CHAPTER ONE HUNDRED FORTY NINE

Improved Formulas for Estimating Offshore Winds

S. A. Hsu*

Abstract

On the basis of many pairs of simultaneous measurements of wind speed onshore, U_{LAND}, and offshore, U_{SEA}, in areas ranging from Somalia, near the equator, to the Gulf of Alaska, and under conditions ranging from breeze to hurricane, it was found that for operational use $U_{SEA} = 3.93\ U_{LAND}^{1/2}$ for $U_{LAND} < 10\ m\ s^{-1}$ (or 20 kt); and $U_{SEA} = 1.24\ U_{LAND}$ for $U_{LAND} \geq 10\ m\ s^{-1}$. These formulas were developed mainly from theoretical considerations and were verified by field measurements.

1. Introduction

Differences in onshore and offshore wind speeds have long been known to exist [see, e.g., (2), (15), (16)]. Marine meteorologists in the weather services are required to forecast offshore winds. Many studies related to coastal marine sciences and engineering require wind data or estimates for offshore regions. Yet in situ measurements over water are often lacking. Traditionally, wind measurements over land, preferably near coasts, have been used to estimate offshore winds. However, because simultaneous onshore and offshore observations do not always exist, systematic studies such as simple comparisons between these two environments are also lacking. Only recently the U.S. National Oceanic and Atmospheric Administration (NOAA) deployed a network of buoys for longer term measurements over the continental shelf as well as farther offshore. All of these buoys are located in or near U.S. coastal waters. However, there are still vast regions in other parts of the world where such a network does not exist.

---

*Professor, Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana 70803, U.S.A.

It is the purpose of this paper to synthesize various data sources and to provide simple formulas for operational use. Basic developments have been given in (9). Furthermore, because of the availability of wind difference measurements during hurricane conditions, as shown most recently by (12), the formulas originally proposed by (8) have been improved and extended from breeze conditions to hurricane-force winds.

2. Formulas

In order to understand and estimate wind speed differences across the coastal zone, two models, one theoretical and another semi-empirical, have been developed and verified using available data sets (9). The following discussion is based mainly on that paper.

Assuming that (1) mean horizontal motion occurs perpendicular to the coast and (2) the geostrophic wind does not change appreciably at the top of the planetary boundary layer (PBL), the equation of motion in the direction of the wind can be reduced so that

$$\frac{U_{SEA}}{U_{LAND}} = \left(\frac{H_{SEA}\ C_{D\ LAND}}{H_{LAND}\ C_{D\ SEA}}\right)^{1/2} \qquad (1)$$

where U, H, and C_D are wind speed, height of the PBL, and drag coefficient, respectively. Subscripts LAND and SEA stand for onshore and offshore environments, respectively.

Eq. 1 is based on equations of motion, which work fairly well for synoptic weather systems typically more than one day in time scale and at least 1,000 km (1 km = 0.54 nautical miles) in horizontal scale. These systems include anticyclones (high-pressure systems), monsoons, and trades. Their U_{LAND} values are generally less than 10 m s^{-1} (1 m s^{-1} = 1.94 kt).

According to Large and Pond (10), the drag coefficient, reduced to 10-m height and neutral condition, $C_{D\ SEA}$, is independent of stability and fetch (for fetch/height $\gtrsim$800) but increases with wind speed above

10 m s^{-1}. Using their measurements and many deep-water results of others, Large and Pond (10) obtained

$$10^3 \, C_{D\ SEA} = \begin{cases} 1.2 & 4 \leq U_{10} < 11 \text{ m s}^{-1} \\ 0.49 + 0.065\, U_{10}, & 11 \leq U_{10} \lesssim 25 \text{ m s}^{-1} \end{cases} \tag{2}$$

where U_{10} is the wind speed at a height of 10 m over the water.

For typical low-relief topography and low mountains on land (peaks $<$ 0.5 - 1 km), Garratt (4) obtained

$$C_{D\ LAND} = 10 \times 10^{-3} \tag{3}$$

where $C_{D\ LAND}$ is the drag coefficient at a height of 10 m over the land surface.

According to Hsu (6), variation of H_{LAND} is much more pronounced than H_{SEA} because of larger diurnal variation in heating and cooling over land than farther offshore. This reasoning shows that the most important variable in Eq. 1 is H_{LAND}.

Following Blackadar (1), Plate (11), and many others, during neutral condtions

$$H_{LAND} = \frac{0.2\, U_{*\ LAND}}{f} \tag{4}$$

where $U_{*\ LAND}$ is the friction (or shear) velocity and f is the Coriolis parameter.

Note that, by definition,

$$C_{D\ LAND} = \left(\frac{U_{*\ LAND}}{U_{LAND}} \right)^2 . \tag{5}$$

Substituting Eq. 5 into Eq. 4, one gets

$$H_{LAND} = \frac{0.2}{f} \cdot C_{D\ LAND}^{1/2} \cdot U_{LAND} . \qquad (6)$$

From Eq. 6, Eq. 1 can be written as

$$\frac{U_{SEA}}{U_{LAND}} = \left(\frac{f \cdot H_{SEA} \cdot C_{D\ LAND}}{0.2 \cdot C_{D\ LAND}^{1/2} \cdot U_{LAND} \cdot C_{D\ SEA}} \right)^{1/2} \qquad (7)$$

In other words, for a given coastal zone, if one treats values of f, H_{SEA}, $C_{D\ LAND}$, and $C_{D\ SEA}$ as known factors, as discussed above, then Eq. 7 becomes

$$\frac{U_{SEA}}{U_{LAND}} = A\ U_{LAND}^{-1/2} \qquad (8)$$

where

$$A = \left[\frac{f \cdot H_{SEA} \cdot C_{D\ LAND}^{1/2}}{0.2 \cdot C_{D\ SEA}} \right]^{1/2} \qquad (9)$$

For $U_{SEA} < 11\ m\ s^{-1}$ (or $U_{LAND} \lesssim 10\ m\ s^{-1}$), $C_{D\ SEA} = 1.2 \times 10^{-3}$ (10). In mid-latitudes, $f \simeq 10^{-4}\ s^{-1}$. Adopting the common value of $H_{SEA} = 335\ m$ from Davenport [(12); see also Plate (11)] and $C_{D\ LAND} = 10 \times 10^{-3}$ from Eq. (3),
we have

$$A = 3.74\ m^{1/2} \cdot s^{-1/2} . \qquad (10)$$

For weather systems such as hurricanes, the equations of motion do not work well because the centrifugal force is not considered. Under these conditions, the semi-empirical formula based on the power law wind distribution in the PBL [see, e.g., Plate (11)] may be employed. The power law states that

$$\frac{U}{U_H} = \left(\frac{Z}{H}\right)^P \qquad (11)$$

where U at height Z and U_H at H are the velocity within and above the atmospheric planetary boundary layer (PBL), respectively. The thickness of the PBL is H, and P is an exponent [for details see, e.g., Sedefian (13)].

If we assume that U_H on top of the PBL does not change appreciably across the coastal zone and that Z = 10 m, Eq. 11 becomes

$$\frac{U_{SEA}}{U_{LAND}} = \frac{10^{P\ SEA}}{10^{P\ LAND}} \times \frac{H_{LAND}^{P\ LAND}}{H_{SEA}^{P\ SEA}} \qquad (12)$$

Adopting common values from Davenport [(2); see also Plate (11)], P_{SEA} = 0.10 (at sea), P_{LAND} = 0.16 (for flat and open country), H_{LAND} = 370 m, and H_{SEA} = 335 m, we find from Eq. 12 that

$$\frac{U_{SEA}}{U_{LAND}} = 1.25\ . \qquad (13)$$

Eqs. 8 and 13 are our basis for data analyses.

3. Data Analyses

Many pairs of onshore and offshore measurements have become available recently [see Hsu (9)]. They are summarized in Table 1. Ratios of U_{SEA}/U_{LAND} were analyzed as a function of U_{LAND}. Note that in Hsu (9) wind speeds were below 18 m s^{-1}. The most recent data set was provided by Powell (12), who included hurricane-force wind measurements obtained during Hurricane Frederic in 1979. Although there are differences in measuring distances between onshore and offshore stations as well as lateral distance from the eye of the hurricane, the measurements are simplified here as shown in Table 1 for operational use.

4. Results

The results are shown in Fig. 1. It is interesting to note that

Table 1. Summary of the Ratio of U_{SEA}/U_{LAND} as a Function of U_{LAND} (in m s^{-1}) 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 Buoys vs Onshore Tower[d] (4)	NCSC Platform vs Apalachicola[e] (5)	Ship vs Mogadishu[f] (6)	Ship vs Gardo[g] (7)	Hurricane Frederic, 1979[h] (8)	Avg. by Region[i] (9)
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)[j]
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				1.32±0.02 (3)	1.26±0.08 (2)

Table 1 continued

U_{LAND} Class Interval (1)	U_{LAND} Class Mdpt. (2)	NOAA Buoys vs Coastal Sta.[a] (3)	BNL Buoys vs Onshore Tower[d] (4)	NCSC Platform vs Apalachicola[e] (5)	Ship vs Mogadishu[f] (6)	Ship vs Gardo[g] (7)	Hurricane Frederic, 1979[h] (8)	Avg. by Region[i] (9)
18.0-19.9	19							
20.0-21.9	21						1.14 (1)	1.14 (1)
22.0-23.9	23						1.18 (1)	1.18 (1)
24.0-25.9	25						1.25 (1)	1.25 (1)
26.0-27.9	27						1.21±0.02 (2)	1.21 (1)
28.0-29.9	29							
30.0-31.9	31							
32.0-33.9	33						1.24 (1)	1.24 (1)
34.0-35.9	35						1.29 (1)	1.29 (1)

Table 1 footnotes

[a] From four geographic regions ranging from tropical to arctic (see Fig. 1 in Hsu, 1981).

[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). For this experiment, see Fein and Kuettner (1980) and Hsu (1981).

[g] Merchant ship observations vs. Gardo, Somalia (under conditions of Somali low-level jetstream).

[h] Based on Powell (1982).

[i] Mean ± standard deviation averaged from five columns between (3) and (8)

[j] Total areas studied. Note four areas already included in Fig. 1 in Hsu (1981).

when U_{LAND} is below 10 m s^{-1} the ratio of U_{SEA}/U_{LAND} follows the general trend of Eq. 8, whereas this ratio is a constant for $U_{LAND} \gtrsim 10$ m s^{-1}.

On the basis of Eq. 8, the dashed curve in Fig. 1 indicates that

$$U_{SEA} = 3.93\ U_{LAND}^{1/2}\ . \tag{14}$$

Note that the value of A (= 3.93 $m^{1/2} \cdot s^{-1/2}$ in Eq. 14) is in good agreement with the typical deduction, as shown in Eq. 10. The large standard deviation under low wind speed conditions is due to large variations in H_{LAND} and H_{SEA} because of large temperature differences across the coastal zone [see Hsu (6)]. In addition, averaging time, sampling rate, and heights were not uniformly reported in all pairs.

Under high wind speed conditions, say $U_{LAND} \gtrsim 10$ m s^{-1}, we have

$$U_{SEA} = 1.24\ U_{LAND} \tag{15}$$

as shown in Fig. 1. This equation is in excellent agreement with Eq. 13.

5. Concluding Remarks

On the basis of many pairs of simultaneous measurements of onshore and offshore winds in regions ranging from the tropics to the Arctic and under forces ranging from breeze to hurricane, it is found that, for operational use:

For wind speed over land, i.e., $U_{LAND} < 10$ m s^{-1},

$$U_{SEA} = 3.93\ U_{LAND}^{1/2}$$

and for $U_{LAND} \gtrsim 10$ m s^{-1}

$$U_{SEA} = 1.24\ U_{LAND}.$$

The above formulas are useful over low-relief (< 0.5-1 km in height) and open coasts. They may not be applicable for mountainous or cliffy coast areas. Also, atmospheric mesoscale systems such as low-level jets under special conditions [see Hsu (7)], land- and sea-breeze systems (5), and coastal fronts during the winter season were not taken into account. Although there is still large scatter in the data points as shown in Fig. 1 and many smaller scale meteorological systems were not included because of the different physics involved, it is felt that for engineering applications these simplified formulas should be useful as a first approximation to this complex problem of onshore-offshore wind differences.

Acknowledgments. This study was sponsored in part by the Coastal Sciences Program, Office of Naval Research, Arlington, Virginia. Additional support was provided by the Louisiana Sea Grant College Program, a part of the National Sea Grant College Program maintained by NOAA, U.S. Department of Commerce.

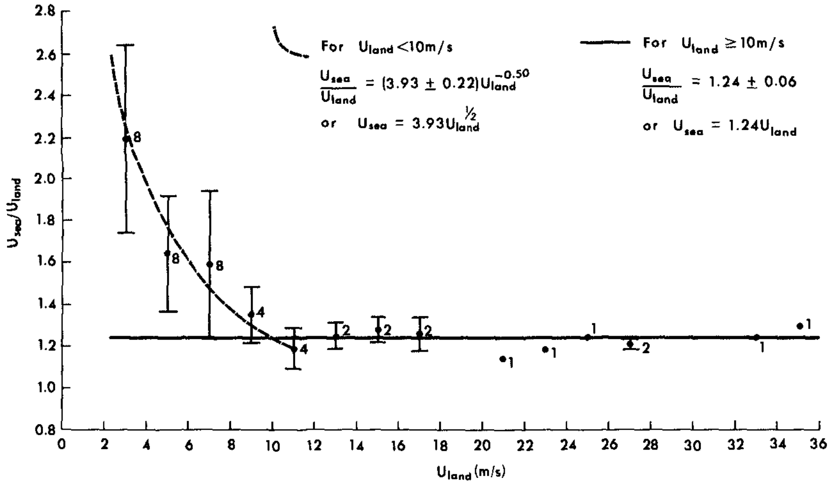

Fig. 1. Ratio of U_{SEA}/U_{LAND} as a function of U_{LAND}. Data were based on Table 1. Vertical bars are the standard deviation, and numbers bside the mean point are the areas incorporated in the computations. Values on the right-hand side of the equations are mean and standard deviations, respectively.

APPENDIX 1.--REFERENCES

1. Blackadar, A. K., "The Vertical Distribution of Wind and Turbulent Exchange in a Neutral Atmosphere," Journal of Geophysical Research, Vol. 67, 1962, pp. 3095-3101.

2. Davenport, A. G., "The Relationship of Wind Structure to Wind Loading," Wind Effects on Buildings and Structures, National Physical Laboratory Symposium No. 16, Her Majesty's Stationery Office, London, 1965, pp. 54-102.

3. Fein, J. S., and Kuettner, J. P., "Report on the Summer MONEX Field Phase," Bulletin of the American Meteorological Society, Vol. 61, 1980, pp. 461-474.

4. Garratt, J. R., "Review of Drag Coefficients over Oceans and Continents," Monthly Weather Review, Vol. 105, 1977, pp. 915-929.

5. Hsu, S. A., "Coastal Air-Circulation System: Observations and Empirical Model," Monthly Weather Review, Vol. 98, 1970, pp. 487-509.

6. Hsu, S. A., "An Operational Forecasting Model for the Variation of Mean Maximum Mixing Height across the Coastal Zone," Boundary-Layer Meteorology, Vol. 16, 1979a, pp. 93-98.

7. Hsu, S. A., "Mesoscale Nocturnal Jetlike Winds within the Planetary Boundary Layer over a Flat, Open Coast," Boundary-Layer Meteorology, Vol. 17, 1979b, pp. 485-495.

8. Hsu, S. A., "On the Correction of Land-Based Wind Measurements for Oceanographic Applications," Proceedings of the 17th Coastal Engineering Conference, American Society of Civil Engineers, Vol. 1, 1980, pp. 708-724.

9. Hsu, S. A., "Models for Estimating Offshore Winds from Onshore Meteorological Measurements," Boundary-Layer Meteorology, Vol. 20, 1981, pp. 341-351.

10. Large, W. G., and Pond, S., "Open Ocean Momentum Flux Measurements in Moderate to Strong Winds," Journal of Physical Oceanography, Vol. 11, 1981, pp. 324-336.

11. Plate, E. J., "Aerodynamic Characteristics of Atmospheric Boundary Layer," Available as TID-25465, National Technical Information Center, Springfield, Virginia, 1971.

12. Powell, M. D., "The Transition of the Hurricane Frederic Boundary-Layer Wind Field from the Open Gulf of Mexico to Landfall," Monthly Weather Review, Vol. 110, 1982, pp. 1912-1932.

13. Sedefian, L., "On the Vertical Extrapolation of Mean Wind Power Density," Journal of Applied Meteorology, Vol. 19, 1980, pp. 488-493.

14. SethuRaman, S., and Raynor, G. S., "Comparison of Mean Wind Speeds and Turbulence at a Coastal Site and Offshore Location," Journal of Applied Meteorology, Vol. 19, 1980, pp. 15-21.

15. Yu, T. W., "Diurnal Variation of Kinetic and Internal Energy in Onshore Winds along the Upper Texas Gulf Coast," Report No. 19, Atmospheric Science Group, University of Texas, Austin, 1970.

16. Zimmerman, J. R., and Burton, W. D., "Late Summer Gale Winds Offshore Coastal Oregon-Washington," National Weather Digest, Vol. 4, 1979, pp. 27-40.