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STABILITY EFFECTS ON GREAT LAKES EVAPORATION[1]

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ABSTRACT. The effects of atmospheric stability on Great Lakes evaporation computed by the modified mass transfer method have been evaluated by analysis of stability effects on the variable mass transfer coefficient, land to lake data adjustments, and ice-cover reduction of evaporation during winter. The Great Lakes which produce extreme results, Lakes Superior and Erie, and a much smaller water body within the Great Lakes chain, Lake St. Clair, were studied. Comparison of these evaporation estimates with previous studies, which excluded variable stability effects, shows that the previous studies of Lake Superior produced generally similar total annual water loss from the lake, but significantly overestimated both the seasonal high evaporation and the condensation rates. These tended to balance each other. The atmospheric conditions over Lakes Erie and St. Clair do not become as strongly stable and they normally do not exhibit large condensation. Previous evaporation studies for these lakes indicate generally higher evaporation rates, with significant overestimation of the total annual water losses (25%).

INTRODUCTION

Evaporation from the Great Lakes represents a major water loss and is an important factor in lake hydrology studies. Considering lake characteristics and data limitations, the most practical approach for determining operational evaporation estimates is the mass transfer method. This method permits determination of long-term lake evaporation from readily available land-based meteorological data, with a minimum delay between data collection and use, but requires adjustments for atmospheric stability differences between land and large water bodies. Research efforts to refine the mass transfer technique for use on the Great Lakes began in the 1950s and culminated with the International Field Year for the Great Lakes (IFYGL), conducted on Lake Ontario during 1972–73. Initial refinements consisted of constant monthly wind and humidity ratios used with the Lake Hefner equation, which contains an empirically determined mass transfer coefficient (Richards 1964). Present refinements, based on IFYGL results, are derived from atmospheric stability considerations and include a variable mass transfer coefficient, variable adjustments for the input data, and ice-cover reduction of evaporation during winter (Derecki 1980). The atmospheric stability is defined by the stability index, which is expressed as the air-water temperature difference, with large positive values indicating strong stability and large negative values indicating strong instability. This paper summarizes air stability effects on evaporation for the highest and lowest Great Lakes in terms of evaporation, Lakes Superior and Erie, and also for a much smaller water body within the chain of Great Lakes, Lake St. Clair (Figure 1). Stability effects for the other, intermediate Great Lakes (Michigan, Huron, and Ontario) should fall between these extremes.

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METHOD

The mass transfer method for computing evaporation is based on the removal of water vapor from the lake surface by turbulent diffusion. It is a function of the overlake wind speed and the vapor pressure difference between the saturated air at the lake surface and the ambient air at some predetermined level. This relationship is expressed by the equation

$$E = M\,(e_s - e_a)\,U,$$

where, in SI units, evaporation (E) is in millimeters per day, mass transfer coefficient (M) is in milli-

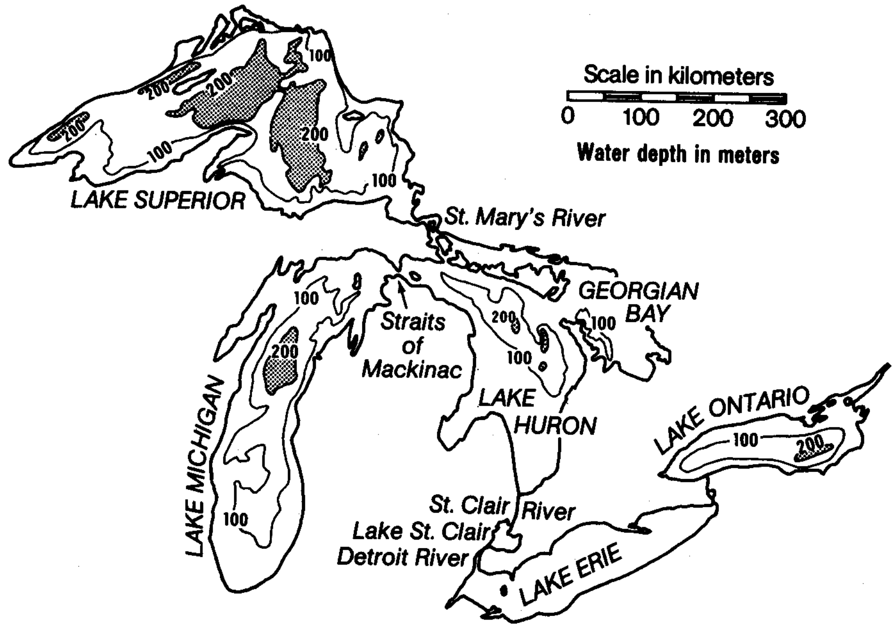

FIG. 1. Great Lakes Basin.

meters per day dividied by 10^{-1} kilopascals (mb) times meters per second, saturated vapor pressure (e_s) and air vapor pressure (e_a) are in 10^{-1} kilopascals (mb), and wind speed (U) is in meters per second.

The above equation, with all input parameters standardized at 8 m, was used to compute evaporation from Lakes Superior, Erie, and St. Clair. Since all long-term data are restricted to lake perimeters, the basic data from land stations were adjusted to overwater conditions, based on atmospheric stability considerations. Air stability was also used in the derivation of the mass transfer coefficient and in the determination of ice-cover effects during winter. The ice-cover effects were obtained by combining the overwater and overice values for individual parameters, based on applicable ice cover. The land to lake data adjustments were derived from values determined by Phillips and Irbe (1978) from the extensive IFYGL data base. These meteorological data adjustments, expressed as variable lake/land wind ratios and land–lake air and dew point temperature differences, are presented as stability dependent equations, grouped by perimeter wind speed classes. The basic long-term meteorological and water temperature data were obtained by averaging records from several perimeter meteorological stations (wind speed, air temperature, and relative humidity) and municipal water intakes located around the lakes. Surface temperature adjustments for these subsurface coastal water temperatures were derived from simultaneous airborne radiation thermometer (ART) survey measurements conducted on the Great Lakes bordering Canada since 1966 by the Atmospheric Environment Service, Environment Canada. These surface temperature adjustments, expressed as intake–surface water temperature differences, are not related directly to the atmospheric stability and the water surface temperatures represent the weakest link in the mass transfer computations. Elimination of this weakness may be feasible in the future when the satellite surface temperature observations become sufficiently accurate.

The mass transfer coefficient was determined by the method presented by Quinn (1979). This method provides a variable mass transfer coefficient based on atmospheric stability, and includes an iterative algorithm for its derivation from the same meteorological variables that are required for normal mass transfer computations. The mass transfer coefficient is defined as a function of the air density and pressure, and the bulk transfer coefficient for latent heat flux. Assuming that bulk transfer coefficients for sensible and latent heat fluxes are equal, derivation of the stability dependent bulk transfer coefficient was based on the analysis of nondimensional wind speed and potential temperature gradients in the surface boundary layer. The analysis involved determinations of frictional velocity, roughness length, Monin-Obukhov stability length, and stability functions for momentum and sensible heat to derive bulk transfer coefficients for momentum (drag) and sensible heat. Separate stability functions were determined for different atmospheric conditions defined by the reference height/Monin-Obukhov stability length relationship. The variable data adjustments, mass transfer coefficient, ice-cover effects, and the basic data for Lake Superior are described in detail by Derecki (1980).

The resulting Lake Superior mass transfer evaporation was verified by the water budget determinations, with good general agreement between the two sets of evaporation values. The average annual difference between water budget and mass transfer evaporation was 7%, which is within normal limits of accuracy for the Great Lakes climatological data (about 10%). In contrast to the other Great Lakes, water budget computations for Lake Superior offer firm estimates of evaporation. All hydrologic components for the water budget of this lake are of the same order of magnitude, with comparable errors, eliminating the possibility of large residual errors in computed evaporation. For the other Great Lakes the inflow and/or outflow by the connecting channels are an order of magnitude larger than the other components.

The mass transfer method derived for Lake Superior was duplicated for Lake Erie and applied to basic data described by Derecki (1976b). This method was also used for Lake St. Clair, except that for this lake stability effects are based on short overwater fetches (11–23 km) instead of all the fetches used for the Great Lakes proper. Basic data for Lake St. Clair are from Derecki (1979).

RESULTS

The long-term average monthly and annual evaporation values from the three lakes, computed for the employed periods of study, are given in Table 1. Listed values are based on applicable overlake atmospheric stability conditions during individual years and represent the best lake evaporation estimates available at the present time. The use of variable air stability effects produced somewhat higher evaporation results for Lake Superior and considerably lower for Lakes Erie and St. Clair than those obtained in previous studies with the Lake Hefner coefficient and constant monthly lake/land wind and humidity ratios (Richards and Irbe 1969; Derecki 1976a, 1976b, and 1977). Evaporation from Lake Superior is higher because

TABLE 1. Average mass transfer evaporation, mm.

Month	Lake Superior 1942–75	Lake Erie 1937–79	Lake St. Clair 1950–75
January	104	39	26
February	56	20	18
March	42	15	15
April	8	2	10
May	-3	4	32
June	-10	13	22
July	-14	52	39
August	-6	93	74
September	29	111	108
October	55	123	95
November	104	134	85
December	118	70	45
ANNUAL	483	676	569

unreasonably high condensation produced by the constant coefficient and the constant monthly lake/land wind and humidity ratios during strongly stable summer months are eliminated. The warm weather atmospheric stability on the other lakes is much weaker, producing smaller and relatively infrequent condensation.

The breakdown of variable stability effects on the annual evaporation of each lake is shown in Table 2. Since previous studies (a through e, Table 2) did not consider ice-cover effects, they indicate only overwater evaporation, which was adjusted by presently-derived ice-cover reduction of evaporation for a more valid comparison. Listed ice-cover reduction values contain partial stability effects on the variable mass transfer coefficient and land to lake data adjustments for both open-water and ice-covered lake surface conditions. Atmospheric stability effects for the variable mass transfer coefficient are compared with the Lake Hefner empirical constant (0.097 for 8-m level), and those for the variable land to lake data adjustments are compared with the constant monthly wind and humidity ratios, which contain partial stability effects (seasonably distributed empirical constants). Average stability effects on Lake Superior due to variable coefficients, data adjustments, and ice cover are roughly of the same magnitude (60, 40, and -70 mm, respectively). Since these adjustments tend to cancel each other, previous evaporation estimates (Richards and Irbe 1969, Derecki 1977) produced a reasonable total annual water loss from the lake but with a seasonal distribution indicating exaggerated amounts for the winter high evaporation and the summer low condensation. Stability

TABLE 2. Average stability effects on annual evaporation, mm.

Evaporation and Effects	Lake Superior	Lake Erie	Lake St. Clair
LAKE HEFNER COEFFICIENT AND MONTHLY RATIOS	a and b	c and d	e/f
Overwater evaporation	450	900	970/850*
Overlake evaporation	(380)	(840)	(890)/750*
STABILITY EFFECTS			
Variable coefficient	60	-110	-180/(-180)
Data adjustments	40	-50	-140/—
Ice cover reduction	-70	-60	-80/-100*
Total stability effect	30	-220	-400/(-280)*
RESULTING EVAPORATION	480	680	570/570

a. Derecki (preliminary, 1977): 443 mm, 1937-75 average.
b. Richards and Irbe (1969): 457 mm, 1959-68 average.
c. Derecki (1976b): 898 mm, 1937-68 average.
d. Richards and Irbe (1969): 909 mm, 1950-68 average.
e. Derecki (preliminary, 1976a): 970 mm, 1950-74 average.
f. Derecki (1979): 750 mm, 1950-75 average.
* Estimates contain stability effects on data adjustments and ice cover, but use Lake Hefner coefficient (0.097).
() Values containing presently-derived adjustments for a more valid comparison (see text).

effects on the other two lakes produced all negative adjustments, and previous evaporation estimates are all too high. The magnitude of average evaporation corrections for the Lake Erie due to overwater data adjustments and ice-cover reduction is similar (-50 and -60 mm), but twice as high for the variable coefficient (-110 mm). The combined effect of these adjustments reduces previous evaporation estimates (Richards and Irbe 1969, Derecki 1976b) by about 25% (-220 mm), producing a considerably smaller water loss from Lake Erie. A similar trend is shown for Lake St. Clair, with even higher average evaporation corrections (from -80 to -180 mm). In a hypothetical comparison with data adjustments based on the empirical Great Lakes monthly wind and humidity ratios (Derecki 1976a), which are not valid for this much smaller lake, total stability effects reduce computed evaporation by over 40% (-400 mm). As in Lake Erie, the most important stability effect of Lake St. Clair is on the mass transfer coefficient. In a more recent study (Derecki 1979) that contains stability effects on data adjustments and ice cover, but retains the Lake Hefner coefficient, average annual evaporation is overestimated by nearly 25%.

Seasonal distribution of the average monthly values for the atmospheric stability index, expressed as the air–water temperature difference; the input parameters (mass transfer coefficient, wind speed, and vapor pressure difference); and the resulting evaporation from each lake are shown in Figures 2 through 6, respectively. Figures 2, 5, and 6 show that only Lake Superior atmospheric conditions become strongly stable during summer and

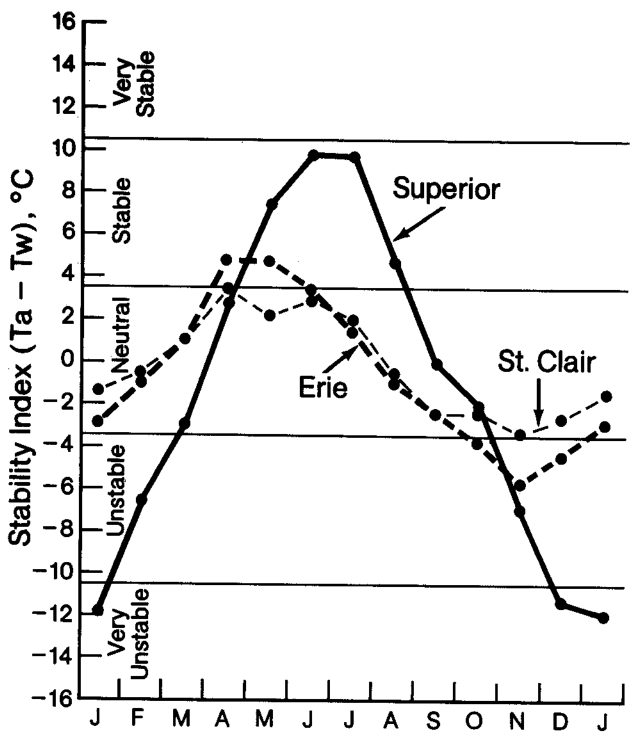

FIG. 2. Seasonal distribution of average monthly stability index.

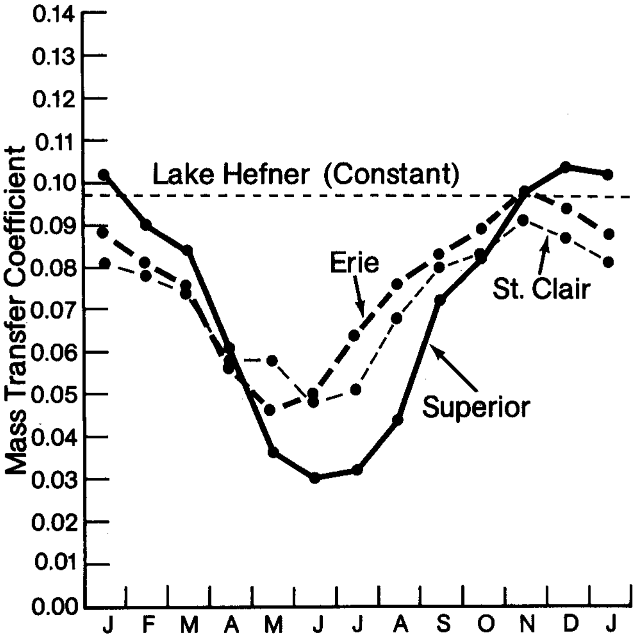

FIG. 3. Seasonal distribution of average monthly mass transfer coefficient for 8 m.

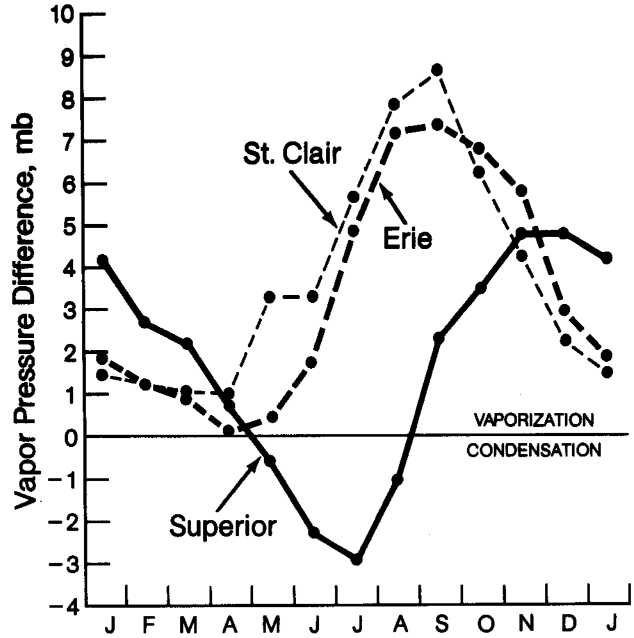

FIG. 5. Seasonal distribution of average monthly vapor pressure difference at 8 m.

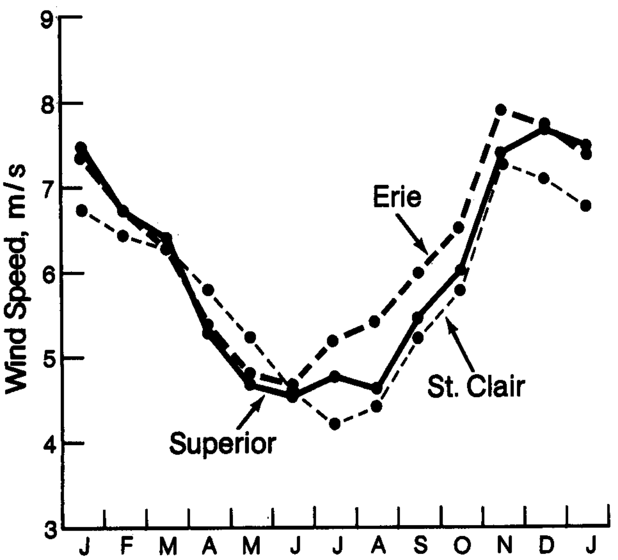

FIG. 4. Seasonal distribution of average monthly wind speed at 8 m.

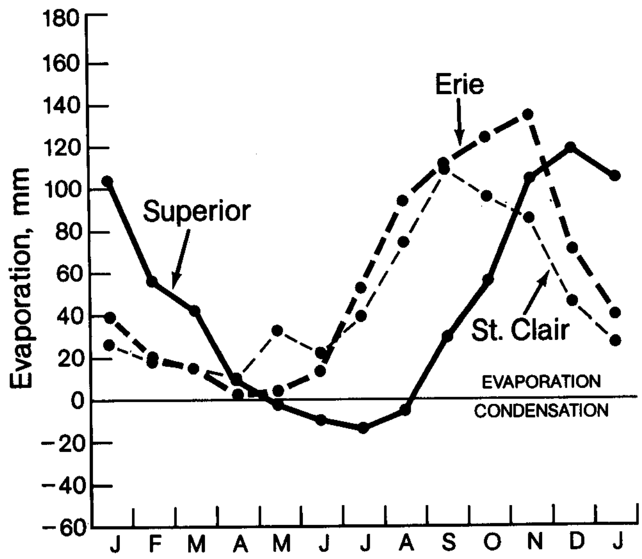

FIG. 6. Seasonal distribution of average monthly evaporation.

strongly unstable during winter, producing a negative vapor pressure difference and condensation during summer and a high vapor pressure difference and high evaporation during winter, despite reduction of winter evaporation by ice cover. Figure 3 shows that the use of the Lake Hefner constant coefficient would tend to overestimate evaporation or condensation, except during late fall and early winter. The Lake Hefner coefficient represents open-water conditions, and its winter fit would be improved for the overwater evaporation that is not reduced by ice cover. Figures 2 through 6 show that generally stable atmospheric conditions during spring and summer (early summer for Lakes Erie and St. Clair) produce low mass transfer coefficients, wind speeds, and vapor pressure differences, with corresponding low evaporations from each lake. During fall and winter (late summer through early winter for Lakes Erie and St. Clair), the atmospheric conditions are generally unstable and produce high values for the input parameters and resulting evaporation. Figures 2, 5, and 6 show the major difference between Lake Superior, the most northerly and deepest of the Great Lakes, and Lakes Erie and St. Clair, the most southerly and shallowest of the Great Lakes. The highest air-water temperature difference and atmospheric stabilities on Lakes Erie and St. Clair are attained in spring, with the lowest vapor pressure differences and evaporation rates, and the lowest air-water temperature differences and atmospheric instabilities are reached in fall, with the highest vapor pressure differences and evaporation rates. On Lake Superior, because of tremendous heat storage capacity, these extremes occur about 3 months later, a full season out of phase.

CONCLUSIONS

1. Atmospheric stability has to be considered for reliable mass transfer evaporation estimates from the Great Lakes.

2. Seasonal variation in the mass transfer coefficient is of similar magnitude to that of the input data (wind, vapor pressure difference) or evaporation and the use of constant coefficient can not be justified.

3. Winter ice-cover reduction of evaporation may be as important as the stability effects on the input data or mass transfer coefficient and should be included for lakes with extensive ice cover.

4. Inclusion of air stability dependent mass transfer coefficient, land to lake data adjustments, and ice-cover effects during winter permits determination of realistic mass transfer operational evaporation estimates from readily available perimeter data.

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