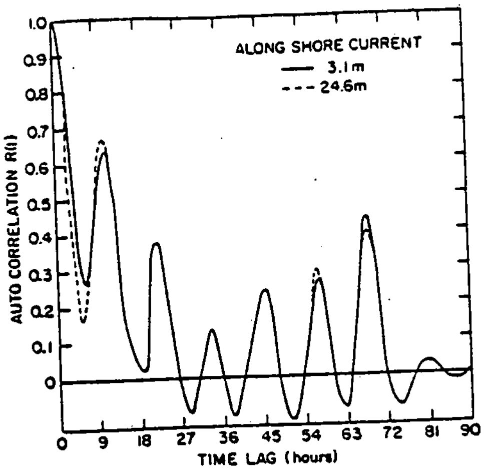

Fig. 12. Autocorrelogram for along-shore currents at 3.1 m and 24.6 m depths.

The atmospheric autocorrelation function falls off rather rapidly, but the autocorrelation for current has several peaks and falls off slowly indicating longer memories and different forcing functions. Semi-diurnal and diurnal peaks can also be seen in Fig. 12. An integral time scale,

$$\tau_u = \int_0^\infty R_u(t)\, dt \qquad (4)$$

can be defined for wind speed and a similar one for current. This time scale was estimated to be about 10.5 hours for wind from Fig. 11 and about 11.5 hours for current from Fig. 12. The closeness of these two values suggests the dominance of atmospheric forcing on the ocean.

Coherence

A measure of the correlation between wave slope, s, and along-shore current, c, as a function of frequency can be obtained by computing the coherence, Coh_{sc}, given by

$$Coh_{sc} = \frac{Co^2_{s,c}(n) + Q^2_{s,c}(n)}{S_s(n)\ S_c(n)} \qquad (5)$$

where Co(n) and Q(n) are the cospectra and quadrature spectra, respectively, and S is the individual spectrum at different frequencies, n. Values of Coh are shown in Fig. 13 as a function of frequencies. A maximum coherence of about 0.55 occurs at a frequency of 0.16 cycles per hour corresponding to a time period of about 6 hours. This indicates that there is a good correlation between wave slope and near-surface current and the maximum currents lag maximum slope by about six hours.

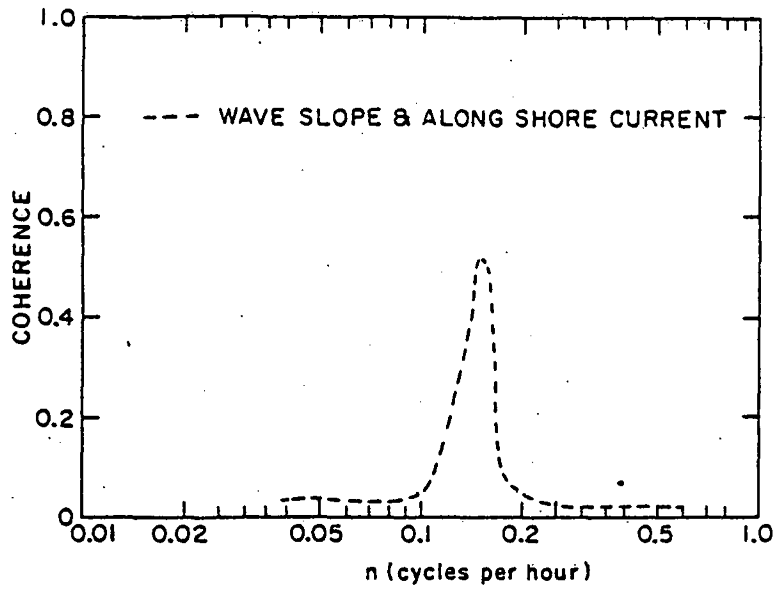

Fig. 13. Coherence between wave slope and along-shore current as a function of frequency.

CONCLUSIONS

Analysis of simultaneous observations of surface wave parameters, wind speed and near-surface current indicates the possibility of wave age playing an important role in the generation of wind drift currents. Maximum currents appear to lag maximum wave slopes by about 6 hours.

ACKNOWLEDGEMENTS

Many members of the Division of Atmospheric Sciences and the Division of Oceanographic Sciences participated in the experiments. Assistance in computer programming was provided by C. Henderson and J. Tichler and in data analysis by J. Glasmann and K. Tiotis. The author wishes to thank T. S. Hopkins and G. S. Raynor for studying the manuscript and offering some valuable suggestions.

The submitted manuscript has been authored under contract EY-76-C-02-0016 with the U. S. Department of Energy. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

REFERENCES

Carruthers, J. N., 1957. A discussion of "A determination of the relation between wind and surface drift." Quar. J. Roy. Met. Soc., 83: 276-277.

Dimmler, D. G., Greenhouse, N. and Rankowitz, S., 1975. A controllable automated environmental data acquisition and monitoring system. Proc. 1975 Nuclear Science Symposium, San Francisco, California, November 1975.

Hughes, P., 1956. A determination of the relation between wind and sea surface drift. Quart. J. Roy. Meteor. Soc. 82: 494-502.

Kitaigorodskii, S. A., 1973. The physics of air-sea interaction. Translated from Russian by A. Baruch, Israel Program for Scientific Translations, Jerusalem, pp. 237.

Kraus, E. B., 1972. Atmosphere-Ocean Interaction. Clarendon Press, Oxford, England, pp. 275.

Neumann, G., 1968. Ocean Currents. Elsevier Scientific Publishing Company, New York, N. Y., pp. 352.

Phillips, O. M. and Banner, M. L., 1974. Wave breaking in the presence of wind drift and swell. J. Fluid Mech., 66: 625-640.

Scott, J. T. and Csanady, G. T., 1976. Nearshore currents off Long Island. J. Geophys. Res., 81: 5401.

Shemdin, O. H., 1972. Wind-generated current and phase speed of wind waves. J. Phys. Ocean. 2: 411-419.

SethuRaman, S., 1977. The effect of characteristic height of sea surface on drag coefficient. BNL Report 21668, pp. 33.

SethuRaman, S., 1978. Influence of mean wind direction on sea surface wave development. J. Phys. Ocean., 8: (in press).

SethuRaman, S. and Brown, R. M., 1977. Temporal variation of suspended particulates at Upton, L. I., N. Y. AMS Conference on Applications on Air Pollution Meteorology, November 28-December 2, 1977. Preprint Volume: 16-18.

SethuRaman, S. and Raynor, G. S., 1975. Surface drag coefficient dependence on the aerodynamic roughness of the sea. J. Geophys. Res., 80: 4983-4988.

SethuRaman, S. and Raynor, G. S., 1978. Effect of changes in upwind surface characteristics on mean wind speed and turbulence near a coastline. Am. Meteor. Soc. Fourth Symposium on Turbulence, Diffusion, and Air Pollution, Reno, Nevada, January 15-18, 1977. Preprint Volume (in press).

SethuRaman, S., Brown, R. N. and Tichler, J., 1974. Spectra of atmospheric turbulence over the sea during stably stratified conditions. Am. Meteor. Soc. Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, California, September 9-13, 1974. Preprint Volume: 71-76.

Wu, J., 1973. Prediction of near-surface drift currents from wind velocity. J. Hyd. Division, ASCE, 99: 1291-1302.

Wu, J., 1975. Wind-induced drift currents. J. Fluid Mech., 68: 49-70.