J. Great Lakes Res. 25(1):78–93
Internat. Assoc. Great Lakes Res., 1999

Mean Circulation in the Great Lakes

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***ABSTRACT**. In this paper new maps are presented of mean circulation in the Great Lakes, employing long-term current observations from about 100 Great Lakes moorings during the 1960s to 1980s. Knowledge of the mean circulation in the Great Lakes is important for ecological and management issues because it provides an indication of transport pathways of nutrients and contaminants on longer time scales. Based on the availability of data, summer circulation patterns in all of the Great Lakes, winter circulation patterns in all of the Great Lakes except Lake Superior, and annual circulation patterns in Lakes Erie, Michigan, and Ontario were derived. Winter currents are generally stronger than summer currents, and, therefore, annual circulation closely resembles winter circulation. Circulation patterns tend to be cyclonic (counterclockwise) in the larger lakes (Lake Huron, Lake Michigan, and Lake Superior) with increased cyclonic circulation in winter. In the smaller lakes (Lake Erie and Lake Ontario), winter circulation is characterized by a two-gyre circulation pattern. Summer circulation in the smaller lakes is different; predominantly cyclonic in Lake Ontario and anticyclonic in Lake Erie.*

***INDEX WORDS:** Circulation, Great Lakes.*

INTRODUCTION

Current flows in the Great Lakes have been studied for many years, but many properties of seasonal circulation remain unreported. The main reason for limited descriptions (even qualitative ones) of seasonal circulation is the variable nature of lake currents. This variability requires costly long-term measurement programs to reliably estimate mean values. In contrast with the relatively stable main oceanic gyres, lake currents lack persistence and depend more on short-term atmospheric forcing because of the relatively small size of lake basins (even for the largest of the Great Lakes). Storm-induced currents in the Great Lakes can be quite strong (up to several tens of cm/s), but the average currents are rather weak throughout most seasons of the year (on the order of only a few cm/s). Nevertheless, this average, or mean, circulation is important for many ecological and management issues because it strongly influences (along with diffusion) the transport pathways of nutrients and contaminants on large time scales.

The first map of mean summer currents in the Great Lakes was presented over 100 years ago by Harrington (1894). Although new summer observations were obtained in the next century in all of the Great Lakes, they have not been presented in a consistent manner, or even simply combined in a single source. No analogous winter circulation map has been presented either, except the one that combined two observation-based winter circulation maps (Lakes Ontario and Huron) with simulated currents in the other three lakes (Pickett 1980). Significant progress in both the quality and quantity of winter observations made in the last three decades finally allows the derivation of mean winter and annual circulation patterns in most of the Great Lakes. The goal of this paper is to present a new set of circulation maps by combining new maps with existing maps in a consistent fashion. Overall, out of 12 presented circulation maps, 7 are entirely new. This

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paper is focused primarily on seasonal and annual lake circulation patterns, but some aspects of interannual variability will also be briefly discussed.

In the next section a history of current measurements in the Great Lakes is presented, followed by an overview of developments in the mean circulation theory. After that, the data are described and the new circulation maps are presented. Finally, various mechanisms that could be responsible for observed summer, winter, and annual circulation patterns in the Great Lakes are discussed.

LONG-TERM CURRENT MEASUREMENTS IN THE GREAT LAKES

In fluid mechanics there are two approaches to study circulation: Eulerian, where time series of observations at fixed points are considered, and Lagrangian, where trajectories of moving tracer particles are used. Historically, the latter approach was the first employed both in oceanography and limnology. Drifting ships or drift bottles naturally indicated the movement of the surface layers. The earliest reported whole-basin Lagrangian studies of lake currents were performed by Harrington (1894). He released drift bottles from ships during the summer months of 1892, 1893, and 1894 and deduced flow patterns based on the locations of bottles that were recovered along the coasts (Fig.1). He also interviewed sailors and fishermen to gain knowledge from their experiences as to the drift of vessels and fishing nets. Most bottles drifted with the prevailing westerly winds more or less directly across the lake basins. However, he felt that enough of them drifted along the coasts for the tendency of flow about the perimeter of the basins to be established. Harrington charted the summer currents around the deeper lake basins as dominantly counterclockwise, with the suggestion of a clear cellular structure within each distinct basin in the largest lakes.

Drift bottle and drift card studies were continued in the early 20th century in Lake Michigan by Deason (1932) (see Van Oosten 1963), and later by Johnson (1960). Deason's drift bottle recoveries in 1931–32 were of a pattern similar to those of Har-

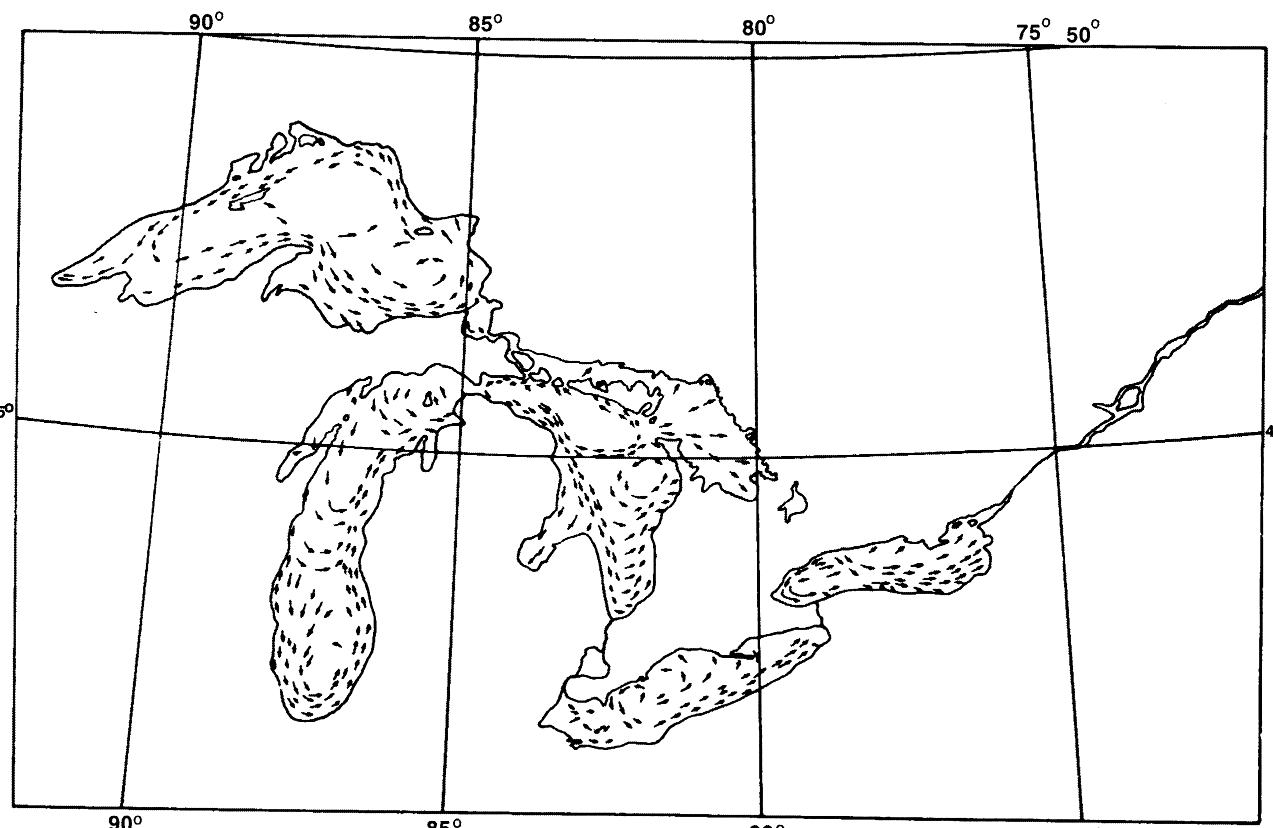

FIG. 1. Surface currents in the Great Lakes (Harrington 1894, Liu **et al.** *1976).*

rington, while Johnson's 1954–55 studies were less conclusive, for although he observed a general west to east movement of the drift bottles, he did not observe consistent north or south excursions along either coast. It is of interest that while Harrington recovered less than 10% of drift bottles in this lake, Johnson recovered about 50% of those set adrift. Drift bottles, cards, drogues, and other devices were extensively used later in Lake Michigan (Ayers *et al*. 1958, Monahan and Pilgrim 1975, Pickett *et al*. 1983, Clites 1989) and in other Great Lakes as well. The studies are too numerous to describe for the purpose of this paper, therefore, only references to major Lagrangian type experiments are given in Lake Erie: Olson (1950), Wright (1955), Verber (1953, 1955), Hamblin (1971), Saylor and Miller (1987); in Lake Superior: Ruschmeyer *et al*. (1958); in Lake Huron: Ayers *et al*., (1956); and in Lake Ontario: Casey *et al*. (1966), Simons *et al*. (1985), Masse and Murthy (1992).

The earliest direct open-lake measurements of Eulerian currents were performed by the Federal Water Pollution Control Administration (FWPCA) in the early 1960s (FWPCA 1967) (Table 1). They placed current meters and temperature recorders on more than 30 moorings throughout the Lake Michigan basin during both summer and winter, and later extended the observation program to other lakes. The current measurements were made with early models of self-contained Savonius rotor meters that recorded data on photographic film. Currents were burst sampled for a 50 s-long interval every 20 or 30 minutes. The total number of rotor revolutions in 50 s determined the speed while the direction was an average of current heading recorded at 5 s intervals. A complex data recording scheme used optical fiber and 16 mm photographic film. The data were difficult to transcribe from the film in a timely and accurate fashion, even with the use of an automated light dot scanner developed by the instrument manufacturer. Nevertheless, important accomplishments from these studies included documenting the omnipresent near-inertial period, large-amplitude thermocline displacements, and current rotations that occurred whenever the water mass was density stratified in the open lake. Attempts were made to describe seasonal currents also, and flow patterns were charted for prevailing wind directions. Hamblin (1971) and Blanton and Winklhofer (1972) used data collected with these meters in Lake Erie to describe currents that compare favorably with more recent studies, while Sloss and Saylor (1976b)

TABLE 1. Inventory of major long-term Eulerian current observation programs in the Great Lakes. Asterisks indicate more modern VACM measurements. Data sets that form the basis of this paper are shown shaded.

Lake	Period	Reference
Erie	May 1964–September 1965	FWPCA (1968), Hamblin (1971)
	July-August 1970	Blanton and Winklhofer (1972), Simons (1976), Mortimer (1987)
	May 1979–June 1980*	Saylor and Miller (1987)
Huron	April-September 1966	Sloss and Saylor (1976a)
	November 1974–May 1975*	Saylor and Miller (1979)
Michigan	December 1962–September 1964	FWPCA (1967)
	June-October 1976*	Saylor et al. (1980)
	June 1982–July 1983*	Gottlieb et al. (1989)
Ontario	August 1964–November 1965	Casey et al. (1966)
	May 1972–April 1973*	Saylor et al. (1981)
	May 1982–March 1983*	Simons et al. (1985), Simons and Schertzer (1987), Simons and Schertzer (1989)
Superior	May 1966–October 1967	Sloss and Saylor (1976b), IJC (1977)
	June–September 1973*	Sloss and Saylor (1976b), Lam (1978)

reported FWPCA circulation studies in Lake Superior that yielded results similar to more recent smaller-scale studies. Other whole-basin studies that involved the use of the same technology include observations in Lake Ontario (Casey *et al.* 1966) and in Lake Huron (Sloss and Saylor 1976a).

Instruments for measuring current velocities have greatly improved since the first Lake Michigan current meter studies, especially those features related to realistic in-situ data acquisition and accurate data retrieval. More recently, currents have been measured with arrays of vector-averaging current meters (VACM), which record the east and north components of the current flow past the meter for selected fixed intervals of time (e.g., 15 min averages have been used in numerous surveys). Computation of the velocity vector in a typical instrument is triggered eight times for each revolution of a Savonius rotor current speed sensor. In a 50 cm/s current, 10,400 current vector computations are made in a 15-min sampling period. The averaged current vector, together with a reading of the ambient water temperature (accurate to +0.1°C) from a thermistor in the meter housing, is then stored onto a magnetic tape cassette or solid state memory device at the end of the interval.

The velocity measuring characteristics of the Savonius rotor sensor were described by Gaul *et al.* (1963). An early known defect was the measured overspeeding of the rotor in the presence of surface wave orbital velocities or movements of the moorings themselves because of surface or short period internal waves. The problem was less important after the introduction of vector-averaging sampling methods and the careful design of rotors and current direction sensors.

The vector averaging meters were first used in large numbers in surveys of currents in Lake Ontario in the late 1960s (Sweers 1969). The moorings consisted of a series of current meters placed on a taut line suspended in the water column beneath subsurface floats. This mooring arrangement minimized the vertical movements of the current meters. Following the early deployments in limited areas of Lake Ontario, the first truly whole-basin current measurement program using the new technology was conducted in this lake during the International Field Year for the Great Lakes (IFYGL) in 1972 (Saylor *et al.* 1981). Later, fine-resolution current observations were conducted on a north-south cross-section of the lake (Simons *et al.* 1985; Simons and Schertzer 1987, 1989). The success achieved in describing the lake-scale circulation stimulated rapid progress in abilities to conceptually and numerically model the observed lake physics (Schwab 1992). It also provided impetus for continuing binational (Canada—United States) efforts to measure whole-basin circulation in other Great Lakes, especially Lakes Huron and Erie (Saylor and Miller 1979, 1987). Other circulation experiments were performed in Lake Michigan in 1976 and in 1982–83 by the NOAA Great Lakes Environmental Research Laboratory (GLERL) (Saylor *et al.* 1980, Gottlieb *et al.* 1989), and in Lake Superior by the Canada Centre for Inland Waters (Lam 1978; some data also appeared in Sloss and Saylor 1976b).

CONCEPTUAL MODELS OF MEAN CIRCULATION IN THE GREAT LAKES

Long-term circulation in the Great Lakes is driven primarily by wind stress and surface heat flux (the latter causes density-driven currents). The interplay of these two factors in combination with the influence of lake bathymetry makes circulation patterns in large lakes rather complex. Therefore, a number of conceptual circulation models elucidating the role of different factors have been developed for the Great Lakes. A summary of these model results is given below.

One can argue that the first circulation model was suggested by Harrington when he inferred that his drift bottle trajectories mainly followed lake bathymetry. It is interesting to note that Harrington's lake circulation patterns for Lake Michigan were severely criticized in Townsend (1916) who reported results on studies of Great Lakes winds, water temperature distributions, and currents that he obtained from Congressional papers. Townsend stated that the currents reported were absurd because they were based on curvilinear interpretations of drift bottle trajectories rather than straight line courses based on the location of bottle release and capture. He also noted that as a rule, the currents followed the direction of the surface wind, perhaps with the influence of barometric pressure variations, so that no persistent currents were developed.

Church (1942, 1945) performed studies of the annual temperature cycle of Lake Michigan for 2 years and suggested that current flows obeyed the principles of geostrophy. With geostrophy, the horizontal pressure gradients (determined by distributions of water of varying density in this case) are balanced by the Coriolis force. The distribution of lake water temperature was measured on repeated car ferry crossings of the lake on several transects, and climatological seasonal distributions of water density were established. Counter-clockwise currents in geostrophic equilibrium with the mass distributions generally followed Harrington's descriptions. Church's current flows in winter, based upon the temperature field, were the only reference to winter lake circulation prior to the mid 1960s. Later, Ayers (1956) applied a dynamic height method to determine geostrophic currents in lakes, which was the freshwater analog of the classical oceanographic technique. Recently, Schwab *et al.* (1995) simulated the generation of density-driven cyclonic summer circulation on the order of a few cm/s in a large lake. The circulation was generated by the adjustment of the temperature field to the bottom boundary conditions.

A different type of mean circulation model completely ignores density-driven currents and emphasizes the wind-driven circulation. Unlike the geostrophic density-driven circulation where the horizontal pressure gradient is balanced by the Coriolis force, the resulting wind-driven circulation is an interplay between horizontal pressure gradient and wind stress. As was shown by Bennett (1974), a horizontally uniform wind generates a two-gyre circulation pattern in a lake that has simple bathymetry. In particular, in the nearshore region, the wind stress is the dominant factor, and the transport is in the downwind direction. In the deeper offshore regions, the pressure gradient (caused by the surface water level gradient) generates transport opposite to the wind direction. Obviously, in lakes with complicated bathymetry, the circulation will consist of several cyclonic and anticyclonic gyres. In a stratified basin, Bennett (1975) showed that even a uniform wind field generates stronger currents in the downwelling area compared to the upwelling area due to decreased vertical mixing and bottom friction. This asymmetric response causes residual cyclonic circulation after averaging between various wind directions. Csanady (1975) presented a somewhat similar explanation, but he emphasized horizontal momentum flux instead of vertical mixing.

Another important factor that can change the circulation pattern in the lake is wind vorticity. Any vorticity in the forcing field is manifest as a tendency of the resulting circulation pattern toward a single gyre streamline pattern, with the sense of rotation corresponding to the sense of rotation of the wind stress curl (Rao and Murty 1970, Hoopes *et al.* 1973, Strub and Powell 1986). For example, in the simplest case, there can be a considerable amount of vorticity imparted to the lake by the normal circulation pattern of an extratropical storm as it passes over the lake. There are also theories that take into account more complex lake-atmosphere thermodynamic interactions. In particular, because of the size of the lakes, and their considerable heat capacity, it is not uncommon to see lake-induced mesoscale circulation systems superimposed on the regional meteorological flow, a meso-high in the summer (Lyons 1971) and a meso-low in the winter (Petterssen and Calabrese 1959). According to this theory, lake circulation will have a tendency to be cyclonic in winter and anticyclonic in summer. On the other hand, Emery and Csanady (1973) showed that wind-induced summer upwellings can contribute to the summer cyclonic wind vorticity because of reduced wind stress over upwelled colder water.

There are also other wave-like processes that can contribute to a mean circulation pattern. In particular, Wunsh (1973) suggested that Lagrangian drift associated with internal Kelvin waves can contribute to the cyclonic summer circulation, while Simons (1986) explained cyclonic winter circulation by the non-linear interaction of topographic waves.

DATA AND METHODS

Ideally, a map of climatological currents would be the major outcome of a paper dealing with the mean circulation in the Great Lakes. Unfortunately, the low-frequency band of the current spectrum is an area of limited available observational data (climatological averaging requires several decades of continuous observations). For example, one can find samples of summer or winter currents in each of the Great Lakes (Table 1), samples of annual currents in most of the lakes, but much less data for the assessment of interannual variations, and no data at all to derive climatological (in the definition adopted above) currents. Therefore, the maps presented here should be considered primarily as samples of seasonal circulations rather than climatology. Here, winter and summer currents have a special meaning reflecting the existence of two major dynamical regimes: stratified (May through October), and isothermal (November through April). Similar time periods for averaging were adopted in previous studies of circulation in Lake Ontario (Pickett 1980, Saylor *et al.* 1981, Simons and Schertzer 1989), and Lake Huron (Saylor and Miller 1979).

Data sets used in this paper were collected as part of projects sponsored by the Federal Water Pollution Control Administration, Great Lakes Environmental Research Laboratory, and Canada Centre for Inland Waters. Using a moderate amount of interpretation, a set of summer, winter, and annual circulation maps were produced for each lake to more fully represent the available data. While some maps are entirely new, others represent edited versions of existing maps (for consistency, current vectors were overlaid on the existing circulation maps or vice versa).

To obtain summer and winter maps of circulation in the Great Lakes, current data were averaged over the above mentioned 6-month periods. In most cases, observations matching these periods were 4 to 6 months long. In cases where observations were of shorter duration, only those observations that were at least 3 months long were used. Only three lakes (Lake Erie, Lake Michigan, and Lake Ontario) had consecutive summer and winter observations to derive annual circulation patterns (averaged from May through April). These observations were 10 to 12 months long. Details of original measurement programs can be found in the original publications. Therefore, only a brief description of the data sets is given below. A computer file containing the average currents for each station is available from the authors.

A word on the accuracy of current meter data should be given here because the authors believe that ensemble averaging significantly improves the accuracy of mean currents. The data sets used in this paper were collected with two types of current meters: the earlier FWPCA-type current meters and more modern VACM -type current meters (Table 1). Some details of their technology were presented earlier in the paper. The published accuracy for most of the instruments used (VACM's) is 1 cm/s for speed, 5° for direction, with a threshold speed of 2.5 cm/s. The sampling interval in the majority of experiments was 15 min. The stated accuracy of FWPCA current meters was 1 cm/s for speed and 7° for direction. The threshold speed was the same as in later VACM's because the same Savonius rotor was used as the speed sensor. The sampling interval was 20 minutes in summer measurements and 30 minutes in winter measurements. All FWPCA measurements used in this paper were made beneath subsurface floats moored to minimize vertical motions and rotor speeding effects (Gaul *et al.* 1963).

The long-term current averages used in the paper are small residuals of current vectors that are usually much larger than the threshold velocity in the individual records. Along the coasts they are residuals of nearly rectilinear flow, in deeper water a small drift is superimposed on stronger near-inertial currents. Because both nearshore and offshore instantaneous currents are usually fluctuating in direction, the long-term vector average currents should have better accuracy (because of virtual elimination of negative or positive biases) than the nominal instrument accuracy of 1 cm/s, perhaps as good as 0.1 cm/s. The same reasoning also applies to the current direction.

Lake Erie

We used original 1979–80 observations (Saylor and Miller 1987). Some stations provided current observations only 1 or 2 meters apart in the vertical. Because of their similarity, the 19 and 15.5 meter observations in Long Point Bay (stations C6 and C7 in Saylor and Miller 1987), 14 meter observations offshore of Cleveland (station C18 in Saylor and Miller 1987), and 18 meter observations offshore of Point aux Pins (station C27 in Saylor and Miller 1987) were omitted to avoid redundancy. An eastward flow in the vicinity of the Detroit River was also added, which is a well-known feature of western Lake Erie circulation (Hamblin 1971).

Lake Huron

Original data for the FWPCA study in winter 1965–66 are not available. Therefore, the figure was redrawn from Saylor and Miller (1979) with only minor changes, the 25 meter observations in the vicinity of Bruce Peninsula (station 112 in Saylor and Miller 1979) was replaced with that at 50 m. Summer currents were calculated from monthly averages presented in Sloss and Saylor (1975). Mean currents were overlaid on the existing Lake Huron summer circulation map presented in Sloss and Saylor (1976a), and circulation patterns were added to the existing map of Lake Huron winter currents (Saylor and Miller 1979).

Lake Michigan

Original observations made in 1982–83 (Gottlieb *et al.* 1989) were used.

Lake Ontario

The IFYGL current data archive (Saylor *et al.* 1981) was used. Near-bottom observations were omitted because of questionable quality. (During storms, the current meter could be as high as 10 meters above the bottom instead of 1 to 2 meters above the bottom during quiescent conditions because of the mooring design). A new annual circulation map using IFYGL observations was made and added to the existing summer and winter circulation maps (Saylor *et al*. 1981).

Lake Superior

Original observations for the FWPCA study in 1966 to 1967 are not available. Monthly averaged data presented in Sloss and Saylor (1976b) were used. Mean currents were also overlaid on the existing Lake Superior summer circulation map (IJC 1977).

MEAN CIRCULATION PATTERNS IN THE GREAT LAKES

Summer Circulation

Observations of summer circulation in the Great Lakes are generally more numerous than those of the winter circulation because of harsh conditions in winter. The oldest systematic observations of lake circulation (Harrington 1894) are for the summer period. Since Harrrington's maps provided the first comprehensive description of circulation in all of the Great Lakes, the new maps were compared to Harrington's map. The new data differed from Harrington's in several ways. First, the Eulerian approach was employed instead of Harrington's Lagrangian approach. (One known difference between the two approaches is wave-induced Stokes' drift that would affect surface drift bottles.) Second, Harrington's data include a great deal of interpretation, and in that sense are different from objective data obtained by modern Lagrangian-type devices (which use satellite-tracking, for example). Third, while Harrrington's data describe surface circulation, which is more sensitive to the direct wind drift, only subsurface currents (the minimum depth of observations in the whole data set is 6 meters) are presented here.

It was found that the new observations are generally consistent with Harrington's data, but only in the larger lakes: Lake Huron, Lake Michigan, and Lake Superior. The average magnitude of summer circulation in the Great Lakes is 1.0 to 2.4 cm/s (Table 2). While mean summer currents can be as small as 0.1 cm/s at certain locations and depths in practically all lakes, maximum current speed can be significant, reaching 7.1 cm/s near the tip of the Keweenaw Peninsula in Lake Superior. Currents typically change their direction with depth, and their speed decreases, which reflects the importance of baroclinic effects in the presence of the seasonal thermocline.

The summer circulation pattern is mostly cyclonic in Lake Huron (Fig. 2), Lake Michigan (Fig. 3), and Lake Superior (Fig. 4). The circulation is somewhat less organized in Lake Michigan and in Lake Huron compared to that in Lake Superior. In Lake Michigan, the mean circulation pattern is distinctively cyclonic in the deep basins and anticyclonic in the mid-lake ridge area where current speed reaches (rather unexpectedly) its maximum of 4.5 cm/s. The flow along the west coast is significantly weaker (current speeds of 0.5 cm/s or less) than the flow along the east coast (current speeds around 1.5 cm/s). In Lake Huron, coastal summer currents appear to be stronger than in Lake Michigan, up to 2 to 4 cm/s. Another notable feature of Lake Huron summer circulation is a surface flow into the Georgian Bay that implies the existence of a return flow at deeper depths. The speed of this current is 4.6 cm/s which is the maximum observed mean summer current speed in Lake Huron. In Lake Ontario (Fig. 5), the mean circulation consists of a combination of a large cyclonic gyre where current speed reaches its maximum of 2.5 cm/s and a smaller anticyclonic gyre in the western part of the lake. Harrington's observations show a cyclonic gyre in that area. In Lake Erie (Fig. 6), the anticyclonic gyre dominates, and only a smaller cyclonic gyre located in the western part coincides with Harrington's observations. The strongest summer currents in Lake Erie (4.4 cm/s) were observed south of Point Pelee, Ontario.

TABLE 2. Minimum, maximum, and average mean current speed in the Great Lakes.

	Erie	Huron	Michigan	Ontario	Superior
Summer	0.1/4.4/1.4	0.4/4.6/2.4	0.1/4.5/1.3	0.1/2.5/1.0	0.2/7.1/2.2
Winter	0.3/3.7/1.6	0.2/7.9/2.6	0.8/4.7/2.4	0.4/9.5/2.8	
Annual	0.1/2.9/1.3		0.5/4.3/1.9	0.4/3.3/1.5	

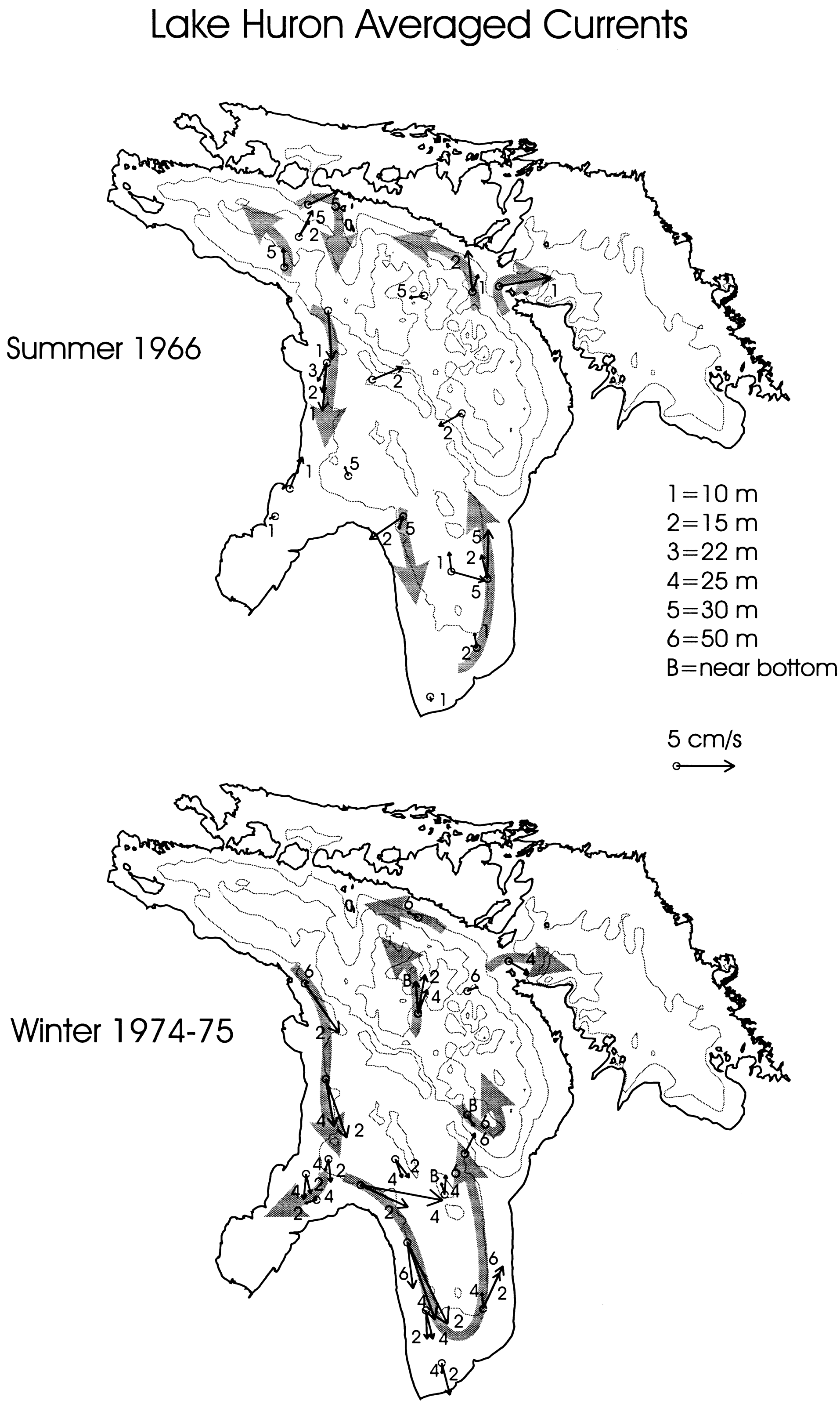

FIG. 2. Summer and winter circulation in Lake Huron. Isobaths every 50 m.

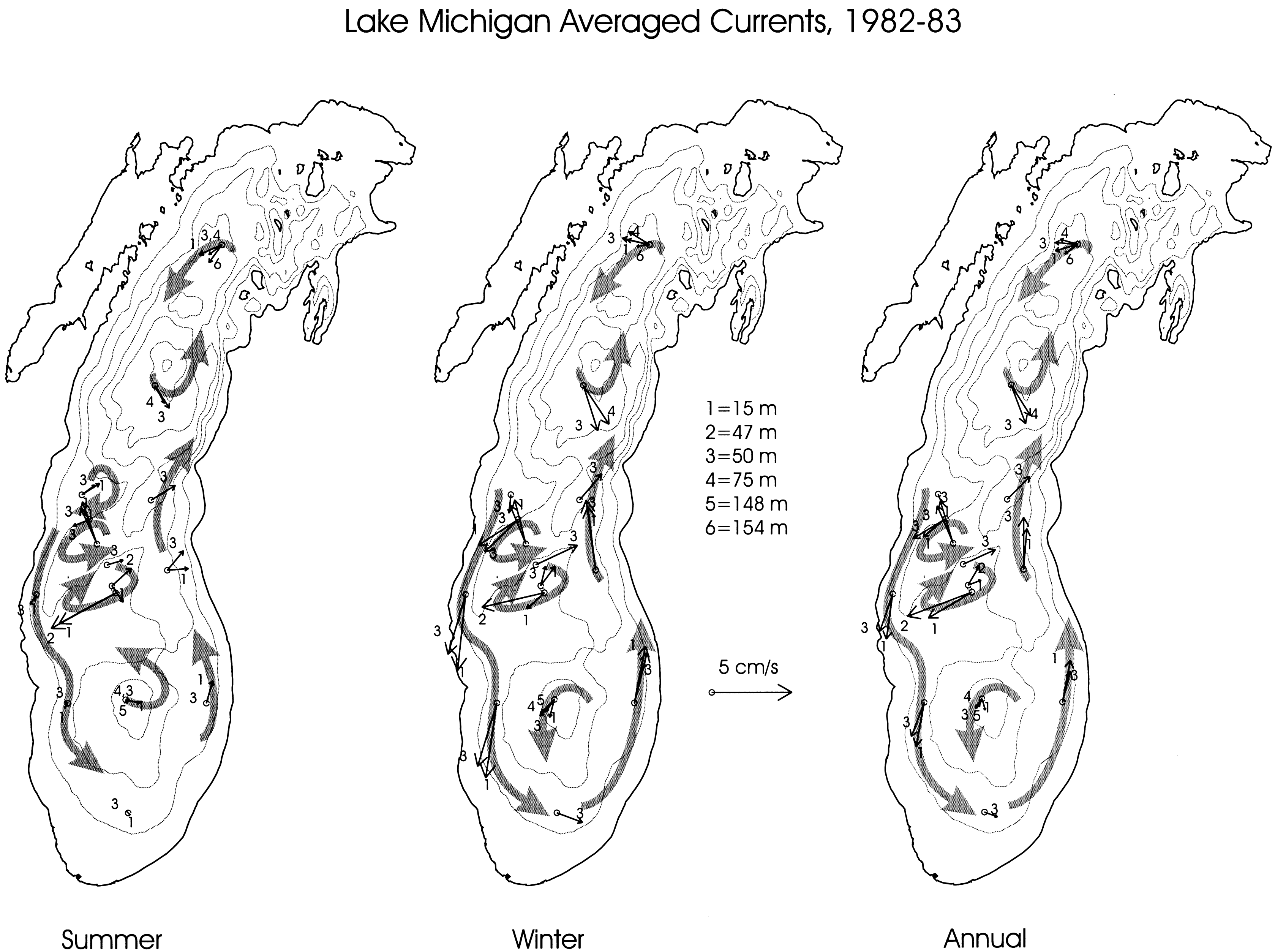

FIG. 3. Summer, winter, and annual circulation in Lake Michigan. Isobaths every 50 m.

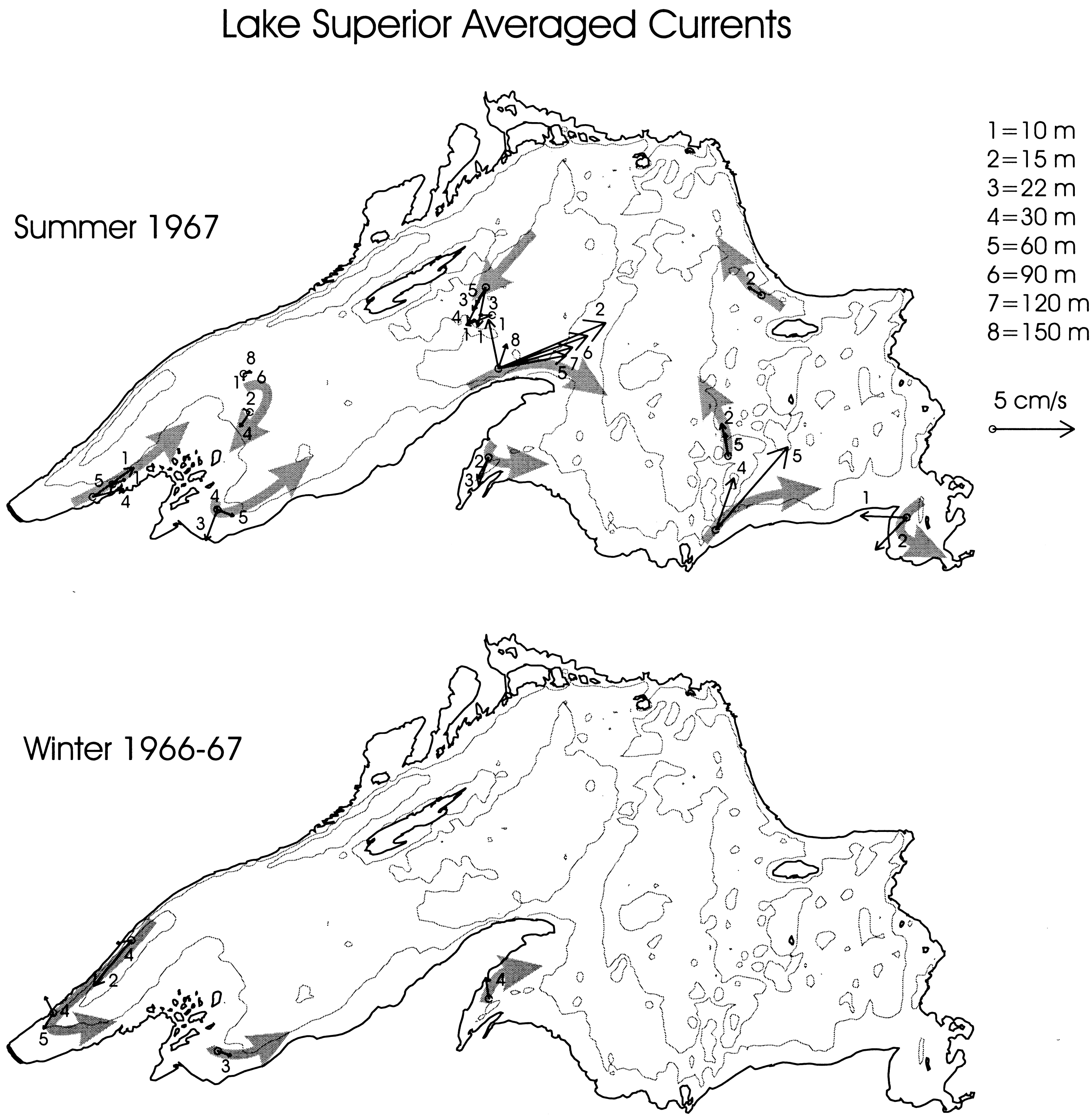

FIG. 4. Summer and winter circulation in Lake Superior. Isobaths every 100 m.

Interannual variability of summer circulation has not been systematically studied in any of the Great Lakes, although there are indications that summer circulation can vary from year to year, as can also be inferred from comparison with Harrington's data. For example, the circulation pattern in western Lake Ontario was different in different years: it was cyclonic in 1965 (Casey *et al.* 1966) and anticyclonic in 1972 according to the IFYGL observations (Fig. 5). On the other hand, certain features of summer circulation appear to be very stable, namely the cyclonic circulation in central Lake On-

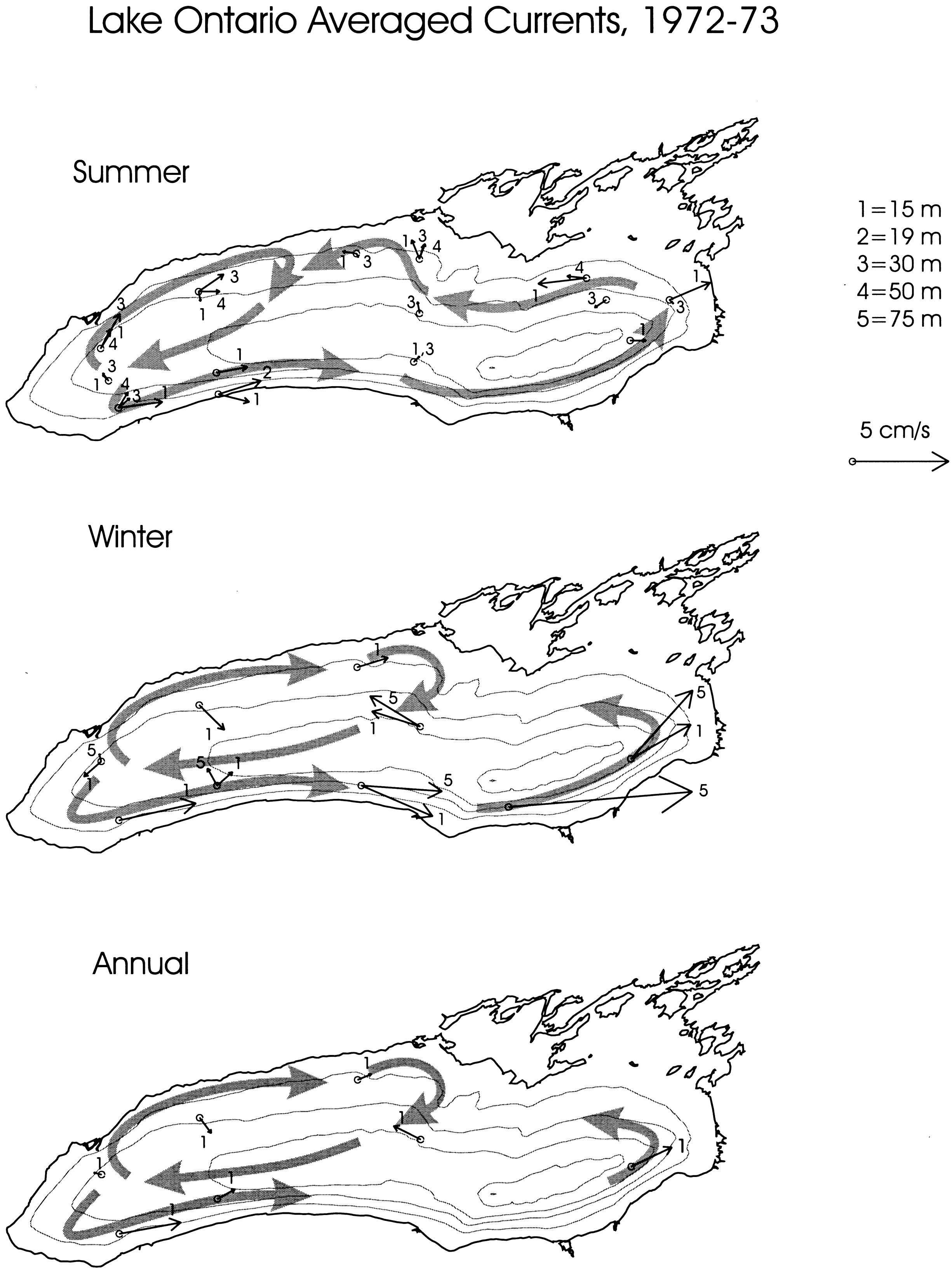

FIG. 5. Summer, winter, and annual circulation in Lake Ontario. Isobaths every 50 m.

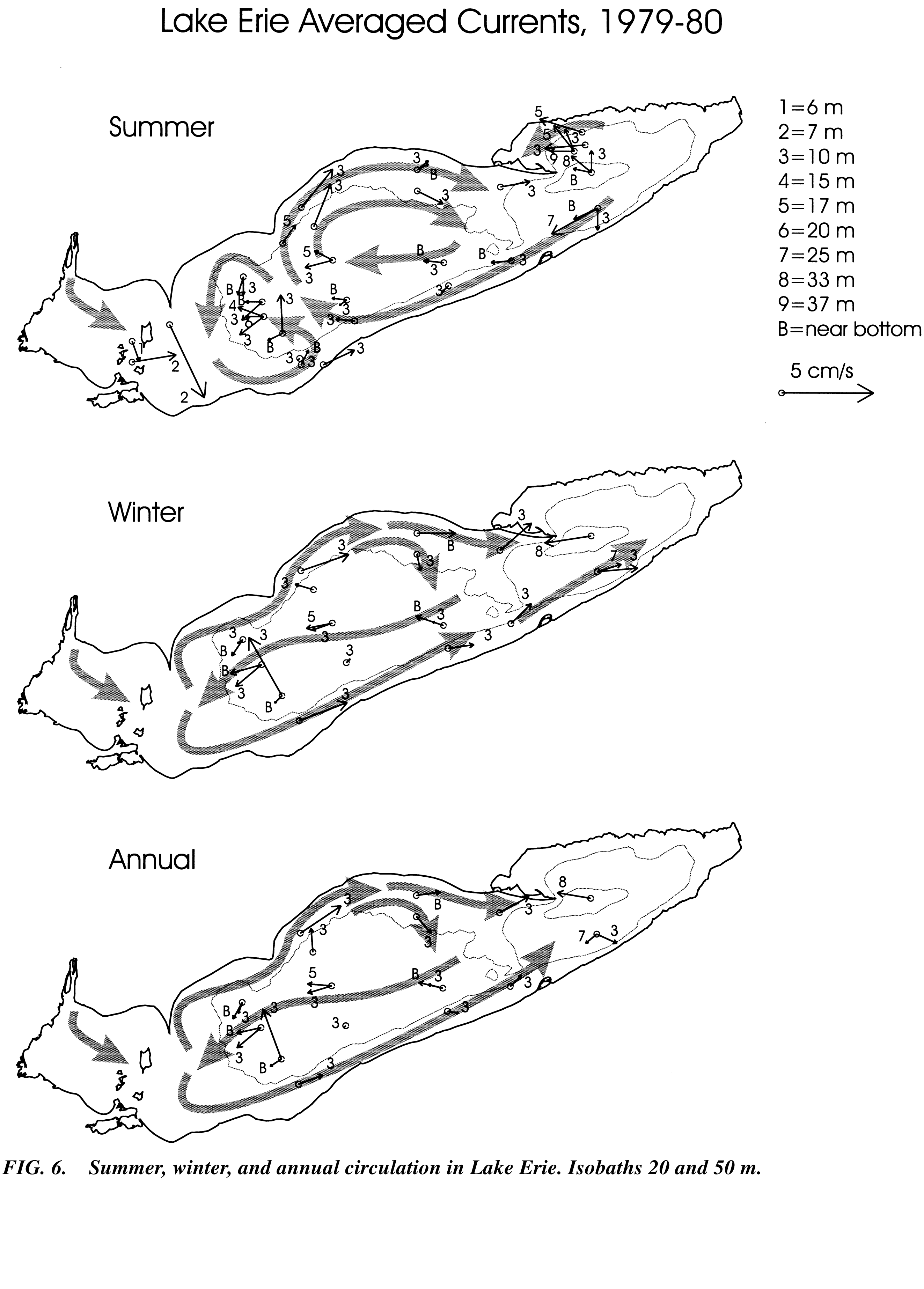

FIG. 6. Summer, winter, and annual circulation in Lake Erie. Isobaths 20 and 50 m.

tario and the eastward current near the south shore of Lake Ontario were both observed in 1972 during IFYGL (Saylor *et al*. 1981) and 10 years later in the 1982 experiment (Simons and Schertzer 1987, Simons and Schertzer 1989). The 1982 data showed stronger coastal currents near the south shore (up to 6 cm/s) probably because of the better nearshore-offshore resolution than during IFYGL.

The Keweenaw current is a persistent feature of summer circulation in Lake Superior (Ragotzkie 1966, Sloss and Saylor 1976b). Lake-wide cyclonic circulation observed in 1967 (Sloss and Saylor 1976b) in Lake Superior was similar to that observed in 1973 (Lam 1978), although Lam (1978) reported much higher velocities in the Keweenaw current (up to 18 cm/s). The difference can probably be explained by spatial variability of currents in this very steep bottom slope area in combination with different meteorological conditions. Westward flow of 1 to 3 cm/s in the open part of central Lake Erie in 1964 (Hamblin 1971) was similar to the 1979 flow (Fig. 6). In addition, a combination of an anticyclonic gyre and a cyclonic gyre in central Lake Erie was observed in both 1970 (Simons 1976) and in 1979 (Fig. 6). In the Lake Michigan case, the FWPCA (1967) study suggests cyclonic flow in the summer of 1963 at 60 meters depth and deeper, similar to the flow observed in 1982 (Fig. 3). Unfortunately, they do not provide analogous circulation maps for the upper layer, but only current maps for prevailing wind directions. Some other earlier reports also lack information on mean current speed and circulation patterns in the Great Lakes which makes the study of interannual current variability even more challenging. In another study of Lake Michigan summer circulation in 1976, Saylor *et al*. (1980) found that the circulation becomes increasingly cyclonic by the end of the stratified period, which also coincides with more recent observations. Average summer currents in that study were about 1 to 2 cm/s which is similar to the 1982–83 findings.

Winter Circulation

Sufficient observational data are now available to describe large-scale winter circulation in all of the Great Lakes except Lake Superior where observations covered only the western part of the lake (Fig. 4). Winter circulation is stronger than summer circulation (especially in coastal areas) because of the stronger winds in winter. The average speed of winter currents is between 1.6 and 2.8 cm/s (Table 2) although some locations yielded very weak mean currents (as low as 0.2 cm/s), just a bit stronger than minimum summer currents. The strongest mean winter currents (9.5 cm/s) were observed in southeastern Lake Ontario (Fig. 5). Winter currents are essentially barotropic, which means that their variations with depth are minor due to the absence of temperature stratification, especially in comparison with summer currents which have more pronounced vertical variation due to the stratification.

Cyclonic circulation persists in the winter both in Lake Huron (Fig. 2) and Lake Michigan (Fig. 3). Winter circulation in these lakes exhibits strong coastal currents (up to 7.9 cm/s in southern Lake Huron and 4.7 cm/s in southern Lake Michigan) and is also more cyclonic than in summer. In Lake Michigan, these winter coastal currents were equally strong along the west and east coast which is in contrast with summer observations. The previously mentioned mid-lake anticyclonic gyre, that was seen in summer observations in Lake Michigan, persists through winter with comparable current speeds. Another stable feature of both summer and winter circulation is a surface flow into Georgian Bay in Lake Huron (Schertzer *et al*. 1979). While circulation in the larger lakes exhibits a tendency toward increased cyclonic circulation in winter, in the smaller lakes a different tendency was observed, i.e., winter circulation in Lake Ontario (Fig. 5) and in Lake Erie (Fig. 6) strongly resembles the classic two-gyre wind-driven circulation of Bennett (1974). In Lake Erie, this two-gyre winter circulation becomes possible because the flow reverses its direction along the south shore to eastward in winter in contrast with westward summer currents. The strongest mean winter currents in Lake Erie (3.7 cm/s) were observed offshore of Cleveland, Ohio (Fig. 6).

Again, some interannual variability is evident. The observations in Lake Ontario revealed a two-gyre winter circulation pattern in central Lake Ontario during the IFYGL winter of 1972–73 (Saylor *et al*. 1981), and a one-gyre pattern during the 1982–83 winter (Simons *et al*. 1985). Some other features of lake circulation appear to be more stable from year to year. For instance, the subsurface circulation in Lake Michigan was cyclonic during both the 1962–63 (FWPCA 1967) and 1982–83 (Fig. 3) winters. Strong eastward currents (up to 8 to 10 cm/s) were observed near the south shore of Lake Ontario during both the 1972–73 winter (Saylor *et al*. 1981) and the 1982–83 winter (Simons *et al*. 1985, Simons and Schertzer 1989). Although

Casey *et al*. (1966) do not provide a map of winter currents in Lake Ontario, both the average winter speed (5 cm/s) and summer speed (2 cm/s) that they report is comparable with the 1972–73 observations. Westward flow of 1 to 3 cm/s in the open part of central Lake Erie during the 1964–65 winter (Hamblin 1971) was also apparent during the 1979–80 winter (Saylor and Miller 1987). In fact, these westward open lake currents generally do not change direction over the whole year.

Annual Circulation

Currently, describing the annual circulation in Lakes Erie, Michigan, and Ontario can only be considered because they are the only lakes with sufficient observational coverage (Table 1). In all lakes, winter circulation appears to be stronger than summer circulation, and, therefore, the annual circulation pattern essentially repeats that of winter. It is cyclonic in Lake Michigan (Fig. 3) and has a two-gyre pattern in Lake Ontario (Fig. 5) and in Lake Erie (Fig. 6). The average speed of annual currents is 1.3 to 1.9 cm/s, maximum annual currents were about 3 to 4 cm/s (Table 2). In Lake Michigan, maximum annual current speed was observed in the mid-lake ridge area as a result of consistently strong summer and winter currents (Fig. 3). The location of maximum annual currents in Lake Erie coincided with the location of the strongest winter currents, offshore of Cleveland (Fig. 6). In the case of Lake Ontario, lack of summer observations at the station in the southeastern part of the lake where the strongest winter currents were observed very likely caused the decrease in maximum annual current speed, which is now shifted to the southwestern part of the lake.

Interannual variability of the annual circulation has probably never been investigated before because of the lack of long-term observations anywhere except Lakes Erie, Michigan and Ontario. Some earlier observations in Lake Ontario (Casey *et al*. 1966) had sufficient duration, but it appears that annual circulation maps based on these data were never compiled. The 1982–83 observations on the north-south transect of Lake Ontario (Simons and Schertzer 1987, Simons and Schertzer 1989) showed cyclonic flow during both summer and winter, which makes annual circulation in this area also cyclonic, which is different from the two-gyre annual circulation during 1972–73 (Fig. 5). On the other hand, year-long observations made in different decades in central Lake Erie (Hamblin 1971, Saylor and Miller 1987) showed a similar westward flow of 1 to 3 cm/s in this area. In Lake Michigan, the circulation pattern at depths exceeding 60 meters was cyclonic during both 1962–63 (FWPCA 1967) and in 1982–83 (Fig.3). More studies are needed to address this question in other lakes.

DISCUSSION AND CONCLUSIONS

In this paper long-term current observations collected during the last three decades are used to update Harrington's (1894) map of summer circulation in the Great Lakes. Two of the five summer circulation maps presented here (Lake Michigan and Lake Erie) are entirely new. Overall, new data correspond more closely to Harrington's in the larger lakes: Lakes Michigan, Huron, and Superior. Maps of winter currents in all of the Great Lakes except Lake Superior are provided. Again, the Lake Michigan and Lake Erie circulation maps are new. Finally, new annual circulation maps in Lakes Erie, Ontario, and Michigan are presented.

Summer circulation is apparently more complex than winter circulation. The reason is the presence of baroclinic effects in summer circulation, while winter circulation is almost entirely wind-driven (density-driven currents are negligible in winter). Winter currents are generally stronger than summer currents, and, therefore, annual circulation patterns closely resemble winter circulation patterns.

Circulation patterns show a tendency to be cyclonic in the larger lakes (Lake Huron and Lake Michigan), especially in winter. (Winter observations in Lake Superior cover only the western part of that lake.) This may indicate the significance of lake-induced mesoscale vorticity in the wind field. Two factors could contribute to this in case of larger lakes: larger surface area, and stronger lake-atmosphere temperature gradients. Lakes with smaller surface areas (Lake Erie and Lake Ontario) exhibit two-gyre circulation patterns in winter which could be a consequence of more uniform wind fields. In particular, the surface area of Lake Ontario is three times less than that of Lakes Michigan or Huron, and four times less than that of Lake Superior (Upchurch 1976). Summer circulation in the smaller lakes was different. In Lake Ontario, it was predominantly cyclonic probably because of the density-driven cyclonic currents (similar to the cyclonic summer circulation in Lakes Michigan, Huron, and Superior). On the other hand, summer circulation in Lake Erie was mostly anticyclonic which could probably only be caused by wind.

The interannual variability of seasonal circulation in the Great Lakes has rarely been studied in the past because of insufficient data. Comparison with historic data shows that while some features of lake circulation appear to be rather stable, others exhibit significant interannual variability. More long-term measurements are needed to address this question more fully.

ACKNOWLEDGMENTS

We would like to thank Gerald S. Miller and Glenn C. Muhr for maintaining original data. We also thank Michael J. McCormick, Gerald S. Miller, W. M. Schertzer and an anonymous reviewer for their suggestions that improved the manuscript. This research was partially supported by the USEPA Lake Michigan Mass Balance Project. This is GLERL contribution 1095.

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Submitted: 16 May 1998
Accepted: 19 October 1998
Editorial handling: Paul F. Hamblin