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Modification of Surface Air Over Lake Ontario in Winter

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ABSTRACT—This paper attempts to estimate over-water air temperatures and dew-point temperatures between about 1 and 15 m above Lake Ontario in winter. Multivariate statistical techniques are used to formulate regression models incorporating readily determined variables such as over-land temperatures, surface water temperatures, wind speed, and over-water fetch. Seventy-one to 92 percent of the variance can be accounted for by the resultant models with average standard errors of 1.1°C for air temperature and 1.4°C for dew-point temperature.

More than half of the modification in the lower atmosphere was found to occur in the first 10 min or over the first 1–2 mi of open water. Usually the change in air temperature from land to lake seldom exceeds 60 percent of the potential because it is limited by surface water temperature and barely reaches 40 percent with very cold air.

For selected winter weather situations, the spatial variations of temperature, humidity, and sensible and evaporative fluxes are examined. Bowen ratios of almost 2.0 were calculated for both warm air and cold air advection across Lake Ontario.

1. INTRODUCTION

The land portion of the Great Lakes Basin contains one of the densest climatological networks in North America. In the heart of the basin and occupying over one-third of its total area, however, is the world's largest single supply of fresh water, which is almost completely devoid of any climatological sampling. Except for some island stations and a few lighthouse operations during the navigation season, no information from fixed locations is available for over-lake temperature, humidity, wind, cloud, and energy fluxes. Ship data are obtained from moving platforms, so it is difficult to incorporate them into a climatological study.

Knowledge of the spatial variation of air temperatures and humidities above the Great Lakes would be useful for forecasting mesoscale weather phenomena such as lake-effect snowstorms, lake- and land-breeze circulations, and pollution-trapping inversions and for predicting the time of ice formation and dissipation at specific locations. Over-water meteorological data would also be of importance in computing energy budget terms.

The present paper aims at determining to what degree the Great Lakes modify air between 1 and 15 m above the lake surface in winter. The investigation is based on a study of the processes by which Lake Ontario exchanges heat and moisture with the lower atmosphere during winter and early spring.

Most studies of air mass modification have been carried out over oceans and seas where over-water trajectories exceed several hundred miles and surface water temperatures are assumed to vary little over large distances. Over the Great Lakes, surface trajectory techniques have been used to assess the lacustrine effect. Odell (1931) and Visher (1943) used stations at similar latitudes but on opposite shores to show the importance of the Great Lakes on shoreline climates and agriculture. Rodgers and Anderson (1961) used climatological data averaged between Toronto, Canada, and Rochester, N.Y., as being typical of over-lake data. From these data, they computed estimates of monthly energy flux for Lake Ontario. Lansing (1965) computed climatic averages from shoreline and island stations in Lake Ontario to describe, qualitatively, the role of the lakes in modifying air masses during nonwinter months. However, all authors recognized that there are errors involved in using only land stations to derive representative midlake estimates of temperature, humidity, wind, and other variables.

It is often incorrectly assumed, for example, that shoreline differences denote total lake modification. From November through April, when water temperatures are several degrees higher than air temperatures, there are periods under light pressure gradients when moderate land breezes occur. Also, during spring and early summer, shallow, intensive "conduction inversions" are created (Lyons 1970) and are confined over the lake surface with little or no spillover onto the land. Using shoreline differences can also lead to errors in heat and moisture flux computations because, as the air moves over the lake, the rate of exchange varies markedly and in a nonlinear way from the initial over-water exposure to that over the opposite shoreline.

The first attempts to use Great Lakes over-water data were made by Bruce and Rodgers (1962). They compared simultaneous meteorological readings observed aboard the Canadian Coast Guard Ship (CCGS) *Porte Dauphine* over Lake Ontario and at Toronto International Airport. The data were combined regardless of type of weather, location of fronts, time of day, season, wind direction, or ship location. A similar but more refined approach was used by Richards and Fortin (1962), Richards and Loewen (1965), and Richards et al. (1966). However, the regional variation of climatic elements is not determined in sufficient detail for some purposes.

2. METHODOLOGY

Selection of Data

Reliable meteorological observations from four research ships were compared with simultaneously observed variables over land, upwind of the ships. All observations taken at 3-hourly intervals during the months November through March from 1965 to 1969 were considered. The method of data selection was based on the following procedure:

1. For each observation, the ship's location and true wind direction were noted. An upwind sector was defined by the ship's wind direction $\pm 30°$.
2. If the wind at the upwind station was no more than 30° off the direction of the wind at the ship, the observation was deemed usable. This criterion assures that both stations were sampled from the same air mass with no fronts, troughs, or other complicating features between the paired locations.
3. The over-water fetch distance was calculated from the ship's location to the shoreline in proximity to the land station along an assumed trajectory.
4. Using fetch distance and wind speed at the ship, time over water (time = distance/wind speed) was computed. Observation times for land stations were taken as the difference between the hour of the ship observation and time over water; that is, a 0600 GMT ship observation with 1 hr of over-water duration was paired with a land reading taken at 0500 GMT. When the new hour was selected, it was tested for the direction criterion again.
5. For each paired observation, 16 observed elements and several derived variables were noted.

Data Sample

Seven first-order stations with complete or partial records were used for over-land data. Such data were stratified by stability class, which was defined by the difference between air temperature over land, T_{AL}, and surface water temperature at the ship, T_W. Table 1 shows the number of observations taken from each station for each stability case.

There is a slight imbalance of daylight hours, with 56 percent of all observations occurring at 1200, 1500, 1800, or 2100 GMT. The diurnal effect upon temperature and humidity modification is examined later. The majority of very unstable cases occurs in January when air–water temperature contrasts are at their maximum. Toronto International Airport and Trenton Airport account for 58 percent of the sample observations selected. This is a reflection of the frequency of occurrence of winds from the northern quadrant and the number of limnological studies along the north shore requiring research vessels. Stations along the south shore of Lake Ontario account for almost 50 percent of the observations during stable surface conditions.

Over the 5-yr period, 814 3-hourly observations were inspected and 515 of them met the selection criteria. Of the ones that failed the selection tests, 206 were eliminated because the wind direction at the land station was not suitable, and 94 were rejected because no stations were located within the upwind sector.

Table 2 is a tabulation of the "present weather" conditions for paired observations. Each observation was sorted into classes of hours with fog, rain, snow, or no precipitation. Two-thirds of the paired observations agree in weather type; that is, snow over the lake occurred with an observation of snow at the upwind land station. This was to be expected since paired observations across frontal discontinuities were eliminated. About 70 percent of the cases accepted were taken during hours of no precipitation occurrence over water.

Besides a "fair weather" bias in using ship observations, there existed another bias in neglecting occurrences of

TABLE 1.—*Time and location characteristics of the sample of over-lake observations used in this study*

	Number of over-water observations				
	Stable	Neutral	Unstable	Very unstable	Total
Hour (GMT)					
00	7	18	21	15	61
03	4	21	26	13	64
06	2	15	22	14	53
09	4	10	18	12	44
12	1	9	21	22	53
15	4	14	27	19	64
18	6	19	56	18	99
21	7	18	40	12	77
Total	35	124	231	125	515
Month					
January	4	30	76	59	169
February	1	11	20	2	34
March	6	24	12	0	42
April	0	1	0	0	1
October	0	0	1	0	1
November	23	49	85	35	192
December	1	9	37	29	76
Total	35	124	231	125	515
Land station upwind of over-water observation					
Hamilton R.B.G.	4	9	12	0	25
Toronto Int. (A)	2	39	100	44	185
Trenton (A)	2	16	42	52	112
Kingston (A)	0	3	0	14	17
Syracuse (A)	2	6	14	2	24
Rochester (A)	6	25	25	8	64
Buffalo (A)	19	26	38	5	88
Total	35	124	231	125	515

TABLE 2—*Weather characteristics of the simultaneous over-land and over-lake observations selected for study*

Present weather over land upwind of Lake Ontario	All stability classes Present weather over Lake Ontario observed aboard ship				
	No precipitation	Fog	Rain	Snow	Total
No precipitation	282	27	25	15	349
Fog	16	12	6	0	34
Rain	22	2	25	2	51
Snow	44	3	10	24	81
Total	364	44	66	41	515

light winds and calm. Such winds over even short distances can result in errors by attributing temperature differences totally to lake effect and ignoring radiation influences.

Statistical Methods

Principal component analysis, a multivariate statistical technique, was used to detect the underlying associations between over-water and over-land data. Principal components or eigenvectors are generated from variables that may be quite highly intercorrelated. The resulting components are orthogonal or independent and, therefore, eliminate the redundancy inherent among a group of interrelated variables. In addition to this advantage of overcoming multicollinearity, principal component analysis has the further advantage over standard multiple regression techniques of ordering the components such that the first component accounts for the highest proportion of the total variance. The number of components derived is equal to the number of variables, and the original variance is preserved.

In meteorology, principal component analysis has been widely used in the realm of statistical weather prediction (Lorenz 1956). The technique has also been used in climatology for estimating climatic variations (Stidd 1967) and for objectively delimiting climatic regimes (Kutzbach 1967). Wong (1963) chose eigenvector analysis to select those variables that best predicted mean annual floods in New England and at the same time were easily measured. In the present study, principal components were generated and the variable best correlated with each component was chosen. Once the important variables were identified, a stepwise multiple linear regression program was used to formulate the predictive model.

A rectangular grid consisting of 88 points, similar to that designed by Webb (1970) to derive mean surface water temperatures, was used. It was then possible to map the areal distribution of certain over-lake elements by using readily measured or derived data for each gridpoint with statistical models already established.

3. RESULTS AND INTERPRETATION

The total sample of 515 data points was entered into a program of principal component analysis. Six eigenvectors or components describing more than 85 percent of the total variance were obtained (table 3). Only six are listed because the remaining components each contributed less than 5 percent of the explained variance. The variable that best correlates with each component is also named in table 3.

Component I was the most significant, accounting for nearly 35 percent of the total variance. Six temperature parameters were related to the first component, but the one with the highest degree of association was over-land air temperature. This agrees with the high association found in the correlation matrix between air temperatures at the land station, T_{AL}, and above the lake surface, T_{AW}.

TABLE 3.—*Significant principal components and their percentage of total explained variance*

Component		% Total explained variance
I	Over-land air temperature	34.3
II	Time over water	17.7
III	Wind speed over water	13.7
IV	Cloud height over water	9.3
V	Surface water temperature	5.6
VI	Wind direction	5.0
	Total	85.7

The over-water dimension was clearly revealed in component II, which accounts for nearly 18 percent of the remaining variance. The two variables that are highly associated with this component were logarithmic values of time and fetch distance over water. (During the compiling of the sample points, it became obvious that logarithmic values of time over water and fetch distance were more highly correlated with surface air modification than were their linear values.)

The degree of temperature and dew-point modification sorted into stability classes and plotted against time over water and fetch distance, revealed some interesting results. The graphs of fetch and time over water closely resembled each other. Since time over water was slightly better correlated with air modification than over-water fetch was, the graphs and discussion will be restricted to the former (fig. 1). Some of the more noteworthy points are:

1. The increase in over-lake modification with time becomes less marked as atmospheric conditions become neutral. For neutral situations, the amount of temperature change appears unaffected by the time the air mass spends over water.
2. For stable cases, over-water temperature decreases from the original temperature at land stations, but the actual change of $T_{AW}-T_{AL}$ with an increase in time is small and somewhat erratic. This may be due to too few data in the sample, but it is also related to the physical fact that temperature inversions created by relatively warm air passing over cold water are shallow and tend to break down, thus minimizing heat exchange downward.
3. For the cases with large $T_{AW}-T_{AL}$, more than half of the total modification occurs in the first 10 min. For example, for very unstable cases, air temperature modification of more than 4°C occurred within the first 10 min, compared to an average total modification of about 8°C after 4 hr. The fact that rapid modification occurs is of major significance to the physical scientist working in the field of over-water energy exchange. Although this concept has received very little attention in the literature, it does have a good physical explanation.

Normal atmospheric soundings in arctic air over upwind land stations in winter reveal a pronounced inversion through a relatively shallow layer near the surface (Wexler 1936). This inversion is rapidly destroyed as the cold air begins to cross the open waters of the Great Lakes. We theorize that the very marked change in temperature over the lakes occurs to the top of the inversion level. Any further increase in temperature would require the heating of a very deep air column, which can occur only with relatively long over-water trajectories. Thus, the change in surface temperature is governed, to a large extent, by the structure of the air mass aloft.

Components III–VI, which each explain at least an additional 5 percent of the original variance, appeared as single-variable components. Of interest is their order of appearance in table 3. Over-water wind speed (which was used to compute time over water) was most highly correlated with the third component, over-water cloud height with the fourth, surface water temperature with the fifth, and wind direction with the sixth.

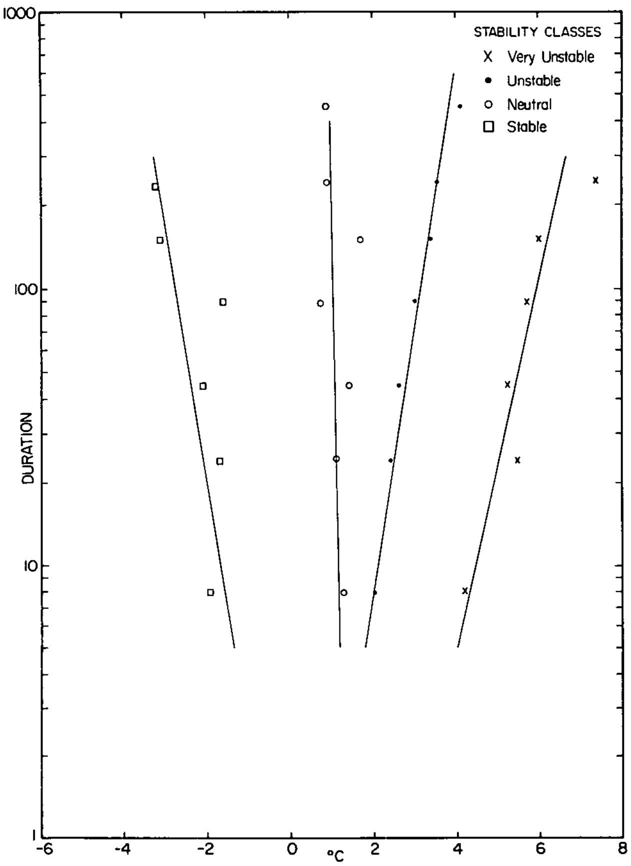

FIGURE 1.—Air temperature (°C) modification ($T_{AW}-T_{AL}$) versus duration (min) that the air spends over the water for various stability classes ($T_{AL}-T_W$).

Over-water cloud amount and height are recognized as important requisites in computing over-lake energy balance terms. Attempts to relate over-land and over-lake cloud regimes were abandoned when available observations produced low correlations and high standard errors. Many researchers are convinced that satellite radiometry, including photography, provides the only practical solution (Bruce et al. 1968).

The component ordering of water temperature was surprising since most studies relating lake or oceanic effects on air temperature and humidity have emphasized the importance of water temperature. Rodgers and Anderson (1961) found that over-water air temperature follows the temperature curve of surface water more closely than it follows the curve of air temperature from land stations. Their conclusion was based upon a synoptic ship survey across Lake Ontario during June. During the winter, however, water temperatures tend to be uniform over large areas and to great depths. Figure 2 illustrates the uniformity of water temperature over a 48-hr period for one location 5 mi south of Toronto. Wind direction during the period remained northerly with speeds averaging 10–12 kt. Air temperature aboard the CCGS *Porte Dauphine* more closely resembled the temperature at Toronto International (A) and Toronto Island than the surface water temperature. It is also of interest to see how closely air temperature at Toronto Island followed that over the water.

It was obvious that a data sort by stability would be required before we could use established techniques to estimate over-water wind data (Richards et al. 1966) and empirical coefficients to compute surface heat and moisture flux. The stability index chosen was $T_{AL}-T_W$. The single

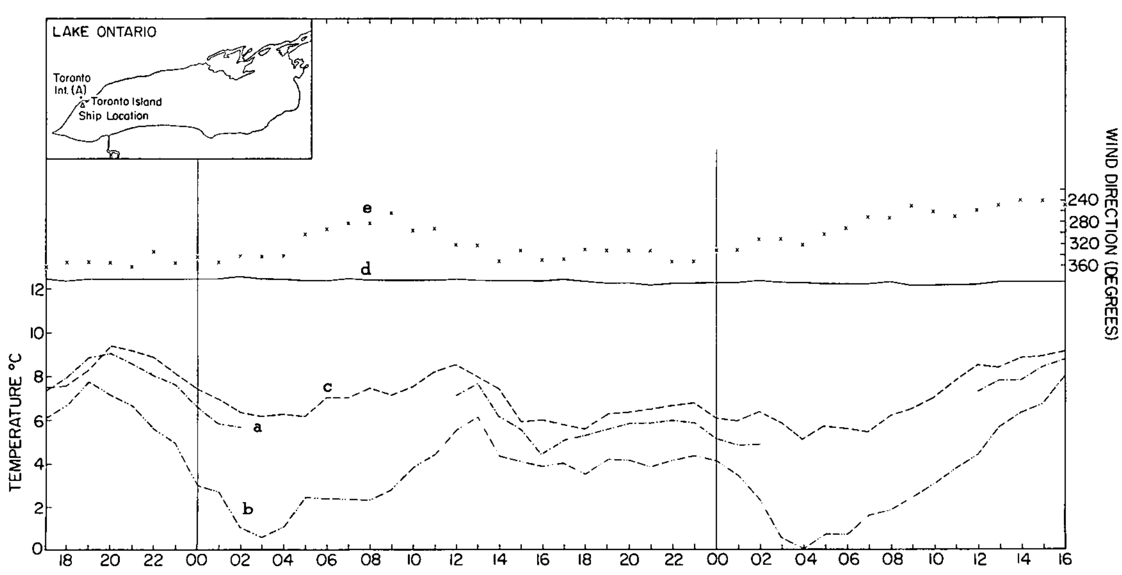

FIGURE 2.—Surface air temperatures (°C) measured at (a) Toronto Island and (b) Toronto International (A) and (c) air temperature, (d) water temperature, and (e) wind direction observed aboard ship on Lake Ontario, Nov. 4–6, 1970.

Table 4.—*Regression equations to estimate over-water air temperature and dew-point temperature and their statistical significance for four stability groupings*

Stability classes ($T_{AL}-T_W$)	Number of observations	Regression equations	Significance level for all regression coefficients	Multiple correlation coefficient	F-value for analysis of variance	Adjusted standard error
(°C)		Over-water air temperature (°C)				(°C)
Stable (≥3.5°)	35	$T_{AW}=4.21+0.48T_{AL}+0.47T_W-1.82$ log time	$t=0.995$	0.95	88	1.1
Neutral (−3.4° to 3.4°)	124	$T_{AW}=0.61+0.49T_{AL}+0.52T_W$	$t=.995$	.96	657	0.9
Unstable (−10.4° to −3.5°)	231	$T_{AW}=-0.26+0.79T_{AL}+0.73$ log time$+0.24T_W$	$t=.995$	.92	414	1.1
Very unstable (≤−10.5°)	125	$T_{AW}=-0.63+0.75T_{AL}+1.55$ log time$+0.11T_W$	$t=.975$	.96	467	1.4
		Over-water dew-point temperature (°C)				
Stable (≥3.5°)	35	$T_{DW}=3.41+0.40T_{DL}+0.51T_W-1.10$ log time	$t=.995$	.94	75	1.0
Neutral (−3.4° to 3.4°)	124	$T_{DW}=1.04+0.73T_{DL}+0.13T_W$	$t=.975$	.92	325	1.4
Unstable (−10.4° to −3.5°)	231	$T_{DW}=-0.43+0.68T_{DL}+0.91$ log time$+0.07T_W$	$t=.975$	.84	162	1.7
Very unstable (≤−10.5°)	125	$T_{DW}=-3.86+0.64T_{DL}+2.25$ log time$+0.24T_W$	$t=.995$	.94	296	1.7

T_{AW}=over-water air temperature (°C)
T_{AL}=over-land air temperature (°C)
T_W=surface water temperature (°C)
T_{DW}=over-water dew-point temperature (°C)
T_{DL}=over-land dew-point temperature (°C)
log time=log of duration of air over water (min)

correlation between this quantity and over-water temperature and humidity exceeded +0.86. The stability classes were arbitrarily chosen as shown in table 4.

Using data from the 515 observations sorted into stability classes, we established regression models for predicting over-water temperatures. Table 4 shows the final equations together with the results of the statistical tests necessary to demonstrate the effectiveness of the regression equations. Inspection of the data in this table leads to a number of observations:

1. For all stability classes, the first independent variable selected was air temperature at the upwind station; the correlation coefficient between this and the temperature at the water location was always higher than +0.8.
2. Surface water temperature is weighted less for unstable and very unstable cases, although it appears more accurate than the log of time as a predictor of over-water temperature for stable cases.
3. For the neutral stability model, log of time over water enters as the third variable. It was not considered in the final analysis, however, since it did not explain any additional variance. Moreover, the inclusion of this variable resulted in a small increase in the standard error.
4. All cumulative multiple correlation coefficients are high, ranging from 0.84 to 0.96. This means that from 71 to 92 percent of the variance in estimating air temperature and dew-point temperature over the water can be accounted for by considering only three or four variables.
5. All the regression coefficients are significant at, at least, the 0.975 level and have the sign corresponding to their possible physical influence.
6. The computed F-value for analysis of variance is everywhere highly significant. The large value of this statistic is an indication of the efficiency of the predictive models.
7. On the average, the standard error (adjusted for degrees of freedom) is 1.1°C for T_{AW} and 1.4°C for the over-water dew-point temperature, T_{DW}. For unstable and very unstable cases, the standard error for T_{DW} is 1.7°C. These errors may be due to the small size of the sample and the pooling of data from days with varying weather conditions. Undoubtedly, the extreme difficulty in measuring dew points at very low temperatures could account for the high standard errors.

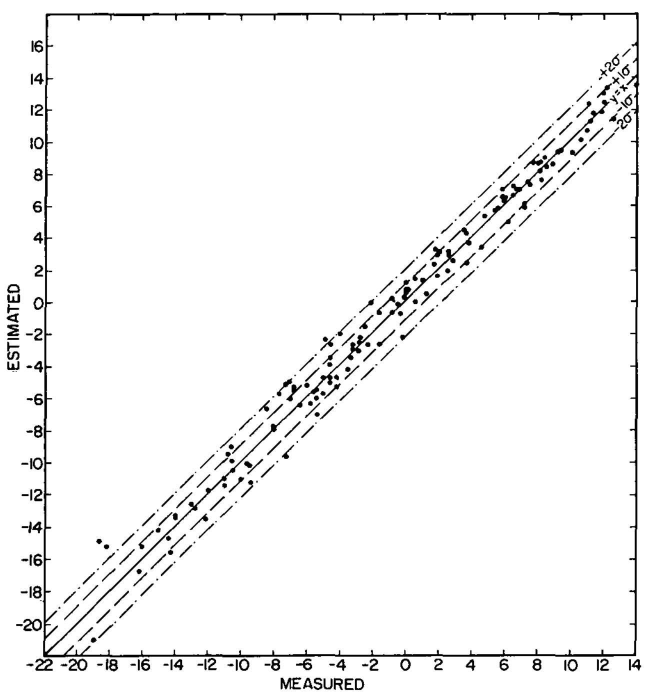

Figure 3.—Estimates of over-water air temperature (°C) from regression equations (table 4) plotted against air temperatures over Lake Ontario measured from ships.

A test was made on the regression equations using more than 100 sets of independent data. Figure 3 presents the residuals of estimates from measured data combined

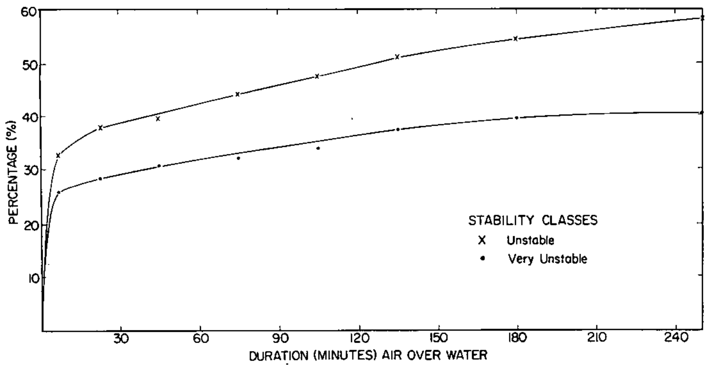

FIGURE 4.—Modification of surface air temperature when air flows from land out over Lake Ontario, as a percentage of total possible change [i.e., $(T_{AW}-T_{AL})/(T_{AL}-T_W)$] as limited by water temperature for unstable and very unstable conditions.

from the four regression models. Results agreed well with those for the data used in developing the models.

One of the major differences between oceanic and lacustrine modification is the change in temperature of the air after it leaves the land. Over the oceans, with trajectories of several hundred miles, the final air temperatures and dew-point temperatures closely approximate the surface water temperature. Burke (1945) found that over the Atlantic, with trajectories over 1,000 mi and differences in air–water temperature averaging 16°C, the average amount of air temperature change exceeded 80 percent of the potential; that is, $|T_{AW}-T_{AL}|/|T_{AL}-T_W|\geq 80$ percent.

Over Lake Ontario for the sample at hand, maximum modification of surface air above 1 m but below about 15 m does not exceed 55 percent of the total possible modification or that limited by the water temperature (fig. 4). During extreme cold air advection, actual modification barely reached 40 percent of the total possible. The scarcity of cases precluded the construction of a curve of total against potential modification for stable conditions.

4. USE OF THE MODELS TO GENERATE OVER-LAKE DATA

The next step was to test the efficiency of the models in generating over-lake air temperatures and dew-point temperatures. Two synoptic situations were chosen to illustrate cold air and warm air advection during midwinter and early spring, respectively. On these occasions, some verification using ship and island data was possible.

In addition, heat and moisture fluxes across the air–water interface were estimated from measurements of water surface temperature and computed values of wind speed, vapor pressure, and air temperatures. The form of the equations to compute turbulent flux is (Roll 1965)

$$H=\rho c_p C_D(\overline{T}_s-\overline{T}_A)\overline{U}_A \tag{1}$$

and

$$E=\rho C_D L(\overline{e}_s-\overline{e}_A)\overline{U}_A \tag{2}$$

where ρ is the air density, c_p is the specific heat of air at constant pressure, C_D is the dimensionless drag coefficient, T_s is the surface water temperature, T_A is the ambient air temperature at 2.5 m above the lake surface, U_A is the wind speed at approximately 10 m above lake surface, L is the latent heat of vaporization, e_s is the saturation vapor pressure at T_s, and e_A is the vapor pressure of the ambient air at 2.5 m above the lake surface.

Although the models were based on lake data taken at about 5 m above the lake surface, their use to obtain air temperature and vapor pressure 2 m above the lake surface is quite accurate. Bruce et al. (1961) studied detailed measurements of temperature, humidity, and wind in the first 15 m above the water and showed that the major part of the change in conditions takes place in the first meter above the surface. Above this level, conditions on the average were found to be relatively uniform to a height of at least 10 m.

Surface water temperatures were available from airborne radiation surveys flown by the Atmospheric Environment Service of Canada, and average water temperatures were obtained from synoptic ship surveys by the Great Lakes Institute. Over-water surface air temperatures and dew-point temperatures across Lake Ontario were generated using regression equations listed in table 4. The ratios of wind over water to wind over land for various stability classes and fetch distances (Richards et al. 1966) were used to estimate over-water winds. Additional cases for unstable and very unstable situations since 1966, from this study, were used to supplement their data.

Few estimates of drag coefficients over lakes have been made. For the present study, a value between 1.2 and 2.1×10^{-3} was selected depending on the stability of the air and the over-water wind speed. Similar values were averaged from a series of wind profiles under different stability situations over Lake Ontario (McCulloch 1971). Estimates of sensible heat flux and evaporative heat flux were obtained using (1) and (2) for each situation sampled.

Maps of over-lake air temperatures and dew-point temperatures, surface water temperature, evaporative and sensible heat flux, total turbulent heat flux, and Bowen ratio were drawn for each situation sampled. The Bowen ratio, R, has been widely used as a measure of the ratio of the energy conducted to or from a surface by the air as sensible heat and that utilized by evaporative processes. Over-lake areas between successive isolines were planimetered, multiplied by an average for the area, and totaled to arrive at a spatial mean.

January 10, 1968

On this occasion, the coldest air of the season passed over the lake. A large, high-pressure area over northern Ontario produced northerly surface winds across Lake Ontario. Through the first 2150 m, the wind maintained this direction with an average wind speed of 15 kt. Along the north shore, surface air temperatures were −22°C compared to the average lake surface temperature of 2°C, as computed from a synoptic ship survey by the CCGS *Porte Dauphine*. A satellite photograph taken at 1550 GMT showed the beginning of a cloud formation over Lake Ontario about 15–20 n.mi. from the north shore. Open water occupied 80 percent of the lake with the remaining area covered with young, thin ice.

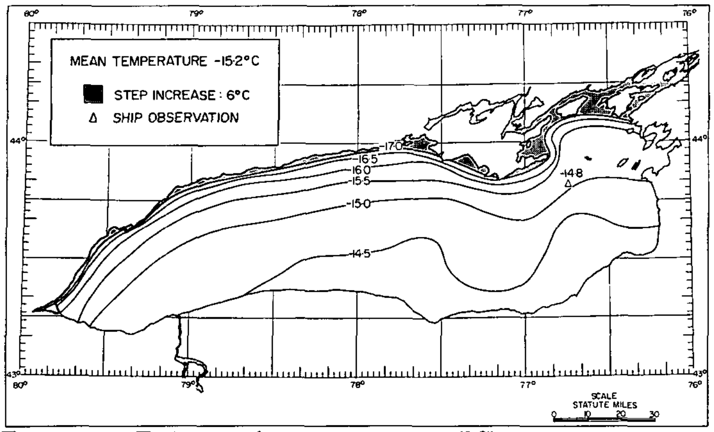

FIGURE 5.—Estimate of air temperature (°C) over Lake Ontario at 1500 GMT, Jan. 10, 1968.

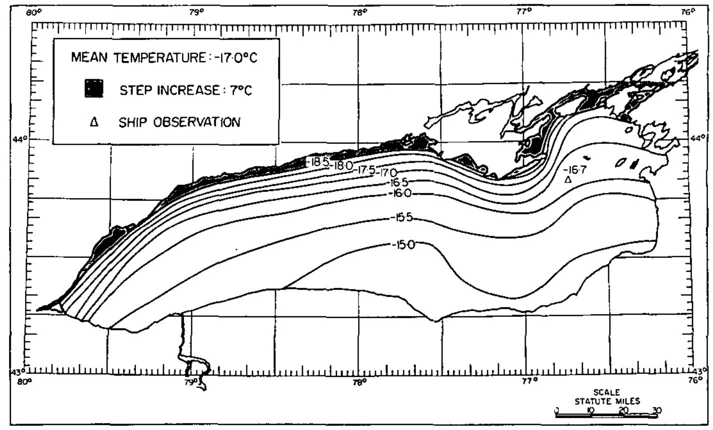

FIGURE 6.—Estimate of dew-point temperature (°C) over Lake Ontario at 1500 GMT, Jan. 10, 1968.

The temperature of the cold air rapidly increased 6°C as the cold air moved across the north shore over open water (fig. 5). The air warmed an additional 2°C as it moved over 15 n.mi. of open water to the edge of the convective cloud layer. An average over-water air temperature of −15.2°C was calculated by planimetry. The configuration of isotherms followed the shape of the north shoreline. Since water temperature had little influence in the regression model for very unstable air, time over water provides the major spatial variate. Verification was good using the CCGS *Porte Dauphine* air temperatures as measured during midmorning on January 10 south of Main Duck Island. Land stations around the shoreline reported air temperatures lower than those over the lake. If over-water air temperatures had been estimated by averaging north and south shore stations as has been the practice, an average midlake air temperature of −19.0°C would have been obtained. On this occasion, the model gave a more realistic estimate of over-lake surface air temperature.

The isoline pattern for dew points (fig. 6) closely reflected that for air temperature. A spatial mean of −17.0°C was calculated, and verification from the CCGS *Porte Dauphine* near Main Duck Island was made.

The distribution of total turbulent heat flux (fig. 7) resembled that of water temperature. Maximum losses appeared over the deepest part of the lake, where winds had increased two-fold and air–water temperature differences were highest. Daily turbulent heat losses ranged from 1700 ly at the center of the lake to less than 1200 ly along the shorelines. The average heat loss calculated from planimetry was 1420 ly/day. This assumes, however, that the flux of heat continued under steady conditions for 24 hr.

The ratio of sensible to evaporative heat loss, the Bowen ratio, ranged from 1.84 over the center of the lake to a high of 2.16 near the shore. The average ratio was 1.96. In other words, the amount of energy gained by the atmosphere through conduction and turbulent transfer was twice that gained through evaporation. Since absolute humidities are small at low temperatures, large air–water vapor pressure deficits cannot occur. Sensible heat flux is linearly dependent upon the air–water temperature difference; hence, large air–water temperature differences correspond to large amounts of heat conduction.

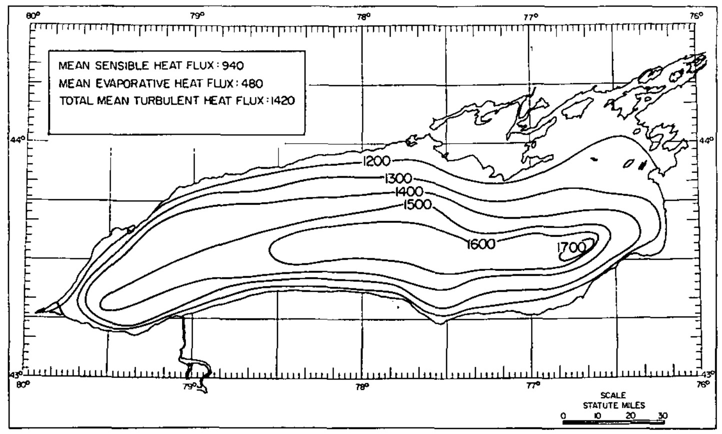

FIGURE 7.—Estimate of mean total turbulent heat flux (ly/day) from Lake Ontario on Jan. 10, 1968.

April 23, 1968

This situation was chosen as an example of a southerly circulation bringing warm air across cool lake waters. The desired flow occurred on Apr. 23, 1968, between a deep, low-pressure area in Wisconsin and a weak ridge of high pressure along the New England coast. From the surface to 2150 m, the winds were southerly with an average speed of 14 kt.

Surface air temperature at Buffalo, Rochester, and Syracuse, N.Y., was 17°C between 1500 and 1600 GMT. Sky conditions along the south shore were clear to scattered with unlimited visibility. Ships located within 10 n.mi. of the south shore reported shallow fog. The mean surface water temperature, computed that morning from an airborne radiation survey by the Atmospheric Environment Service (fig. 8), was 2.1°C. Shallow waters along the shoreline were up to 8° warmer than the surface water in the deeper midlake areas.

After an initial step decrease of 3°C in the air temperature (fig. 9), the air further cooled by 3° within 10 n.mi. The closed cell of cool air less than 8°, located south of Prince Edward County Peninsula, points to one of the

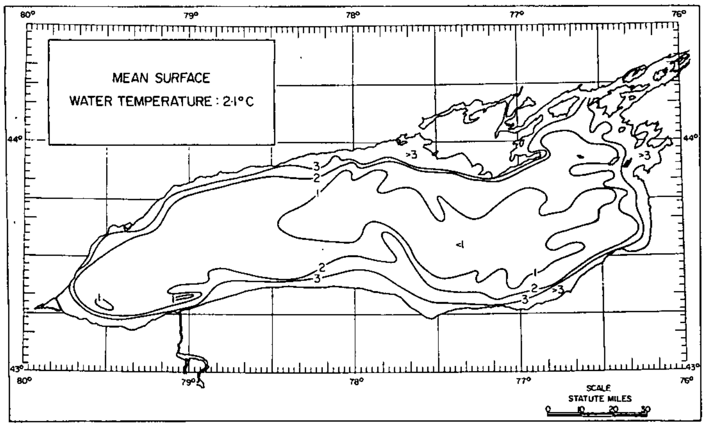

FIGURE 8.—Lake Ontario surface water temperature (°C), Apr. 23, 1968, Atmospheric Environment Service (ART survey).

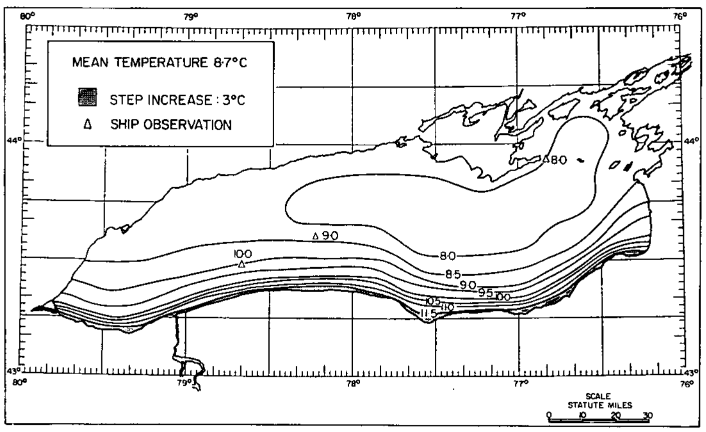

FIGURE 9.—Estimate of air temperature (°C) over Lake Ontario at 1500 GMT, Apr. 23, 1968.

shortcomings of the present model. During stable conditions, surface water temperature influences the modifying process more than any other variable. As the air moved over warmer water near the northern shore, the model produced an increase in air temperature even though the water was still colder than the air. It is possible that a value of water temperature integrated over the fetch distance would eliminate this objection.

Three different ship observations taken at 1500 GMT confirmed the power of the prediction model for estimating air temperature. The airports at Toronto, Trenton, and Kingston, Canada, all reported air temperatures 4–8°C higher than those from the ships. Surface air temperatures at seven airport stations around the lake for 1500 GMT on Apr. 23, 1968, averaged 16°C. At the same hour, a ship in midlake observed a temperature of 9°C. This compared to the 8.6°C estimated from the regression equations for stable air. This point again emphasizes the potential error involved in assuming a linear temperature variation between stations on opposite shores.

There was a downward flux of heat from the atmosphere to the water (fig. 10). Calculations suggested that the water was gaining heat from the air at an average rate of 265 ly/day. Maximum daily gains were above 280 ly along the south shore where the temperature contrast between air and water was very large and over the deepest

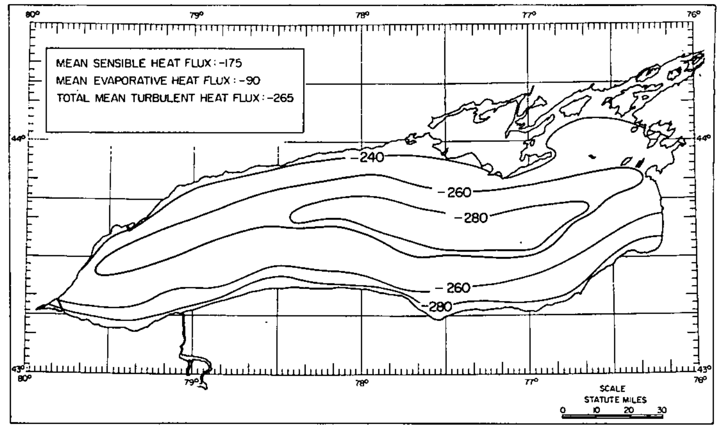

FIGURE 10.—Estimate of mean total turbulent flux (ly/day) from Lake Ontario on Apr. 23, 1968.

central area of the lake where differences in temperatures are high and winds, stronger. Minimum gains by the lake, less than 240 ly/day, occurred along the north shore where modified air temperatures and dew-point temperatures approach the surface water temperature. It was apparent, however, that the spatial variation of heat flux was smaller than the errors inherent in the method of calculation.

A downward flux of heat and moisture over the lake results in a positive Bowen ratio. The ratio varies slightly from 1.82 to 1.98 with an overall average of 1.94. The average evaporative flux is −90 ly/day, a rate which, if projected for 1 mo, would condense 1 in. of water over Lake Ontario.

5. CONCLUSIONS AND FURTHER RESEARCH

The present study has attempted to facilitate an understanding of the processes involved in modifying the air between 1 and 15 m above Lake Ontario in winter. The major contribution is the development of models to estimate over-water air temperatures and dew-point temperatures from easily measured variables. An average of 86 percent of the variance can be explained by incorporating only three variables: surface temperatures of the air mass as measured at upwind land stations, surface water temperature, and length of time the air spends over the water.

A number of important considerations remain to be explored. Distributions of over-water air temperature, humidity, and turbulent exchange fields on a monthly time period for various air mass types are being analyzed over Lake Ontario. It is important to analyze the errors introduced into the calculation of turbulent fluxes by the uncertainty in the estimated variables and by the assumed similarity of the coefficients of proportionality in the "bulk aerodynamic" equation. One of the major goals of the International Field Year on the Great Lakes (IFYGL) in 1972/73 will be to obtain direct measurements of the energy fluxes from micrometeorological tower facilities using eddy correlation techniques. This background of data will then be employed to derive empirical coefficients for the formulas relating the surface fluxes to free atmospheric variables.

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Another task proposed for the IFYGL is the determination of the regional evaporation estimates over Lake Ontario for various time scales. Important inputs to such studies are over-water air temperatures and dew-point temperatures and surface water temperatures. Tower, buoy, and ship observations should provide detailed regional coverage during the summer months. Because of the incidence of storms and icing conditions from November to April, however, tower and buoy observations will have to be discontinued during this period, and ship observations will be limited during "stormy weather" days. Airborne radiometer surveys and satellite flights will provide measurement of surface water temperatures, but surface air temperatures and dew-point temperatures will have to be estimated from shoreline network data using empirical ratios. Techniques similar to those described in this paper will generate regional estimates of the required variables. By collecting data during particular synoptic situations, such as lake-effect snowstorms, improvements to within the necessary bounds of accuracy can be made. Further research is also needed into the modification of air masses by changing lake characteristics—current fluctuations, extent of ice cover, changing volume, and surface area.

There can be little doubt that the Great Lakes impose strong controls over the winter climate of the surrounding areas. It is hoped that a greater understanding of the climatological significance of over-lake conditions has been imparted by this investigation. It is also hoped that others will be encouraged to use the wealth of over-water information that already exists in the form of synoptic reports from ships sailing the Great Lakes.

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