

ESTIMATION OF OVERLAKE WIND SPEED FROM OVERLAND WIND SPEED: A COMPARISON OF THREE METHODS¹

David J. Schwab and Julie A. Morton

National Oceanic and Atmospheric Administration
Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan 48104

ABSTRACT. Meteorological data gathered by buoys in Lake Erie and recorded at overland weather stations were used to test three different methods for determining overlake wind speed as a function of overland wind speed and the difference between overland air temperature and water temperature. The overall root mean square differences between estimated and observed overlake wind speed ranged from 2.02 to 2.11 m s⁻¹. Overall correlation coefficients ranged from 0.63 to 0.69. These values are close to the best values possible for a simple statistical formula relating overlake wind speed to overland wind speed and air-water temperature difference. The conclusion is that statistical methods for determining overlake wind speed from overland wind speed have not improved markedly in over a decade and new methods are called for. It is also shown that for the Great Lakes, as opposed to the open sea, air-water temperature difference is a significant factor in determining overlake from overland wind speed.

ADDITIONAL INDEX WORDS: Meteorological data collection, Lake Erie, statistical methods, air-water interfaces, temperature effects.

INTRODUCTION

Overlake wind is required by mariners for navigation purposes, by meteorologists for weather forecasts, by hydrologists for evaporation calculations, and by oceanographers for estimation of waves, currents, and water level fluctuations on the lakes. Routine measurements of overlake winds have recently become available from buoys operated by the U.S. National Data Buoy Office (Mariners Weather Log 1981), but the buoy network does not cover all of the lakes and does not operate during winter. Regular, year-round meteorological observations are only taken at the weather stations operated by the United States National Weather and the Canadian Meteorological Services. In many cases, these are the only observations available to serve as a basis for estimating overlake winds.

Several previous studies have attempted to relate wind speed observed at weather stations near the lake shore to overlake wind speed measured by ships or buoys. These studies used wind speed and air-water temperature difference at upwind

weather stations with the notion that the modification of the atmospheric boundary layer with overwater fetch was basically a two-dimensional, steady-state process that only depended on upwind meteorological conditions and overwater fetch distance. Therefore overlake wind speed could be determined as a function of these variables. The purpose of this paper is to compare three of these methods by using a single set of simultaneous overlake-overland meteorological data.

It should be noted at the outset that the methods being tested were developed from very selective data. Overland and overlake observations were carefully matched and any unusual or exceptional cases were discarded. However, for the purposes stated above, overlake wind speed is required under many varying meteorological conditions. We intend here to test the applicability of these methods for routine estimation of overlake wind speed under all meteorological conditions.

DATA

From May to November of 1979 the Canada Centre for Inland Waters (CCIW) operated six mete-

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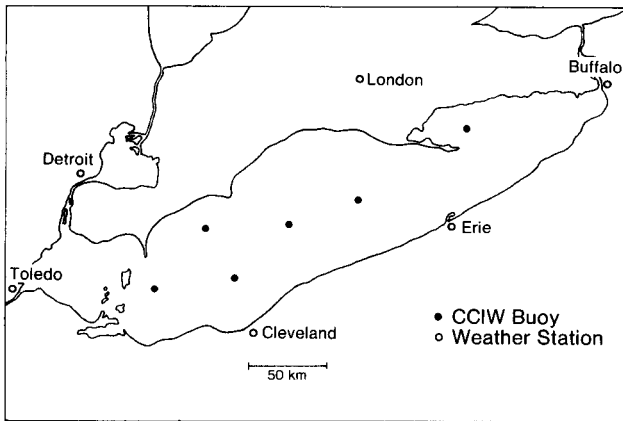


FIG. 1. Location of meteorological buoys and weather stations.

ological buoys (in addition to other instrumentation) in Lake Erie. The locations of these buoys are shown in Figure 1. They recorded wind speed, wind direction, and air temperature 4 m above the water surface in addition to surface water temperature. Measurements were made at 10-min intervals and averaged to obtain hourly values.

Six weather stations are close enough to Lake Erie to be useful for comparing overland to overlake wind speed observations. (See Fig. 1.) Wind speed, wind direction, and air temperature observations at 3-hr intervals (0, 3, 6, 9, 12, 15, 18, 21 GMT) were obtained from the Local Climatological Data-Monthly Summary for the U.S. stations and from the Monthly Meteorological Summary for London, Ontario. Since the anemometer at London is 10 m above ground level and the anemometers at all U.S. stations are 6.1 m above ground level, we used the power law for the wind speed profile with an exponent of $1/7$ (Richards *et al.* 1966, Davenport 1960) and reduced the wind speed at London by a factor of $(6.1/10)^{1/7} = 0.93$ to be compatible with the other wind speeds.

A separate problem involved in using winds from land stations is the inaccuracy of the measurements and the effect of exposure on wind speed. As pointed out by Fujita and Wakimoto (1982), mesoscale obstruction can reduce measured surface wind speeds as much as 50% from unobstructed values. However, without any *a priori* knowledge of the exact exposure correction for each weather station or the prevailing instantaneous mesoscale meteorological conditions, we have not attempted to make these corrections to reported overland wind speeds.

METHODS

The first method tested was that developed by Richards *et al.* (1966). They related wind speed observations from ships in Lakes Erie and Ontario to wind speed at upwind weather stations. Using the following equations, we approximated the lines in Figure 2 of their paper relating overlake wind speed at 10 m above the water surface to overland wind speed and air-water temperature difference for various wind speed classes:

$$\begin{aligned} U_w &= U_L(1.02 - 0.018 \Delta T) & U_L \geq 7.5 \text{ m s}^{-1}, \\ U_w &= U_L(1.26 - 0.023 \Delta T) & 5 \text{ m s}^{-1} \leq U_L < 7.5 \text{ m s}^{-1}, \\ U_w &= U_L(1.48 - 0.029 \Delta T) & 2.5 \text{ m s}^{-1} \leq U_L < 5 \text{ m s}^{-1}, \\ U_w &= U_L(2.14 - 0.047 \Delta T) & U_L < 2.5 \text{ m s}^{-1}, \end{aligned}$$

Here U_w is overwater wind speed, U_L is upwind overland wind speed, and ΔT is the difference between overland air temperature and water temperature in $^{\circ}\text{C}$. We again used the power law for wind speed profile with an exponent of $1/7$ and multiplied the results for U_w by $(4/10)^{1/7} = 0.88$ before comparing them to wind speed measured at the CCIW buoys to account for the difference in the height of the overwater measurements.

The second method tested is from Resio and Vincent (1977). They used the theoretical results derived by Cardone (1969) to develop curves relating the overland-overlake wind speed ratio to air-water temperature difference and overland wind speed. Their curves can be approximated by the following formula (Schwab 1978):

$$U_w = U_L \left(1.2 + \frac{1.85}{U_L} \right) \left\{ 1 - \frac{\Delta T}{|\Delta T|} \left(\frac{|\Delta T|}{1920} \right)^{1/3} \right\}.$$

Here U_L is in m s^{-1} and ΔT in $^{\circ}\text{C}$. Since their method was developed for overwater wind speed at 20 m, we used the power law for wind speed profile with an exponent of $1/7$ and multiplied results from this formula by $(4/20)^{1/7} = 0.79$ before comparing to wind speed measured at the buoys.

The third method was developed by Phillips and Irbe (1978) from Lake Ontario data taken in 1972 during the International Field Year for the Great Lakes. Overwater measurements were obtained with the same type of CCIW buoy used in Lake Erie in 1979. Phillips and Irbe tested wind speed, air temperature, humidity, atmospheric pressure, surface water temperature, overwater fetch, residence time, air-water temperature difference, and air mass modification as possible dependent varia-

bles in a stepwise multiple linear regression to determine which variables explained the highest amount of variance between paired overland and overlake measurements of wind speed, air temperature, and dew point temperature. Their results for wind speed were

$$U_w = 3.28 + 0.32 U_L + 0.00001 D - 0.02 T_A, \\ \Delta T \geq 10.5^\circ\text{C};$$

$$U_w = 2.65 + 0.49 U_L + 0.00001 D - 0.02 T_A, \\ 3.5^\circ\text{C} \leq \Delta T < 10.5^\circ\text{C};$$

$$U_w = -3.55 + 0.92 U_L - 0.28 \Delta T + 1.29 \log D, \\ -3.5^\circ\text{C} < \Delta T < 3.5^\circ\text{C};$$

$$U_w = -2.50 + 1.01 U_L + 1.33 \log D, \\ -10.5^\circ\text{C} < \Delta T \leq -3.5^\circ\text{C};$$

$$U_w = -2.79 + 1.05 U_L + 1.46 \log D, \\ \Delta T \leq -10.5^\circ\text{C};$$

where T_A is overland air temperature in $^\circ\text{C}$ and D is the duration of air over water (fetch divided by wind speed) in seconds. Since their formulas were developed for wind speed at 4 m above the water surface, no adjustment for height was necessary.

In order to test the three methods on an independent data set, we developed a procedure to generate pairs of overland and overlake measurements. For each CCIW buoy measurement of overlake wind speed from 0, 3, 6, 9, 12, 15, 18, or 21 GMT, we calculated a corresponding upwind overland wind speed and air temperature as follows:

1. An "overland" wind direction at the buoy location was calculated by interpolating the overland weather station wind vectors to the buoy location. The interpolation scheme weighted the overland vectors by the inverse square of the distance between the buoy and the weather station.
2. The upwind point on the lake shore corresponding to this wind direction was determined.
3. Overland wind speed and air temperature at this point were interpolated from the weather station observations with inverse square distance weighting.
4. Air-water temperature difference was calculated as the difference between interpolated air temperature at the upwind point and water temperature at the buoy.

Overland wind speed and air-sea temperature difference were then paired with the buoy observations. Interpolated wind speeds less than 0.5 m s^{-1} were discarded. In all, 5,754 pairs of observations were obtained. Admittedly, this interpolation

scheme can produce misleading results for some synoptic and mesoscale conditions (strong fronts, lake breeze, etc.) and other more complicated methods of generating the overland-overlake pairs could have been used, but we felt this procedure would be applicable to a wide variety of problems and could be easily implemented on a computer.

Before testing the three methods for estimating overlake wind speed from overland wind speed, we separated the paired overland-overlake observations into 2.5 m s^{-1} overland wind speed and 5°C air-water temperature difference classes and calculated the values

$$C_{ij} = \frac{\sum U_w U_L}{\sum U_L^2}$$

for wind speed class i and air-water temperature difference class j . These values constitute a fourth method for estimating overlake wind speed from overland wind speed that is based entirely on dependent data. Specifically, we calculate overlake wind speed as

$$U_w = C_{ij} U_L$$

with the appropriate C_{ij} for U_L and ΔT . By minimizing the sum of the squares of the differences between estimated and observed values, it can be shown that the above expression for C_{ij} yields the minimum root mean square error between estimated and observed overwater wind speed for each air-water temperature difference and overland wind speed class.

RESULTS

In Figure 2 the values of C_{ij} are plotted as a function of wind speed and stability. Within each air-water temperature difference class, the values decrease significantly as a function of wind speed. For a given wind speed, the values decrease significantly as air-water temperature difference increases. These results are consistent with previous studies.

The overall correlation coefficient between the paired overland and overlake wind speed values, before any estimation formula was applied, was 0.50. The root mean square difference for the 5,754 pairs was 2.57 m s^{-1} . The correlation coefficients and root mean square differences between overland wind speed and overlake wind speed as estimated by the three methods and by the C_{ij} values are listed in Table 1. The results from

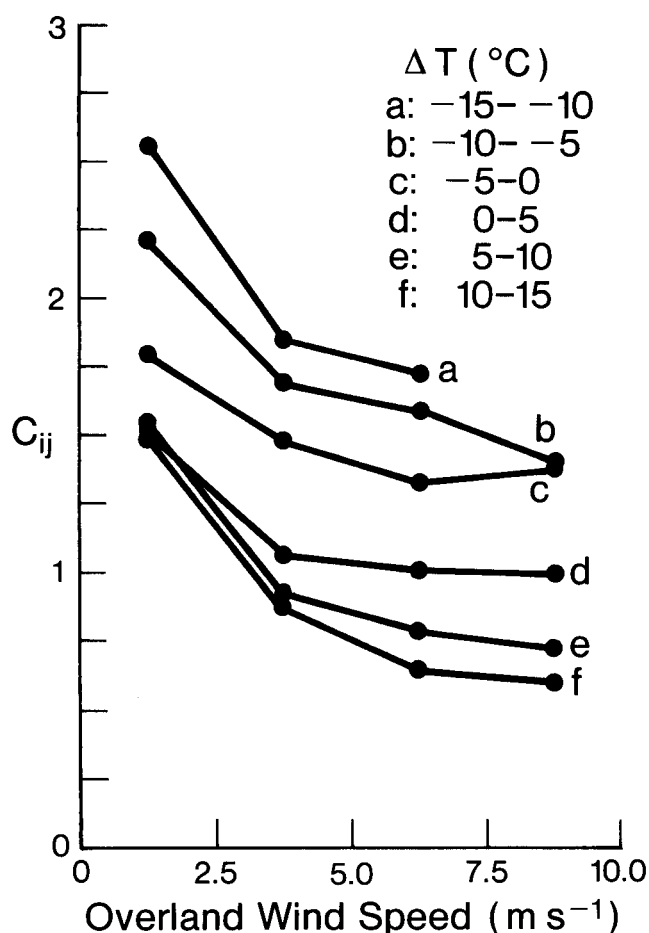


FIG. 2. Values of C_{ij} (see text) as a function of wind speed and stability.

Richards' method are not quite as good as those from the two more recent methods, but the correlation coefficients and root mean square error for all three methods are very close to the best possible values that can be obtained for a C_{ij} -type formula

TABLE 1. Correlation coefficients and root mean square differences between observed overlake wind speed and (1) overland wind speed and (2) estimated overlake wind speed.

	Correlation Coefficient	Root Mean Square Difference ($m s^{-1}$)
Overland wind	.50	2.57
Overlake wind estimated by:		
Richards <i>et al.</i> (1966)	.63	2.11
Resio and Vincent (1977)	.67	2.02
Phillips and Irbe (1978)	.69	2.03
C_{ij}	.70	1.94

based solely on wind speed and air-water temperature difference—0.70 for the correlation coefficient and $1.94 m s^{-1}$ for the root mean square error.

If the ratio of overlake to overland wind speed is assumed to be a constant, independent of wind speed and air-water temperature difference, the value of the constant that produces the minimum root mean square error between estimated and observed overlake wind speed is 1.18 and the minimum root mean square error is $2.45 m s^{-1}$. Even a power law relation between overlake and overland wind speed such as that recently proposed by Hsu (1981) for the open ocean does not significantly reduce the overall root mean square error or increase the correlation coefficient. It appears, then, that air-water temperature difference is a significant factor in determining overlake from overland wind speed in the Great Lakes. This dependence is supported by the C_{ij} values plotted in Figure 2, which vary as significantly with air-water temperature difference as they do with wind speed.

CONCLUSIONS

Three different statistical methods of estimating overlake wind speed from overland wind speed were tested on an extensive data set from Lake Erie. The results for the three methods were very similar and also very close to the best possible results that could be obtained from a simple statistical formula relating overlake wind speed to overland wind speed and air-water temperature difference. The estimated overlake wind speeds were able to account for almost twice as much of the variance between overland and overlake wind speed as the raw overland wind speeds (40 to 48% versus 25%). The root mean square difference between estimated overlake wind speeds and observed speeds ranged from 2.02 to $2.11 m s^{-1}$ compared to a $2.57 m s^{-1}$ root mean square difference between raw overland speed and observed overlake speed. For the Great Lakes, air-water temperature difference appears to be a significant factor in determining overlake from overland wind speed. We conclude that refinement of statistical formulas for estimating overlake wind speed from overland wind speed over the last decade has not significantly improved their accuracy. For a significant improvement to be made, a different approach may be called for, perhaps involving the time history of the wind field, the vertical structure of the atmospheric boundary layer, or the three-dimensional variation of the wind field. Some

improvement might also result from making corrections to measured overland wind speeds for exposure and mesoscale effects if these can be simply determined.

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REFERENCES

- Cardone, V. J. 1969. *Specification of the wind distribution in the marine boundary layer for wave forecasting*. Tech. Rept. 69-1, Geophys. Sci. Lab., New York Univ., New York, N.Y. [Available from the National Technical Information Service, Springfield, Va. 22151, NTIS AD# 702-490.]
- Davenport, A. G. 1960. Rationale for determining design wind velocities. *Amer. Soc. Civil Eng. Struct. Div. J.* 86:39-68.
- Fujita, T. T., and Wakimoto, R. M. 1982. Effects of miso- and mesoscale obstructions on PAM winds obtained during Project NIMROD. *J. Appl. Meteor.* 21:840-858.
- Hsu, H. A. 1981. Models for estimating offshore winds from onshore meteorological conditions. *Boundary-Layer Meteor.* 20:341-351.
- Mariners Weather Log. 1981. Great Lakes buoy network. *Mariners Wea. Log* 25:260-261.
- Phillips, D. W., and Irbe, J. G. 1978. *Lake to land comparison of wind, temperature, and humidity on Lake Ontario during the International Field Year for the Great Lakes (IFYGL)*. Atmos. Env. Service Rept. CLI-2-77, 4905 Dufferin ST., Downsview, Ont. M3H 5T4.
- Resio, D. T., and Vincent, C. L. 1977. Estimation of winds over the Great Lakes. *Amer. Soc. Civil Eng. Waterway, Port, and Coast. Ocean. Div. J.* 102:265-283.
- Richards, T. L., Dragert, H., and McIntyre, D. R. 1966. Influence of atmospheric stability and over-water fetch on winds over the Great Lakes. *Mon. Wea. Rev.* 94:448-453.
- Schwab, D. J., 1978: Simulation and forecasting of Lake Erie storm surges. *Mon. Wea. Rev.* 106:1476-1487.