# Mirex and the Circulation of Lake Ontario

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13 September 1978

## ABSTRACT

The observed pattern of mirex in Lake Ontario's sediments is consistent with what is known about the Lake's long-term circulation. A reasonable simulation of the mirex pattern was obtained using a steady-state circulation model coupled to a simple water quality model. The equivalent 10-year mirex accumulation on the lake bottom from these numerical models is similar to the observed mirex pattern.

## 1. Introduction

In a recent article on mirex, Kaiser (1978) gave the history, chemistry, applications (insecticide for fire ants, marine antifouling agent, fire retardent, smoke generator, etc.) and environmental impacts of the compound. He also discussed how mirex, escaping during production and processing, ended up in Lake Ontario sediments. According to Kaiser, the long-lived substance probably leaked into the Niagara and Oswego rivers for about 10 years starting around the late 1950's or early 1960's. Apparently aided by the lake's circulation, the mirex spread and settled along the south shore and in the eastern end of the Lake. This accumulation made headlines in September 1976 when the New York Department of Environmental Conservation imposed a Lake Ontario fish ban.

The final pattern of the chemical in the sediments raised two questions. Did the spread of mirex from sources in the Niagara and Oswego River conform with what was known about the Lake's long-term circulation? And if it did, could the sediment pattern be reproduced with a simple model?

To answer the first question, we examined Lake

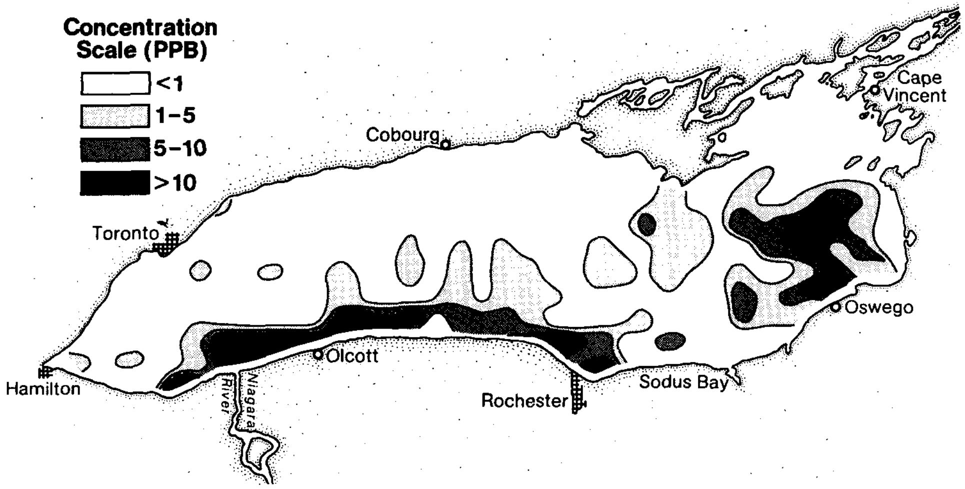

FIG. 1. Observed mirex deposits in the top 3 cm of Lake Ontario bottom sediments.

Ontario currents recorded during 1972–73 and found mean flows in the same directions as the mirex spread.

For the second question, we added simple water quality calculations to a steady-state numerical circulation model and produced sediment patterns similar to the observed mirex pattern.

## 2. Data

Fig. 1 (from Holdrinet *et al.*, 1978) shows the mirex concentrations observed in Lake Ontario sediments. Since the only known sources were in the Niagara and Oswego Rivers, lake currents must have carried the settling mirex eastward from the Niagara River as far as Rochester, New York. Similarly, the mirex sediment pattern off Oswego, New York, probably resulted from currents carrying mirex northward from the Oswego River mouth.

The circulation pattern surmised above can be verified with the observations in Pickett and Bermick (1977). Fig. 2 shows Lake Ontario currents vector-averaged over the stratified season from June through October 1972. The lakewide summer flow seems to follow two counterrotating gyres, with the counterclockwise gyre being larger. Regardless of the overall pattern, however, there is definitely a resultant eastward flow of 2–4 cm s$^{-1}$ off the mouth of the Niagara. Off Oswego the resultant flow is also eastward, but the direction must change to northward (to avoid the eastern lake shore) just beyond the river mouth.

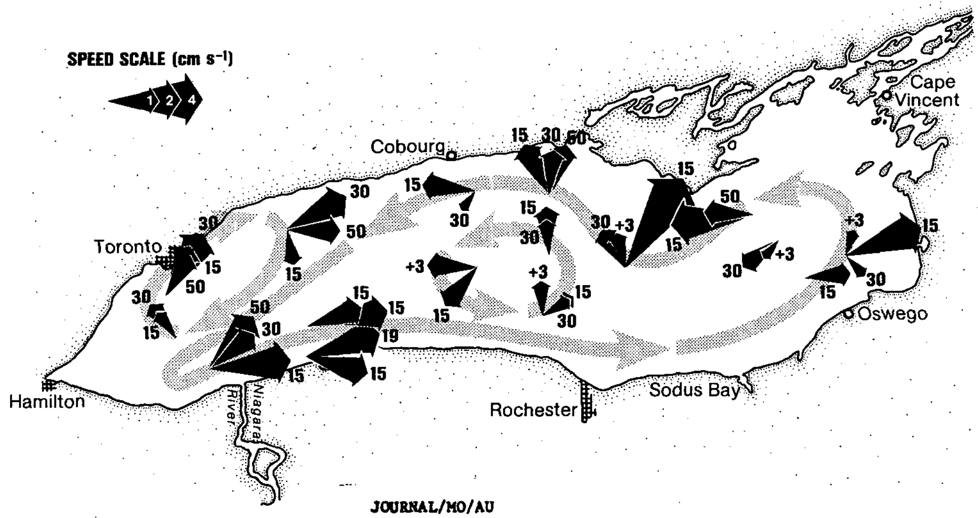

FIG. 2. Lake Ontario observed currents (depths in meters at arrow tips; +3 indicates 3 m above bottom), vector averaged from June through October 1972.

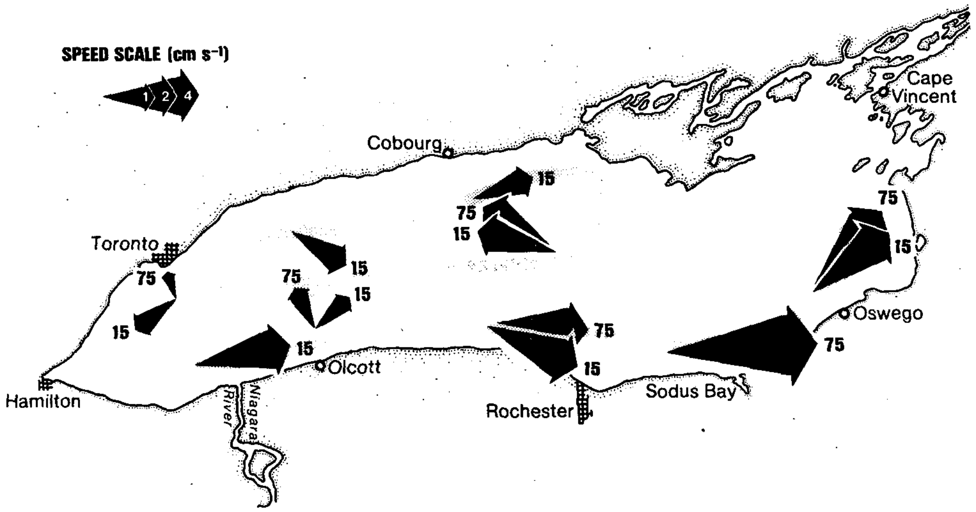

FIG. 3. As in Fig. 2 except for November 1972 through March 1973.

A similar current pattern can be obtained from Lake Ontario winter data. Fig. 3 is a composite (from Pickett, 1977) showing currents averaged from November 1972 through March 1973. Although fewer data were recorded during winter, the overall pattern still seems to be two gyres. In contrast to summer, the winter gyres seem to be more comparable in size and have higher speeds. Along the south shore, for example, the eastward speeds are 4–9 cm $s^{-1}$.

## 3. Model

### a. *Circulation*

These observed circulation patterns are reminiscent of the two-counterrotating-gyre pattern predicted for Lake Ontario by Rao and Murty in 1970. Their steady-state model showed that the lake would have two gyres if the dominant driving force were the prevailing wind.

This simple model seemed reasonable for simulating the circulation for the mirex distribution. First, both winter and summer observed currents do seem to have the predicted two counterrotating gyres. Second, the wind must be the important driving force over a period of some 10 years. There is no other significant force during the winter, and differential warming (which would enhance counterclockwise flow) is important during only a relatively small portion of the year. Also, climatological data from around Lake Ontario (National Climatic Center, 1975) show that both the most frequent and the strongest winds come from the west. Since the driving force of the wind (stress) is proportional to the wind speed squared, one would expect that the two-gyre pattern set up by these strong west winds would dominate the long-term average circulation.

Using the above assumptions, we ran the Rao and Murty steady-state numerical model with the climatological mean west wind (7 m $s^{-1}$, which is equivalent to $\sim 1$ dyn $cm^{-2}$). This was a linear homogeneous model in which vertical integrated transports were calculated for the given wind stress. Bottom topography and the earth's rotation were incorporated. Inflows were added at the Niagara and Oswego Rivers (5700 and 180 $m^3$ $s^{-1}$, respectively) and an outflow at the St. Lawrence (5880 $m^3$ $s^{-1}$). Bottom friction was taken to be of the form

$$\mathbf{F} = k\mathbf{M}/H^2,$$

where **F** is the bottom friction vector ($cm^2$ $s^{-2}$), **M** the current transport vector ($cm^2$ $s^{-1}$), $H$ the depth (cm) and $k$ (a constant) = 270 $cm^2$ $s^{-1}$. The constant $k$ was selected by successive model runs to produce currents comparable to those observed.

The transport lines from this model are shown in Fig. 4. Transport is parallel to both the north and the south shores, with a return flow down the middle of the lake. This pattern agrees fairly well with the observed currents in Figs. 2 and 3—especially in the southern and eastern portions of the lake where mirex was found.

### b. *Water quality*

Next, steady-state water quality calculations were added to this circulation model. Sources of mirex were placed at the Niagara and Oswego River mouths and allowed to advect, diffuse and settle according to

$$H(\partial C/\partial t) + \nabla\cdot\mathbf{M}C = A\nabla\cdot H\nabla C - \lambda C,$$

where $C$ is the mirex concentration (Oswego, $3.3 \times 10^{-12}$; Niagara, $1.14 \times 10^{-13}$), $t$ time (s), $A$ the

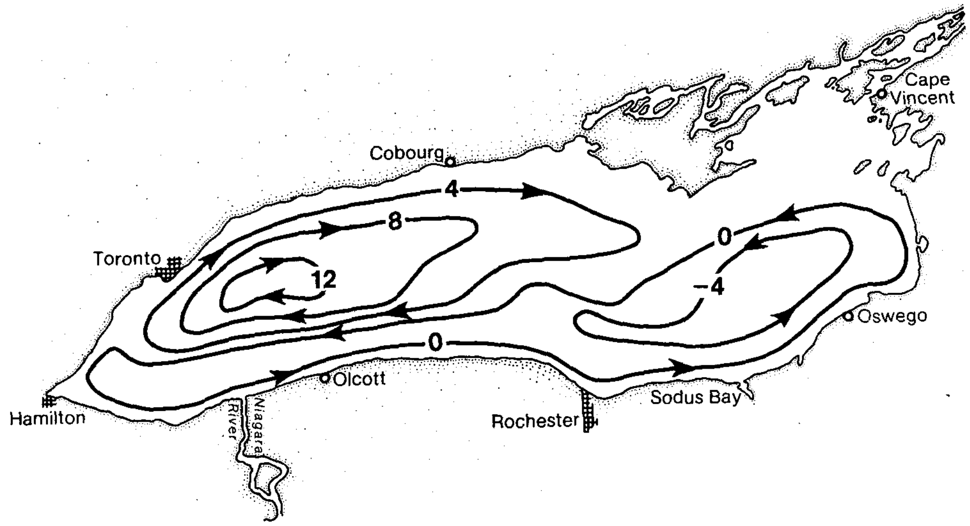

FIG. 4. Steady-state model transport lines ($10^{10}$ cm$^3$ s$^{-1}$) in Lake Ontario for 7 m s$^{-1}$ west wind.

horizontal diffusion (= $1.5 \times 10^5$ cm$^2$ s$^{-1}$) and $\lambda$ the settling speed (= $4 \times 10^{-3}$ cm s$^{-1}$ or 3 m day$^{-1}$). The finite-difference form of this equation was taken from Schwab *et al.* (1974).

Mirex concentrations at the two sources were unknown, so they were adjusted until the above values gave final bottom concentrations comparable to those observed. The value of horizontal diffusion ($A$) was taken from Kullenberg *et al.* (1973). They used large-scale dye experiments in Lake Ontario and related scale size to the appropriate value of diffusion. Finally, a settling speed ($\lambda$) corresponding roughly to that of fine sediment was used (we assumed mirex attached to fine sediment and then settled), and the water quality equation was integrated to a steady state. Next the mirex deposited on the bottom from this model was calculated for the equivalent of a 10-year period.

## 4. Results

The results of this accumulation are shown in Fig. 5. Some 200 kg of mirex ended up on the bottom according to the model. If this accumulation were well mixed in the first few centimeters of sediment (as was assumed in the data for Fig. 1), then the concentrations would be those shown in Fig. 5.

Most mirex from the Niagara River source moved parallel to the shoreline, spreading east as far as Rochester. Mirex from the Oswego River moved in response to the counterclockwise gyre in an offshore direction. A comparison of the water quality model results in Fig. 5 with the mirex observations

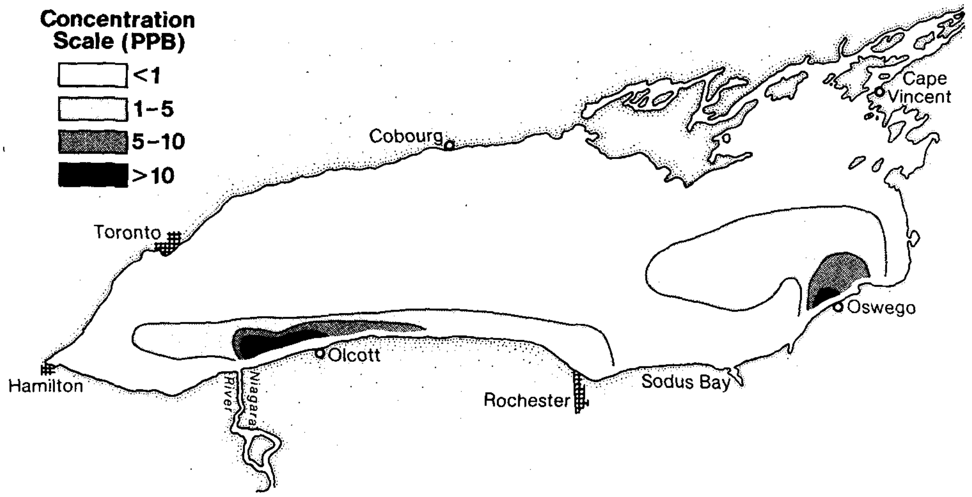

FIG. 5. Ten-year simulation of mirex deposits in Lake Ontario bottom sediments.

in Fig. 1 shows reasonable agreement. The main difference between the two is that the model results are too smooth, probably because we used a steady wind and a steady-state model. Storms from various directions over the years undoubtedly stirred up the mirex and produced the larger irregular patterns.

The five factors required to operate this model were wind, bottom friction, source concentrations, diffusion and settling speed. Our selection procedure was to use climatological winds, to adjust bottom friction to match observed currents, to choose river concentrations to match observed mirex accumulations, to select horizontal diffusion from dye studies and to use a settling speed for fine sediments.

With all these choices, we wondered how sensitive our results were to our particular selections. To find out, we ran tests over ranges of these values and found that the factors did not compensate. For example, in the circulation model, decreasing the wind required the bottom friction to decrease in order to match the observed current speeds. But decreasing the bottom friction also altered current directions. Thus only a moderate range of wind (±1 m $s^{-1}$ and 30°) and bottom friction (±50 $cm^2$ $s^{-1}$) produced currents, and hence mirex patterns, comparable to those observed. Similar results were found in the other choices. Large changes in diffusion or settling speed (>25%), for example, could not be compensated by altering other factors.

We also found that in the model the two sources of mirex were independent. Neither source by itself could be adjusted to produce anything similar to the observed pattern. Also, altering the mirex concentration in either river only altered the mirex accumulation, in the exact ratio, in the adjacent patch.

The model also allowed us to crudely estimate a mirex budget for the 10-year period. Based on the river concentrations required for our bottom accumulations, about half the mirex entered via each of the two source rivers. About half of this total settled out and the other half either stayed in the lake water or left through the St. Lawrence River.

In summary, our results suggest that the spread of mirex in Lake Ontario was consistent with what is known about the Lake's circulation, and that very simple models can be useful for studying distributions of lake pollutants.

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