ON THE CORRECTION OF LAND-BASED WIND MEASUREMENTS FOR OCEANOGRAPHIC APPLICATIONS

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Abstract

Simultaneous offshore and onshore wind measurements were made at stations ranging from Somalia, near the equator, to the Gulf of Alaska. Offshore data obtained from standard U.S. NOAA buoys, research platforms, and merchant ships were compared with data from coastal stations. The results indicated that, under the commonly observed speed of 5-6 m/s, land measurements of mean wind speed are only 63% of the offshore mean speed. Furthermore, it was found that only those stations located in the beach area that measure wind speed above both the internal boundary layer and the nocturnal inversion height represent offshore conditions. In order to correct land-measured wind data, a formula is developed and verified by all existing data sets. A simplified equation, i.e., $U_{sea} = 3\ U_{land}^{2/3}$, is proposed for offshore applications. Criteria for in situ wind measurements near the coast are outlined. Data reduction procedures for inland stations are also provided.

1. Introduction

For some time, differences in onshore and offshore wind speeds have been known to exist (see, e.g., Davenport, 1965; Yu, 1970; Hsu, 1979; Zimmerman and Burton, 1979). Many studies related to coastal marine sciences and engineering require wind data from offshore regions. Yet, in situ measurements over water are often lacking. Therefore, engineers as well as scientists traditionally rely on wind measurements over land, preferably near coasts. However, because simultaneous onshore and offshore observations do not always exist, systematic studies such as simple comparison between these two environments are also lacking. Only recently the U.S. National Oceanic and Atmospheric Administration (NOAA) deployed several buoys for longer term measurements over the continental shelf as well as farther offshore. It is the purpose of this paper to study the systematic variations in wind speed between offshore and onshore areas by comparing these buoy data with data from coastal and inland stations operated by NOAA.

In order to substantiate the results, four specialized experiments have been selected. The phenomenon of wind variability across the coastal zone is described in section 2. In order to correct onshore measurements a formula is developed in section 3. Experimental results are summarized in section 4. Since existing stations are not necessarily located near the shore, in situ measurements may be required for certain engineering projects. Furthermore, height correction for those data obtained from existing urban stations should be made. All these problems are discussed and correction criteria are outlined in section 5. Finally, conclusions are drawn in section 6.

2. Wind Variability across the Coastal Zone

In this study U.S. NOAA data from six buoys and twelve land stations for a period of 1 year (July 1977 through June 1978) are utilized. Information on these data buoys may be found in Hamilton (1980). Data from each buoy are compared to those of the two nearest land stations: one located on the coast, i.e., keys, capes, and islands, and another a few kilometres inland, preferably less than 20 km. Two buoys are located in the Atlantic Ocean, two are in the Gulf of Mexico, and one each is in the Pacific Ocean and Gulf of Alaska. In order to avoid height variations between wind sensors, only those land stations whose height is within 20 m above sea level are used.

The results are shown in Figure 1. They indicate that, contrary to common practice, even stations such as those located on a small, flat, open area (e.g., Key West, Florida, and Cape Hatteras, North Carolina) cannot represent monthly mean offshore conditions. Furthermore, at stations located in an estuarine environment such as Homer, in Cook Inlet, Alaska, the mean wind speed on the average is less than half that offshore. Figure 1 also shows that the largest difference between onshore and offshore conditions usually occurs in winter, when offshore storms are more frequent because of the more pronounced aerodynamic roughness or drag effect on land. During the warmer part of the year higher speeds may be recorded, at times, for diurnal onshore (sea breeze) winds than for offshore winds (Fig. 1). As expected, the wind speed decreases inland (Fig. 1).

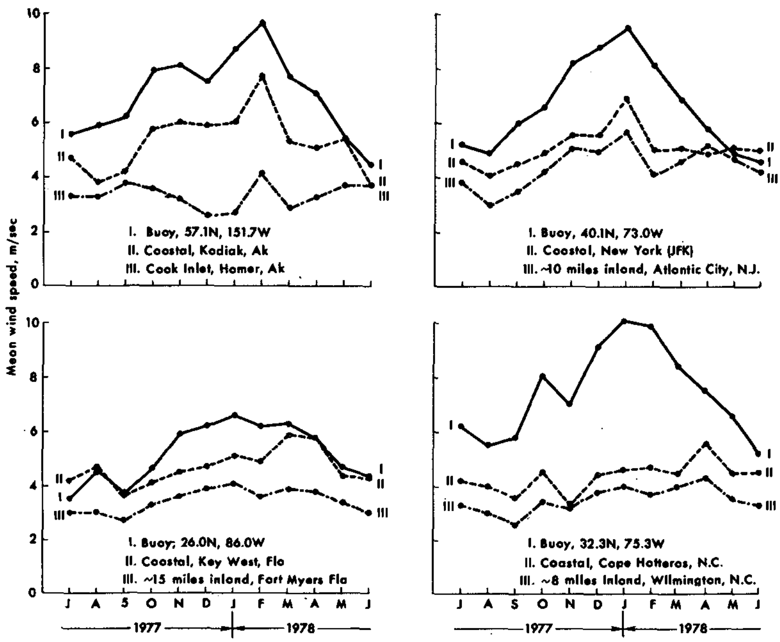

Figure 1. Examples of differences in monthly wind speed (meters per second) at stations ranging from offshore to coastal to inland (from July 1977 through June 1978).

The average of all buoys and land stations indicates that the ratio of buoys to land stations is 1.60 $\pm$ 0.28 (mean $\pm$ standard deviation). In other words, the average land-based mean speed is only 63% of that offshore. Two pairs of buoy data not shown in Figure 1 are incorporated in the above statistics. They are a buoy located at 26.0°N, 93.5°W, which was compared to Corpus Christi and Brownsville, Texas, stations, and a buoy at 41.1°N, 137.8°W, which was compared to stations at Astoria, Oregon, and San Francisco, California.

Figures 2 and 3 represent some diurnal variations across the upper Texas coastal zone (Yu, 1970). Nine mechanical weather stations were used to record surface temperature, wind speed, and wind direction. The offshore station was located about 19 km directly offshore (station SOC, shown in Fig. 2). The instrument at that location was mounted on top of an oil drilling platform, which placed it about 20 m above the water surface. The others were located inland at distances of approximately 0.01, 0.09, 1.7, 3.5, 5.2, 8.0, 10.7, and 14.0 km from the coastline. The instruments at these eight inland stations were set up at a height of 2 m above the ground. In order to compare SOC (offshore) data with that from the other

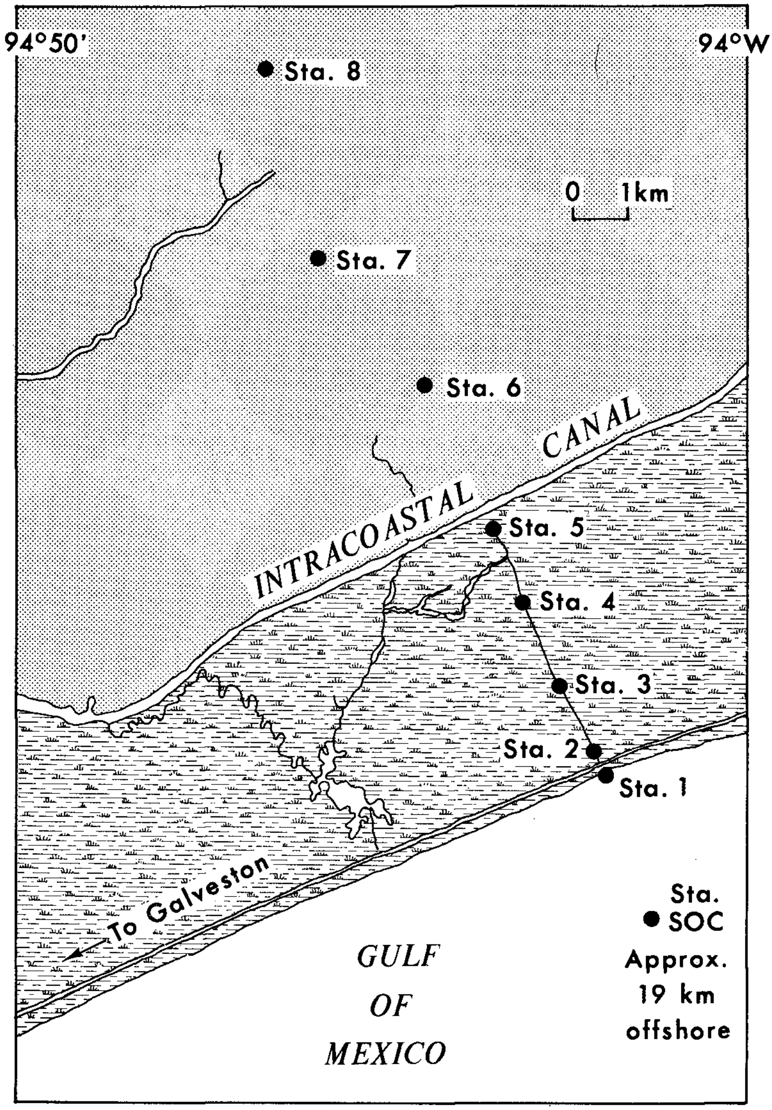

Figure 2. Locations of the nine mechanical weather stations (eight onshore and one about 19 km offshore on a platform). They were located approximately along a line perpendicular to the shoreline. (After Yu, 1970.)

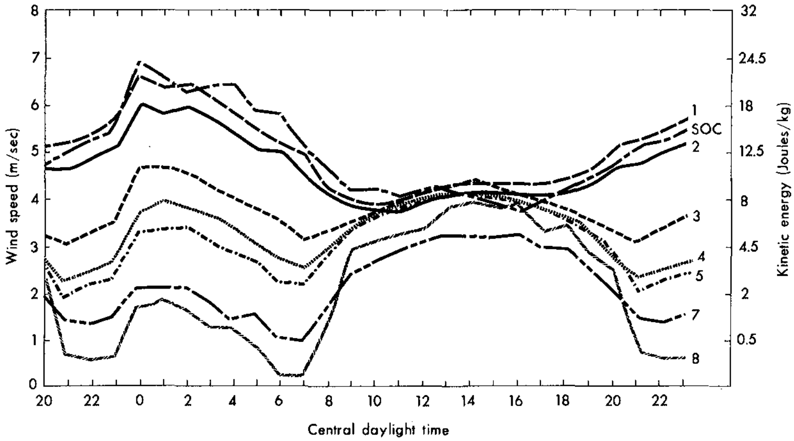

Figure 3. Diurnal variation of wind speed measured from eight stations (cf. Fig. 2 and text) deployed on the upper Texas coast and averaged for the period 9-11 June 1968. (After Yu, 1970.)

stations, the data were all reduced to the 2-m level. As shown in Figure 2, the nine stations were located along a line almost perpendicular to the coast. A 1-hour average time centered on the hour was used, that is, 0830 to 0930 for the 0900 value, etc. Accuracy is limited to the reading accuracy of the record, which is approximately ± 0.1 mi/hr (±0.045 m/s) (for further details, aee Yu, 1970).

The diurnal variation of wind speed at the various stations is shown in Figure 3. Curves are drawn on the basis of a 3-day average, i.e., June 9, 10, and 11 taken together. The most important feature shown in this figure is that there are two different types of curves. The curves for stations SOC, 1, and 2 are similar; we shall call these marine-type stations. Stations 3, 4, 5, 7, and 8 we shall call inland-type stations. Data for station 6 are missing because that instrument did not function properly. At the marine-type stations maximum wind speeds occurred about midnight and minimum wind speeds occurred about noon. More detailed examination of the figure reveals that at the offshore station (SOC) the minimum wind speed occurred at 1600 central daylight time (CDT), while at nearshore stations 1 and 2 minimum speeds occurred at 1000 CDT and 1100 CDT, respectively. At inland stations the primary maximum wind speeds occurred at 1400 CDT, primary minimum wind speeds occurred at 0600 CDT or 0700 CDT, a secondary maximum occurred at 0000-0100 CDT, and a secondary minimum occurred at 2100-2200 CDT.

It is clear from Figure 3 that only those stations (i.e., 1 and 2) that are within about 100 m of the surf zone represent offshore conditions. Since most coastal weather stations worldwide are not located that close to the shoreline, inland wind measurements may not be extended to the offshore unless proper corrections are made.

Figure 4 shows that on the tropical (trade-wind-dominated) island of Barbados wind speeds were also different along a horizontal grid that extended from the beach to 10 km inland (Aspliden et al., 1977). Note that the station located on the shore (Fig. 4) agrees closely with the 1968 upper Texas coast beach station shown in Figure 3. About 2 km inland nighttime and daytime peaks are about equal, and 10 km inland only a strong daytime maximum is indicated. This also resembles the inland data from the upper Texas coast (compare Figs. 3 and 4) (for explanation of the variability see Yu, 1970, and Aspliden et al., 1977). The prevailing wind

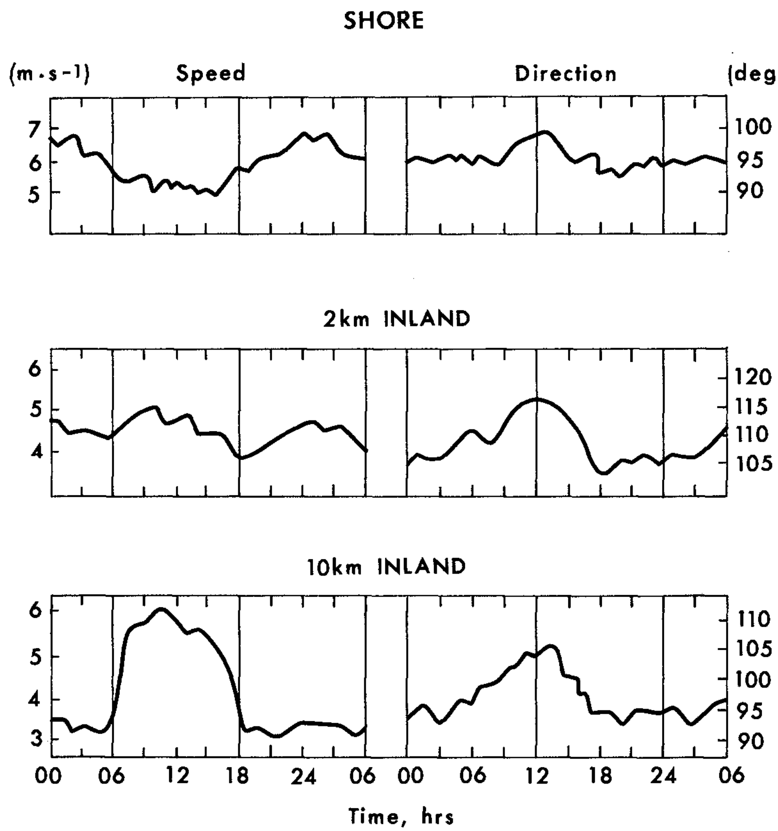

Figure 4. Diurnal variations of wind speed and direction at three locations on the eastern shore of the tropical island Barbados in August 1972. (After Aspliden et al., 1977.)

direction at Barbados was from 90° to 120° at all stations.

3. Development of the Correction Formulas

It has been demonstrated in the preceding section that large differences exist between wind measurements made onshore and those made offshore. Corrections, therefore, should be made to inland station data before they are applied to offshore regions. In order to facilitate such a correction, the following formula, based on the power law wind distribution in the PBL (see, e.g., Davenport, 1965), is proposed (see Fig. 5)

$$\frac{U}{U_H} = \left(\frac{Z}{Z_H}\right)^P \tag{1}$$

where U at height Z and U_H at Z_H are the velocity within and above the atmospheric planetary boundary layer (PBL), respectively. The thickness of the PBL is Z_H (=H), and P is an exponent that depends on atmospheric stability and surface roughness, Z_o. (For determination of P, see, e.g., Sedefian, 1980.)

The power law, equation (1), has two significant characteristics that make it very useful for work involving the whole of layer H: the law is a good average representation of the velocity profile over the entire PBL, and integral relations based on this easily integrated law are not far from correct (see, e.g., Blackadar, 1960; Plate, 1971).

If we assume that equation (1) is valid both onshore and offshore, we get

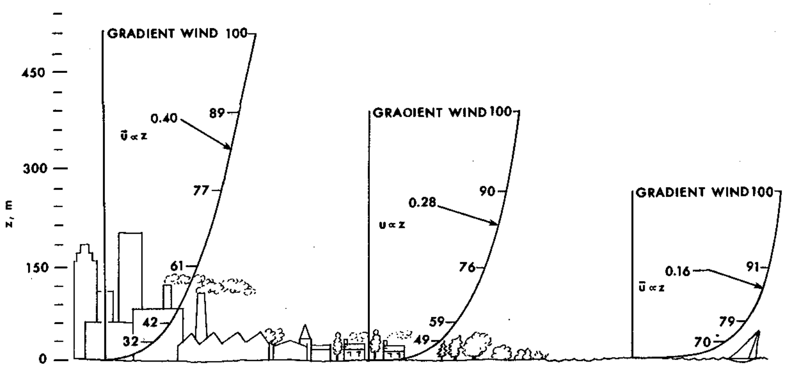

Figure 5. The power law (equation 1) over different terrain. The profile on the left represents the vertical variation of the wind over sn urban area; the center profile, over a forest; and the one on the right over flat, open country. (After Davenport, 1965.)

$$\frac{(U/U_H)_{sea}}{(U/U_H)_{land}} = \frac{(Z/H)_{sea}^{P\ sea}}{(Z/H)_{land}^{P\ land}} \tag{2}$$

If we assume that U_H on top of the PBL does not change appreciably across the coastal zone and that Z = 10 m, equation (2) becomes

$$\frac{U_{sea}}{U_{land}} = \frac{10^{P\ sea}}{10^{P\ land}} \cdot \frac{H_{land}^{P\ land}}{H_{sea}^{P\ sea}} \tag{3}$$

According to Hsu (1979a)

$$H_{sea} = H_{land} - 123\ (T_{land} - T_{sea}) \tag{4}$$

where T_{land} (°C) and T_{sea} (°C) are the temperatures at 2 m over the land and the sea, respectively, and the corresponding H is in metres. Furthermore, according to Hsu (1970)

$$U_{land} \propto (T_{land} - T_{sea}) \tag{5}$$

Since H_{land} is routinely available from twice-daily radiosondings, it may be considered as a known value. Using this reasoning, and with equation (5), equation (4) may be written as

$$H_{sea} \propto U_{land} \tag{6}$$

and, since H_{land} is known, equation (3) becomes

$$\frac{U_{sea}}{U_{land}} \propto U_{land}^{-P\ sea} \tag{7}$$

or

$$\frac{U_{sea}}{U_{land}} = a\ U_{land}^{-b} \tag{8}$$

where a and b are positive numbers.

Equation (8) is our formula for the correction of land-based observations for offshore conditions.

4. Experimental Results

Equation (8) is verified in this section. In addition to the data presented in Figure 1, four more specialized experiments were conducted to substantiate this equation.

Table 1 summarizes all available data pairs measured simultaneously onshore and offshore. Column 3 provides the data obtained from Figure 1, and column 4 shows data from SethuRaman and Raynor (1980). Column 5 was based on field experiments (Hsu, 1979a) from an offshore (stage 1) platform and an existing NOAA weather station at Apalachicola, Florida, during February and again in November-December 1977. Since wind speeds in previous experimental data were low, except those from SethuRaman and Raynor (1980), another special experiment was conducted in Somalia, where a low-level atmospheric jet exists during summer (see Fein and Kuettner, 1980).

Our experiments were conducted in May and June. For comparison, ship data obtained from the National Climate Center were employed. Pairs of Gardo-ship data (8-12°N and 51-55°E) and Mogadishu-ship (0.0-7.9°N and 41-50°E) were collected during June, when the jet is more pronounced between Gardo and the downwind region offshore than at Mogadishu and its offshore area (Fein and Kuettner, 1980). In fact, station Gardo was located very close to the area where the jet core passed. Note that wind measurements from merchant ships are considered reasonable when compared with standard ocean weather ship measurements (see Quayle, 1980). All the available data were analyzed and compiled in Table 1.

Figure 6 shows the result of these comparisons. The constants a and b of equation (8) are determined experimentally to be

$$a = 2.98$$
$$b = 0.34$$

with high correlation coefficient,

$$r = 0.95 \ .$$

We therefore have

$$\frac{U_{sea}}{U_{land}} = 2.98\ U_{land}^{-0.34} \qquad (9)$$

Table 1. Summary of the Ratio of U_{sea}/U_{land} as a Function of U_{land} (in m/s) as Measured at Coastal Stations and Offshore Buoys, Ships, and Research Platforms

U_{land} Class Interval (1)	U_{land} Class Mdpt. (2)	NOAA Buoys vs Coastal Sta.[a] (3)	BNL Buoy vs Onshore Tower[b] (4)	NCSC Platform vs Apalachicola[e] (5)	Ship vs Mogadishu[f] (6)	Ship vs Gardo[g] (7)	Avg. by Region[h] (8)
2.0-3.9	3	1.51±0.42[b] (5)[c]	2.30	1.99±0.70 (102)	2.64±0.94 (5)	2.52±1.52 (7)	2.19±0.45 (8)[i]
4.0-5.9	5	1.34±0.32 (39)	2.02	1.42±0.54 (35)	1.72±0.71 (25)	1.72±1.20 (7)	1.64±0.27 (8)
6.0-7.9	7	1.36±0.08 (4)	1.59	1.33±0.43 (8)	1.50±0.62 (39)	2.19±1.26 (14)	1.59±0.35 (8)
8.0-9.9	9		1.35	1.19 (1)	1.38±0.47 (13)	1.52±0.72 (5)	1.35±0.13 (4)
10.0-11.9	11		1.23	1.09 (1)	1.13 (1)	1.31±0.32 (15)	1.19±0.10 (4)
12.0-13.9	13		1.20			1.29±0.21 (7)	1.25±0.06 (2)
14.0-15.9	15		1.20			1.35±0.25 (2)	1.28±0.06 (2)
16.0-17.9	17		1.20				1.20 (1)

a. From Figure 1
b. Mean ± standard deviation
c. Total number of observational pairs (onshore and offshore)
d. Averaged data pairs between beach tower at Long Island, New York, and offshore Brookhaven National Laboratory buoy (from SethuRaman and Raynor, 1980)
e. U.S. Naval Coastal Systems Center platform offshore from Panama City, Florida, and NOAA Apalachicola station (see Hsu, 1979a)
f. Merchant ship observations vs. Mogadishu, Somalia (under conditions of general summer monsoon, but away from the Somali jet)
g. Merchant ship observations vs. Gardo, Somalia (under conditions of Somali low-level jetstream)
h. Mean ± standard deviation averaged from five columns between (3) and (7)
i. Total areas studied. Note four areas already included in Figure 1.

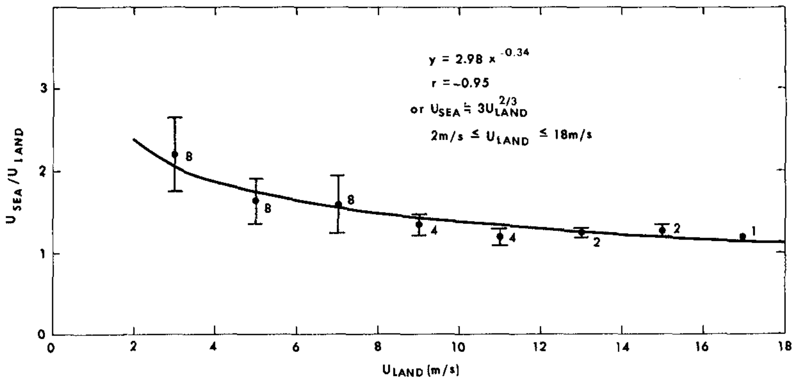

Figure 6. Ratio of U_{sea}/U_{land} as a function of U_{land}. Data were based on Table 1. Vertical bars are the standard deviation, and numbers beside the mean point are the areas incorporated in the computations.

or approximately

$$U_{sea} = 3\ U_{land}^{2/3} \tag{10}$$

where 2 m/s $\leq U_{land} \leq$ 18 m/s.

Equation (10) is an average that encompasses many geographic regions as well as various climatic conditions. For a specific location the coefficients a and b of equation (9) may vary, but the general relationship will not be altered appreciably. It is therefore recommended that equation (10) be used as an average condition.

5. Criteria for Wind Measurements near the Coast

The preceding discussions presuppose a wind measurement station near the coast. However, in many places such coastal stations are not available. In other cases the station may be located not on flat and open country but on rugged terrain, where local topographic effects are large and measurements therefore may not represent offshore conditions. For certain engineering projects in situ measurements may be required but because of logistical problems shore stations must be substituted. Under these and similar conditions we suggest a set of criteria which will alleviate the problems or at least reduce them to a minimal and acceptable level. Before we outline these criteria, some theoretical considerations may be helpful.

As air passes from land to sea or vice versa, it must readjust to a new set of boundary conditions. The adjustment is not immediate throughout the depth of the air layer but is generated at the surface and diffuses upward. The layer of air whose properties have been affected by the new surface is referred to as an internal boundary layer (IBL), and its depth grows with increasing distance, or fetch, downwind from the shoreline (see, e.g., Hsu, 1971). Since a simple but accurate model for the IBL has been formulated by Elliott (1958) (see, e.g., SethuRaman and Raynor, 1980), we adapt Elliott's relationship for the height of the IBL, h, given by

$$\frac{h}{Z_o''} = \left[0.75 + 0.03 \ln \frac{Z_o'}{Z_o''}\right] \left(\frac{x}{Z_o''}\right)^{0.8} \tag{11}$$

where Z_o' and Z_o'' are the upwind and downwind roughness lengths and x is the downwind distance. We require the anemometer to be higher than the IBL, i.e., higher than h. An example is given by SethuRaman and Raynor (1980). If the wind blows from sea to land and the beach is 50 m wide, Z_o' = 0.05 cm (offshore condition) and Z_o'' = 10 cm (onshore condition), the anemometer should be at least 8 m above the surface in order for the wind to represent the offshore condition.

The average condition for $Z_{o\ sea}$ is 0.01 cm (Hsu, 1974), and $Z_{o\ land}$ in coastal areas is given in Figure 7. For longer $Z_{o\ land}$ values, see, e.g., Sellers (1965). From these roughness parameter values, and if the landward fetch from the surf zone is known, equation (11) may be used to compute the optimum height for the wind sensors. For example, suppose a small dune about 2 m high is located 100 m from the mean water line, i.e., the average beach width is 100 m. If the wind is blowing from sea to land, we set Z_o' = 0.01 cm, Z_o'' = 1 cm, and x = 10,000 cm; the height of the anemometer should be at least 9.7 m above the dune ridge. On the other hand, assuming Z_o is the same but the beach is only 10 m wide, the height of the wind sensor needs to be only 2 m above the dune. Note that all examples given above assume that winds are perpendicular to the shoreline. For certain regions, the mean wind may have some angle to the beach; then the over-beach fetch (length) will be larger. This effect should be used in the computation rather than the simple beach width.

The foregoing discussions are valid for onshore winds, i.e., when the wind blows from sea to land. However, when the wind blows from land to sea the anemometer must be located as close to the water's edge as possible because nocturnal cooling will produce calm winds only a short distance from the beach. This phenomenon has been explained by Hsu (1979b) and is shown in Figure 8. It can be seen that higher wind speeds near the beach and farther offshore are the results of a combination of Venturi and gravity-wind effects. For more detail see Hsu (1979b).

For offshore engineering design extreme winds are usually inferred from long-term onshore measurements. However, the reference station must be located on an open and flat country. Certainly data from rugged places must be corrected. An example is given in Figure 9, which shows that the 100-year return period wind at Guantanamo Bay, Cuba (station 13), is only 71 knots, whereas at San Juan, Puerto Rico (station 14) the 100-year return

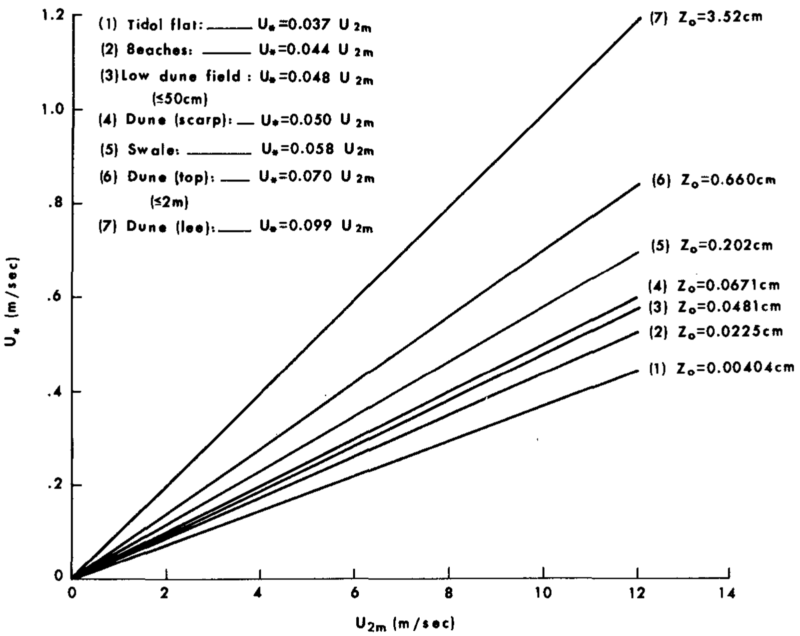

Figure 7. Summary of the aerodynamic roughness length Z_o and the relationship between shear velocity U_* and the wind velocity at 2-m height U_{2m}, measured in various coastal environments. Note that (1) was obtained from Ecuador; (2) is a synthesis of six beaches, Barbados, Ecuador, Texas, Brazil, Florida, and the Alaskan Arctic; (3) is from Texas; and (4) through (7) are all from Brazil. (For more detail, see Hsu, 1977.)

period wind is expected to be 124 knots. The lower value for Guantanamo is probably due to the sheltering effects of the nearby mountains and the island of Hispanola to the sea, whereas San Juan is exposed to the full force of Atlantic hurricanes (Atkinson, 1971).

For completeness, wind variation with height should be taken into account. Some average conditions are already shown in Figure 5. If analysis of wind loading as a function of height for offshore structures is needed, equation (1) may be applied. Values of the exponent P for different terrain are also shown in Figure 5, for example, for open and flat country, P = 0.16. Therefore, this condition may be applied to the offshore, or existing measured winds may be extrapolated to the height required and then corrected by applying equation (10).

We now outline the criteria for wind measurements near the coast:

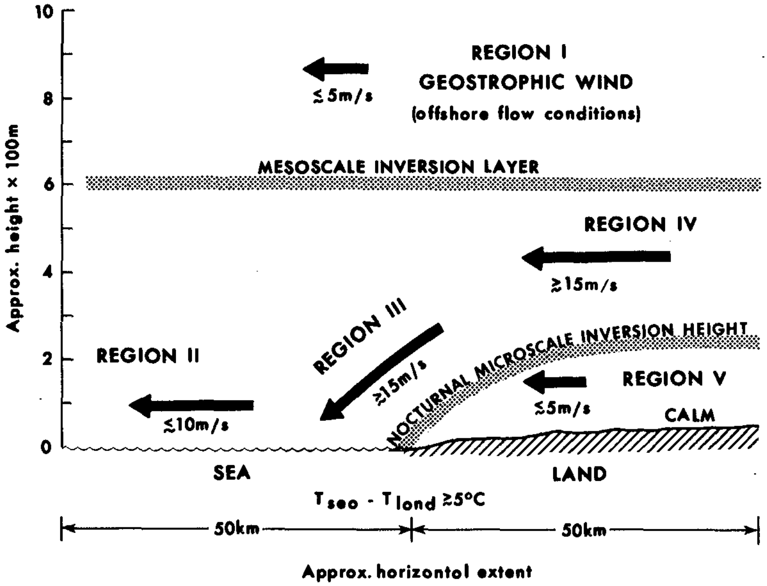

Figure 8. An example of higher wind speed near the shoreline and farther offshore but nearly calm wind inland under the influence of nocturnal cooling over land (for more detail, see Hsu, 1979b).

(1) The anemometer site must be located on flat, open country, preferably on the ridge of the first dune field next to the beach, to represent both onshore and offshore winds. If a small island, cape, or key is located offshore, it should be used instead of the coastal dune fields.

(2) The anemometer height may be optimized by applying equation (11). Proper roughness parameter and beach width should be used.

(3) Existing wind data may be corrected to the proper height by applying equation (1) and Figure 5. Equivalently, one could apply the ratio obtained from the same height above ground level. For example, at the height of 30 m the wind over flat, open country is about 70/32 (from Fig. 5) or 2.19 times higher than that over a large urban area, and about 70/49 or 1.43 times higher than that over a woodland forest.

(4) After the data have been measured from the nearshore area on the basis of (1) and (2) or have been reduced from existing inland measurements by (3), one then corrects them by applying equation (10). If a certain height above the sea surface is needed, one

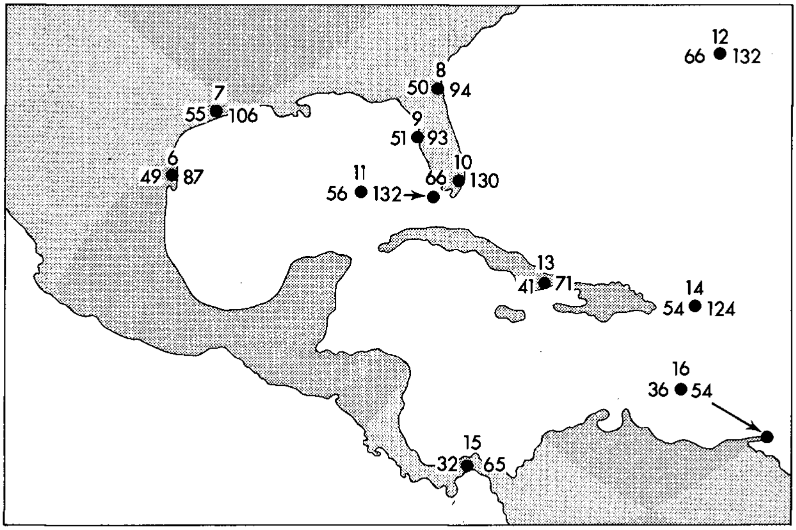

Figure 9. Examples of expected extreme wind gusts (knots) for 2-year and 100-year return periods for selected stations. Station numbers are located on the tops of the dots, 2-year return period on the left, and 100-year on the right. (After Atkinson, 1971.)

may apply equation (1) to the desired height with P = 1/7.

6. Conclusions

Several conclusions may be drawn from this study.

(1) Monthly averages of six standard U.S. NOAA buoys and coastal stations in areas ranging from the Gulf of Mexico to Alaska indicated that the land-based mean wind speed is only 63% of the offshore.

(2) Simultaneous hourly wind observations based on four more specialized experiments both onshore and offshore in various coastal environments showed that not only were there large differences, as indicated above, but also that only those stations located near the beach area above both the internal boundary layer and the nocturnal inversion height can represent offshore conditions.

(3) In order to correct land-based wind data, a formula is developed which has been verified by existing data sets. A simplified equation, i.e., $U_{sea} = 3\ U_{land}^{2/3}$, is also proposed for offshore applications.

(4) Criteria for in situ wind measurements near the coast are outlined. It is recommended that the anemometer be deployed on open, flat country and that the optimum height for wind sensors be based on the local roughness parameter and the height of the internal boundary layer. Data reduction procedures for inland stations should begin by correcting the data to the beach environment from the proper speed ratio for the same height because of differences in roughness parameters. Then the beach data may be applied to offshore conditions by employing the simplified equation given above.

Acknowledgments

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