INFLUENCE OF ATMOSPHERIC STABILITY AND OVER-WATER FETCH ON WINDS OVER THE LOWER GREAT LAKES

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ABSTRACT

Five years of wind observations taken by the research vessel C.C.G.S. *Porte Dauphine* on Lake Erie and Lake Ontario have been compared to simultaneous observations taken at land stations upwind of the ship. The resultant ratios of over-lake winds/over-land winds have been sorted by speed classes, conditions of atmospheric stability, and the length of the over-water fetch to assess the relative influence of each factor on the over-lake wind.

The effect of changes in atmospheric stability as created by air-water temperature differences is shown quantitatively with results confirming that wind speeds increase over water during unstable conditions and decrease during stable conditions. It is also shown that these changes are greatest in low winds and least in high winds.

An increase in the length of the over-water fetch up to about 25 mi. contributes to an increase in wind speeds during unstable conditions. Under very stable conditions the lake winds become lighter with longer fetches but the changes are highly erratic. This is likely due to intermittent breakdowns of the shallow atmospheric inversion layer associated with the stable conditions. An increase in fetch beyond 25 mi. does not appear to contribute to any further change in speeds.

1. INTRODUCTION

One of the major problems confronting the Great Lakes physical scientist is that of precisely describing the wind field over a particular lake. For any given moment the wind pattern over the land areas around each lake is adequately known through reports from fixed land-based anemometers. However over-water observations are taken from irregularly spaced and always moving ships, the data are sparse, and the reports are still plagued by communication delays. As a result, all too frequently the wind field over the lake is, at best, only partially defined.

There are many reasons why an adequate knowledge of the true over-lake wind is required and these cover a broad spectrum of scientific and commercial activities:

(i) The meteorological forecaster must begin with the correct data and valid theories to formulate his marine and lakeshore forecasts.

(ii) The mariner (commercial or small craft operator) must have the best possible indication of present and future winds and wind-driven waves.

(iii) Water level fluctuations caused by wind-induced set-up and seiche can seriously affect navigation and the water supply for power developments and domestic intakes.

(iv) Winds and the resultant waves and currents can cause damaging shore erosion and are also factors in the formation, movement, and dissipation of ice.

(v) Finally, but not necessarily least in importance, evaporation (by far the greatest water loss from the Great Lakes system) is a function of the speed of the over-water wind.

For these, and other less evident reasons, the Great Lakes meterologist must continue to seek ways and means of better defining the over-lake wind field.

PREVIOUS STUDIES

A number of earlier studies have approached the problem of defining the over-lake wind by evaluating an empirical relationship between the winds over the water as compared to simultaneously observed winds over the land; i.e., to evaluate a wind ratio

$$R=\frac{U_w}{U_l}$$

where U_w=wind speed over water, and U_l=wind speed over land.

Without further interpretation the ratio R has the effect of lumping all the various influences which cause the winds over water to vary from winds over land; i.e.:

(i) difference in frictional effect between land and water;

(ii) difference in atmospheric stability created by air-water temperature differences; and

(iii) the length of the over-water fetch.

Hunt [2] was one of the first to employ the wind ratio technique in a well-documented study of southwesterly winds on Lake Erie and their effect on set-up and seiche activity in that very shallow body of water. Employing

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data from commercial shipping for the navigation seasons of 1950–56 he found an average value for R of 1.59 (table 1). In addition he also found values of R for three broad classifications of atmospheric stability (stable, neutral, and unstable) based on average monthly air and lake temperatures.

Lemire [3] in extending a study by Bruce and Rodgers [1] used early data from the research vessel C.C.G.S. *Porte Dauphine* to obtain a value for R of 1.63, again based only on the navigation season. He also evaluated R for each of the months of March to November and noted seasonal values of R=1.38 for spring and 1.87 for fall (table 1).

In an effort to produce improved evaporation estimates for each month of the year, Richards [4] used more recent *Porte Dauphine* data to extend Lemire's figures by calculating values of R for the late fall and winter months (table 1). An average of the 12 monthly values produced a mean annual R of 1.66.

Although these studies indicated qualitatively the importance of atmospheric stability in the lake/land wind relationship, only Hunt established a quantitative relationship and this was for only very broad classifications of stability based on average monthly temperatures. None indicated qualitatively or quantitatively the influence of the length of the over-water fetch.

TABLE 1.—*Estimates of Wind Ratio R for the Great Lakes*

Author:					
Hunt [2]		Lemire [3]		Richards Extension [4]	Richards, Dragert and McIntyre (1966)
			Jan.	1.96	
			Feb.	1.94	
			Mar. 1.88	1.88	
			Apr. 1.81	1.81	
Spring	1.35	1.38	May 1.71	1.71	
			June 1.31	1.31	
			July 1.16	1.16	
			Aug. 1.39	1.39	
Fall	1.82	1.87	Sept. 1.78	1.78	
			Oct. 1.99	1.99	
			Nov.	2.09	
			Dec.	1.98	
Average	1.56*	*1.63		**1.66	**1.56

*Navigation Season.
**Annual.

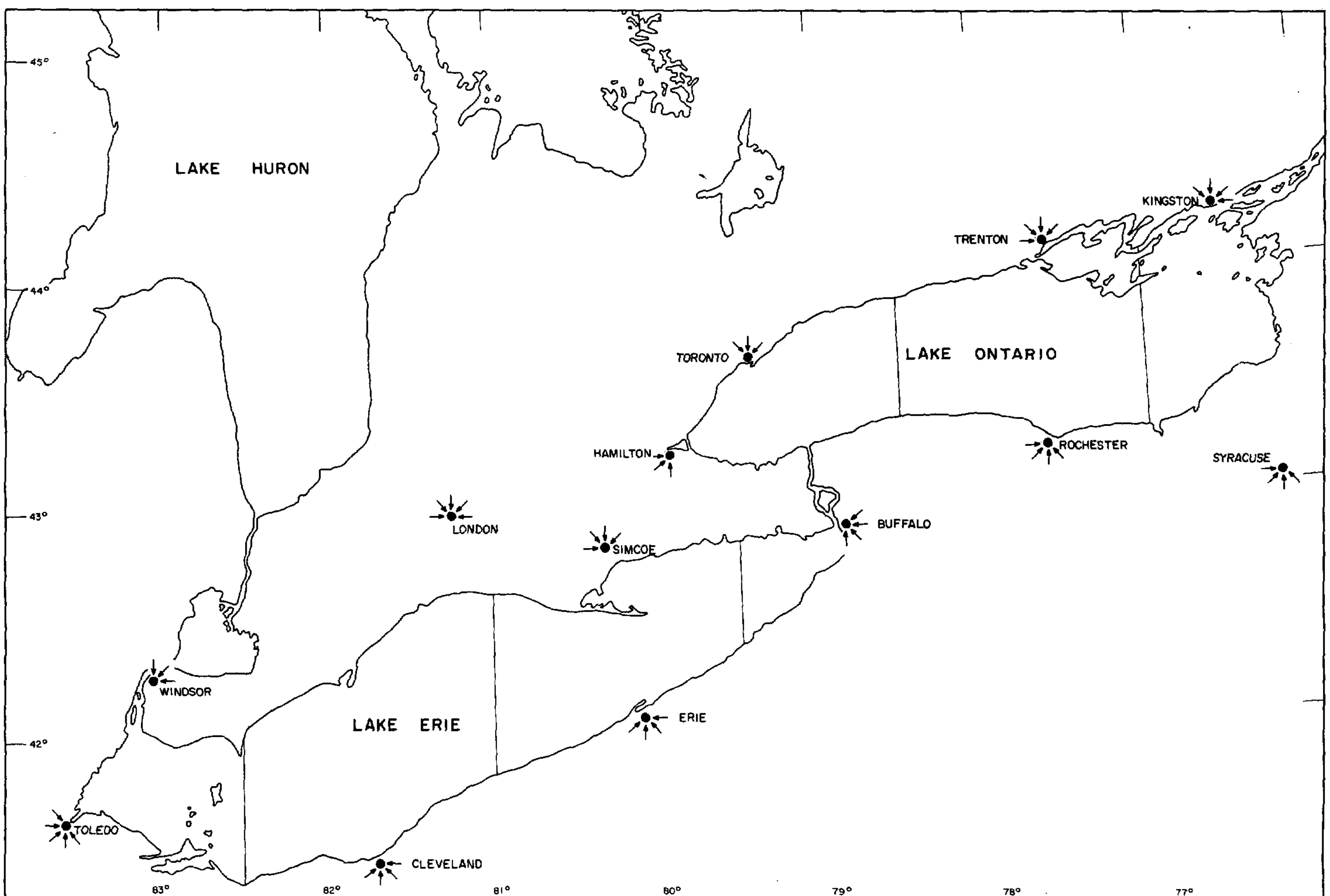

FIGURE 1.—Map of Lower Great Lakes showing lake sectors and location of land-based observing stations.

2. METHOD

It was the purpose of this study to compare a substantial period of reliable wind observations from the research vessel C.C.G.S. *Porte Dauphine* with simultaneously observed winds upwind of the ship; i.e., to evaluate the wind ratio R for predetermined ranges of atmospheric stability and over-water fetch in order to assess as accurately as possible the influence of these factors on winds as they move from land to lake. After consideration of the available data the study was limited to Lakes Erie and Ontario, mainly because of the lack of a suitably dense anemometer network around the other lakes.

The two lakes were divided into a total of seven sectors (fig. 1). Each sector was assigned two or three land observing stations and, as indicated on the map in figure 1, each station was assigned a sector of winds considered to be solely off-land. For each ship's observation the position of the ship was noted and its wind U_w was compared to a simultaneous observation U_l from the appropriate upwind anemometer. The resultant wind ratio $R=U_w/U_l$ was then tabulated. Also recorded were the air temperature at the land station (T_A) and the surface water temperature at the ship (T_W) as well as the distance from the ship to the upwind shore along the direction of the wind (fetch F). To assure that this distance was close to the true fetch and that there were no intervening discontinuities such as fronts or pressure troughs, only those observations in which the ship's wind and land winds agreed to within 30 deg. were used. The difference between the land air temperature and the ship's water temperature (T_A-T_W) was taken as an index of the stability of the lower level of the atmosphere over the lake.

To assess the effect of atmospheric stability the wind ratios R were tabulated according to five stability classes and five wind speed classes. To assess the effect of the over-watch fetch the above tabulation was further sorted over six classes of fetch distances.

3. DATA

SHIP

The study was based on five years (1960–64) of year-round over-water meteorological data from the C.C.G.S. *Porte Dauphine,*—a 400-ton weather ship and research vessel operated by the Marine Service of the Canadian Department of Transport. The Great Lakes Institute, University of Toronto is responsible for the ship's scientific program and the Meteorological Service of Canada (Meteorological Branch, Department of Transport) provides the regular and specialized meteorological instrumentation.

The ship's wind sensor is an M.S.C. U2A cup-wheel located on the main mast at a height of 10 m. or approximately 33 ft. above water level. Water temperatures are observed by the usual bucket technique. For most of the 5-yr. period observations were taken hourly while the ship was "at sea".

The ship's data have two areas of potential bias although neither is considered important to the study: (i) between mid-December and early April the observing program was restricted to Lake Ontario because of ice conditions in Lake Erie, and (ii) the ship occasionally had to take cover in especially violent storms thus introducing a small "fair weather" bias.

LAND

Thirteen observing stations were used for the over-land data. These were assigned to the lake sectors as shown in figure 1 and are listed below showing the height of each wind sensor.

Western Lake Erie
- Windsor—M.S.C. (Meteorological Service of Canada) 10 m., (33 ft.)
- Toledo—U.S.W.B. (United States Weather Bureau) 6.1 m., (20 ft.)

West-Central Lake Erie
- London—M.S.C. 12.5 m., (41 ft.)
- Cleveland—U.S.W.B. 6.1 m., (20 ft.)

East-Central Lake Erie
- Simcoe—M.S.C. 10 m., (33 ft.)
- Erie—U.S.W.B. 15.2 m., (50 ft.)

Eastern Lake Erie
- Buffalo—U.S.W.B. 6.1 m., (20 ft.)

Western Lake Ontario
- Buffalo
- Hamilton—M.S.C. 17.4 m., (57 ft.)
- Toronto—M.S.C. 16.8 m., (55 ft.)

Central Lake Ontario
- Trenton—M.S.C. 10 m., (33 ft.)
- Rochester—U.S.W.B. 6.1 m., (20 ft.)

Eastern Lake Ontario
- Kingston—M.S.C. 13.1 m., (43 ft.)
- Syracuse—U.S.W.B. 6.1 m., (20 ft.)

Because the heights of wind sensors varied from one location to another, a check was made using the power law equation:

$$\frac{U_1}{U_2}=\left(\frac{Z_1}{Z_2}\right)^{1/7}$$

where U_1=wind speed at anemometer 1, U_2=wind speed at anemometer 2, Z_1=height of anemometer 1, Z_2=height of anemometer 2. This check indicated that even the greatest height difference between the ship and land station anemometers would require a correction considered negligible compared to possible errors introduced by the variability in exposures.

Over the 5-yr. period 3240 hourly observations were inspected and 1940 of them were deemed usable.

4. INFLUENCE OF ATMOSPHERIC STABILITY

As indicated earlier, in order to assess the relative influence of the over-lake atmospheric stability (as represented by the index T_A-T_W) on over-water winds,

TABLE 2.—*Definition of stability classes*

Class	Range $(T_A - T_W)$, °F.	Median Value of Range, °F.
Very unstable	≦−23	−32
Unstable	−8 to −22	−15
Neutral	−7 to 7	0
Stable	8 to 22	15
Very stable	≧23	29

the wind ratios R were tabulated according to five stability classes and four wind classes (table 3). The stability classes were arbitrarily chosen as shown in table 2.

The four wind speed classes were also arbitrarily chosen as 1–5, 6–10, 11–15, and ≧16 kt. Speed classes of 16–20 and 21–30 kt. were originally employed but the sparseness of the data in the higher classes did not warrant the additional tabulations.

Inspection of section 3.1 of table 3 and the graphical presentation of the data in figure 2 leads to a number of observations:

(i) The average annual value of R for all the data was 1.56. This is comparable to evaluations made in earlier studies (table 1) and helps to confirm the representativeness of the data.

(ii) Wind ratios become larger as the over-lake instability (represented by the negative values of the index $(T_A - T_W)$) becomes greater. This confirms the theory that the resultant convective turbulence in the atmosphere associated with unstable conditions increases the surface wind speed to closer to the geostrophic wind speed. This increase was found in each speed class as well as for all the data regardless of speed.

TABLE 3.—*Effect of atmospheric stability on over-lake winds; wind ratio R for lower Great Lakes*

3.1. Tabulated According to Atmospheric Stability $(T_A - T_W)$ and Wind Speed Classes. 1960–1964

Stability $(T_A - T_W)$ (° F.)		Wind Speed Classes (kt.)				
Range	Median	1–5	6–10	11–15	≧16	All Speeds
−47 to −23	−32	3.00	1.70	1.73	1.35	2.24
−22 to −8	−15	2.65	1.80	1.41	1.29	1.88
− 7 to 7	0	2.09	1.48	1.27	0.96	1.44
8 to 22	15	1.71	1.14	1.02	0.83	1.06
23 to 42	29	1.40	1.13	0.94	0.80	0.92
All Ranges		2.65	1.55	1.26	1.02	1.56

3.2. Tabulated According to Atmospheric Stability $(T_A - T_W)$ and Wind Speed Classes and including Standard Deviations (s.d.) and Number of Occurrences (n). 1960–1964

Stability $(T_A - T_W)$ (°F.)		Wind Speed Classes (kt.)			
Range	Median	1–5 R/s.d./n	6–10 R/s.d./n	11–15 R/s.d./n	≧16 R/s.d./n
−47 to −23	−32	3.00/1.71/50	1.70/0.78/33	1.73/0.47/16	1.35/0.30/13.
−22 to −8	−15	2.65/1.38/151	1.80/0.68/254	1.41/0.47/125	1.29/0.39/62.
−7 to 7	0	2.09/1.39/142	1.48/0.64/390	1.27/0.47/250	0.96/0.35/132.
8 to 22	15	1.71/0.87/21	1.14/0.50/95	1.02/0.36/98	0.83/0.33/69.
23 to 42	29	1.40/—/1	1.13/0.45/6	0.94/0.41/14	0.80/0.25/18.

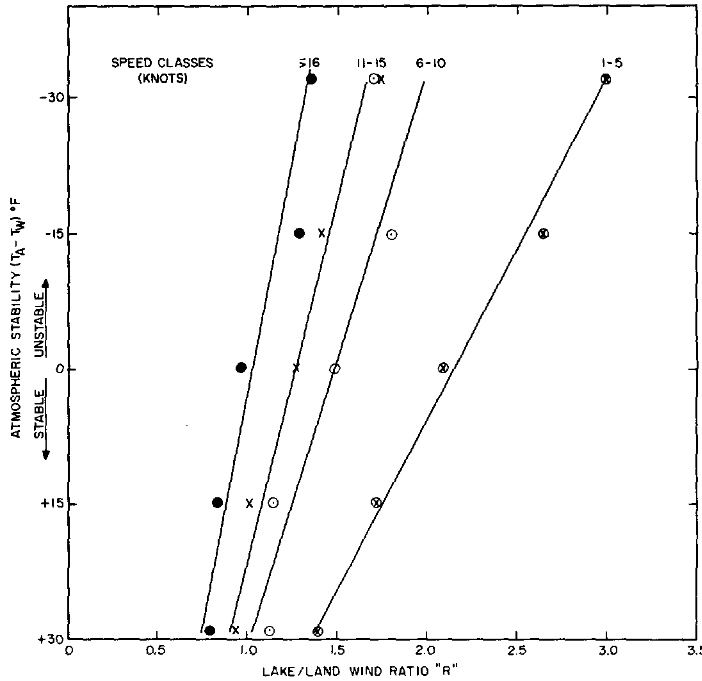

FIGURE 2.—The lake/land wind ratio R versus atmospheric stability $(T_A - T_W)$ (° F.) for four speed classes.

(iii) For any given stability range (described by $T_A - T_W$) the ratio becomes smaller as the wind speed increases.

(iv) For strong winds and neutral stability conditions $R=1$; i.e., there is no difference between over-water and overland winds.

(v) Strong winds are least affected by changes in atmospheric stability:

—Under very unstable over-lake conditions the average value of R was 1.35 in strong winds as compared to 3.00 in light winds; i.e., strong winds were increased by only 35 percent with passage over the lake in unstable conditions as compared to a 200 percent increase in light winds.

—Under very stable over-lake atmospheric conditions the average value of R in strong winds was 0.80; i.e., the strong winds decreased by about 20 percent after passage over the lake in stable conditions.

The fact that strong winds are increased by only 35 percent even in very unstable conditions is of major significance to the physical scientist working in the field of over-lake winds and wind effects. Although this concept has received very little attention in the literature it does have a good physical explanation. Strong winds blowing over land areas are subject to mechanical turbulence in the lower layer of the atmosphere which has much the same effect as convective turbulence in increasing the surface wind speed to closer to the geostrophic speed. The changes in the strong mechanically-turbulent winds as they pass over the relatively smoother water are a function of the atmospheric stability regime over the lake:

—If the over-lake passage is under stable conditions, as denoted by the index $T_A - T_W$, an inversion is created in the lower layer of the atmosphere. This counteracts the land-induced mechanical turbulence and reduces the wind speed; i.e., $R<1$.

—If the over-lake passage is under unstable atmospheric conditions the additional convective turbulence adds to the land-induced turbulence to increase the wind speed ($R>1$) but the percentage increase is not nearly as great as when the land winds are light and there is little or no land-induced mechanical turbulence.

—If the over-land passage is under neutral conditions there is little or no change in the wind speed, $R \doteq 1$.

Section 3.2 of table 3 repeats the previous tabulation of R found in the first section (3.1) but adds the standard deviations (s.d.) and the number of observations (n) for each set of data. As might be expected the standard deviations are highest in the low speed classes and the most unstable conditions and become lower with the increased wind speeds and more stable conditions.

5. INFLUENCE OF THE LENGTH OF OVER-WATER FETCH

In order to assess the relative effect of the length of the over-water fetch the data in table 3 were subdivided according to five ranges of fetch, 1–5, 6–15, 16–25, 26–35 and ≧36 n. mi. The results are shown in a rather complex table 4 which indicates:

(i) In general, in unstable atmospheric (as denoted by $T_A - T_W$) conditions an increase in fetch is accompanied by an increase in the wind ratio R up to and including the fetch class of 16–25 n. mi.;

(ii) In stable conditions an increase in fetch is not always accompanied by a corresponding decrease in R as might be expected from physical considerations.

To help overcome this and several other inconsistencies apparent in table 4 which might be due to sparseness of data, and to indicate more clearly the effect of the over-water fetch, the speed classes in table 4 were amalgamated to produce table 5. This condensed table groups values of R under the same five stability ranges and four fetch classes of 1–5, 5–15, 16–25, and ≧26 n. mi.

Table 5 and the corresponding graphs in figure 3 indicate more clearly that:

(i) With unstable atmospheric conditions there is an increase in the wind ratio with an increase in fetch up to the fetch class of 16–25 n. mi.; an increase of fetch beyond this class apparently does not increase the over-lake wind speed.

(ii) The increase in over-lake winds with fetch becomes less marked as atmospheric conditions become more stable but is still evident under neutral conditions.

(iii) Under very stable conditions the lake winds become lighter than the corresponding land winds ($R<1$), but as noted earlier the actual change of R with an increase in fetch is highly erratic. This may be due to too few data in the sample, but it is more likely associated with the physical fact that the temperature inversions created

TABLE 4.—*Effect of fetch on over-lake winds; wind ratio R for lower Great Lakes tabulated according to atmospheric stability ($T_A - T_W$) and speed classes for five ranges of fetch and including number of occurrences (n).*

Stability ($T_A - T_W$) (° F.)	Wind Speed Classes (kt.)					
Range	1–5	6–10	11–15	16–20	21–30	All Speeds
Fetch: 1–5 n. mi.						
−47 to −23	2.48/7	1.66/7	1.54/5	1.39/3		1.86/22.
−22 to −8	2.14/22	1.55/45	1.11/26	1.00/13		1.50/106.
−7 to 7	1.63/17	1.38/67	1.19/20	0.97/21	0.80/6	1.29/131.
8 to 22	1.35/3	0.63/5	1.03/10	0.94/4	0.96/4	0.96/26.
23 to 42		1.00/1	0.66/2	0.81/1		0.78/4
Fetch: 6–15 n. mi.						
−47 to −23	2.43/18	1.60/7	1.83/3	1.38/1	1.14/1	2.10/30.
−22 to −8	2.68/40	1.88/64	1.51/32	1.19/14	1.33/1	1.95/151.
−7 to 7	1.92/43	1.37/84	1.18/67	1.00/29	0.91/8	1.36/231.
8 to 22	2.50/2	1.01/22	1.00/18	0.79/14	0.96/1	1.00/57.
23 to 42	1.40/1	0.54/2	1.12/3	0.82/5	0.27/1	0.85/12.
Fetch: 16–25 n. mi.						
−47 to −23	3.37/12	1.78/8	1.96/4	1.25/3		2.46/27.
−22 to −8	2.58/39	1.82/44	1.40/23	1.31/4	1.28/2	1.97/112.
−7 to 7	2.09/33	1.49/78	1.31/38	1.09/13	0.84/5	1.52/167.
8 to 22	1.65/4	1.15/22	0.90/17	0.93/10	0.98/4	1.06/57.
23 to 42			0.71/6	0.58/1	0.57/1	0.68/8.
Fetch: 26–35 n. mi.						
−47 to −23	4.13/5	1.37/6	1.68/3	1.71/2		2.33/16.
−22 to −8	2.53/22	1.74/27	1.27/18	1.23/10	1.38/1	1.78/78.
−7 to 7	2.37/17	1.44/51	1.23/38	0.85/9	0.98/5	1.44/120.
8 to 22	1.90/3	1.12/10	1.02/18	0.48/7	0.76/2	1.00/40.
23 to 42				0.53/1		0.53/1.
Fetch: 36 n. mi.						
−47 to −23	3.50/8	2.14/5	1.60/1	1.22/2	1.19/1	2.58/17.
−22 to −8	3.19/28	1.90/74	1.71/26	1.62/15	1.44/2	2.08/145.
−7 to 7	2.44/32	1.64/110	1.37/87	1.00/25	0.86/11	1.55/265.
8 to 22	1.62/9	1.26/35	1.10/35	0.81/19	0.90/4	1.14/102.
23 to 42		1.57/3	1.42/3	0.98/7	0.73/1	1.18/14.

TABLE 5.—*Effect of fetch on over-lake winds; wind ratio R for lower Great Lakes tabulated according to atmospheric stability $T_A - T_W$ and over-water fetch for all wind speeds, 1960–1964*

Stability ($T_A - T_W$) (° F.)		Fetch (n. mi.)			
Range	Median	1–5	6–14	16–25	≧26
−47 to −23	−32	1.86	2.10	2.46	2.46
−22 to −8	−15	1.50	1.95	1.97	1.97
−7 to 7	0	1.29	1.36	1.52	1.52
8 to 22	15	0.96	1.00	1.06	1.10
23 to 42	29	0.78	0.80	0.68	1.14

by relatively warm air passing over cold water are frequently shallow and are known to break down from time to time. This phenomenon may be more pronounced with the ship's wind sensor located 10 m. above the water.

6. CONCLUSIONS

From analyses of five years of data employing almost 2000 sets of simultaneous observations from the Lower

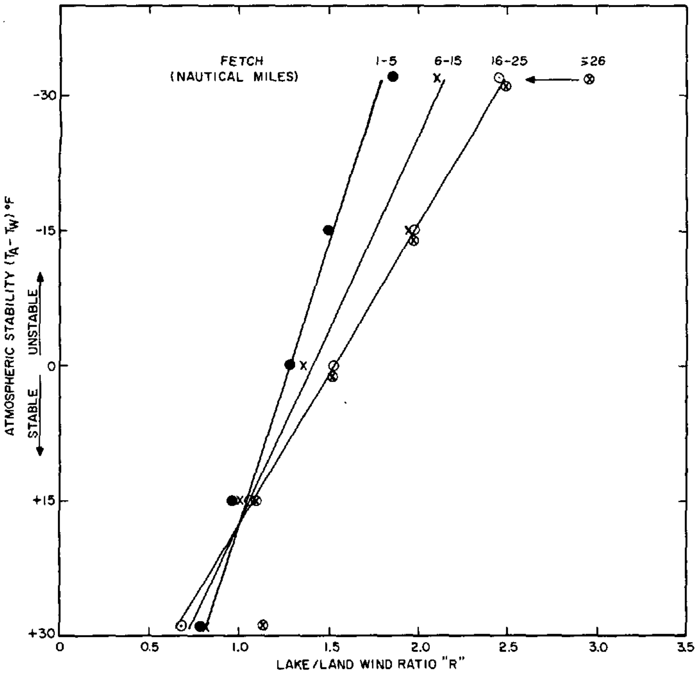

FIGURE 3.—The lake/land wind ratio R versus atmospheric stability ($T_A - T_W$) (° F.) for four fetch classes.

Great Lakes area it may be concluded that the value of the lake/land wind ratio $R = U_W/U_l$ is influenced by the atmospheric stability created by the air temperature–water temperature difference ($T_A - T_W$) and the length of the over-water fetch. In summary:

(i) R increases as the over-lake atmospheric instability increases.

(ii) Of major significance is that this increase is most pronounced in light winds (200 percent) and least pronounced in strong winds (35 percent).

(iii) Under unstable over-lake conditions R increases as the over-water fetch increases, but only up to a fetch of about 25 n. mi.

(iv) Under stable over-lake conditions the relationship between R and the length of fetch is highly erratic. This is likely due to the shallowness and variability of the resultant inversion.

These conditions are outlined qualitatively in sections 5 and 6 and are shown quantitatively in tables 3, 4, and 5 and in the graphs of figures 2 and 3. Although derived empirically the results have been shown to be theoretically sound and should be useful for improving estimates and forecasts of over-lake winds.

Although the study was confined to Lake Erie and Lake Ontario the results have been spelled out in terms of atmospheric stability and fetch and so should be valid for the other Great Lakes and for all bodies of water of comparable size.

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[*Received April 4, 1966; revised May 12, 1966*]