Influence of Mean Wind Direction on Sea Surface Wave Development[1]

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ABSTRACT

Momentum flux measurements made from an instrumented ocean buoy indicate that the surface drag coefficient C_D is strongly dependent on changes in mean wind direction. A change in mean wind direction is accompanied by a change in wave propagation direction and associated variations in wave steepness and stage of wave development. From simultaneous wind-stress and wave measurements, a critical value for the relative motion of air and surface waves is suggested beyond which the dominant waves reach the fully developed stage and the drag decreases.

1. Introduction

It has long been recognized that the effective roughness of the sea surface with respect to the transfer of momentum from air to sea must be wave dependent, which is in turn wind dependent. Charnock (1955) was perhaps the first to offer a rational parameterization for the effective roughness due to waves in terms of Froude scaling, which was explored in some detail by Wu (1969). There has been a renewed interest in attempting to relate the surface drag coefficient C_D over the sea to some measure of surface roughness in more recent studies (DeLeonibus, 1971; Manton, 1971; Kitaigorodskii, 1973; Kondo *et al.*, 1973; Hsu, 1974; SethuRaman and Raynor, 1975). Kitaigorodskii (1973) has suggested on physical grounds that, due to the mobility of the water surface, the drag should be caused by those waves with phase velocity less than that of the wind speed at a height comparable to the wave height. It is the higher frequency waves which would satisfy this condition and an appropriate measure of their amplitude could be employed as a characteristic roughness height.

In the present note, the stage of wave development as influenced by changes in the local wind direction is shown to be an important factor in causing substantial variations in the effective roughness and hence in C_D. These results are based upon measurements of momentum flux by the eddy correlation technique and high-frequency water level variations. These measurements were made for four days in October 1975 in an attempt to verify previous results regarding C_D obtained from wind profiles and to try to determine independently the characteristic roughness height from the measured elevational spectra.

2. Methods

The experiments were conducted with the help of a stable buoy positioned about 5 km off the south shore of Long Island. The island has a straight shore in this area (near Westhampton) with a bearing of 70°–250° marking the shoreline. The location of the buoy relative to the shore is shown in Fig. 1. A meteorological tower at the beach helped in obtaining continuous wind direction measurements. Simultaneous meteorological and smoke dispersion measurements are being made at this site (Raynor *et al.*, 1975) although no dispersion experiments were conducted for the period reported here.

A general view of the buoy above water is shown in Fig. 2. The buoy is designed for simultaneous meteorological and oceanographic measurements with the provision of overwater and underwater measurement platforms. The buoy accelerated with the dominant swell, the maximum values occurring at the frequency of these waves, typically between 0.1–0.2 Hz. Due to the substantial weight (9000 kg) the motion of the buoy in the vertical direction was minimal even at these frequencies and there was virtually no response for waves of higher frequencies. Typical vertical velocities of the buoy for the range of mean wind speeds for the experiments reported here varied from 1 to 4 cm s^{-1}. The maximum tilt of the buoy was about 4° during adverse conditions with regard to water current and wind speed. In order to offset even these small tilts, a two-dimensional friction-free gimbal mount designed and fabricated to isolate the instrument from

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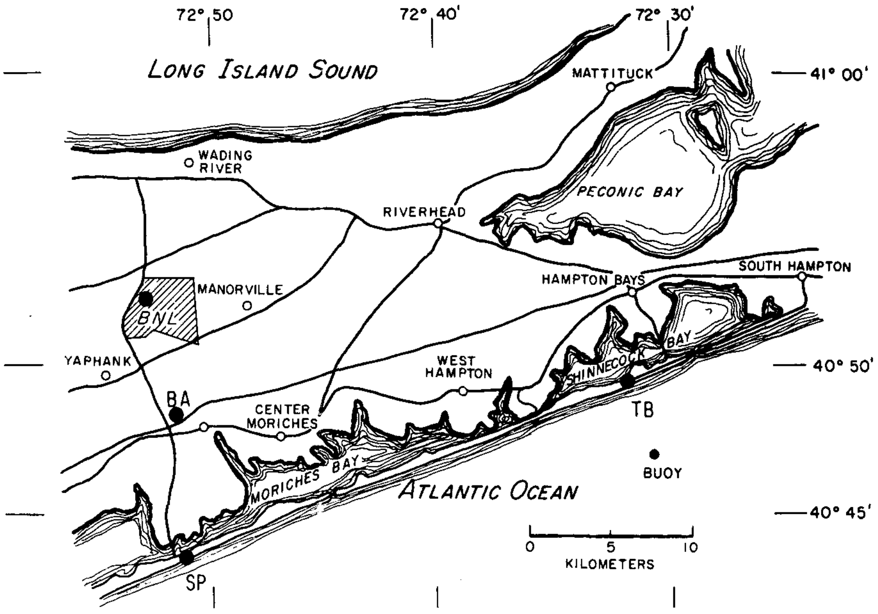

FIG. 1. Site of the overwater experiments. Buoy is about 5 km offshore from Tiana Beach (indicated as TB). A 24 m tower is located at TB.

buoy motion was used. Depth of water at the measurement site was about 33 m and the buoy was submerged to a depth of about 25 m.

The eddy correlation technique was used to obtain momentum fluxes. Longitudinal velocity fluctuations were measured with a single-sensor, temperature-compensated, vertical hot wire. The metal-clad hot-wire sensor had a frequency response of 5 Hz and the calibrations were found repeatable after prolonged use in the atmosphere. The effect of a tilt of about 4° on the response of the hot wire was found to be negligible. Vertical velocity fluctuations were measured by an induction-type bivane fabricated at Brookhaven National Laboratory (SethuRaman and Tuthill, 1977). The frequency response of the bivane is about 2 Hz for wind speeds in the range of 2 to 10 m s^{-1}.

A capacitance type wave staff was used to measure high-frequency water level variations. It consisted of a square wave oscillator whose frequency varied linearly with a small change in sensor capacitance. This square wave frequency was integrated and smoothed in an operational amplifier to yield a voltage output proportional to a change in sensor capacitance that exists between the water and the center conductor of an insulated wire 2 mm in diameter. The frequency response of the wave staff thus depended only on the physical dimensions of the wire. The response was estimated to be valid to about 40 Hz.

The hot-wire sensor and the bivane were positioned at a height of 8 m above the mean water surface. Mean wind speed and temperature were recorded continuously at the buoy using a cup anemometer and thermistor, respectively, at the same height. Mean wind directions were obtained with a directional vane at the beach. Sea surface tem-

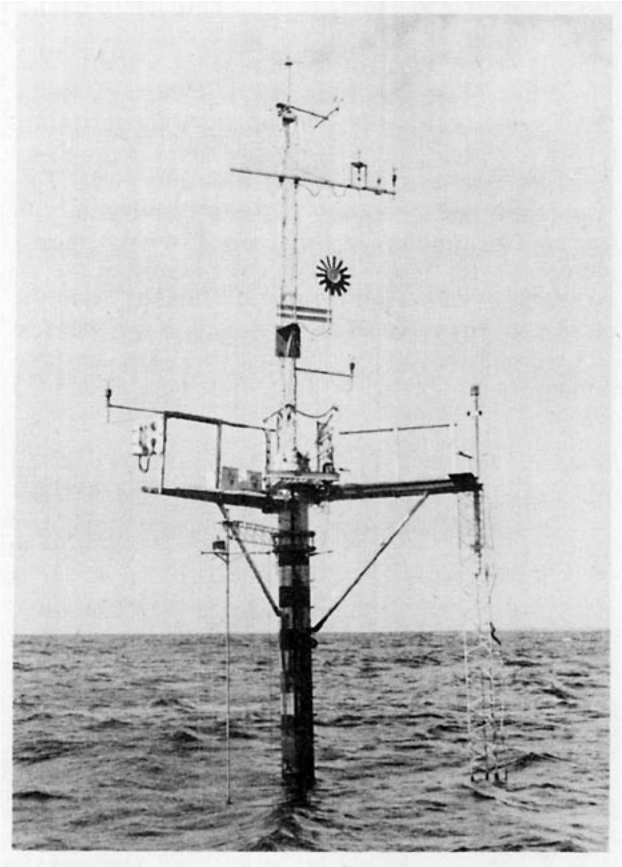

FIG. 2. General view of the buoy above water.

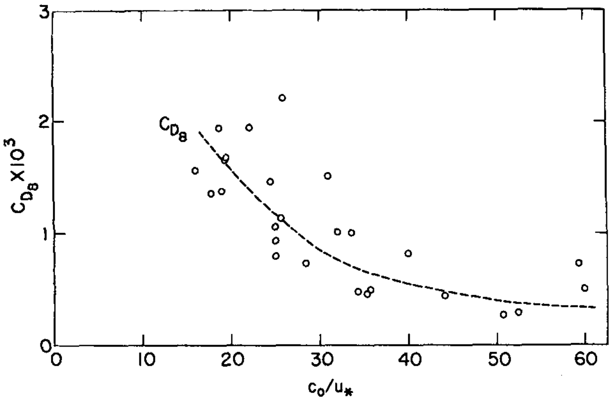

FIG. 3. Surface drag coefficient C_{D_8} as a function of c_0/u_*. The dotted line was fit as an eye average.

perature was measured with a thermistor attached to a float during the experiments. The analog outputs from the hot wire, bivane and wave staff were recorded on magnetic tapes. Each 10 min of data was then passed through a low-pass analog filter with the cutoff at the Nyquist frequency, then digitized and analyzed.

3. Results

Several investigators have attempted to define wave development in terms of a nondimensional phase velocity c_0/u_* of the dominant wave (Kitaigorodskii, 1973; Davidson, 1974), where c_0 is the phase velocity. Another method of parameterization for wave development is $c_0/\bar{u}$, where $\bar{u}$ is the mean wind speed at a reference height usually 10 m. This type of normalization has a serious disadvantage of having a parameter, in this case $\bar{u}$, which sharply increases with height in the lower layers of the atmosphere. Values of C_D as evaluated from the measured Reynolds stress and mean wind speed at 8 m are plotted versus c_0/u_* in Fig. 3. The observations were grouped into 10 min time periods and the dominant frequencies identified from individual wave height spectra. The dotted line shows the trend. There is a considerable scatter for $c_0/u_* < 30$, a range of c_0/u_* representing initial stages of wave development. As the waves fully develop, C_D tends to decrease. Although there are not enough data for higher ranges of c_0/u_* in Fig. 3, one would expect the downward flux to continue to near zero at large c_0/u_* under conditions when the mean wind speed has low values after a storm and the swells caused by the storm dominate. If $\bar{u}$ at 6 m is used to normalize c_0, an equivalent value for $c_0/\bar{u}$ for this critical c_0/u_* ratio will be roughly equal to 1 since $u_* \approx 0.033\ \bar{u}$ (SethuRaman and Raynor, 1975; Ruggles, 1970). One would wonder why c_0/u_* does not reach a value close to 1 for the change in roughness condition. This is because c_0 is the speed of the dominant wave and the characteristics of this wave indicate the condition of the wave development. The higher frequency waves are the ones that cause drag, in general, due to their phase velocities being smaller than the wind speed near the surface and due to their random directional variations (Mitsuyasu *et al.*, 1975). During initial stages of wave development, even the dominant wave moves slower than the wind causing pronounced drag. The critical value of about 30 for c_0/u_* is also reported by Kitaigorodskii (1973) based on previous studies.

The effect of the development of waves on C_D can also be demonstrated by a comparison with changes in mean wind direction. Fig. 4 shows the mean wind direction during the momentum flux measurements on 6 October 1975. The wind was southwesterly and remained fairly constant from 0900 EST. Generally, it seems to take about 2 h for the waves to become fully developed. The flux measurements were obviously made over a fully developed wave field explaining the low C_D values. Fetches were in excess of 100 km.

Results from another experiment shown in Fig. 5

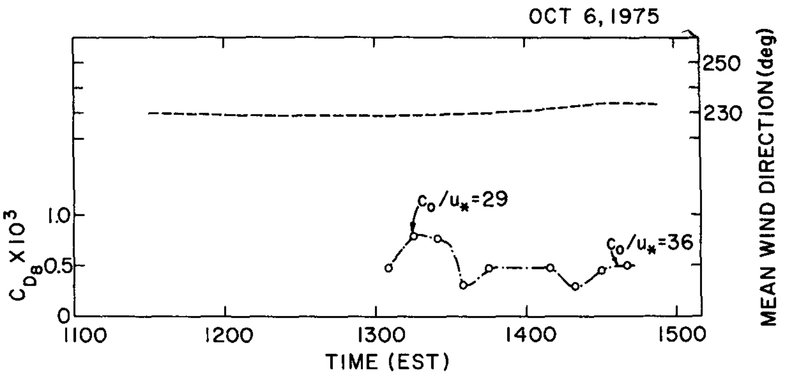

FIG. 4. Variation of C_{D_8} with time during a period when mean wind direction was steady. The wind direction averaged around 230° from 0900 EST on this day. The dotted line shows the mean wind direction.

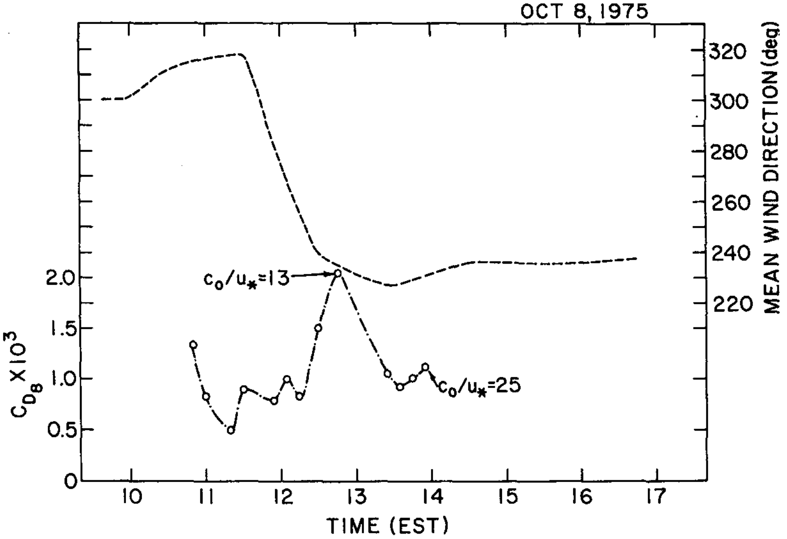

FIG. 5. Time history of C_{D_8} during a period when mean wind direction changed by about 80° within an hour. The dotted line shows the mean wind direction.

illustrate the effect of changing wind direction. The experiment spanned a period when the mean wind direction changed from northwesterly to southwesterly due to the passage of a weak high pressure system. Although the change in the wind direction was not as dramatic as that occurring during the passage of a sharply defined cold front, the effect of this slow change in wind direction is still seen in the variation of C_D. The change in wind direction caused a change in the direction in which waves were propagating resulting in a sharp increase of C_D. As the waves became fully developed and the air "adjusted" itself to the configuration of the waves, C_D dropped to an average value less than 1×10^{-3}.

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