Structure of Turbulence over Water during High Winds[1]

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ABSTRACT

Turbulence fluctuations over water are found to change for wind speeds more than 10–12 m s^{-1}. Increase in turbulence level beyond this critical wind speed may be attributed to the formation of helical roll vortices. Integral scales of turbulence estimated over water are found to be several times larger than corresponding values over land.

1. Introduction

Turbulence in the atmospheric surface layer induces different degrees of mixing leading to various boundary-layer processes. Diffusion of various contaminants released in the atmosphere depends on the scales and levels of turbulence. A knowledge of the variation of turbulence parameters such as the variances of the velocity fluctuations is important to estimate atmospheric diffusion. Random fluctuations of velocity and pressure in the atmosphere can also cause random motions of structures, sometimes resonant in structure, depending on the structural characteristics. Structural failures mostly occur during high wind conditions when the amplitudes of fluctuations are the highest and the scales of turbulence the smallest. Turbulence over land in the atmospheric surface layer has been extensively studied (Lumley and Panofsky, 1964). But data regarding turbulence over water are scarce, particularly during high wind conditions. Due to the differences in the characteristics of large bodies of water as compared with land, the results found over land cannot be extrapolated without taking into consideration these differences (SethuRaman and Raynor, 1978). The purpose of this paper is to examine the variation of a few turbulence parameters over water during low- and high-wind speed conditions and to compare scales of turbulence for atmospheric flows over water and over land.

Most of the data reported here were part of the observations made during an air-sea interaction experiment conducted by Brookhaven National Laboratory (SethuRaman *et al.*, 1978a) with a stabilized buoy anchored 5 km offshore near Tiana Beach, Long Island (Fig. 1). Measurements at the buoy consisted of longitudinal, lateral and vertical velocity fluctuations at one level, mean wind speeds at four levels, air and sea temperatures, wave heights and buoy motions which consisted of vertical acceleration and tilts. The bivane used for measuring lateral and vertical velocity fluctuations was gimbal-mounted to eliminate the effects of mean and oscillating tilts. Oscillating tilt of the buoy was of the order of ±5° during high winds. Vertical displacements (5–15 cm) occurred only due to long waves. Characteristics of the buoy and the details of instrumentation and data acquisition are given elsewhere (SethuRaman *et al.*, 1978b). Vertical acceleration of the buoy induces maximum errors in σ_w, estimated to be a maximum of about 10% during periods of swells caused by strong, persistent wind with long fetches over water. But a correction can be made with simultaneous acceleration measurements. Errors in σ_u and σ_v will be about 1–2% (Pond, 1968). Instantaneous velocity fluctuations were sampled at 150 min^{-1} and standard deviations computed for 10 min sampling periods.

2. Turbulent fluctuations offshore

It is generally known that turbulence in the atmospheric surface layer over water has to be less as compared with a typical flat overland terrain due to the water surface being smoother. This reduces the mechanical roughness of the surface, but the turbulence caused by thermal instabilities still remains. Although the surface seems to be smooth for a quick look, the mobile sea surface goes through various phases of aerodynamic roughness depending on the degree of interplay between the atmosphere and the oceans (SethuRaman and Raynor, 1975; SethuRaman, 1977a, 1978; Kitaigorodskii, 1973). In addition, wave-generated atmospheric turbulence is significant within the first 100 m (SethuRaman, 1977b; Kondo *et al.*, 1972). With all these conflicting contributions it will be

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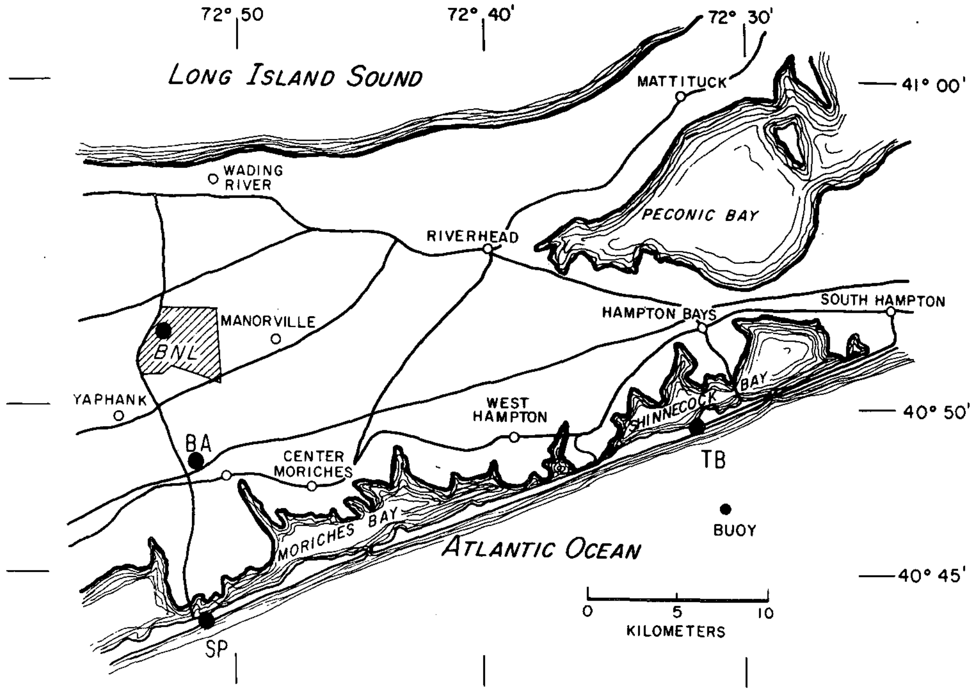

FIG. 1. Map of eastern Long Island showing relative locations of measurement sites. Brookhaven National Laboratory (BNL), Brookhaven Airport (BA), Smith's Point (SP), Tiana Beach (TB) and air-sea interaction buoy (Buoy).

difficult to completely ignore the mechanical turbulence over water.

Restricting ourselves to fluctuations due to turbulence, represented by the variances or the standard deviations of the velocity fluctuations over water, let us examine their behavior with increasing wind speeds over water. A relationship between the standard deviations of velocity fluctuations, σ_u in the mean wind direction, σ_v in the lateral direction and, σ_w in the vertical direction and the mean wind speed $\bar{u}$ can be derived from a knowledge of the mean wind profile and a relationship between turbulent fluctuations and friction velocity u_* based on Monin-Obukhov similarity theory. For overwater atmospheric flows (SethuRaman *et al.*, 1978c), ratios A are found to be the following for each of the three wind components:

$$\left.\begin{aligned}\sigma_u/u_*&=2.6\\ \sigma_v/u_*&=2.0\\ \sigma_w/u_*&=1.4\end{aligned}\right\}. \tag{1}$$

These are not significantly different from overland values for uniform terrain (Lumley and Panofsky, 1964; Merry and Panofsky, 1976). For near-neutral conditions, assuming a logarithmic velocity profile,

$$\bar{u}=\frac{u_*}{0.4}\ln(z/z_0), \tag{2}$$

where $\bar{u}$ is the mean wind speed at a height z above the surface and z_0 is the roughness length. Combining Eqs. (1) and (2) the relationship for the standard deviation of turbulence velocity fluctuations σ_t becomes (Lumley and Panofsky, 1964)

$$\sigma_t=\frac{0.4A\bar{u}}{\ln(z/z_0)}. \tag{3}$$

The relationship σ_t versus $\bar{u}$ will be a straight line if z_0 is constant and thus independent of $\bar{u}$. In practice, z_0 seems to depend on mean wind speed, atmospheric stability and for overwater flows on the wave age (SethuRaman, 1978).

Turbulence measurements were made at a height of 10 m over water. Mean wind speeds ranged from 4–28 m s^{-1}. Variations of σ_w with $\bar{u}$ is given in Fig. 2 with the relationship given by Eq. (3) shown as a line. Roughness length z_0 was assumed to be 0.076 mm—an appropriate value for moderately rough conditions (SethuRaman and Raynor, 1975), and a value of 1.4 assumed for A. Eq. (3) with this value of z_0 underestimates σ_w at high speeds and overestimates slightly at low wind speeds. A relationship $\sigma_w=0.05\bar{u}$ satisfied most of the data and gives us a value of 0.14 mm for roughness length with $A=1.4$. In a previous study, z_0 was found to vary between 0.015 and 0.15 mm for moderately rough sea conditions. Lumley and Panofsky (1964) indicate coefficient values ranging from 0.1 for a smooth terrain, i.e., O'Neill, to about 0.2 for a rough terrain, i.e., Brookhaven, for the relationship between σ_w and $\bar{u}$.

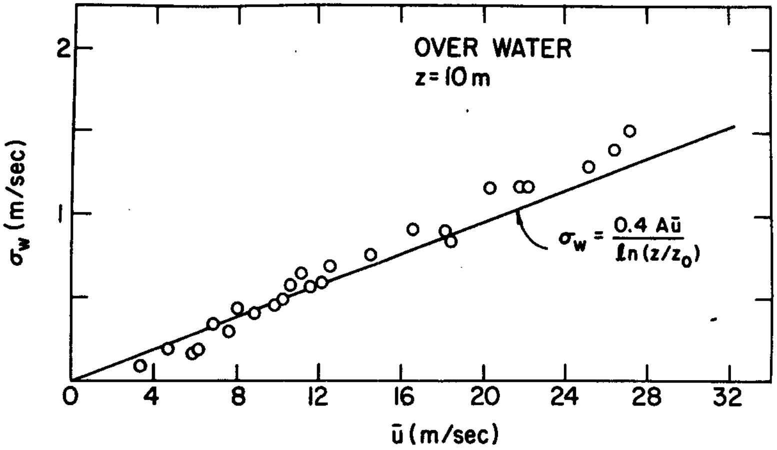

FIG. 2. Variation of σ_w with mean wind speed $\bar{u}$. Height of measurement was 8 m over water. $A=1.4$ and $z_0=0.2$ mm for the relationship shown.

Variation of σ_u as a function of $\bar{u}$ is shown in Fig. 3 with lines of best fit. There is a significant change in slope for wind speeds higher than 12 m s^{-1}. Relationships of the form

$$\sigma_u=\begin{cases}0.08\bar{u}, & \bar{u}<12\text{ m s}^{-1}\\ 0.20\bar{u}-1.5, & \bar{u}\geqslant 12\text{ m s}^{-1}\end{cases}\tag{4}$$

can be fitted to the observations. Variation of σ_v with $\bar{u}$ with best-fit lines are shown in Fig. 4. The characteristics of the variation of the standard deviations with wind speeds in Figs. 3 and 4 are very similar with the slopes changing at a wind speed of about 12 m s^{-1}. No such change was found for σ_w (Fig. 2). The scatter of data for σ_v is less than for σ_u. The observations in Fig. 3 indicate

$$\sigma_v=\begin{cases}0.08\bar{u}, & \bar{u}<12\text{ m s}^{-1}\\ 0.16\bar{u}-1.06, & \bar{u}\geqslant 12\text{ m s}^{-1}.\end{cases}\tag{5}$$

It is interesting to note that σ_u and σ_s have similar variations with $\bar{u}$ for wind speeds up to 12 m s^{-1}. This is probably due to roughly homogeneous surface of the ocean. Over land, $\sigma_v/\bar{u}$ varies with the site conditions and usually differs from $\sigma_u/\bar{u}$ due to inhomogeneous surface. σ_u seems to increase faster with wind speed as compared with σ_v for $\bar{u}\geqslant 12$ m s^{-1}. Thus the structure of turbulence over water at high wind speeds may be different for lateral and longitudinal components. There are at least two possible reasons for this change in turbulence beyond a wind speed of 12 m s^{-1}. One possibility is the increase in sea surface roughness at high speeds which may be significant during transient stages of waves. The variation of σ_w which will be at least as sensitive to the surface roughness as σ_u and σ_v contradicts this hypothesis. Another possibility is the formation of longitudinal roll vortices which are found to occur over water during near neutral conditions (Woodcock and Wyman, 1947). A schematic diagram

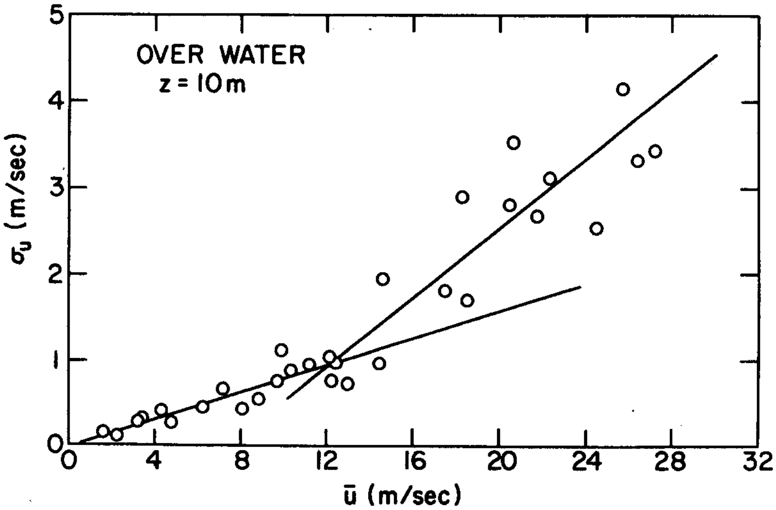

FIG. 3. Variation of σ_u with $\bar{u}$. Measurements were made at 8 m over water. Best-fit lines are shown.

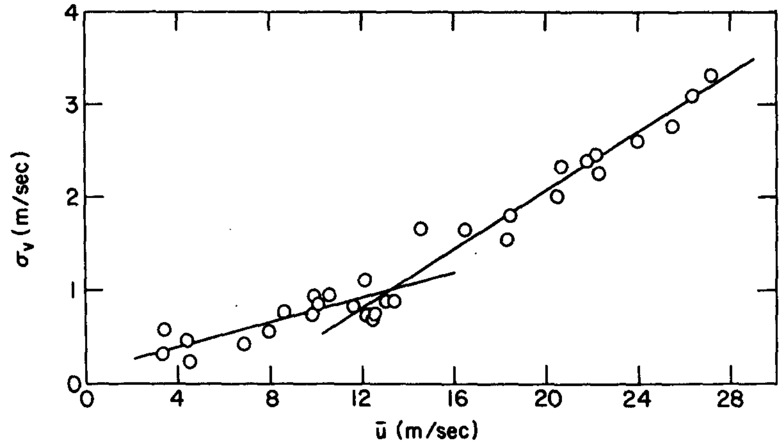

FIG. 4. Variation of σ_v with $\bar{u}$. Measurements were made at 8 m over water. Best-fit lines are shown.

of the longitudinal cells with helical motions is shown in Fig. 5. Keuttner (1959, 1971) has given theoretical and physical explanations for the formation of these vortices due to the restoring inertial forces created by differential vorticities along the flow direction. These restoring forces counteract buoyancy forces caused by convection in vertical planes along the flow direction. This inhibits convective circulations in these planes. Convective circulations normal to the flow are not affected by the above restoring forces, thus leading to the formation of roll vortices (Keuttner, 1959). Orientation of the roll vortices in the direction of mean wind might cause increases in turbulence in longitudinal and lateral directions as compared with vertical. This is believed to be the reason for the increase in the variation of σ_u and σ_v values beyond a wind speed of 12 m s^{-1}. Near-neutral stability conditions conducive for the formation of these vortices tend to occur during high winds. Vertical temperature profiles were not available to estimate mixing heights. Helical vortices have been observed under convective conditions in wind tunnel flows (SethuRaman and Cermak, 1974), in field studies over land (Gifford, 1953; Angell *et al.*, 1968; Lemone, 1973) and over water (Nicholls, 1978). Spectral analysis of the data to determine energy contents at low frequencies will help in understanding the formation of these vortices. This will be the subject of a future paper.

3. Scales of turbulence

A knowledge of the atmospheric scales of turbulence is important for predicting diffusion and for the design of structures. Several scales, depending on the practical application, can be computed. The turbulence scale that may be most appropriate for design of structures and for diffusion estimates is the integral scale of turbulence which is closely related to the eddy size with maximum energy. The Eulerian integral scale L is defined as

$$L=\bar{u}\int_0^\infty R(t)dt, \tag{4}$$

where $\bar{u}$ is the mean wind speed and $R(t)$ is the autocorrelation coefficient. The integral scales L_u, L_v and L_w, estimated for longitudinal, lateral and vertical directions, respectively, for a typical coastal storm are shown in Table 1. A comparison between the longitudinal scales of turbulence obtained from simultaneous overwater and overland turbulence measurements is also shown in the table for the same storm. Overwater results are based on turbulence measured at a height of 10 m at the buoy. Overland results correspond to a height of 109 m at Brookhaven National Laboratory. The longitudinal scale of turbulence over land is about four times smaller than that near the coast over water.

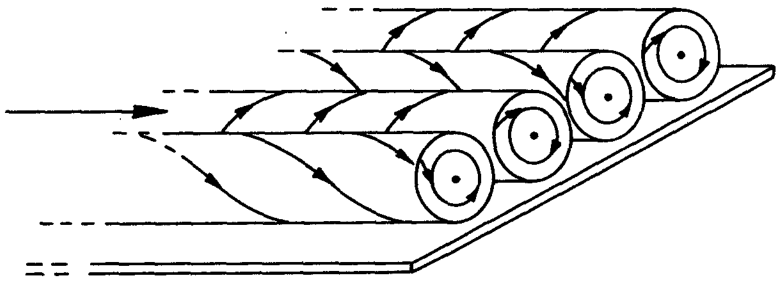

FIG. 5. A schematic diagram of the longitudinal roll vortices.

TABLE 1. Comparison of scales of turbulence.

Location	$\bar{u}$ (m s^{-1})	L_u (m)	L_v (m)	L_w (m)	$\sigma_u/\bar{u}$
Coastal overwater	23.60	116	66	31	0.08
Inland	14.10	26	—	—	0.16

This is to be expected due to the increased roughness. The vertical scale of turbulence over water is about four times smaller than the longitudinal scale over water and the lateral scale is intermediate between these values. Unfortunately, lateral and vertical turbulence measurements are not available at the inland location for this storm. Longitudinal turbulence level σ_u increased by a factor of 2 as the air moved inland, but the mean wind speed $\bar{u}$ decreased. This example demonstrates the significant differences in atmospheric turbulence behavior in the surface layer between a coastal site and an inland site for onshore flows.

4. Conclusions

Variances of velocity fluctuations in the atmospheric surface layer over the ocean indicate an abrupt increase for wind speeds beyond 12 m s^{-1}. This increase is found to be significant for longitudinal and lateral velocity fluctuations. Helical vortices that form during near-neutral conditions is thought to be the source of enhanced turbulence. Integral scales of turbulence are found to be several times higher over water as compared with overland values.

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