

A carbon budget for Lake Ontario

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With 3 figures and 3 tables in the text

Introduction

Although the cycling of carbon within and through lake systems is obviously of utmost significance to these systems, few attempts have been made at the calculation of a carbon budget for a lake. TAKAHASHI et al. (1968) and SCHINDLER et al. (1973) have determined the carbon budget for two small North American lakes and O'MELIA (1972) provides a preliminary estimate of this budget for the larger Swiss Vierwaldstättersee. However, there seem to have been no attempts to estimate the carbon budget for a very large lake.

During 1972 and early 1973 the United States and Canada conducted an intensive, interdisciplinary study on Lake Ontario. This program, entitled the International Field Year for the Great Lakes (IFYGL), provided a great deal of data on many different limnological and meteorological properties. Taking advantage of this large body of data, we have calculated the carbon budget for the IFYGL period (EADIE & ROBERTSON 1974). While this is the first carbon budget for a large lake, it applies only to one year which is known to have been rather atypical, being much cooler and wetter than normal. Thus, the study reported in this paper was conducted to determine a more generalized carbon budget for Lake Ontario and to compare the results to those obtained during the intensive IFYGL study.

Methods and data sources

The calculations presented in this paper are based on data collected prior to 1972 by a number of U. S. and Canadian organizations. The analytical techniques used to acquire these data can be obtained from the data sources specified below and will not be covered here. The methods of data screening and of calculating the various budget terms have been explained in EADIE & ROBERTSON (1974). The present paper includes only brief descriptions of these methods in the sections dealing with the separate budget terms.

The chemical data needed to calculate the inflow of inorganic and organic carbon in the rivers were obtained primarily from the U.S. Environmental Protection Agency's STORET data storage system and from information made available by the Water Quality Branch of Canada's Department of the Environment. The data on river flows were taken primarily from DECOOKE & WITHERSPOON (1973).

The measurements needed for calculation of properties within the lake were obtained primarily from data gathered and published by the Canada Centre for Inland Waters (1966—69). Supplemental information was obtained from the University of Toronto's Great Lakes Institute (1971) and from KRAMER (1968).

Results and discussion

Carbon Budget Equation

The calculation of the carbon budget is based on the following equation:

$$(IC)_I + (OC)_I + \Delta P = (IC)_O + (OC)_O + \Delta E + \Delta(CP) + \Delta(OS)$$

where

$(IC)_I$ = inorganic carbon in the inflowing rivers

$(OC)_I$ = organic carbon in the inflowing rivers

ΔP = net carbon fixed by primary production

$(IC)_O$ = inorganic carbon in the outflow water

$(OC)_O$ = organic carbon in the outflow water

ΔE = net exchange of carbon between the atmosphere and the inorganic carbon pool in the lake

$\Delta(CP)$ = net $CaCO_3$ precipitation-dissolution

$\Delta(OS)$ = net sedimentary deposition-decomposition of organic matter.

Terms for ground water carbon flux and carbon added by municipal and industrial sources have been omitted from this equation as the IFYGL study indicated the contributions from these are negligible. The equation also assumes that the amounts of carbon added to the lake by dry dust fall, by precipitation, and by ground water outflow are negligible in terms of the overall budget.

An attempt has been made to calculate the magnitude of each of the budget terms on a monthly basis based on all available pre-IFYGL data. The results of these calculations are presented for each term in the following sections.

Inorganic carbon in the rivers

The concentrations of total inorganic carbon in each of the major rivers were calculated for each month from average monthly values of alkalinity, pH, and temperature using the equation in Li et al. (1969). These results were then multiplied by the appropriate river flow measurements to obtain the values for flow of inorganic carbon presented in Tab. 1. As no chemical measurements were

Tab. 1. River inorganic carbon for the average (1965—72) year ($kg\ C/month \times 10^{-6}$).

Month	St. Lawrence	Niagara	Oswego	Genesee	Black
1	380	390	17.3	—	2.4
2	390	294	14.5	—	2.0
3	401	361	24.0	—	3.5
4	406	355	22.9	12.8	6.3
5	432	361	20.8	10.3	4.2
6	403	377	—	—	2.4
7	425	317	13.1	—	1.9
8	403	376	5.3	—	1.2
9	397	353	5.1	—	1.4
10	407	376	6.7	—	1.6
11	392	348	14.9	—	3.1
12	420	366	20.0	—	3.0
Mean*	405	356	15.0	(11.6)	2.8
IFYGL Ave. month*	424	373	(26.0)	5.9	3.0

* Does not include small river discharge which is estimated as $30 \times 10^{-6} kg\ C/month$ during the average year and $45 \times 10^{-6} kg\ C/month$ during IFYGL.

available for the small rivers, an estimate of the yearly inflow from these rivers was obtained by multiplying the average yearly inorganic carbon flow of the Oswego, Genesee, and Black Rivers by the ratio of the flow of the small rivers to that of the three larger rivers. The result of this calculation shows a yearly contribution from the small rivers of 3.6×10^9 kgC.

Tab. 1 includes a comparison with the monthly averages obtained for the IFYGL period. Obviously the Niagara is the main source of river-borne inorganic carbon in both estimates, as would be expected from the fact that this river provides over 85 per cent of the river inflow to the lake. The general magnitudes of the estimates in the two studies agree, with the unmonitored small rivers accounting, in both years, for more than half of the inorganic carbon inflow from rivers other than the Niagara.

Organic carbon in the rivers

Monthly averages for total organic carbon were multiplied by the appropriate river flow values to obtain the monthly organic carbon flows presented in Tab. 2. No values for organic carbon in the Niagara River were available other than those acquired during IFYGL. Thus, we have estimated the Niagara inflow of organic carbon by multiplying the IFYGL value for each month by the ratio for that month of the river flow during the average year to that during IFYGL. Also no organic carbon values were available for the small rivers, and these values have been estimated in a manner analogous to that used to estimate inorganic carbon flow in these rivers.

Tab. 2. River organic carbon for average year (1965—72) (kg C/month $\times 10^{-6}$).

Month	St. Lawrence	Niagara*	Oswego	Genesee	Black
1	—	37	2.1	1.2	2.1
2	—	23	3.3	1.4	1.2
3	—	24	4.8	3.0	3.6
4	45	39	6.6	2.6	4.2
5	42	51	6.3	2.5	3.6
6	27	49	3.3	1.5	2.1
7	42	38	3.6	1.5	1.8
8	30	14	2.4	0.7	1.2
9	24	37	1.8	0.6	1.5
10	39	54	1.8	1.0	1.5
11	33	29	3.6	1.6	2.4
12	—	38	5.1	1.4	1.8
Mean**	35	36	3.7	1.6	2.2
IFYGL					
Ave. month	44	42	3.8	0.9	(2.0)

* Niagara values estimated as explained in text.

** Does not include small river discharge which is estimated as 8.8×10^{-6} kg C/month during the average year and 11.0 kg C/month during IFYGL.

As expected a large proportion (about 70 %) of the organic carbon entered the lake with the Niagara River. The proportion of the organic carbon entering with this river is substantially lower, however, than the comparable proportion of inorganic carbon (over 85 %). The comparison in the table with the IFYGL results shows rather similar values for the two periods.

Carbon fixed by net primary production

GLOOSCHENKO et al. (1974) determined the primary production of Lake Ontario during 12 cruises in 1970. The daily rates for each cruise given in their paper have been converted to monthly estimates using the method they employ to obtain estimates for such periods of time. The monthly estimates are included as part of the overall carbon budget in Tab. 3. GLOOSCHENKO et al. made their measurements by the C^{14} method using a five-hour incubation. This method probably provides estimates of net primary production that are somewhat too high but these are the best values available for estimating the carbon added to the lake by primary production. As discussed by GLOOSCHENKO et al., the production values were highest in the spring, less in summer, up a little in the fall, and lowest during the winter. The seasonal cycle of net phytoplankton production caused the lake to gain carbon in the warmer months.

Tab. 3. Carbon budget for the average year ($\text{kg C} \times 10^{-6}$).

Month	Input			Output				Net	
	Inorganic		Organic	Inorganic			Organic		
	Rivers	Rivers		Rivers	Gas	CaCO_3			Rivers
			Primary produc- tivity						
1	4.6	0.5	0.9	3.8	8.3	-0.1	0.4	0.06	-6.4
2	3.6	0.4	1.2	3.9	2.5	0.2	0.4	0.05	-1.9
3	4.7	0.6	2.6	4.0	0.9	0.2	0.4	0.07	2.3
4	4.7	0.8	4.4	4.1	0.3	0.2	0.5	0.15	4.7
5	4.3	0.8	2.8	4.3	-0.1	0.1	0.4	0.25	3.0
6	4.2	0.6	4.1	4.0	-0.1	0.1	0.3	0.16	4.3
7	3.4	0.5	3.6	4.3	-0.2	0.1	0.4	0.23	2.5
8	4.0	0.2	3.1	4.0	-0.2	0.0	0.3	0.20	2.8
9	3.8	0.4	3.4	4.0	0.2	0.0	0.2	0.18	3.0
10	4.2	0.6	3.9	4.1	1.6	-0.1	0.4	0.19	2.6
11	4.0	0.4	2.3	3.9	5.6	-0.2	0.3	0.22	-3.1
12	4.3	0.5	1.1	4.2	8.6	-0.1	0.4	0.13	-7.2
Total	49.8	6.3	33.4	48.6	27.6	0.4	4.4	1.9	6.6
	89.5			82.9					

Net exchange of carbon between the air and the dissolved inorganic pool

Carbon dioxide continually exchanges across the air-lake interface. Part of the incoming gas is used to replace carbon fixed in net primary production and the effect of this has been estimated above. Another part of the gas exchanges with the dissolved inorganic carbon pool in order to compensate for solubility changes due to temperature fluctuations, and the net amounts of carbon flux into or out of this pool need to be estimated. To do this we have adopted the relationship developed by KANWISHER (1962) and LISS (1973) to estimate the net flux (see EADIE & ROBERTSON 1974 for a more complete description of this method). Our estimates are included in Fig. 1, which shows the movement is strongly out of the lake during the winter and weakly into the lake in the late spring and the summer. This pattern is similar to that found for CO_2 flux by WEILER (1974). The large amounts of carbon dioxide lost during the winter result from waters strongly supersaturated with this compound being brought to the surface of the lake during the mixing of the entire water column in this season. The supersaturation results, of course, from the decomposition in the hypolimnion of part of the organic matter produced by primary production.

Fig. 1 also includes a line representing the estimated net gas exchange values during IFYGL. The values from the average year tend to follow this line, indicating similarity in the seasonal patterns obtained in the two studies.

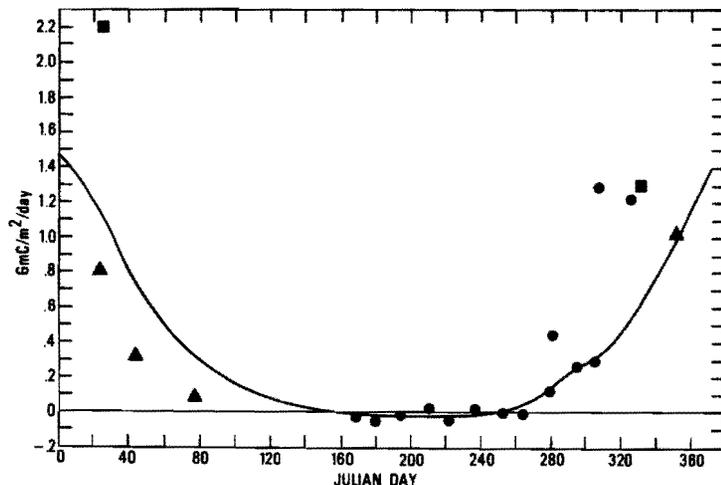


Fig. 1. The estimated net carbon flux between the atmosphere and the inorganic carbon pool in the lake. The line presents our subjective judgement of the flux during IFYGL based on the estimates obtained for that year. (The circles represent values calculated from CCIW data, the triangles values calculated from Great Lakes Institute data, and the squares values calculated from data in KRAMER 1968.)

Net carbon exchange in precipitation-dissolution of calcium carbonate

In the report on the IFYGL year budget, we estimated a net addition of calcium carbonate carbon to the sediments of 4.1×10^7 kg C/yr. This value is based on the data of THOMAS et al. (1972) using a mean deposition rate of 500 g/m²/yr and an average sedimentary calcium carbonate concentration of 0.43 per cent. Their study is actually based on data gathered before IFYGL and so the same estimate is used here.

The seasonal cycle of calcium carbonate deposition-dissolution, calculated from thermo-dynamic considerations as explained in EADIE & ROBERTSON (1974), is included in Tab. 3. Deposition predominated from February through July and dissolution from October through January with little net change in August and September. This cycle is related both to the seasonal temperature fluctuations and especially to the cycle of decomposition of organic matter.

Net carbon exchange in sedimentary deposition-decomposition of organic matter

As with the sedimentary calcium carbonate flux, values from THOMAS et al. (1972) were used to obtain estimates of net organic sedimentation. Based on their sedimentation rate and a sedimentary concentration of 1.98 per cent, the net organic carbon accumulation in the sediments is estimated at 1.9×10^8 kg/yr. A rough estimate of the seasonal distribution has been obtained by proportioning this total value to the months in relation to primary production in the previous month. These estimates are included in Tab. 3.

The average year carbon budget

An examination of the budget for the average year presented in Tab. 3 shows an approximate balance of the inflow-outflow terms. The total estimated carbon output is 92.6 per cent of the total estimated input. The minor discrepancy between these values can be easily explained as arising due to inaccuracies inherent in the measurement of some of the terms especially the primary production and gas exchange contributions.

Fig. 2 presents a comparison between the budget terms calculated for the average year and those calculated for the IFYGL year. The budgets obtained for the two periods are quite similar suggesting that the contributions of the major budget terms are probably roughly constant from year to year.

Tab. 3 includes an estimate of the net carbon flux for each month. These values show a net input in the spring and summer and a net output in the fall and winter. A further comparison between the input and output is provided by Fig. 3. As suggested earlier this shows a peak in input during the warmer months due to primary production. The output, on the other hand, peaks in the winter when the supersaturated hypolimnetic waters mix into the upper layers and release carbon dioxide to the atmosphere. The figure includes lines showing estimates of the outflow and inflow during the IFYGL period. The average-year

points correspond quite closely with the line, again indicating agreement between the results from the average year and those from the IFYGL period.

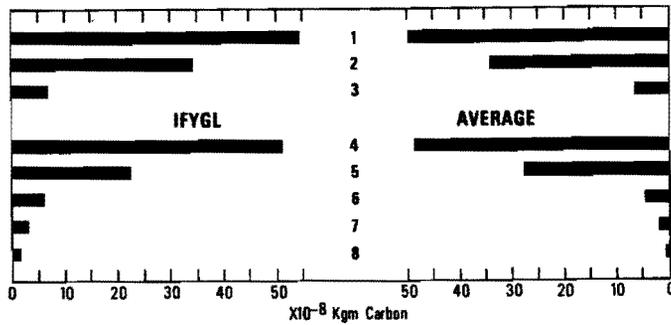


Fig. 2. A comparison between the carbon budget estimates for the average year and those for the IFYGL period. 1 = inorganic carbon in the inflowing rivers, 2 = carbon input due to net primary production, 3 = organic carbon in the inflowing rivers, 4 = inorganic carbon outflow in the St. Lawrence River, 5 = net exchange of carbon between the air and dissolved inorganic carbon pool, 6 = organic carbon outflow in the St. Lawrence, 7 = net carbon exchange in sedimentary disposition-decomposition of organic matter, 8 = net carbon exchange in precipitation-dissolution of CaCO_3 .

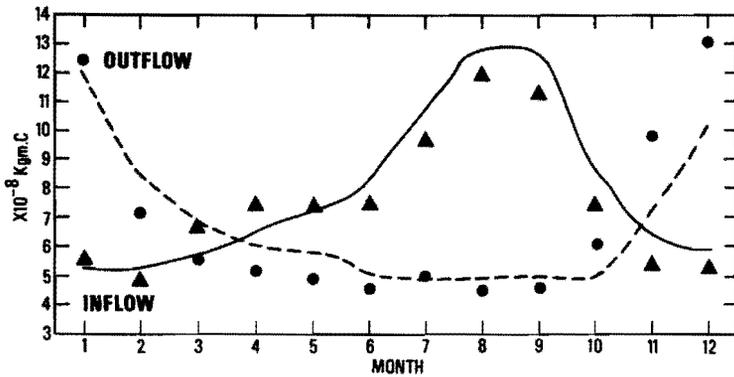


Fig. 3. Monthly means of carbon inflow (triangles) and outflow (circles) during the average year. The lines represent our subjective judgement of the trends of these properties based on the values calculated for the IFYGL period.

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References

- CANADA CENTRE FOR INLAND WATERS, 1966—69: *Limnological data reports — Lake Ontario*. — Canad. Oceanogr. Data Centre (a number of published reports obtained from CCIW, Burlington, Ontario).
- DECOOKE, B. G. & WITHERSPOON, D. F., 1973: A preliminary Lake Ontario water balance during IFYGL. — *Proc. 16th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res.* 675—683.
- EADIE, B. J. & ROBERTSON, A., 1974: An IFYGL carbon budget for Lake Ontario. — Abst. 17th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res. (Manuscript — submitted to *Limnol. Oceanogr.*).
- GLOOSCHENKO, W. A., MOORE, J. E., MUNAWAR, M. & VOLLENWEIDER, R. A., 1974: Primary production in Lakes Ontario and Erie: A comparative study. — *J. Fish. Res. Bd. Canada* 31, 253—263.
- GREAT LAKES INSTITUTE, 1971: *Data record, surveys of 1964*. — Univ. of Toronto, Rept. PR 42, 238 p.
- KANWISHER, J., 1963: On the exchange of gases between the atmosphere and the sea. — *Deep-Sea Res.* 10, 195—207.
- KRAMER, J. R., 1968: Mineral water chemistry, Great Lakes. — *Univ. of Mich., Great Lakes Res. Div., Spec. Rept.* 38, 59 p.
- LI, Y.-H., TAKAHASHI, T. & BROECKER, W. S., 1968: Degree of saturation of CaCO_3 in the oceans. — *J. Geophys. Res.* 74, 5507—5525.
- LISS, P. S., 1973: Processes of gas exchange across an air-water interface. — *Deep-Sea Res.* 20, 221—238.
- O'MELIA, C. R., 1972: An approach to the modeling of lakes. — *Schweiz. Z. Hydrol.* 34, 1—33.
- SCHINDLER, D. W., KING, H., SCHMIDT, R. V., PROKOPOWICH, J., FROST, V. E., REID, R. A. & CAPEL, M., 1973: Eutrophication of Lake 227 by addition of phosphate and nitrate: the second, third, and fourth years of enrichment, 1970, 1971, and 1972. — *J. Fish. Res. Bd. Canada* 30, 1409—1552.
- TAKAHASHI, T., BROECKER, W., LI, Y.-H. & THURBER, D., 1968: Chemical and isotopic balances for a meromictic lake. — *Limnol. Oceanogr.* 13, 272—292.
- THOMAS, R. L., KEMP, A. L. W. & LEWIS, C. F. M., 1972: Report on the surficial sediment distribution of the Great Lakes. Part I — Lake Ontario. — *Geol. Surv. of Canada, Paper* 72—17, 52 p.
- WEILER, R. R., 1974: Exchange of carbon dioxide between the atmosphere and Lake Ontario. — *J. Fish. Res. Bd. Canada* 31, 329—332.

Discussion

SALBACH: What is the relative significance of municipal input as a percentage of the total carbon input?

ROBERTSON: Mun. input represents less than one per cent of total C input.

WEILER: (1) In the gas exchange calculations, your choice of values for the gas exchange coefficient would underestimate the amount of exchange since field measurements of exchange coefficients are considerably higher. — (2) DOWNING & TRUESDALE have shown from wind profiles that wind speeds at 10 cm and 10 m differ by a factor of 2 rather than 3.

ROBERTSON: (1) Our choice for the exchange coefficient falls well within the previous measurements and more closely reflects laboratory values than field measurements. We feel that the measurements of this parameter are quite imprecise and that the value we use is as likely to be valid as a higher one. More studies are urgently needed in this area. — (2) Basic PRANDTL-VON KARMEN

boundary layer theory and environmental data (DEACON et al., 1956, *Aust. J. Physics* 9, 511) indicate a log relationship in the boundary. This would produce a correction of 3 but scatter in observed measurements would allow some variation from this.

EMERSON: (1) How did you make the gas exchange calculation? — (2) What measurements and assumptions did you use to calculate the mass transfer coefficient?

ROBERTSON: (1) Gas exchange was calculated using the equation:

$$F = 10(0.3 W^2 + 1) \cdot \Delta P \cdot a$$

where

F = carbon flux (moles/m²/hr)

ΔP = Partial pressure of CO₂ in surface waters — atmospheric pressure

a = Solubility of CO₂ in water (moles/l)

(2) We made no measurements to calculate the mass transfer coefficient. Our coefficient was chosen from literature values so that the mass transfer coefficient approximates the molecular diffusion coefficient at zero wind speed.