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WINTER CIRCULATION IN LAKE ONTARIO

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ABSTRACT. Data from a high resolution array of self-recording current meters in a north-south cross section of Lake Ontario are presented. The measurements cover a 140-day period from 4 November 1982 to 23 March 1983. Nearshore current fluctuations are large and generally coherent with wind variations while currents in deep water tend to flow in the opposite direction and are quite uniform in the vertical. Time-averaged currents show a pronounced maximum of eastward flow along the south shore balanced by westward flow in the central part of the cross section, while the net transport near the northern shore tends to vanish. The total transport in the belt of eastward flow is ten times larger than the hydraulic transport associated with the Niagara-St. Lawrence flow, thus suggesting a recirculation of 90% of the river inflow. Corroboration of the south shore current measurements is provided by satellite-tracked drogues.
ADDITIONAL INDEX WORDS: Water transport, mixing, current meters, hydrodynamics, remote sensing.

INTRODUCTION

The circulation of large lakes is characterized by complicated variations in space and time. Detailed measurement of such circulations would require deployment of self-recording current meters at numerous locations and various depths, which is not a practical proposition. In the past, therefore, lake circulation studies have generally relied on a sparse network of instruments covering the whole lake and have tried to fill the voids by interpolation and by recourse to hydrodynamical models (see e.g., Pickett 1976). While circulation models of large lakes appear to give adequate simulations of the current response to strong wind impulses, their overall reliability is less impressive (Allender 1977, Simons 1980, Schwab 1983). Clearly, it would be desirable to design a measurement program which permits unambiguous interpolation between instruments and allows for verification of mass conservation requirements. This suggests a high resolution array of current recorders in one or more cross sections of a lake. Such an experiment was carried out in Lake Ontario in the winter of 1982/1983 and will be reviewed in this paper.

A wealth of information on water movement in Lake Ontario has been obtained during the 1972 International Field Year for the Great Lakes (IFYGL). For an extensive bibliography and review of results of the program, reference is made to Saylor *et al.* (1981). The IFYGL study was primarily concerned with the stratified season and in particular the nearshore observations were limited to that season. Although a network of mid-lake moorings was maintained during the following winter, the resolution of the array was insufficient to arrive at a clear picture of the winter circulation. Furthermore, the current meter data were often difficult to reconcile with available model results. Thus the IFYGL study left a number of questions unanswered and actually raised some new ones.

One of the most striking observations during the 1972 Field Year was a strong eastward current along the south shore of Lake Ontario. During the stratified season this boundary current formed part of the lake-wide counterclockwise circulation associated with generally warmer water in the shore zones (Saylor *et al.* 1981). The limited observations during the winter of 1972/73 indicated that this current persisted during the homogeneous season but the origin and extent of the phenomenon was not clear. The 1982/83 measurements to be discussed in the present paper provide a much more detailed description of this eastward flow along the south shore of Lake Ontario. In addition, the present measurements show how this flow is balanced by a westward flow in the interior of the lake. Furthermore, the current meter observations were complemented by Lagrangian experiments with satellite-tracked drogues. The drogue displacements confirm the earlier observations and will also be reviewed in this paper.

CURRENT MEASUREMENTS

During the winter of 1982/1983 extensive current measurements were made in Lake Ontario. Current meters were deployed in two arrays, the first one following the 50-m depth contour along the north shore, the second one extending across the lake from Port Hope, Ontario, to Point Breeze, New York (Fig. 1). Instruments were located at depths of 12 m below the surface and 1 m above the bottom and at an intermediate depth in the cross-lake array. A total of 34 complete records were obtained for the 140-day period of measurement, 4 November 1982 to 23 March 1983. Data from the alongshore array were used to study alongshore propagation of topographic waves and the results have been described by Simons (1984). The present analysis is concerned with the cross-shore array. The offshore location of the stations and measurement depths are summarized in Table 1. The depth profile of the section is shown in Figure 2, with instrument positions indicated by black circles. The contour lines shown in Figure 2 will be discussed presently.

Currents were decomposed into alongshore and onshore components with the alongshore direction defined to be 80° from north. Our primary concern is with the alongshore current and the distribution of this flow throughout the cross section. All time series were smoothed by a digital low-pass filter. The filter is designed to eliminate fluctuations shorter than one day without affecting current variations with periods longer than one day. This eliminates all effects of free surface seiches and any wave-induced noise in the current meter records.

For many practical considerations it is important to determine long-term mean water movements in a lake. The cross-lake distribution of the alongshore current averaged over the entire period

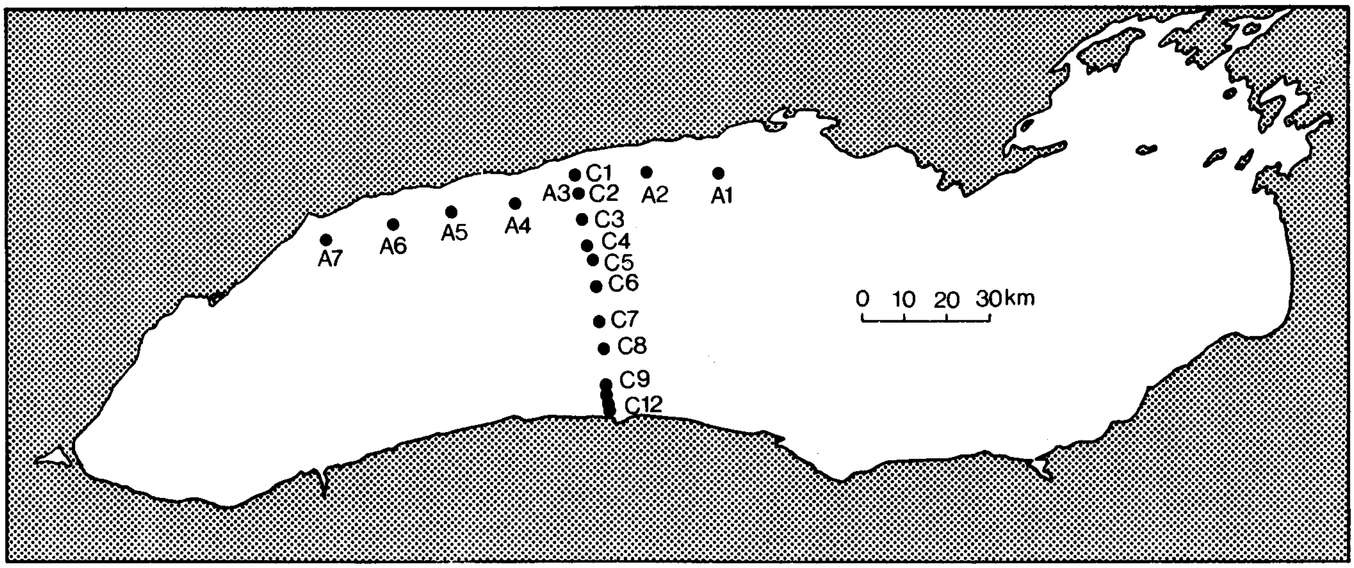

FIG. 1. Current meter moorings in Lake Ontario, 4 November 1982–23 March 1983.

TABLE 1. Current meter moorings in Lake Ontario with complete data records for 140-day period, 4 November 1982–23 March 1983.

Station	Distance from north shore (km)	Water depth (m)	Instrument depths (m)		
C1	5.2	28	12		
C2	8.3	54	12		53
C3	15.1	74	12		73
C4	21.7	100	12		99
C5	24.0	112	12	50	111
C6	30.7	147	12	50	146
C7	40.2	180	12	50	179
C8	47.4	171	12	50	170
C9	55.6	95	12	50	94
C10	57.3	74			73
C11	59.2	52			51
C12	61.4	29	12		28
South shore	64.2				

from 4 November 1982 to 23 March 1983 is presented in Figure 2. Positive contour values indicate eastward currents, negative values represent westward currents. The currents show remarkable consistency in the vertical as should be expected under homogeneous conditions. Most striking is the strong eastward current along the south shore with compensating return flow in deep water. This seasonal-mean circulation will be discussed in more detail in the next section.

Alongshore current variations in time and space are illustrated in Figure 3. The first record shows the current 12 m below the surface at a distance of 5 km from the north shore with a sounding depth of 28 m. The current is characterized by large-amplitude oscillations with periods of 5 to 10 days. It was analyzed as part of the data from the alongshore current meter array by Simons (1984). In essence, the current fluctuations are caused by local wind impulses, with secondary effects of wind-induced topographic waves propagating around the perimeter of the lake in a counterclockwise direction.

The three records in the centre of Figure 3 represent currents in the deepest part of the cross section at 12 m and 50 m below the surface and 1 m above the bottom. They show that the current is essentially uniform in the vertical and generally runs against the direction of the coastal current. This deep return current is primarily driven by pressure gradients associated with the slope of the free surface against the wind (Bennett 1974). In addition, deep currents exhibit low-frequency oscillations due to topographic vorticity modes of rotating basins (see e.g., Saylor *et al.* 1980).

Finally, the last current record of Figure 3 shows the near-surface current at a distance of 3 km from the south shore with a water depth of 29 m. The fluctuating component of the current is very similar to that observed at the north shore, both in amplitude and in phase. However, the long-term mean component is quite different, with a pronounced eastward net flow raising the overall level of the south shore current record. A similar contrast between the south shore and north shore currents clearly emerged from the extensive coastal observations during the stratified season of 1972

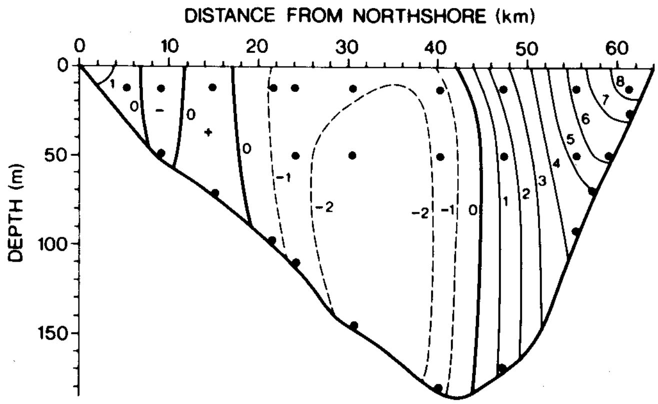

FIG. 2. Time-averaged eastward current (cm/s) in Lake Ontario cross section of Figure 1, 4 November 1982–23 March 1983. Instrument locations are denoted by black circles.

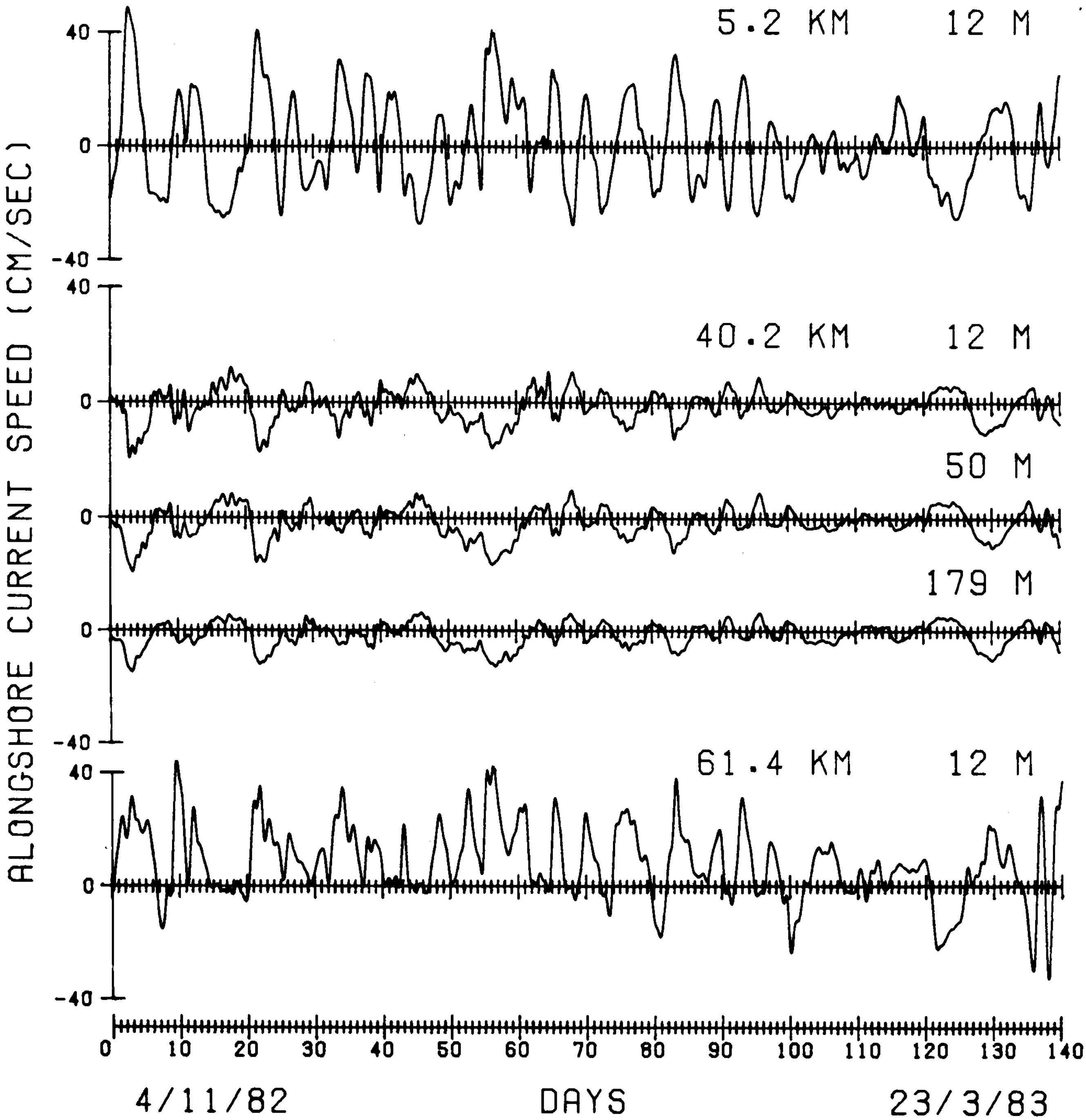

FIG. 3. Filtered time series of alongshore currents in Lake Ontario cross section of Figure 1 at indicated depths and distances from north shore.

(IFYGL) and also was suggested by the more limited winter data of 1972/73. The dynamics of this phenomenon in presence of stratification have been presented in the IFYGL literature (see Saylor *et al.* 1981 for a review). The properties of this circulation during the homogeneous season will be presented in the following pages.

TRANSPORT CALCULATIONS

The spatial resolution of the above current measurements should be adequate to compute an accurate distribution of water transport through the cross section. The first step is to obtain vertically integrated currents or transports per unit width for each vertical string of current meters. Since the currents are quite uniform in the vertical, as illustrated by the example of Figure 3, a simple linear interpolation should be acceptable. Thus, for strings of three current meters, the integrated current, U, is obtained as follows:

$$U = 50 \frac{u_1 + u_2}{2} + (h - 50)\frac{u_2 + u_3}{2} \quad (1)$$

where u_1, u_2, and u_3 are the currents at depths of 12 m and 50 m below the surface and 1 m above the bottom and h is the local water depth in meters.

For moorings with observations at two depths, the formula used is

$$U = h \frac{u_1 + u_2}{2} \quad (2)$$

where u_1 and u_2 are the currents at 12 m and the bottom. The latter approximation is also used for moorings with observations at a single depth. In that case the missing current is estimated as follows. First, the ratio of standard deviations between surface (12 m) and bottom currents is obtained for stations where both measurements are available. For moorings in water shallower than 100 m the values range from 1.2 to 1.4. Thus, the missing surface records in stations C10 and C11 are obtained by adding one third to the bottom current and the missing bottom current for station C1 is estimated by subtracting one quarter from the surface current.

The vertically-averaged current is equal to the vertically-integrated current divided by the local water depth. The long-term mean values of the vertically-averaged currents for each string of current meters are presented by black circles connected by solid lines in the left hand panel of Figure 4. Positive values represent eastward flow. The standard deviations of the fluctuations around the long-term means are denoted by triangles connected by broken curves in the same drawing. The current fluctuations are large in both coastal zones and decrease with offshore distance much more rapidly near the steep south shore than over the gently sloping bottom of the north shore.

The long-term mean values and standard deviations of the vertically-integrated currents or transports per unit width are presented in the right hand panel of Figure 4. Integration of the area under the mean transport curve gives a total eastward water transport of 70 × 10^3 m^3/s and a total westward transport of 66 × 10^3 m^3/s, the net transport being 4 × 10^3 m^3/s to the east. This may be compared with the hydraulic flow associated with the Niagara inflow and St. Lawrence outflow which is approximately 7 × 10^3 m^3/s as illustrated by the shaded rectangle in Figure 4. Expressed in terms of the one-way transport, the error is about 4%. This small error in the total water balance, together with the horizontal and vertical consistency of the current observations shown in Figures 2 and 3, lend considerable credence to the data.

The cross-lake distribution of water transport divides the lake into three zones. In the northern part, the mean transport tends to vanish but the fluctuating component of the transport is very large. This is consistent with concurrent wind observations which show large day-to-day variations in speed and direction but a nearly vanishing net forcing when averaged over the entire period of measurement. The southern part of the section, on the other hand, shows a strong eastward mean transport which is apparently compensated by return flow in the central part of the basin. Here, the standard deviations reach a maximum at the

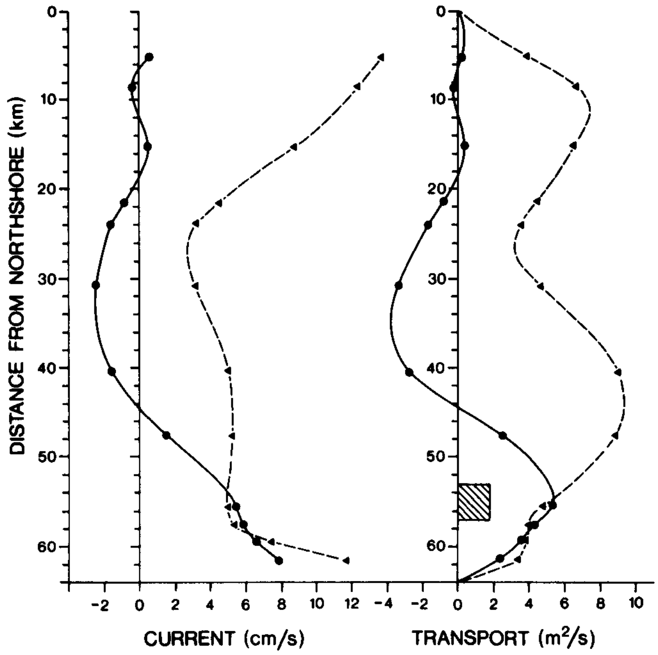

FIG. 4. Left: long-term means (solid lines) and standard deviations in time (dashed) of vertically-averaged currents in Lake Ontario cross section of Figure 1, 4 November 1982–23 March 1983. Right: Same for vertically-integrated currents. Shaded rectangle illustrates contribution from river flow.

line separating the belts of mean eastward and mean westward transport. This suggests a north-south meandering of the eastward and westward flow maxima at this point, in contrast to the northern border of the return flow which appears quite stable with low standard deviations of fluctuating transport components.

At first glance, the cross-lake distribution of the seasonal-mean water transport (solid lines of Fig. 4) seems to reflect the results of analytical and numerical model studies (see Simons 1980 for a review). Upon closer inspection, however, significant discrepancies become apparent. If the seasonal-mean circulation is visualized as the quasi-steady response of the lake to the mean wind, the corresponding model solutions display narrow wind-driven boundary currents along both shores with adjacent bands of return flow and cross-wind drift in the interior. In this particular cross section of Lake Ontario, typical numerical solutions for the mean wind stress during the period of observation (1.1×10^{-2} Nm^{-2} to the east) are dominated by a relatively large clockwise circulation cell near the north shore while the counterclockwise cell along the south shore is quite weak and only a few km wide. In contrast to these solutions, the observations show negligible net transport near the north shore, the return flow is concentrated in the central part of the cross section, and the band of south-shore flow extends to the point of maximum depth (see Figure 2). Thus, the strong eastward flow along the south shore is not a narrow boundary current but, together with the return flow, forms a counterclockwise circulation cell centered in mid-lake. Simons (1985) has used these observations to evaluate the reliability of circulation models and found that the seasonal-mean flow was due to nonlinear interactions of topographic waves.

As noted above, the one-way transport averaged over the period of observation is ten times as large as the hydraulic flow. If it is assumed that the eastward flowing Niagara River water is mixed throughout the belt of eastward transport, then it follows that 90% of this inflow must be recirculated, since only 10% of the total eastward transport can leave through the St. Lawrence River. With a mean speed of 5 km/day in the belt of eastward transport and a length of the lake less than 300 km, the time scale of the recirculation is a few months. In reality, the recirculation must be expected to be greater than 90% since the Niagara River water will not be confined to the belt of easterly transport as illustrated by the following Lagrangian drogue experiments.

To conclude this discussion of the current meter data, cross-lake distributions of vertically-integrated currents as a function of time for the entire period of observation, 4 November 1982 to 23 March 1983, are shown in Figure 5. Solid lines denote reversals from eastward to westward transport and vice versa. Vertical shading represents eastward transport greater than 10 m^2/s, horizontal shading represents westward transport greater than 10 m^2/s. The meandering of the transport maxima in the southern part of the basin is quite noticeable.

LAGRANGIAN DROGUE EXPERIMENTS

With a view to establish the long-term fate of the Niagara River plume and its relationship to the strong and persistent eastward transport along the south shore of Lake Ontario, two Lagrangian drogue experiments were conducted in the fall of 1983. Two satellite tracked drifters were released at the Niagara River mouth and their movement was followed during two periods: 3–18 October 1983 and 20 October–1 November 1983. The current drifters used in these experiments were of the Mini-TOD type manufactured by Polar Research Laboratory of Carpinteria, California. The buoy hulls are constructed of aluminum and fibreglass, weighing 33 kg with batteries in place. The buoys are 1.5 m long and have a maximum diameter of 0.3 m. The drogue, which is tethered one meter below the hull, is 0.6 m wide and 3.65 m long (Fig. 6).

The transmitter inside the buoy emits a 401 MHz pulse every 54 seconds. The doppler shift of this frequency as it reaches a satellite is used to calculate the buoy position. Successive locations are stored in files on a computer system. When plotted in sequence these positions show the trajectory or "track" of the buoy.

Remote tracking of the buoys was made possible by the Argos Satellite-Based Data Collection and Platform Location System. The system consists of a user platform, in this case a buoy, two polar orbitting Tiros-N satellites, a data processing centre in Toulouse, France, and a computer system to permit user access to the data. After the buoy signal is received by the satellite, it is transferred to the NESS (National Environmental Satellite Service) center at Suitland, Maryland, U.S.A. Here the Argos data are separated from the other information the satellite collects and are transmitted to the CNES (Centre National d'Études Spatiales)

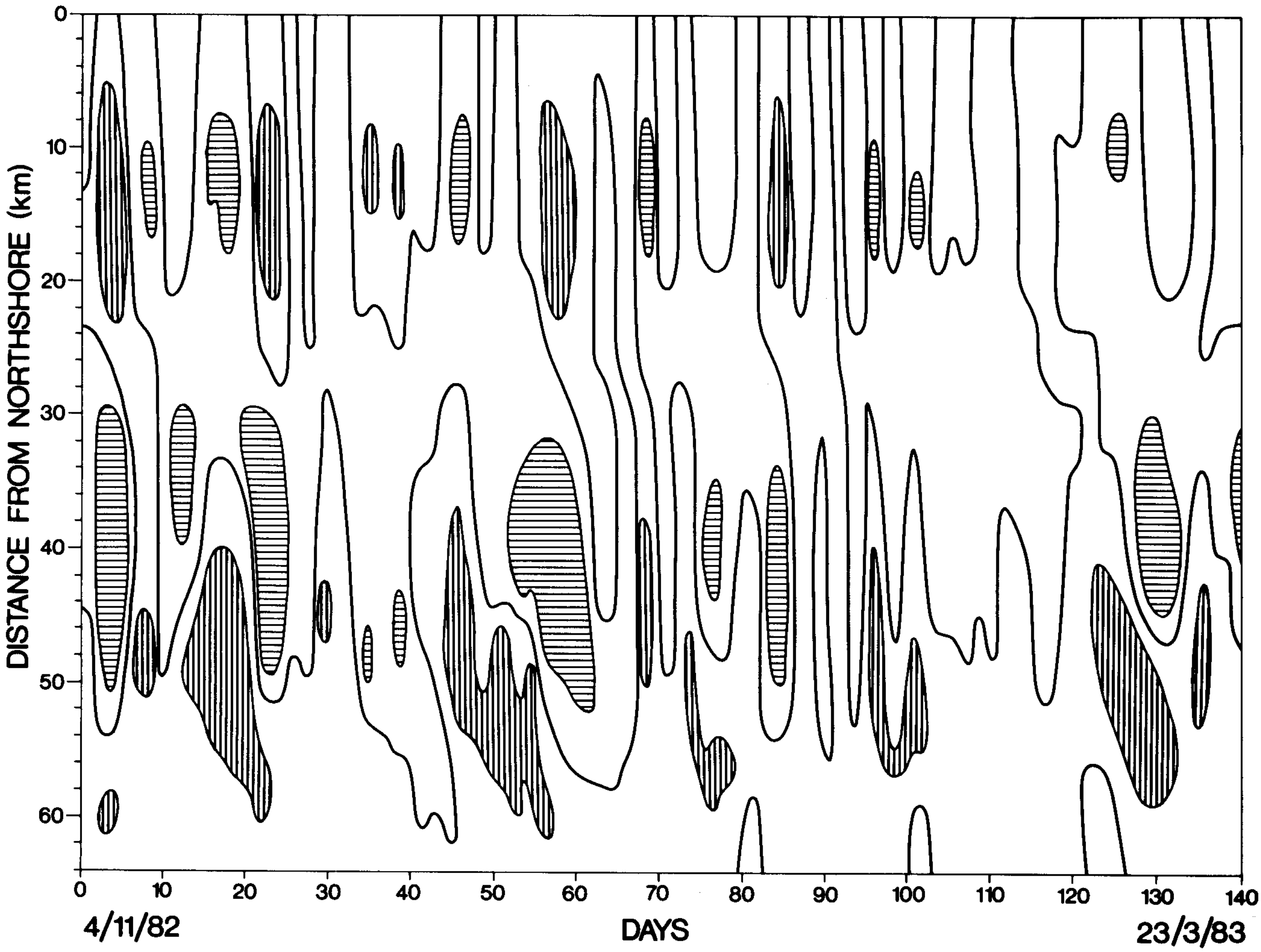

FIG. 5. Cross-lake distribution of vertically-integrated currents as a function of time. Solid lines denote current reversals (zero transport), vertical shading represents eastward transport greater than 10 m²/s, horizontal shading is westward transport greater than 10 m²/s.

Space Centre in Toulouse, France. The data are processed in Toulouse and then sent to the computer system at NESS. The position of the buoy, as calculated from the doppler shift of its signal, is accurate to ± 0.5 km (Pickett *et al.* 1983).

Restrictions on the NESS computer limit the storage of accessible data to the last five positions. Since the file is continuously updated, interrogation by the user must also be continuous to avoid data loss. In this case, a Hewlett Packard minicomputer interrogated the NESS system at hourly intervals and stored the data points in a file.

RESULTS OF LAGRANGIAN EXPERIMENTS

Satellite-tracked current drifters have been successfully used in other circulation studies in the Great Lakes (Pickett *et al.* 1983, 1984). The present two experiments were also quite successful and have provided valuable data for independent verification of the winter circulation in Lake Ontario as inferred from the current meter observations presented above. In particular, the Lagrangian experiments confirm the existence of a belt of strong eastward water movement along the south shore.

The Lagrangian drogue tracks for the two experiments are shown by the heavy solid and dashed lines in Figures 7 and 8. For comparison, the thin solid lines show progressive vector diagrams of the wind stress with the origin located at an arbitrary point in the lake. Note that in each experiment the two drogues were released at the same point and the same time. In spite of this fact, the two drogue tracks of the first experiment are totally different, thus providing a glimpse of the effect of small-

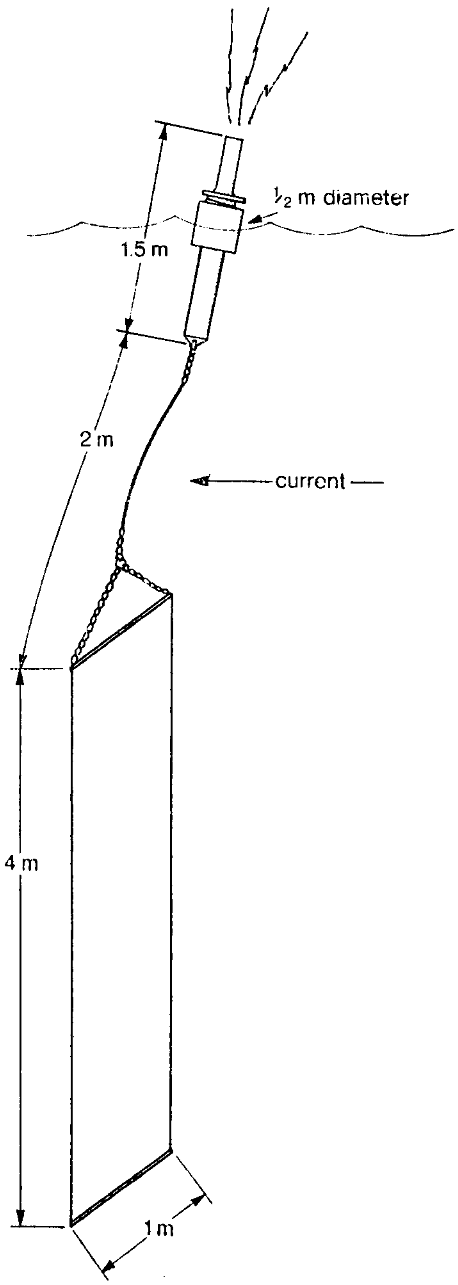

FIG. 6. Sketch of satellite-tracked drogue.

scale turbulent motions in lakes and the resulting unpredictability of water displacements. At the same time, however, the drogue tracks also exhibit clear evidence of the significant effects of wind impulses and large-scale current regimes.

Wind impulses are primarily responsible for sudden changes in direction of drogue movements such as those observed on 9 October during the first experiment and 26 October during the second. On the other hand, large-scale current regimes determine the actual displacements of the drifters. For example, in the first experiment one of the drogues (solid line) is immediately trapped in the belt of eastward currents along the south shore and consequently moves to the east about four to five times as far as the track of the wind stress vector. At the same time, the second drogue (dashed line) is temporarily pushed out of this belt of fast currents and, as a result, it stays far behind the first drogue. The strong westward winds of 9–10 October cause both drifters to move out of the boundary current into the interior of the lake. As illustrated in Figures 3 and 4, the currents here are much weaker and the drogue displacements are due partly to direct wind effects and partly to free topographic current oscillations mentioned in the discussion of Figure 3.

The results of the second experiment are equally interesting since they reveal the remarkable variability of the Niagara River plume. An extensive field study of this phenomenon was carried out in 1982 and the results have been published by Murthy *et al.* (1984). One of the principal conclusions of that study concerned the dominating effects of winds and large-scale circulations on the path of the Niagara River outflow. Thus, the concept that the Niagara River effluent hugs the south shore and does not directly affect the open lake is clearly too limited. On numerous occasions, the Niagara River plume bends to the west as illustrated by the second drogue experiment and also by hydrodynamic model studies (Simons 1972). Again, the second experiment shows large drogue movements when the drogues are trapped in the eastward boundary currents, while the displacements are smaller than those of the wind stress vector plot when the drifters move into open water.

A statistical summary of currents calculated from the drogue tracks is given in Table 2. Maximum speed range from 60–75 cm s^{-1} while mean speeds range from 20–25 cm s^{-1}. These values agree quite well with the foregoing current meter data, with the high speeds being associated with the strong and persistent eastward flow along the south shore.

In conclusion it is of interest to illustrate the correlation between these observed circulation features and the distribution of toxic contaminants such as mercury and mirex in the sediments of Lake Ontario. Figures 9 and 10 show examples of such distributions reproduced from Thomas (1983). The dominating effect of the year-round boundary current along the south shore is evident.

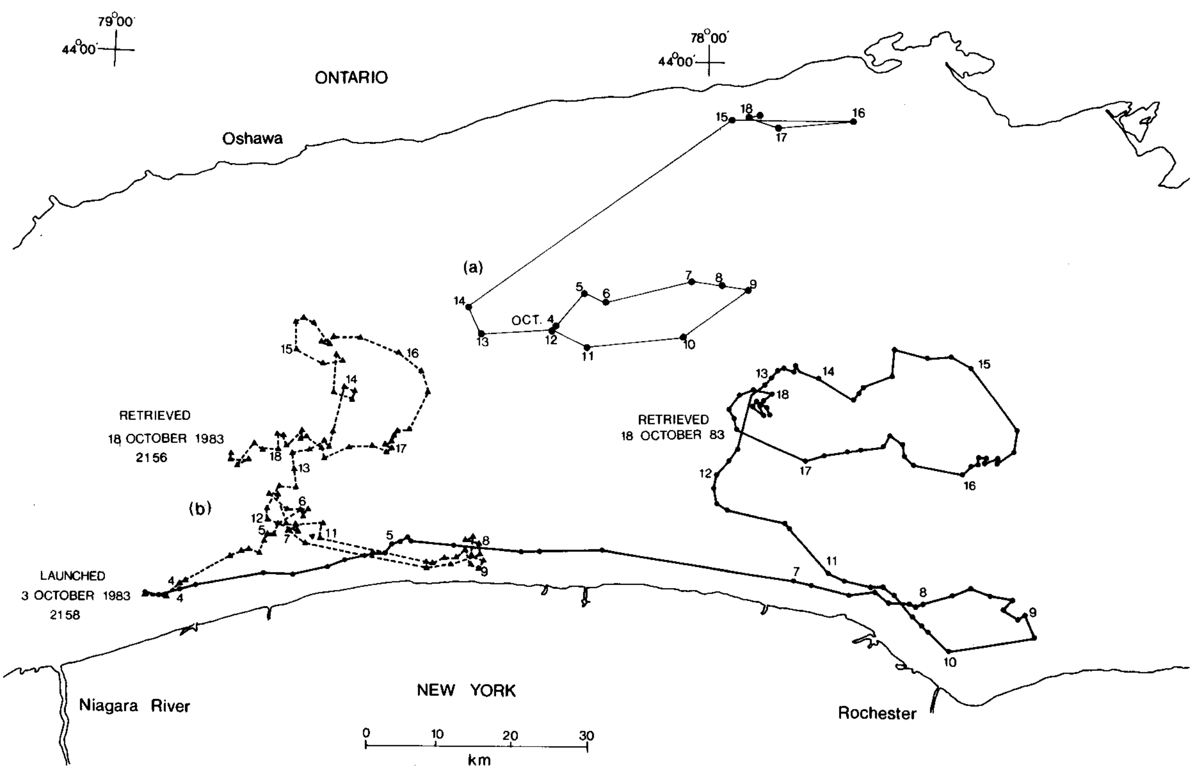

FIG. 7. Drogue tracks of first Lagrangian experiment (heavy solid and dashed lines) and progressive vector diagram of wind stress (thin line).

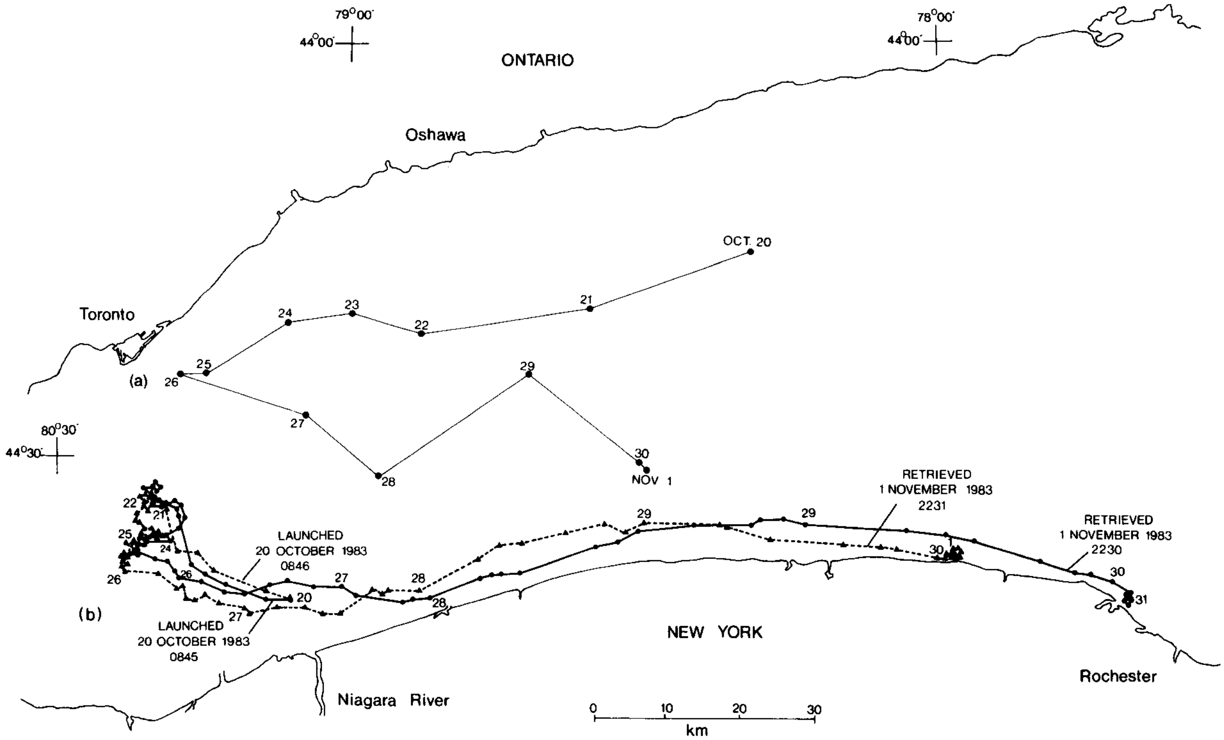

FIG. 8. Same as Figure 7 but for second Lagrangian experiment.

TABLE 2. Statistical summary of Lagrangian currents.

	Drogue No.	Maximum Speed cm sec^{-1}	Mean Speed cm sec^{-1}	Standard Deviation cm sec^{-1}
Experiment #1	D3387	61.2	18.2	15.0
3-18 Oct 83	D3389	77.6	20.1	18.8
Experiment #2	D3387	66.3	18.4	12.1
20 Oct - 1 Nov 83	D3389	64.2	25.1	14.3

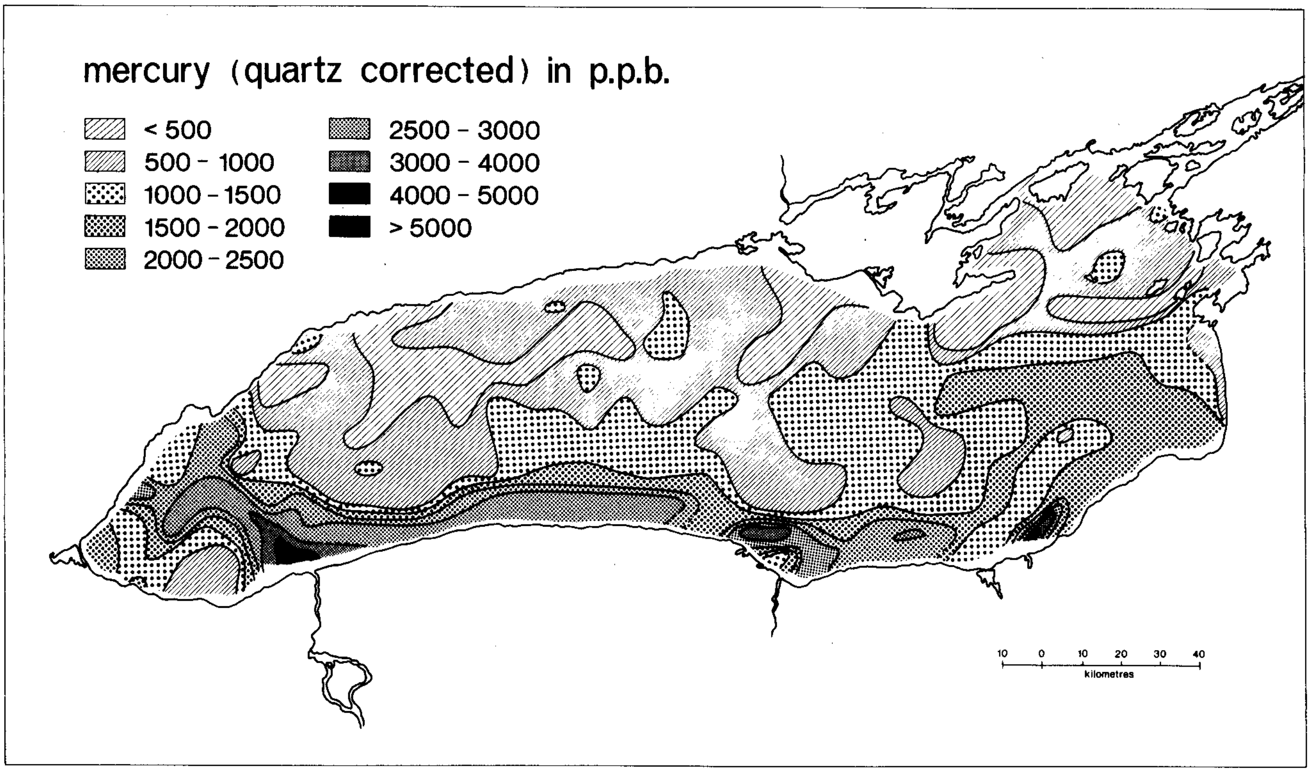

FIG. 9. Mercury distribution in Lake Ontario sediments (from Thomas 1983).

In particular, the mercury distribution, however, exhibits clear indications of westward displacements of the Niagara River plume. Also, the recirculation of up to 90 percent of the water masses at the eastern end of the lake, as inferred from the foregoing transport calculations, is quite apparent in the sediment distributions.

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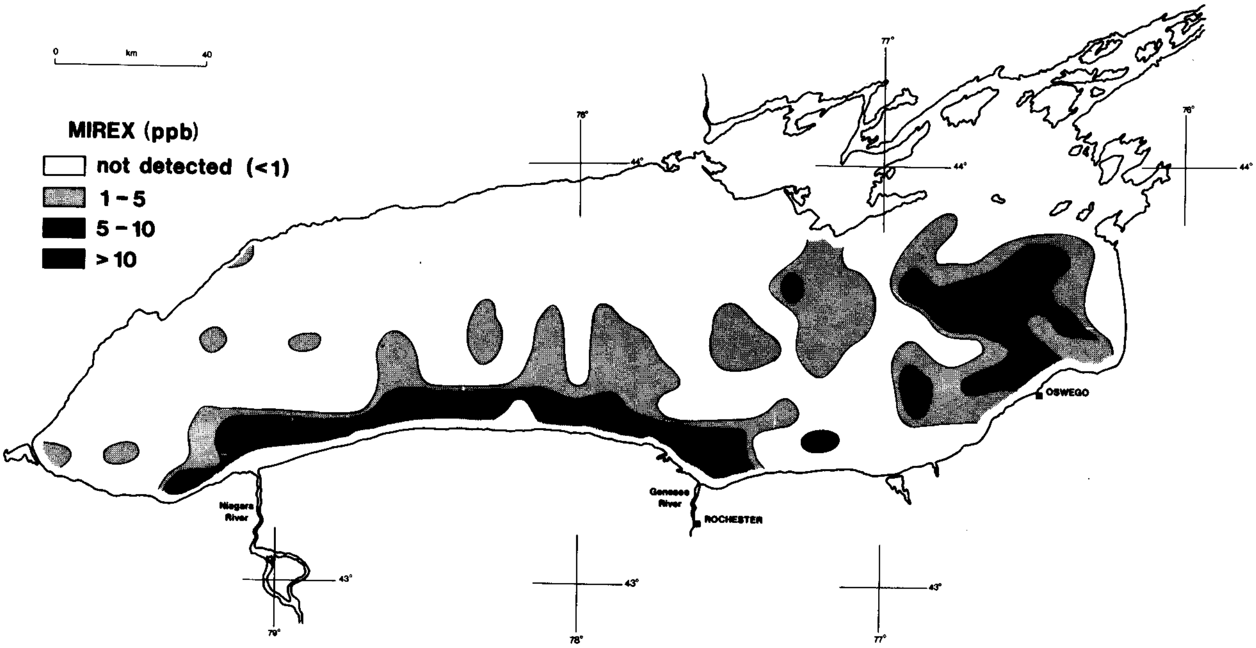

FIG. 10. Mirex distribution in Lake Ontario sediments (from Thomas 1983).

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