Heat Storage and Advection in Lake Erie

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Heat content and net advection based on long-term monthly mean input data covering 17 yr (1952–1968) were derived for Lake Erie. The lake heat storage changes and net advection, with major components, are presented for the average monthly periods, indicating normal values for these parameters. Data limitations for the lake heat content precluded computation of monthly values by individual years. Derivation of the necessary input data (water temperature profiles, water supply and loss factors with appropriate temperatures, and ice conditions) is briefly described.

INTRODUCTION

Because of their great size and depth the Great Lakes have a tremendous heat storage capacity, a very important factor in the heat budget studies of the lakes. The lake heat content and its seasonal changes are of primary interest in the determination of evaporation, lake freeze-up, and ice melt or snowmelt. With intensified research activities on the Great Lakes in recent years, short-term data for the determination of heat content in the lakes are becoming increasingly available, but similar long-term information is extremely sparse. The long-term heat content information is needed for determination of the normal values.

This paper describes the derivation and presents long-term monthly heat storage changes and net advection in Lake Erie. The results presented are largely based on a comprehensive Lake Erie evaporation study [*Derecki,* 1975], which employed the energy budget as one of several methods to compute lake evaporation. The period of record for the energy budget computations covered 17 yr, 1952–1968. Because of data limitations, primarily, the lack of continuous information on the lake heat content, the energy budget computations were limited to average monthly values.

HEAT STORAGE

Heat storage in the lake was determined from water temperature profiles based on temperature surveys. The energy required for the energy budget computations was the change in heat storage during monthly intervals. This change in heat storage is the difference in heat content at the beginning and at the end of the month. If the specific heat and density of water (1.0 cal/cm³ and 1.0 g/cm³, respectively) are omitted, the change in heat storage is expressed by

$$Q_t = (V_2T_2 - V_1T_1) \qquad (1)$$

where

- Q_t change in heat content, cal;
- V_2 volume of the lake at the end of the month, cm³;
- T_2 average temperature of the lake at the end of the month, °C;
- V_1 volume of the lake at the beginning of the month, cm³;
- T_1 average temperature of the lake at the beginning of the month, °C.

The change in lake volume during monthly intervals is determined by the monthly rise or fall in lake levels, since the area of the lake remains constant for practical purposes. Because monthly increments in lake levels are small in comparison with the total depth of the lake, the relative difference between V_1 and V_2 is also small, and the average volume of the lake may be used without significant error. Thus the above heat storage equation may be modified to a more convenient form:

$$Q_t = V(T_2 - T_1) \qquad (2)$$

where V is the average volume in cubic centimeters of the lake from long-term records.

The heat content in the lake was computed by summing energy contents calculated at the surface and at several predetermined depth layers. This procedure was dictated by irregularities in the lake depths and stratification of the water temperature with depth. The lake was divided into depth layers of 7.6–15.2 m, as is indicated in Figure 1. The average volume for each layer was determined from the resulting constant depth areas and depth segments to midpoints between layers. By using (2) the energy content for each layer was computed from these volumes and the mean temperatures at the beginning and at the end of each month.

Temperature profile data. The average water temperature at each layer was determined from the water temperature profiles which were derived from Lake Erie temperature surveys published by the Great Lakes Institute of the University of Toronto. The resulting average monthly temperature profiles for the period of published records, 1960–1963, are shown in Figure 2, and the corresponding temperature differences are listed in Table 1. There were no temperature data for the winter months, since temperature measurements were limited to the open-water season. During winter months the water temperature profiles were estimated by using a range of 2°C, from 0°C at the surface to 2°C at the maximum depth layer of 61 m.

The water temperature profiles for the period of study, 1952–1968, were estimated by adjusting the average temperature at each depth layer. Monthly temperature adjustments ΔT_w were derived from the water surface temperatures for both periods and out of necessity were applied to the entire depth. Because of lake stratification during most of the year this procedure seems questionable, especially for depths below the thermocline (about 15 m) but represents the only means available. Temperature stability should increase with depth, but temperature profile data (1960–1963) showed similar scatter at various depths. Derived temperature adjustments are shown in Table 2. Water surface temperatures for the 1952–1968 period are discussed under the section on net advection.

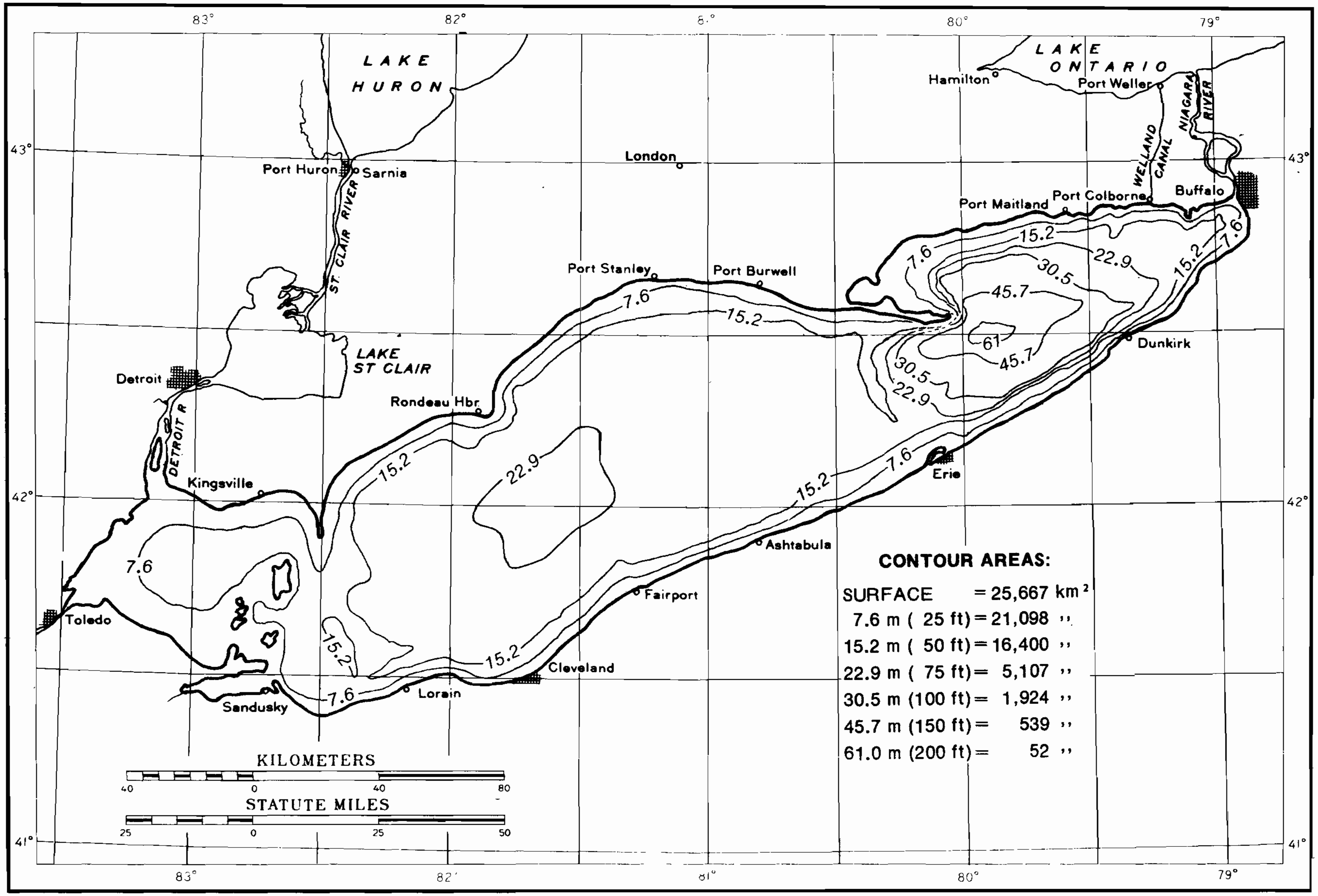

Fig. 1. Bottom topography of Lake Erie.

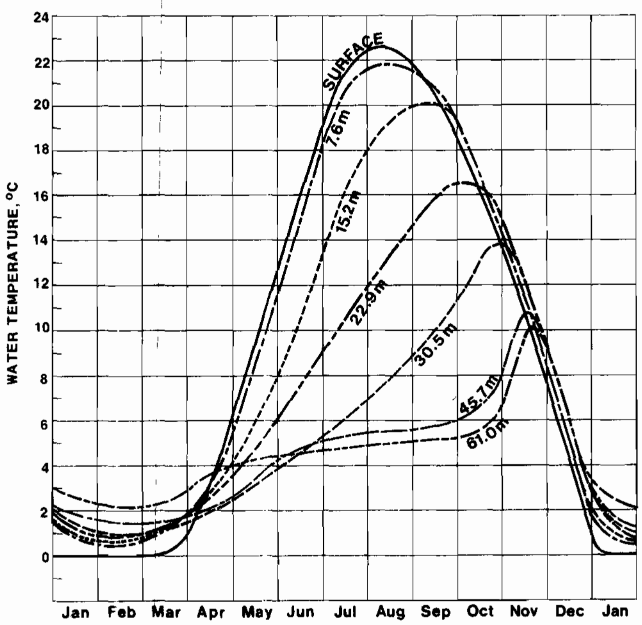

Fig. 2. Lake Erie monthly water temperature as a function of water depth, 1960–1963.

Results. The determination of Lake Erie heat content for the 1960–1963 period based on measured temperature profile data is shown in Table 3. The estimates of Lake Erie heat content for the 1952–1968 period are given in Table 4. Comparison of the average monthly heat content for the two periods is shown in Figure 3.

The monthly changes in heat content converted to langleys per day are listed in Table 4. During the 1952–1968 period the average monthly heat storage in Lake Erie varied from about 350 Ly/d in May to about −360 Ly/d in November, the total range of variation exceeding 700 Ly/d. The lake gained heat during spring and summer and lost heat during fall and early winter. On an annual basis, heat storage is insignificant, since seasonal heat gains and losses balance each other.

The change in heat storage based on estimated water temperature profiles is subject to errors inherent in the estimates, which were determined from the water surface temperature differences. Because of the small percentage of lake volume below 19 m, variations in total heat content below this depth are relatively small. Consequently, for the determination of heat storage changes the most important temperature variations are those occurring in the upper 19 m, which correspond roughly to the lake depth above the thermocline. Thus employment of surface temperature differences for the temperature profile estimates in Lake Erie appears to be reasonable. For the average monthly temperatures the maximum error should not exceed 1°C, which is equivalent to a change of about 50 Ly/d in the total heat storage.

NET ADVECTION

Advected energy is the net energy gained or lost by the lake due to the exchange of water masses resulting from the inflow-outflow balance. It consists of the total inflow and total outflow energies and the heat transfer involved in ice formation and melting of ice and snow at 0°C and is expressed by the equation,

$$Q_v = Q_i - Q_o + Q_f - Q_m \tag{3}$$

where

Q_v net advected energy, Ly/d;
Q_i energy content of water entering the lake, Ly/d;
Q_o energy content of water leaving the lake, Ly/d;
Q_f ice formation heat gain, Ly/d;
Q_m ice melt and snowmelt heat loss, Ly/d.

The energy content of water entering or leaving the lake was determined from Lake Erie water budget computations and appropriate temperatures [*Derecki,* 1975]. Water supplied to Lake Erie consists of overwater precipitation, runoff from the drainage basin, and inflow from the upper lakes; water leaving the lake consists of evaporation and lake outflow. During the winter, Lake Erie conserves heat by forming a substantial ice cover. This heat gain is subsequently dissipated by the melting of the ice cover. Additional heat loss correction is required during the winter for the melting of snow falling over the open-water area. Thus a detailed form of the net advection equation becomes

$$Q_v = (V_pT_p + V_rT_r + V_iT_i) - (V_eT_w + V_oT_o) + (Ld_iV_f) - (Ld_iV_m + Ld_sV_s) \tag{4}$$

TABLE 1. Lake Erie Temperature Differences for Predetermined Depths in Degrees Centigrade, 1960–1963

	Depth, m						
	0–3.8	3.8–11.4	11.4–19.0	19.0–26.7	26.7–38.1	38.1–53.4	53.4–64.0
January*	0.0	−1.0	−0.8	−0.8	−0.7	−0.5	−0.8
February*	0.0	0.1	0.1	0.0	0.0	0.0	0.0
March*	1.0	1.2	1.0	0.7	0.4	0.3	0.7
April	5.2	3.5	2.3	1.9	0.8	0.8	1.0
May	6.4	6.4	3.9	2.6	1.7	1.6	0.6
June	6.5	6.5	5.4	3.0	1.5	1.0	0.2
July	3.2	3.5	4.6	2.9	1.6	0.2	0.2
August	−0.4	−0.1	1.9	2.7	1.8	0.2	0.1
September	−3.6	−2.3	−0.6	1.8	2.5	0.3	0.2
October	−5.0	−5.2	−5.2	−1.6	2.4	2.3	1.7
November	−6.1	−6.2	−6.2	−5.9	−4.8	0.8	2.1
December	−7.2	−6.4	−6.4	−7.3	−7.2	−7.0	−6.0
Annual	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The heat storage equation is $Q_t = V(T_2 - T_1)$, and the temperature difference is $T_2 - T_1$.
* During the winter (January–March), temperatures were estimated.

TABLE 2. Lake Erie Water Temperature Adjustments in Degrees Centigrade

Period	T_w 1952–1968	T_w 1960–1963	Adjustments ΔT_w
January	0.2	0.0	0.2
February	0.1	0.0	0.1
March	0.5	0.4	0.1
April	3.2	3.7	−0.5
May	9.1	9.1	0.0
June	15.9	15.7	0.2
July	20.3	21.3	−1.0
August	21.9	22.3	−0.4
September	19.4	20.5	−1.1
October	15.1	16.0	−0.9
November	10.1	10.5	−0.4
December	3.1	4.2	−1.1
Annual	9.9	10.3	−0.4

Water temperature adjustments are based on surface temperatures.

where

V_p volume of overwater precipitation, cm³;
T_p wet bulb temperature (T_a − 2°C was used on the basis of comparison of dry bulb and wet bulb temperatures), °C;
V_r volume of runoff from drainage basin, cm³;
T_r air temperature T_a (with winter minimum at 0°C), °C;
V_i volume of inflow through Detroit River, cm³;
T_i Detroit River temperature, °C;
V_e volume of lake evaporation, cm³;
T_w lake surface temperature, °C;
V_o volume of outflow through Niagara River and Welland Canal, cm³;
T_o Niagara River temperature, °C;
L latent heat of freezing or melting, equal to 80 cal/cm³ at 0°C, °C;
d_i ice density (used average value for lake ice of 90%), percent;
V_f volume of ice formation (freezing), cm³;
V_m volume of ice melt, cm³;
d_s snow density (used average value for fresh snow of 10%), percent;
V_s volume of overwater snowfall, cm³.

The correction for heat loss due to snowmelt has been applied in previous Great Lakes energy budget studies on Lake Ontario [*Rodgers and Anderson*, 1961] and on Lake Erie [*Derecki*, 1975]. However, snowmelt provides only partial correction for the winter heat budget, which includes additional effects of ice cover. The energy exchange processes involved in ice formation and melting have been ignored generally in previous studies because of the difficulties in the determination of typical ice conditions and thicknesses. *Rodgers and Sato* [1971] suggest that the omission of the ice cover effect is largely responsible for the heat balance discrepancy on Lake Ontario.

Hydrologic data. Except for the ice thickness a detailed description of the input data needed to compute net advection was given by *Derecki* [1975] and is beyond the scope of this paper. The summarized description of the input data included in this paper is given for general information. Listed parameters represent average values for the 1952–1968 period.

The precipitation over Lake Erie was determined by averaging records from 10 perimeter stations adjusted to overwater conditions. The precipitation adjustments were derived for monthly periods as lake-land precipitation ratios based on island and perimeter data. The island data, especially from larger islands, may contain substantial land effect, but they are still the most direct observations of the overwater precipitation available. Derived precipitation ratios indicate a slight reduction in the annual overwater precipitation (96%), with a monthly variation range of 12% (103–91%). The resulting average values of the overwater precipitation, along with other hydrologic factors, are given in Table 5. The volume of water entering or leaving the lake due to these factors is obtained in conjunction with the water surface area of Lake Erie (25,700 km²).

Runoff from the drainage basin is based on the streamflow records of the tributary rivers. The gaged area of the basin increased substantially during the study period and in the final years covered 69% (42,200 km²) of the total drainage basin (61,100 km²). Runoff from the ungaged streams and the lake periphery was obtained by using runoff per unit area from the nearby gaged stations. The magnitude of annual runoff is similar to that of the overwater precipitation, but the seasonal distribution of runoff is quite different (Table 5). While precipitation is generally well distributed throughout the year, most of the runoff occurs during late winter–early spring.

The inflow to Lake Erie from the upper lakes through the

TABLE 3. Change in Lake Erie Heat Content in 10^{17} cal, 1960–1963

	D = 0–3.8 V = 97.5	D = 3.8–11.4 V = 160.3	D = 11.4–19.0 V = 126.3	D = 19.0–26.7 V = 38.8	D = 26.7–38.1 V = 21.9	D = 38.1–53.4 V = 8.2	D = 53.4–64.0 V = 0.4	Total V = 453.4
January	0.0	−1.6	−1.0	−0.3	−0.2	0.0	0.0	−3.1
February	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.3
March	1.0	1.9	1.3	0.3	0.1	0.1	0.0	4.6
April	5.1	5.6	2.9	0.7	0.3	0.1	0.0	14.6
May	6.3	10.2	4.9	1.0	0.4	0.1	0.0	22.9
June	6.4	10.4	6.8	1.2	0.3	0.1	0.0	25.2
July	3.1	5.6	5.8	1.1	0.4	0.0	0.0	16.0
August	−0.4	−0.2	2.4	1.1	0.4	0.0	0.0	3.3
September	−3.5	−3.7	−0.8	0.7	0.6	0.0	0.0	−6.7
October	−4.9	−8.3	−6.6	−0.6	0.5	0.2	0.0	−19.7
November	−6.0	−9.9	−7.8	−2.3	−1.1	0.1	0.0	−27.0
December	−7.1	−10.2	−8.1	−2.8	−1.6	−0.6	0.0	−30.4
Annual	0.0	0.0	−0.1	0.1	0.0	0.0	0.0	0.0

The heat storage equation is $Q_t = V(T_2 - T_1)$, and the heat content is $V(T_2 - T_1)$.
D is the depth in meters, and V is the volume in cubic kilometers.

TABLE 4. Change in Lake Erie Heat Content in 10^{17} cal, 1952–1968

	D = 0–3.8 V = 97.5	D = 3.8–11.4 V = 160.3	D = 11.4–19.0 V = 126.3	D = 19.0–26.7 V = 38.8	D = 26.7–38.1 V = 21.9	D = 38.1–53.4 V = 8.2	D = 53.4–64.0 V = 0.4	Total V = 453.4	Change in Heat Storage Q_t, Ly/d
January	−0.6	−1.8	−1.0	−0.3	−0.1	0.0	0.0	−3.8	−48
February	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	3
March	1.1	1.8	0.8	0.2	0.0	0.0	0.0	3.9	49
April	4.4	4.5	2.5	0.6	0.1	0.0	0.0	12.1	157
May	6.7	12.8	6.0	1.4	0.6	0.2	0.0	27.7	348
June	5.8	8.5	5.9	0.9	0.2	0.0	0.0	21.3	276
July	3.1	5.0	5.4	0.9	0.2	−0.1	0.0	14.5	182
August	−0.3	0.5	2.5	1.2	0.5	0.2	0.0	4.6	58
September	−3.8	−5.3	−1.6	0.4	0.4	−0.2	0.0	−10.1	−131
October	−4.7	−6.9	−5.3	−0.2	0.6	0.4	0.0	−16.1	−202
November	−5.6	−10.6	−7.6	−2.6	−1.1	0.0	0.0	−27.5	−357
December	−6.3	−8.5	−7.7	−2.4	−1.3	−0.5	0.0	−26.7	−335
Annual	0.0	0.0	−0.1	0.1	0.1	0.0	0.0	0.1	0

Water temperatures below surface for this period are based on surface temperature differences.
The heat storage equation is $Q_t = V(T_2 - T_1)$, and the heat content is $V(T_2 - T_1)$.
D is the depth in meters, and V is the volume in cubic kilometers.

Detroit River and the outflow from the lake through the Niagara River and the Welland Canal constitute by far the major portion of the water supply and losses of the lake. The volumes of inflow and outflow are approximately an order of magnitude greater than other hydrologic factors (Table 5). The seasonal variation of these two factors is relatively small because of the natural regulation provided by the Great Lakes.

Evaporation values determined by various methods usually differ somewhat in magnitude, but these differences are generally well within the limits of accuracy required for the computations of advected energy. The water budget evaporation determined for Lake Erie was considered the most reliable; therefore these values (Table 5) were used to determine the advection heat loss due to the evaporation of lake water. For the Great Lakes, any reasonable evaporation values would be satisfactory for this purpose.

The values for snowfall on the lake were determined by averaging monthly records from lake perimeter stations. The volume of lake snowmelt was obtained from the snowfall over the ice-free surface area (obtained from Table 7) and snow density.

Temperature data. The air temperature was determined from four first-order weather stations located on opposite ends of Lake Erie to give a good approximation of average conditions around the lake. The average values for air temperature obtained by averaging monthly records from these stations (Buffalo, New York, Cleveland and Toledo, Ohio, and London, Ontario) are given in Table 6. Modified air temperatures were used to indicate the heat content contained in the precipitation and runoff (see (4)).

Temperatures for the inflow and outflow were obtained from the municipal water intake records for the Detroit and Niagara rivers, respectively (Table 6). These temperatures are recorded some distance below the surface and should be reasonably good indicators for the heat content of the water mass entering and leaving the lake through the connecting channels.

The water surface temperatures of Lake Erie were determined by adjusting water intake records from Erie, Pennsylvania, and Avon Lake, Ohio, to open-lake conditions. The average temperature from these two stations was considered to be sufficiently representative of the whole lake by *Powers et al.* [1959]. Water intake temperatures are obtained in the coastal waters at some depth below the surface and are the only source of long-term water temperature data. These data do not represent water surface temperatures in the open lake and require adjustments. The required adjustments were derived from the lake surface temperatures presented by *Millar* [1952] and simultaneous records from the water intake stations. Due to insufficient data during the winter, Millar excluded winter temperatures, which had to be estimated. Adjustments to the monthly shore temperatures are mostly negative, an annual value being −1.6°C. The average 1952–1968 water surface temperature values obtained for Lake Erie are listed with the other temperature data in Table 6. Derived water temperatures agree reasonably well with those presented by *Richards and Irbe* [1969] for a comparable period, 1950–1968. Their average temperatures are generally comparable with monthly variations of 0.6°–22.2°C and an annual average of 10.3°C. During most months the two sets of water surface temperatures agree within 0.5°C, maximum differences being approximately 1°C.

Ice data. The areal extent of ice cover on Lake Erie was determined from ice surveys which have been conducted regularly since 1962 by the Lake Survey Center of the National Oceanic and Atmospheric Administration (NOAA) and the Ice Forecast Centre in Canada. Estimates of the average monthly ice cover on the lake obtained from the individual surveys during December through April from 1962 to 1968 are given in Table 7. Extensive ice cover normally occurs during

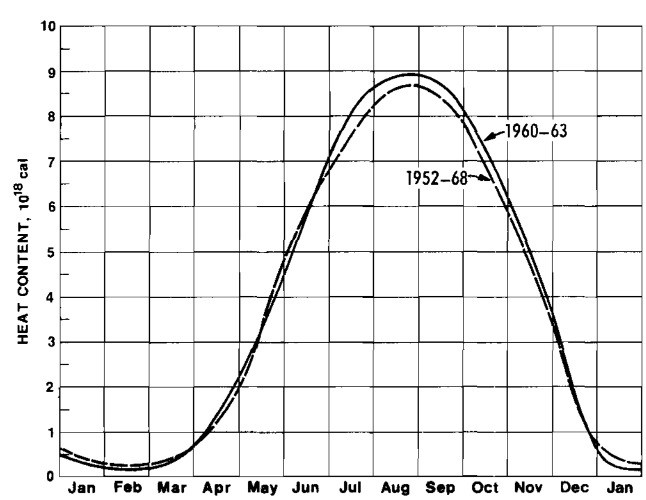

Fig. 3. Monthly heat content of Lake Erie.

TABLE 5. Average Values for Lake Erie Water Supplies and Losses in Centimeters, 1952–1968

	Precipitation P	Runoff R	Inflow I	Outflow O	Evaporation E	Snowfall S
January	6.4	7.0	49.6	56.8	7.2	31.8
February	4.9	8.1	44.6	51.8	3.6	25.9
March	6.3	14.0	54.3	58.5	1.8	21.1
April	8.9	11.9	53.7	59.2	1.2	5.6
May	7.2	6.5	56.6	63.9	2.6	
June	6.8	3.1	55.2	61.1	3.6	
July	7.0	2.2	57.9	61.6	10.1	
August	9.1	1.8	57.7	60.8	13.9	
September	6.2	1.3	55.6	57.7	16.5	
October	6.0	2.2	56.8	58.6	16.0	
November	6.7	3.6	54.3	56.6	12.0	17.5
December	6.2	6.5	55.2	58.5	8.3	28.4
Annual	81.7	68.2	651.5	705.1	96.8	130.3

January through March and is usually very light during December and April. Listed normal monthly values may vary considerably from year to year.

The ice thickness on the lake was determined from the Great Lakes Environmental Research Laboratory of NOAA ice thickness measurement observations conducted during 1968–1974 at a number of shoreline stations and NASA short-pulse radar observations obtained during the 1975–1976 ice season. Normal monthly values listed in Table 7 for the ice formation and melting phases and the average monthly ice cover represent preliminary estimates for the total ice thickness, including snow ice, which was relatively small. The preliminary aspects of these estimates should be emphasized, but the seasonal distribution and total ice accumulation (and melting) of 50 cm appear to be reasonable for Lake Erie, which is known for its extensive ice cover. The volume of water for the ice cover effects was obtained from the ice formation and melting values in conjunction with the ice-covered surface areas and ice density.

Results. Values for the major components of advected energy (Q_i, Q_o, Q_f, and Q_m) and the net advection are listed in Table 8. The resulting net advected energy is rather small because major portions of the water masses entering and leaving the lake (lake inflow and outflow) have sufficiently similar temperatures to produce energies which tend to balance each other. The advected energy is the smallest energy term in the Lake Erie energy budget [*Derecki*, 1975]. Net advection was also found to be the smallest term in the energy budget of Lake Ontario [*Rodgers and Anderson*, 1961] and was eliminated in more recent studies on that lake [*Rodgers and Sato*, 1971; *Elder et al.*, 1974]. The previous studies did not include ice cover, which appears to have a significant seasonal effect (results based on weak data). This omission would be more critical on Lake Erie, which has a much more extensive ice cover.

The average monthly net advection in Lake Erie for the 1952–1968 period varied from 21 Ly/d in February to −25 Ly/d in March, reflecting major ice formation and melting periods. The seasonal effect of ice cover is considerably higher than that of snowmelt. The snowmelt heat loss from the lake becomes relatively important only during the winter months with extensive open-water area, where ice cover effects are small. The inflow and outflow advection components are extremely small during winter because of low temperatures, approaching 0°C. Lake Erie gained heat through net advection during midwinter, spring, and early summer months and lost heat during the rest of the year.

TABLE 6. Average Temperatures for Lake Erie Water Supplies and Losses in Degrees Centigrade, 1952–1968

	Temperature			
	Air T_a	Inflow T_i	Outflow T_o	Lake Surface T_w
January	−4.4	0.7	0.3	0.2
February	−3.4	0.7	0.0	0.1
March	0.9	1.3	0.0	0.5
April	8.3	6.0	2.5	3.2
May	13.7	11.8	7.2	9.1
June	19.6	18.2	12.5	15.9
July	21.7	21.7	18.6	20.3
August	20.8	22.2	20.8	21.9
September	17.1	19.3	17.8	19.4
October	11.1	13.8	13.6	15.1
November	4.7	7.5	9.2	10.1
December	−1.8	2.1	3.1	3.1
Annual	8.8	10.4	8.8	9.9

SUMMARY AND CONCLUSIONS

Lake Erie monthly changes in heat storage and net advection were determined from long-term data, which indicates normal monthly values. The results presented are to a large extent based on the energy budget computations of a comprehensive Lake Erie evaporation study [*Derecki*, 1975] which covered 17 yr, 1952–1968. The energy budget computations were limited to average monthly values because of data limitations, primarily, the lack of continuous information on the lake heat content (water temperature profiles).

The average long-term (17 yr) monthly heat storage in Lake Erie varied from 348 Ly/d in May to −357 Ly/d in November, a total range of variation being 705 Ly/d. This total range of variation in the monthly heat storage represents the highest energy change in the Lake Erie energy budget. The corresponding average monthly advected energy varied from 21 Ly/d in February to −25 Ly/d in March and represents the

TABLE 7. Estimates of Lake Erie Average Monthly Ice Cover

Period	Lake Area Covered,* %	Ice Thickness,† cm		
		Formation	Melting	Average
December	6	4	2	2
January	50	18	7	11
February	86	23	13	18
March	54	5	24	17
April	8	0	4	1
Total		50	50	

*Areal ice coverage is based on ice flight observations for the 1962–1968 period.

†Ice thickness is based on 1968–1974 shoreline measurements and 1976 overwater radar observations.

TABLE 8. Lake Erie Advected Energy in Langleys per Day, 1952–1968

	Advection Components				
	Total Inflow Energy Q_i	Total Outflow Energy Q_o	Ice Formation Heat Gain Q_f	Ice Melt and Snowmelt Heat Loss Q_m	Net Advected Energy Q_v
January	0	1	21	12	8
February	0	0	50	29	21
March	2	0	6	33	−25
April	16	5	0	2	9
May	26	15	0	0	11
June	39	28	0	0	11
July	46	43	0	0	3
August	48	51	0	0	−3
September	39	45	0	0	−6
October	28	34	0	0	−6
November	15	21	0	5	−11
December	3	7	1	7	−10
Annual	22	21	6	7	0

smallest energy term in the energy budget of the lake. On an annual basis the heat storage and net advection are insignificant because the seasonal heat gains and losses balance each other. The lake gains heat through heat storage and net advection during the spring, the summer, and some winter months and loses heat during the rest of the year.

A comparison of heat storage and net advection values (Tables 4 and 8) shows that net advection is relatively important only during February and March, when the change in heat storage is minimal and ice cover produces maximum effects. During the other months the heat storage is much higher, exceeding net advection in most instances by more than an order of magnitude. Thus heat storage changes are of primary interest. The change in heat storage depends primarily on the monthly variations of water temperature profiles. For the estimated maximum monthly error of 1°C in the water temperatures the corresponding change in heat storage is approximately 50 Ly/d. Errors during most months should not exceed one half of the maximum. Thus presented estimates of heat storage give a reasonable indication of normal monthly values, which are generally lacking at this time.

NOTATION

- d_i ice density.
- d_s snow density.
- E lake evaporation.
- I lake inflow.
- L latent heat of freezing or melting.
- O lake outflow.
- P overwater precipitation.
- Q_i energy content of water entering the lake.
- Q_f ice formation heat gain.
- Q_m ice melt and snowmelt heat loss.
- Q_o energy content of water leaving the lake.
- Q_t change in energy storage within the lake.
- Q_v net advected energy.
- R runoff from drainage basin.
- S overwater snowfall.
- T_1 average temperature of lake at beginning of month.
- T_2 average temperature of lake at end of month.
- T_a air temperature.
- T_i inflow water temperature (Detroit River).
- T_o outflow water temperature (Niagara River).
- T_p wet bulb temperature.
- T_r air temperature with winter minimum at 0°C.
- T_w water surface temperature.
- V average volume of lake.
- V_1 volume of lake at beginning of month.
- V_2 volume of lake at end of month.
- V_e volume of lake evaporation.
- V_f volume of ice formation (freezing).
- V_i volume of lake inflow.
- V_m volume of ice melt.
- V_o volume of lake outflow.
- V_p volume of overwater precipitation.
- V_r volume of runoff from drainage basin.
- V_s volume of overwater snowfall.
- ΔT monthly change in lake temperature.
- ΔT_w water temperature adjustments.

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REFERENCES

Derecki, J. A., Evaporation from Lake Erie, *NOAA Tech. Rep. ERL 342-GLERL 3*, Great Lakes Environ. Res. Lab., Ann Arbor, Mich., 1975.

Elder, F. C., F. M. Boyce, and J. A. Davis, Preliminary energy budget of Lake Ontario for the period May through November, 1972 (IFYGL), *Proceedings of the 17th Conference on Great Lakes Research*, pp. 713–724, International Association for Great Lakes Research, Ann Arbor, Mich., 1974.

Millar, F. G., Surface temperatures on the Great Lakes, *J. Fisher. Res. B. Can.*, *9*(7), 329–376, 1952.

Powers, C. F., D. L. Jones, P. C. Mundinger, and J. C. Ayers, Exploration of collateral data potentially applicable to Great Lakes hydrography and fisheries, Phase 2, *Spec. Rep. 7*, Great Lakes Res. Inst., Univ. of Mich., Ann Arbor, Mich., 1959.

Richards, T. L., and J. G. Irbe, Estimates of monthly evaporation losses from the Great Lakes, 1950 to 1968, based on the mass transfer technique, *Proceedings of the 12th Conference on Great Lakes Research*, pp. 469–487, International Association for Great Lakes Research, Ann Arbor, Mich., 1969.

Rodgers, G. K., and D. V. Anderson, A preliminary study of the energy budget of Lake Ontario, *J. Fisher. Res. B. Can.*, *18*(4), 617–636, 1961.

Rodgers, G. K., and G. K. Sato, Energy budget study for Lake Ontario, *CMRP 1/71*, Environ. Can., Atmos. Environ. Serv., Downsview, Ont., 1971.

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