The Observed Winter Circulation of Lake Ontario

R. L. PICKETT

Great Lakes Environmental Research Laboratory, NOAA, Ann Arbor, Mich. 48104

28 May 1976 and 14 September 1976

ABSTRACT

Observations of Lake Ontario's monthly mean properties during the winter of 1972–73 suggest that currents and temperatures are nearly constant with depth and that the lake-wide mean circulation pattern consists of either one counterclockwise or two counterrotating gyres.

1. Introduction

Lake Ontario's winter circulation had not been observed prior to 1972. In both previous whole-lake studies [Harrington (1895) via surface drift bottles; Casey *et al.* (1966) via moored current meters] harsh weather and lake ice discouraged the extension of observations past autumn. However, there were predictions of the lake's winter currents.

Since the hydraulic circulation (from inflow–outflow) is always small, and thermally driven flow in nearly isothermal water must be small, winter currents should be wind driven. Both Rao and Murty (1970) and

Paskausky (1971) proposed wind-driven patterns for Lake Ontario's winter circulation based on homogeneous, vertically integrated numerical models. Both linear models calculated transport for a given wind, and both friction and the earth's rotation were incorporated. Rao and Murty's steady-state model predicted two counterrotating gyres induced by the bowl-shaped bathymetry. Transport was with the wind nearshore, and against the wind offshore. Paskausky's time-dependent model, however, showed only a one-gyre pattern rotating in the direction of the applied wind curl. The dominant pattern, according to Pickett and Rao's (1976) comparison of the models, depends on the relative strength of the bathymetric-wind curl effects. If the change in mean wind speed across the lake in any direction is comparable to the mean wind, then one gyre prevails. Otherwise two gyres prevail.

During the International Field Year for the Great Lakes (IFYGL) in 1972–73, the winter circulation of Lake Ontario was finally observed. Currents, along with winds and temperatures, were recorded several times an hour at buoys and towers throughout the lake for one year. An analysis of just the November 1972 currents was given by Pickett (1976), but this paper summarizes all the winter data. Results show that in winter Lake Ontario's temperatures and currents are nearly constant with depth, and the mean circulation does seem to be around either a one- or a two-gyre pattern.

2. Data

The buoy and tower sensors were designed to record surface winds within 1 m s^{-1} and 5°, water temperatures within 0.2°C, and currents within 2 cm s^{-1} and 5°. However, five months of data from an intercomparison station showed that electronic drift, fouling, data processing errors, etc., introduced operational errors about twice the design accuracies (Pickett, 1975). For more details on accuracies, equipment, sampling and processing procedures, see "Data Acquisition Systems," IFYGL Technical Plan, Vol. 2 (IFYGL Project Office, 1972).

Data from sensors recording less than 15% of a full month's record were discarded and the remaining data were edited. Currents were vector-averaged (by scalar averaging each component, then recombining) for each current meter to show net water movement for each month.

TABLE 1. Lake Ontario horizontally averaged temperature (°C).

	Depth (m)	May 1972	Nov. 1972	Dec. 1972	Jan. 1973	Feb. 1973	March 1973
Air	0	9	4	−1	−2	−6	4
Water	0	4	—	—	—	—	—
	10	5	9	—	—	—	—
	15	4	8	5	4	2	2
	16	—	8	5	4	2	2
	30	4	—	—	—	—	—
	50	4	—	—	—	—	—
	75	—	—	5	4	2	2

TABLE 2. Lake Ontario horizontally averaged winds and currents (cm s^{-1}).

	Depth (m)	May 1972	Nov. 1972	Dec. 1972	Jan. 1973	Feb. 1973	March 1973
Wind speed/dir.	0	260/E	480/NE	430/SW	470/W	430/NW	420/SE
Current speed	10	3	7	—	—	—	—
	15	3	9	8	10	8	7
	16	—	10	9	11	8	7
	30	3	—	—	—	—	—
	50	3	—	—	—	—	—
	75	—	—	7	9	7	6

3. Results

The monthly temperature data indicate that the lake was nearly isothermal during each winter month. The largest horizontal temperature change, for example, occurred in May 1972. A patch of 8°C inflow water occupied the surface layer over the Niagara Bar in an otherwise 4°C lake. The lack of vertical temperature gradients can be seen in the horizontally averaged temperatures (for each depth with at least three thermometers) shown in Table 1. Monthly temperatures vary only about 1°C with depth. Considering these small horizontal and vertical gradients, thermal contributions to the circulation should be small.

Table 2 contains monthly mean wind and current speeds. These scalar speeds and vector-averaged wind directions were obtained by combining data from all sensors at each level. Monthly changes in wind direction in the table are probably due to variations in storm tracks. For example, in December and January storms

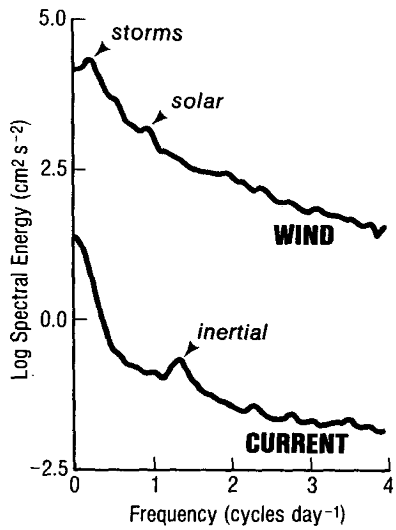

FIG. 1. Average spectra of east-west wind components at surface and east-west current components at −15 m.

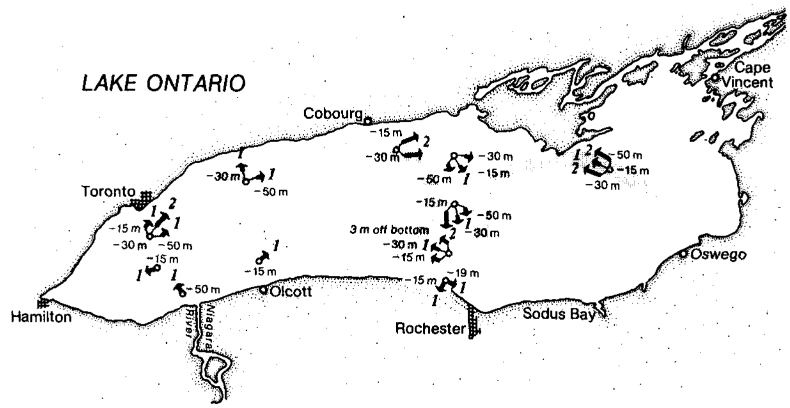

FIG. 2. Lake Ontario May 1972 observed currents (speeds cm s^{-1} at arrow tip, depths at arrow tail).

generally passed north of Lake Ontario and generated stronger west to southwest winds. Regardless of direction, however, monthly changes in scalar wind speed are reflected in the monthly variations in scalar current speeds (given for each depth with at least 3 current meters). Higher wind speeds produce higher current speeds at all depths. Also the small variations in current speed between observed levels suggest that Lake Ontario winter currents are barotropic.

A question early in the analysis was: Over what time interval should the currents be vector-averaged to produce stable background circulation patterns? To help answer this question, power spectra of the currents and winds for all winter were computed (sample in Fig. 1). Current spectra showed no significant energy peak corresponding to the four- to eight-day storm period occurring in the wind spectra. The lack of an energy spike in this region was also confirmed by calculating and comparing weekly average and monthly average current patterns. The similarity between weekly and monthly patterns, along with the spectral results, suggested that monthly current averages would be sufficient to depict the winter background circulation.

Monthly vector-averaged current charts for May and November 1972 through March 1973 are given in Figs. 2–7. Since models had predicted either one counterclockwise or two counterrotating gyres, the figures have big shaded arrows drawn to whichever pattern best fits the data. Since these meters operated unattended all winter, some errors undoubtedly crept in; hence, some of the meters in the figures do not match the patterns. But the major emphasis should be on the overall patterns deduced from the majority of current meters.

In May current speeds are low (Fig. 2), but meters at all depths from 15 m below the surface to 3 m above the bottom generally show the same pattern. There seems to be two gyres—counterclockwise in the east and clockwise in the west. The nonconforming meter off Olcott may be influenced by the previously mentioned warm water patch near that region.

The November data (Fig. 3) are all from about the same depth, but the pattern is entirely different from the pattern for May. The flow is mostly counterclockwise and much stronger in the west, and there is not much evidence of a second gyre in the east.

From November to December (Fig. 4), the current pattern changes again. There are large speed variations within an apparent two-cell structure that seems to

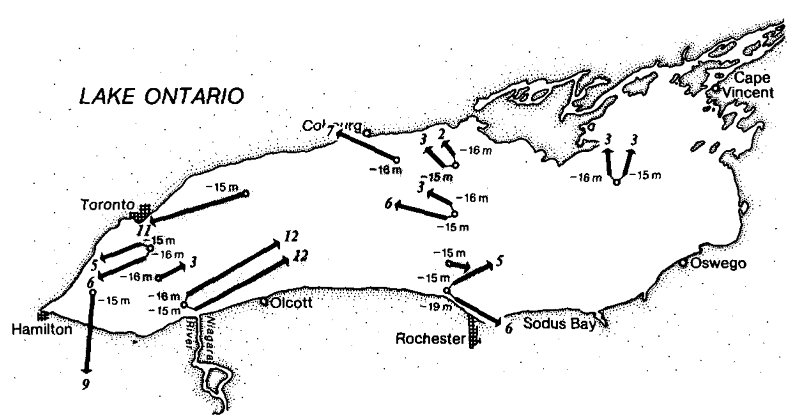

FIG. 3. As in Fig. 2 except November 1972.

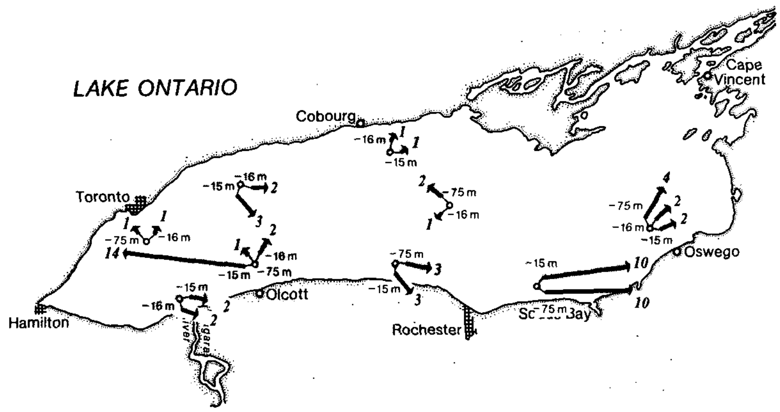

FIG. 4. As in Fig. 2 except December 1972.

have a clockwise center in the northwest and a counterclockwise center in the southeast portion of the lake. This same pattern tends to persist through January 1973 (Fig. 5), with higher speeds occurring in flow moving directly downwind.

Finally, in February and March (Figs. 6 and 7) the circulation seems to revert to one large counterclockwise gyre, with a pattern similar to November's.

4. Discussion

The current patterns in the figures are mean patterns. As such, they probably never exist. At each station currents speed up, slow down, and change direction from hour to hour and day to day. Even so, inspection of the original data confirms that most of the time, especially when speeds are high, the meters conform to the monthly mean pattern. Hence, one should be able to consider this mean pattern as the steady background flow driven by the monthly mean wind, but disturbed by wind variations.

This steady background flow is also what a steady-state model predicts. Since the data showed nearly uniform temperatures and currents with depth, patterns from a homogeneous, vertically integrated numerical model such as Rao and Murty driven with the mean wind should agree with the observed patterns.

If the monthly winds in Table 2 are assumed to be uniform over the lake, the Rao and Murty model will always produce two counterrotating gyres. In general, the dividing line between the gyres will run parallel to the wind direction with transport downwind in the shallow regions. Higher transports will occur if the wind is either stronger or directed more nearly down the lake's long axis.

These two-gyre model patterns matched the observed current patterns in December and January when the model was driven by the mean wind for that month. The uniform wind model results disagreed, on the other hand, with the two-gyre May observations. During May the observed flow was clockwise in the west, whereas the model flow was counterclockwise there. However, May was unusual in that winds were light and variable, and the air was much warmer than the lake. Under these conditions an appropriate wind stress for driving any model is difficult to choose.

The Rao and Murty model with uniform wind could not match, of course, the observations in months where the data seemed to show only one gyre. Why were these

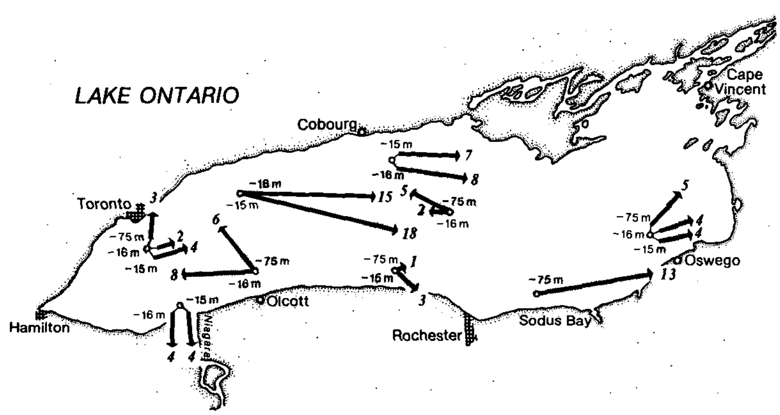

FIG. 5. As in Fig. 2 except January 1973.

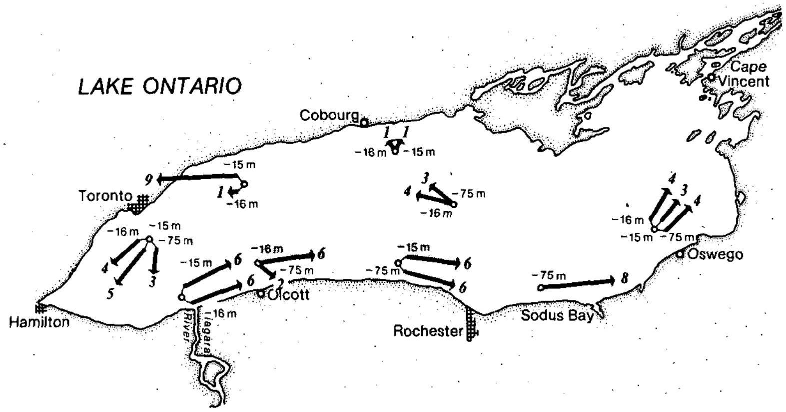

FIG. 6. As in Fig. 2 except February 1973.

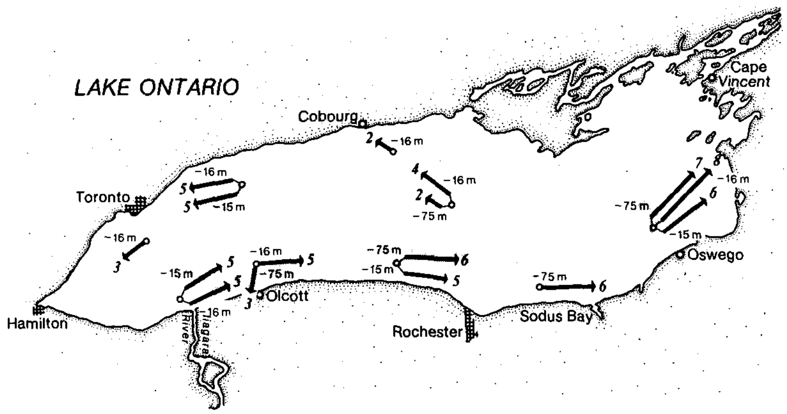

FIG. 7. As in Fig. 2 except March 1973.

months different? The obvious answer would be that winds injected more cyclonic vorticity into the lake during these months. Paskausky's model showed that the close passage of a storm with strong cyclonic winds can produce a one-gyre pattern. The effect of numerous, strong storms could be a mean cyclonic wind vorticity sufficient to overpower the clockwise gyre of the two-gyre pattern. Unfortunately, the wind data do not back up this explanation. Changes in the mean wind speed across the lake in any direction during any winter month were insufficient to overpower the two-gyre pattern according to the criterion of Pickett and Rao (typical monthly mean vorticities were on the order of 10^{-7} s^{-1}.)

In summary, the monthly winter current patterns in Lake Ontario seem uniform with depth, and seem to have either one counterclockwise (November, February, March) or two counterrotating gyres (May, December, January). The two-gyre pattern is probably due to the influence of the bathymetry on the mean wind-driven flow, but the single gyre pattern is unexplained.

REFERENCES

Casey, D. J., W. Fisher and C. O. Kleveno, 1966: Lake Ontario environmental summary—1965. EPA-902/9-73-002, U. S. Environmental Protection Agency, Region II, Rochester, N. Y., 73 pp.

Harrington, M. W., 1895: The currents of the Great Lakes. U. S. Weather Bureau Bull. B., U. S. Dept. Agric., Washington, D. C., 23 pp.

International Field Year for the Great Lakes Project Office, 1972: Data acquisition systems. IFYGL Technical Plan, Vol. 2, NOAA, Rockville, Md., 462 pp.

Paskausky, D. F., 1971: Winter circulation in Lake Ontario. *Proc. 14th Conf. Great Lakes Res.*, Intern. Assoc. Great Lakes Res., 593–606.

Pickett, R. L., 1975: Intercomparison of Canadian and U. S. Automatic Data Buoys. *Marine Tech. Soc. J.*, **9**, 20–22.

——, 1976: Lake Ontario Circulation in November. *Limnol. Oceanogr.*, **5**, 775–781.

——, and D. B. Rao, 1976: One- and two-gyre circulations in homogeneous lakes. IFYGL Bulletin 19, NOAA, Rockville, Md., 101 pp.

Rao, D. B., and T. S. Murty, 1970: Calculation of the steady state circulations in Lake Ontario. *Arch. Meteor. Geophys. Bioklim.*, **A19**, 195–210.