Comparison of Mean Wind Speeds and Turbulence at a Coastal Site and an Offshore Location

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ABSTRACT

Observations of mean wind speed and longitudinal turbulence at a height of 8 m over the Atlantic ocean, 5 km off Long Island, New York, were compared with simultaneous observations at the beach. Results were grouped into wind direction classes characteristic of changes in roughness and fetch. Mean winds over the ocean were 15–100% higher than those at the beach. Changes in turbulence seem to depend on variations in the aerodynamic roughness of the sea surface and the thermal processes that take place over the water. A decrease in turbulence over the ocean relative to that at the beach due to a decrease in sea surface roughness for alongshore flows could be predicted reasonably well with a simple logarithmic wind profile relationship.

1. Introduction

Changes in heating and surface roughness occur almost everywhere over the earth's surface due to natural and artificial boundaries. One such boundary of practical importance is the urban-rural discontinuity which has been studied by several investigators (Bowne and Ball, 1970; Clarke, 1969; SethuRaman and Cermak, 1974; etc.). Here the discontinuity is not abrupt. There is a changing roughness length and heating with distance due to the nonhomogeneity of man-made structures and the problem is essentially three-dimensional. Another such boundary of differing surface roughness and heating is the land-sea interface. Here the change in surface characteristics is rather abrupt and the problem can be considered two-dimensional for a straight coastline. Differences in surface roughness lengths are several orders of magnitude (SethuRaman and Raynor, 1975) and the variation in surface temperatures are significant (Raynor *et al.*, 1979). The problem of the land-sea interface differs from the urban-rural flow in two other aspects—a mobile oceanic surface and the lack of significant diurnal changes in sea surface temperature.

A knowledge of the changes in the wind near a coastline has several applications such as the sitting of power plants, industries and wind power generators, and taking preventive measures during the approach of a storm. Development of internal boundary layers has been studied experimentally (Raynor *et al.*, 1979) and with numerical models (Peterson, 1969; Taylor, 1970). The sea breeze circulation which is an effect of the difference in land-sea temperatures has been extensively studied by numerous investigators with field experiments and numerical models (Raynor *et al.*, 1979; Lyons and Olsson, 1972). In most of the experimental studies, offshore measurements have been absent making it difficult to draw conclusions regarding the relative wind fields over the ocean and the land. The purpose of this paper is to describe and discuss results from an experiment conducted to determine the changes in the near surface mean wind speed and longitudinal turbulence at a beach as compared to the corresponding simultaneous observations at an offshore site 5 km away. These data were collected as part of an air-sea interaction experiment conducted by Brookhaven National Laboratory (BNL) off Tiana Beach, Long Island, New York (SethuRaman *et al.*, 1978a).

2. Measurements

The relative locations of the 24 m meteorological tower and the buoy are shown in Fig. 1. The stabilized air-sea interaction buoy was anchored 5 km offshore in the Atlantic Ocean and was instrumented with BNL cup anemometers at four levels, a bivane, air and water temperature sensors and a wave staff. Horizontal and vertical motions of the buoy were continuously monitored with a two-dimensional tilt sensor, a vertical accelerometer and a compass. Data were continuously transmitted to the shore station at Tiana Beach (TB) by RF telemetry four times a second and recorded with a digital tape recorder simultaneously with measurements made from the meteorological tower located

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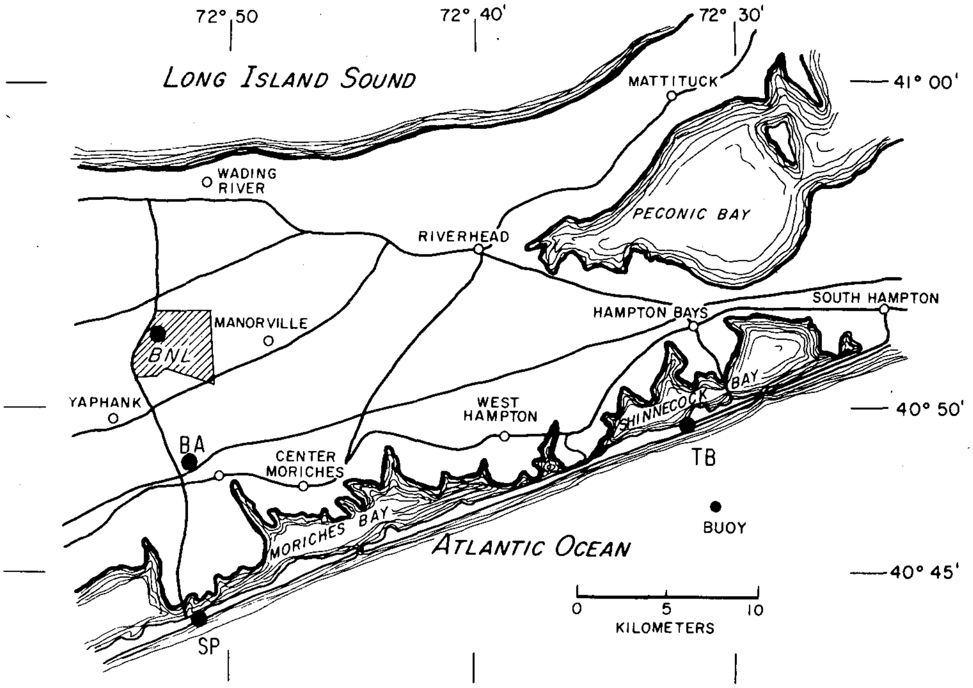

FIG. 1. Map of eastern Long Island showing relative locations of the stable air-sea interaction buoy (BUOY) and the meteorological tower at Tiana Beach (TB).

on the beach. Observations were recorded automatically 10 min every hour by a timer-controlled recorder. Measurements at the beach consisted of turbulence at 24 m with a bivane and mean wind speed and longitudinal turbulence at 8 m with a BNL cup anemometer. Mean wind speed and turbulence were also measured at a height of 8 m at the buoy. These anemometers have a distance constant of ~3 m thus making it possible to compute the standard deviation of the longitudinal velocity fluctuations, σ_u, an indicator of turbulence. The instruments were calibrated often to ensure accuracy of the data. The mean and longitudinal velocity fluctuations at the buoy and the beach measured at a height of 8 m are compared and discussed in this paper. The data reported here were observed between May and October 1977 for selected periods and 418 simultaneous observations were used for this analysis.

The mean tilt of the buoy was close to zero and the oscillating tilt varied from 3–5° depending on the sea state. These motions have little effect on longitudinal turbulence (Pond, 1968). Spectral analysis of the longitudinal velocity fluctuations revealed no significant peaks at the wave frequencies. Hence no corrections were made to σ_u for buoy motion.

The observations of the mean wind speed U and the standard deviation of the longitudinal velocity fluctuations σ_u were divided into three categories with regard to wind direction—onshore, offshore and alongshore. This was done to group data of similar upwind terrain conditions. The coastline at the site is oriented approximately east-west at about 70–250°. Hence winds from 92° to 228° through 180° were considered onshore, from 272° to 48° through 360° were considered offshore and the rest alongshore.

3. Discussion of results

The intensity of turbulence defined as σ_u/U over the ocean varied from about 2 to 16% for different stability conditions. A stability parameter, the bulk Richardson number, defined as

$$\mathrm{Ri}_4 = \frac{g}{\bar{\theta}} \frac{(\theta_A - \theta_O)z}{U_z^2}, \qquad (1)$$

where g is the gravitational acceleration, θ_A the air temperature, U_z the mean wind speed at a height z, θ_O the ocean surface temperature and $\bar{\theta}$ the mean absolute temperature, was computed for all the observations made at the buoy. This parameter is smaller than the conventional gradient Richardson number by at least a factor of 2. However, this parameter is more convenient to estimate from measurements made very close to the surface since it is difficult to obtain reliable air temperature differences over short height intervals. Of course, the use of the Monin-Obhukov length L remains the best way of defining stability, if fluxes of momentum

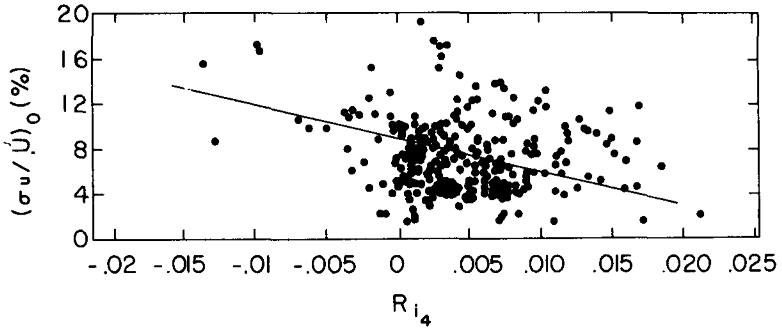

FIG. 2. Variation of turbulence intensity with the bulk Richardson number Ri_4.

and heat are measured simultaneously. For the experiments reported here, momentum flux measurements were made but not the heat flux; hence L could not be computed. The bulk Richardson number Ri_4 was estimated from observations at 8 m and at the surface.

Fig. 2 shows the scatter diagram of the intensity of turbulence σ_u/U over the ocean expressed as a percentage. Some scatter might be due to various other processes contributing to the turbulence over water and atmospheric stability is just one of them; but a definite trend is apparent as shown by the regression line with the intensity of turbulence decreasing with increasing Ri_4. A linear regression relationship of the form

$$(\sigma_u/U)_O = -3Ri_4 + 0.09 \qquad (2)$$

may be obtained from Fig. 2. The correlation coefficient was 0.8. An independent evaluation of σ_u/U can be obtained for near-neutral conditions from a knowledge of the relationships between the friction velocity u_* on one hand and σ_u and U on the other. Assuming $\sigma_u \approx 2.6u_*$ (SethuRaman *et al.*, 1978b) and $u_* = 0.033U$ for moderately rough conditions (SethuRaman and Raynor, 1975), $\sigma_u/U = 8.6\%$ which is very close to the value from Eq. (2) for $Ri_4 = 0$. A similar analysis of the data at the beach could not be made due to lack of continuous temperature measurements.

Previous experiments at Tiana Beach (Raynor *et al.*, 1975) have shown that the internal boundary layer intersects the tower at ~10 m during onshore flows. This agrees with Elliott's (1958) relationship for the internal boundary layer h given by

$$h/z_0'' = [0.75 + 0.03 \ln(z_0'/z_0'')](x/z_0'')^{0.8}, \qquad (3)$$

where z_0' and z_0'' are the upwind and downwind roughness lengths and x is the downwind distance. For $z_0' = 0.05$ cm (SethuRaman and Raynor, 1975), $z_0'' = 10$ cm and $x = 50$ m, $h \approx 8$ m. For offshore flow, assuming the same roughness lengths, at a downwind distance of 5000 m, $h \approx 185$ m. Thus both the measurements have been made within the respective internal boundary layers.

For neutral stability conditions when the logarithmic wind profile relationship is valid, the mean wind speed U at height z is given by

$$\frac{U}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z}{z_0}\right), \qquad (4)$$

where u_* is the friction velocity, z_0 the roughness length and κ von Kármán's constant (~0.4). Using subscript O and B for values at the ocean and the beach and dividing one by the other yields

$$\left(\frac{U_O}{U_B}\right)\left(\frac{u_{*B}}{u_{*O}}\right) = \frac{\ln[z/(z_0)_O]}{\ln[z/(z_0)_B]}. \qquad (5)$$

For near neutral conditions, $\sigma_u \approx cu_*$ where c is a constant with a value between 2 and 3 (Lumley and Panofsky, 1964; SethuRaman *et al.*, 1978b). Hence Eq. (5), the ratio of turbulence intensity over the ocean to the one at the beach, can be written as

$$\frac{(\sigma_u/U)_O}{(\sigma_u/U)_B} = \frac{[\ln(z/z_0)]_B}{[\ln(z/z_0)]_O}, \qquad (6)$$

where σ_u/U is the intensity of turbulence. Assuming $z_{0_O} = 0.05$ cm and $z_{0_B} = 10$ cm for onshore flow conditions and with $z = 8$ m, the ratio for near-neutral conditions can be estimated as

$$(\sigma_u/U)_O/(\sigma_u/U)_B \approx 0.5. \qquad (7)$$

In practice z_{0_O} depends on the aerodynamic roughness of the sea surface and to some extent on the atmospheric stability.

The comparison between the measurements at the beach and offshore were made by means of ratios of the variables with the values at the beach being used as the normalizing quantity. In the absence of Ri at both stations, the mean wind speed at the beach was chosen as the independent variable for all comparisons due to the following reasons: 1) it is an easily measurable quantity, 2) it has an indirect effect on atmospheric stability with the

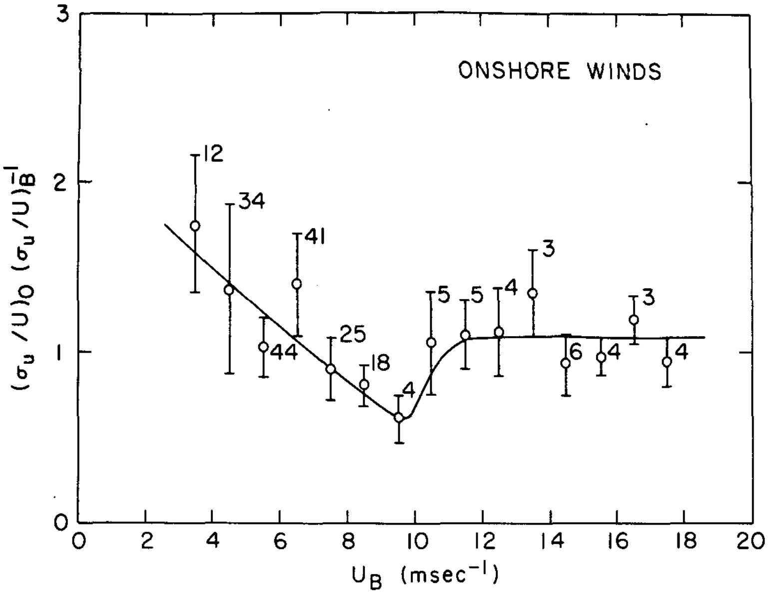

FIG. 3. Variation of the mean ratios of turbulence intensities with the mean wind speeds at Tiana beach for onshore flows. *O* indicates over ocean and *B* at the beach. The number of observations and the 95% confidence interval for each wind speed interval are also indicated.

stability becoming near neutral at high wind speeds, and 3) the aerodynamic roughness of the sea depends to some extent on the wind speed.

Ratios of the intensities of turbulence at the buoy to the corresponding values at the beach for onshore flows are shown in Fig. 3. The observations were grouped into wind speed classes of 1 m s^{-1} and the resulting mean values plotted with 95% confidence intervals. The number of observations for each wind speed class are also shown. Standard deviations of the ratios varied from 10 to 50% of the mean with the smaller values at wind speeds >8 m s^{-1}. Variability of the ratio is probably due to other factors such as atmospheric stability, wave age, etc., affecting its value, particularly at lower wind speeds. The mean ratios varied from about 2 to 0.6 and an average curve following the variations is also shown in Fig. 3. Variation of this turbulence intensity ratio with the mean wind speed can be explained as follows:

- At low wind speeds, atmospheric stability and the variability of mean wind direction seem to dominate. Strong stable conditions are associated with low wind speeds at night over land. Due to the inertia of large bodies of water such as oceans, diurnal variation in sea surface temperature is minimal. Moreover, at low wind speeds wind direction tends to vary significantly leading to partially developed waves and hence higher drag and turbulence (SethuRaman, 1978). These may be the reasons for the ratio being systematically higher at low wind speeds. As the mean wind speed increases, differences in stability between the beach and the ocean become small as does the variability in wind direction causing smaller ratios. The turbulence intensity ratios seem to approach a value of ~0.5 for a mean wind speed of about 10 m s^{-1} as predicted by Eq. (7) for near-neutral stability conditions.
- At high wind speeds (U > 12 m s^{-1}), the ratio becomes approximately equal to one. This is probably due to the onset of roll vortices which occur during near-neutral conditions (Woodcock and Wyman, 1947). It has been observed that $U \approx 12$ m s^{-1} is a critical wind speed beyond which longitudinal and lateral components of turbulence over water are enhanced, possibly due to the occurrence of these vortices (SethuRaman, 1979). Since the scale of these vortices is usually of the order of several hundreds of meters and the fetch over the beach for onshore flows is less than 100 m, the turbulence intensity at the beach tends to be the same as offshore.

Variation of the mean ratios of turbulence intensities as a function of mean wind speed at the beach is shown in Fig. 4 for alongshore wind directions. For this wind direction, measurements at the buoy correspond to winds with a long fetch over water and the observations at the beach pertain to winds with a long fetch over land. Variation of the ratios at low wind speeds showed a relationship similar to that for onshore flows, but for mean

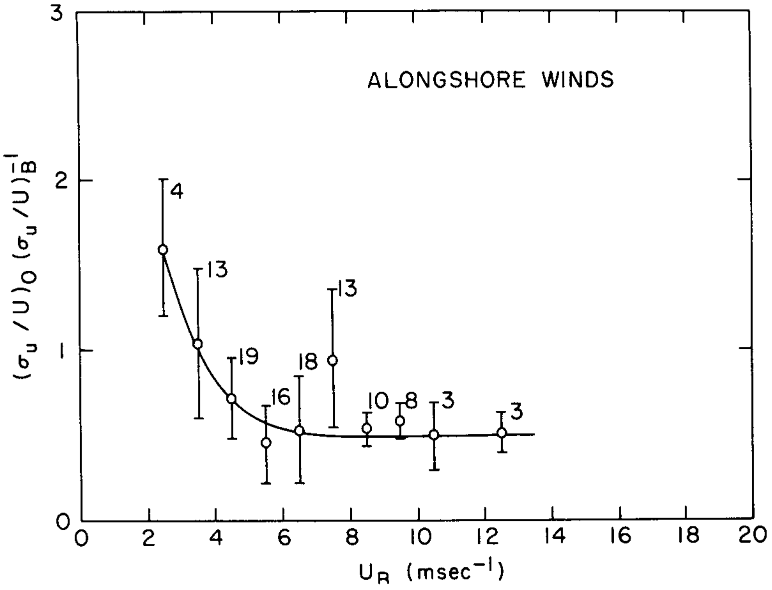

Fig. 4. As in Fig. 3 except for alongshore flows.

winds >6 m s^{-1}, a constant value of ~0.5 was reached as predicted by Eq. (7) for near-neutral stability conditions. Thus the contrast between the overland and overwater roughness lengths seems to govern the changes in turbulence. The number of observations in each wind speed class varied from 3 to 12 and the standard deviations of the ratios from about 10 to 30% of the mean.

Variation of the mean ratios of turbulence intensities with the mean wind speed at the beach is shown in Fig. 5 for offshore wind directions. For this direction, measurements at the beach corresponded to overland flow with varying fetch on the beach depending on the distance from the bay to the tower (see Fig. 1). Measurements at the buoy were representative of overwater flow with a short fetch (~5 km). The mean ratios seem to have an average value of about 1, invariant with wind speed which suggests that the z_0's are of the same order of magnitude. Partially developed waves due to short fetch are known to present an aerodynamically rough surface (SethuRaman, 1979) and this

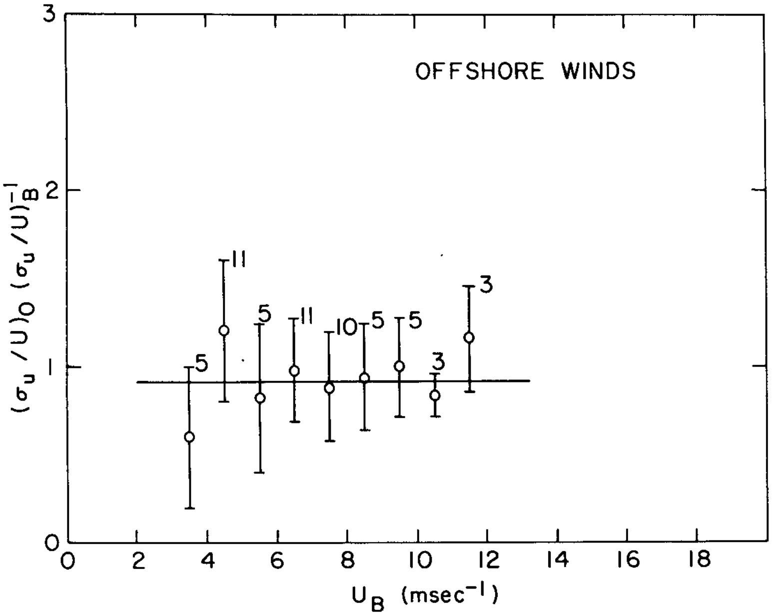

Fig. 5. As in Fig. 3 except for offshore flows.

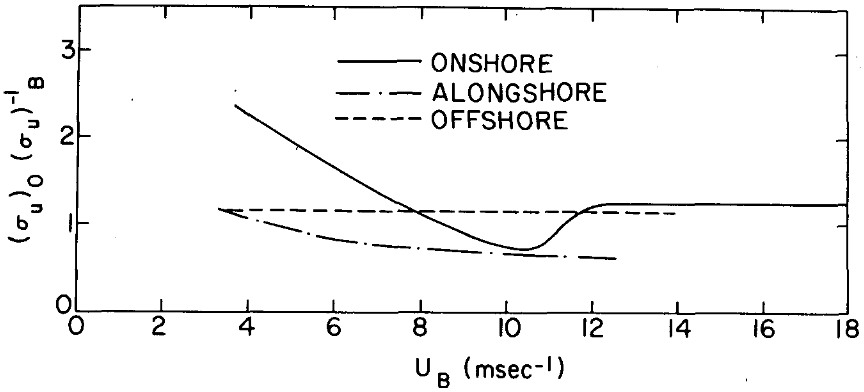

FIG. 6. Variation of the mean ratios of the standard deviations of longitudinal velocity fluctuations with the mean wind speeds at Tiana beach for onshore, alongshore and offshore flows.

might be part of the reason for the nearly equal turbulence intensities. Another possibility is that the anemometer at Tiana beach might have been in a developing internal boundary layer due to the presence of the bay (see Fig. 1). The number of observations for each wind speed category varied from 3 to 10 and the standard deviations of the ratios from 20 to 50% of the mean.

Variation of the σ_u ratios with the mean wind speed at the beach for different wind directions is shown in Fig. 6. The mean ratios of the σ_u's varied from about 0.5 to 2.5 for all three cases and generally followed the same trend as for the turbulence intensities.

A change in surface roughness modifies both the mean wind speed and turbulence. For example, an increase in roughness decreases mean wind but increases turbulence and vice versa. Mean wind speeds over the ocean normalized by the mean wind speed at the beach have been plotted as a function of the wind speed at the beach in Fig. 7. Wind speeds over the ocean were found to be larger for $U_B < 10$ m s^{-1} beyond which mean winds over ocean and the beach were about the same. This indicates that at higher wind speeds the local pressure gradients caused by the roughness effects become negligible as compared to synoptic gradients. A typical example of the effect of a change in roughness on mean wind speed is shown in Fig. 8. The mean winds were from the west-southwest, parallel to the beach at 5 m s^{-1}; but as the wind direction changed slightly to an overwater fetch, the speed increased by a factor of 2 to ~10 m s^{-1}. This factor agrees with the mean value of the ratio given by Fig. 7. There was no significant synoptic changes such as frontal passages during the period of observations in Fig. 8.

4. Conclusions

Comparisons of mean winds and longitudinal turbulence at a coastline and 5 km over the ocean revealed the effects of changes in surface roughness. Some of these effects were expected such as the increase in mean wind speed and decrease in turbulence due to decrease in surface roughness, particularly for alongshore flows. But there were effects that were not readily apparent before analysis

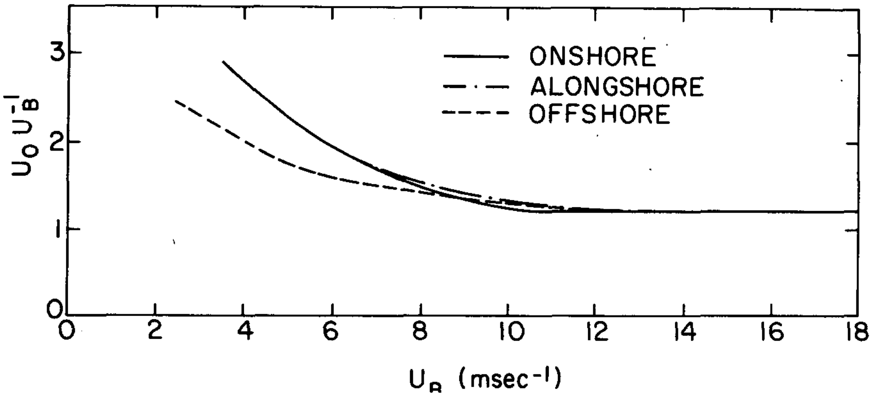

FIG. 7. Variation of the ratios of mean winds with the mean wind speeds at Tiana beach for different wind direction sectors.

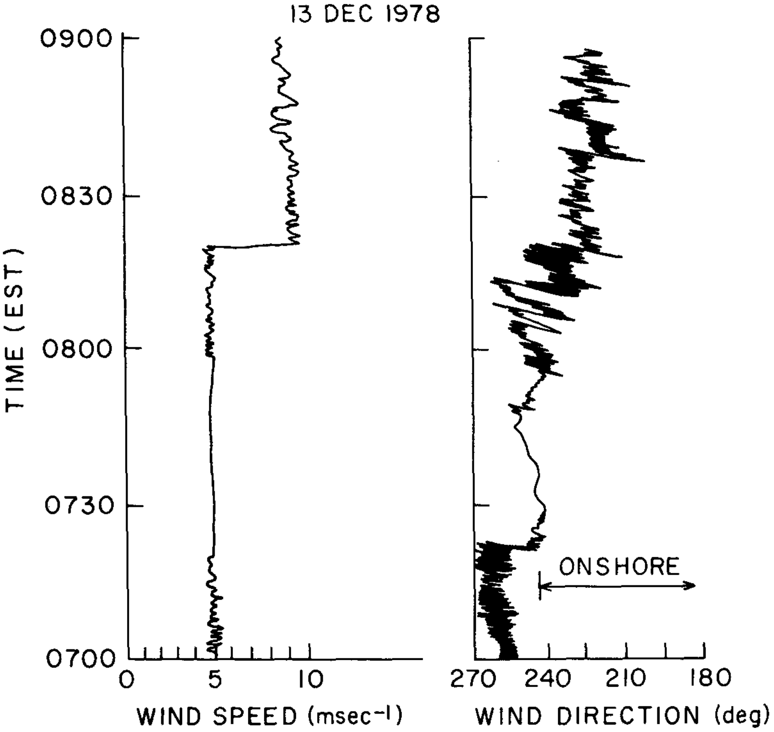

FIG. 8. Increase in Tiana beach mean wind speed as the wind changed from alongshore to onshore direction.

such as the increase in turbulence over water during low wind speeds ($U < 6$ m s^{-1}) and at very high wind speeds ($U > 12$ m s^{-1}) for onshore flows and for all winds with offshore flows. These effects are probably due to the unique air-sea exchange processes that take place in a coastal zone—sea state conditions, wave age, inertia of the water column and the development of roll vortices. A more comprehensive observational program that includes atmospheric stabilities and boundary-layer structure will be essential to critically examine several features noted in the analysis reported in this paper.

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