INLAND WATERS BRANCH

Circulation and Water Movement in Lake Erie

P.F. HAMBLIN

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DEPARTMENT OF ENERGY,
MINES AND RESOURCES

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DEPARTMENT OF ENERGY, MINES AND RESOURCES
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Contents

Illustrations

Preface

This report was prepared in response to a request by the International Joint Commission for a written report on the presently available knowledge on the circulation and water movement in Lake Erie. A condensed version of this report appears in Subsection 2.1 of Vol. II of the Report to the International Joint Commission on the Pollution of Lake Erie. As well as offering a more complete analysis and documentation of work presented heretofore, this report includes the results of the most recent circulation studies of Lake Erie undertaken at the Canada Centre For Inland Waters (CCIW).

The author is indebted to the personnel at the Lake Erie Program Office of the Federal Water Pollution Control Administration who provided generous amounts of limnological data on Lake Erie and wind and current metering instrumentation for his use.

The Meteorological Branch of the Federal Department of Transport is thanked for supplying meteorological data on Lake Erie to the author.

Abstract

This report provides a summary of presently available knowledge of the circulation, water movements and diffusive processes occurring in Lake Erie compiled from published works and results of recent studies conducted at the Canada Centre For Inland Waters. In addition, the residence time, theory of lake circulation and diffusion are discussed. An atlas of monthly averaged currents is provided in an appendix.

CHAPTER 1

Introduction

Studies of water circulation and diffusion processes provide a means of gaining insight into certain physical processes and mechanisms occurring within a lake. From a pragmatic viewpoint, an important aspect of these studies is to provide sufficient knowledge to be able to predict the response of the water quality of a lake to changing levels of inputs.

A direct measure of lake water movements by methods such as drift object releases or metered current stations is of consequence to the advection of contaminants within a lake, while the dilution of pollutant level by turbulent diffusion processes is best studied by the tracking of artificial contaminants such as dye stuffs. The additive effects of advection by the lake circulation and of dilution by turbulent diffusion on the dispersal of material entering the lake can under certain requisites, be determined by the synoptic mapping of water properties. In the ensuing discussion these studies are referred to as indirect studies.

For convenience, the descriptions of the directly and indirectly determined circulations and the measurements of diffusion, are divided into three separate sections for each of the western, central and eastern basins of Lake Erie. The boundaries of these regions and geographical names are provided in Figure 1.

CHAPTER 2

Water Circulation in the Western Basin of Lake Erie

Water circulation in the western basin of Lake Erie has received the attention of the majority of investigators of the lake. No doubt the economic importance of the high concentration of population and industry surrounding this basin has warranted this attention. Further contributing factors are the more rapid response of this basin to changing environmental conditions necessitated by the relatively small volume of water, and the logistical advantage offered by the smaller horizontal extent of the basin.

In one respect the western basin of Lake Erie is not appropriate for the measurement of currents. The use of the modern *in situ* recording current meter is precluded in the region, since the standard current sensor rectifies water particle oscillations associated with surface waves near the surface. Consequently, few reliable metered current observations exist. Water movements are mainly inferred, from techniques in which marked particles of fluid are followed, such as dye releases and drift objects.

DIRECT CIRCULATION STUDIES

(1) In his classic study of the surface circulation of the Great Lakes from 1892 to 1894, Harrington (1895) remarked upon 42 drifting bottles released and recovered in

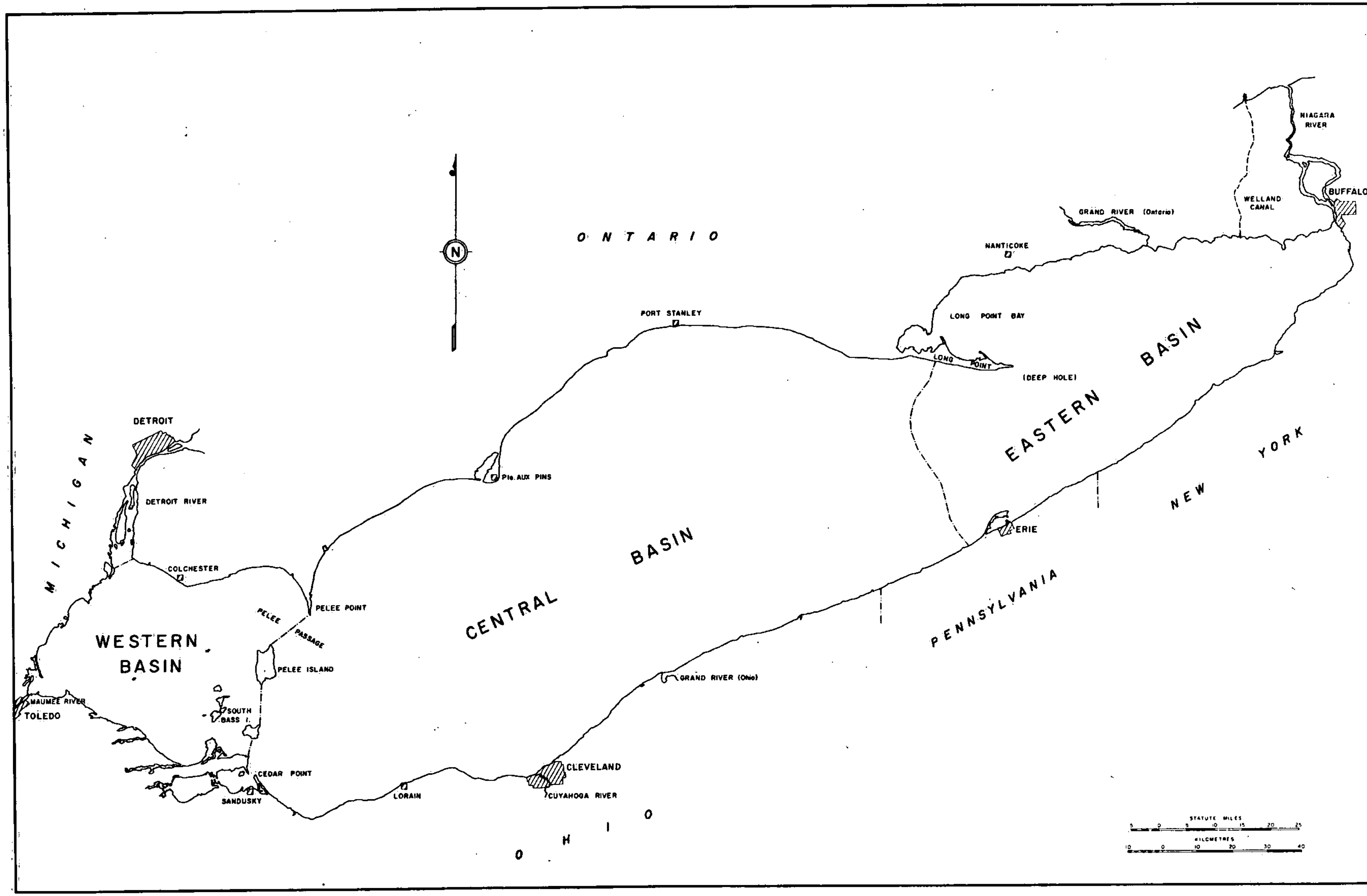


Figure 1. Lake Erie.

the western end of Lake Erie. His recovery data attest to a general eastward drift in the basin with the main current passing between Point Pelee and Pelee Island. He pointed out the possibility of a westward flow south of Pelee Island, a feature which has preoccupied his successors.

(2) Wright (1955) gives some attention to the currents in the western basin in his survey of the limnology of the area. From 54 recoveries of "drogued" drift bottles released in the spring of 1928, Wright indicates the dependence of the recovery positions on the wind direction, presumably at the time of release, and hence the inconsistency in the direction of the currents.

(3) Among the more comprehensive studies of this type to the present time is one conducted by Olson during 1949 and 1950 (Figure 2). Olson (1950) conceived of several improvements in the drift object technique, namely the multiple release of 10 drift cards at a time, an improved drift object design, and the repetition of releases in the basin throughout the entire navigation season. His conclusions are reached on the basis of 624 returns.

Although not stated explicitly it is assumed that there is not sufficient seasonal dependence in the distribution of recoveries to warrant their classification by season. Furthermore, Olson does not categorize the derived circulation patterns on the basis of wind direction. Unlike Wright, he apparently felt that his observations define the circulation pattern resulting when immediate wind influences have been removed.

Olson subdivided the western basin into several distinct "rivers" or regions of flow, each depending on its characteristic behaviour. The salient features of his current regime were the Pelee Island gyre, the Michigan shore drift, and the Pelee Island Drift. He considered that water emanating from the Detroit River stays for the most part in the northern half of the basin and passes out to the central basin via Pelee passage. He also indicated the clockwise movement called, the Pelee Island gyre. The study was the

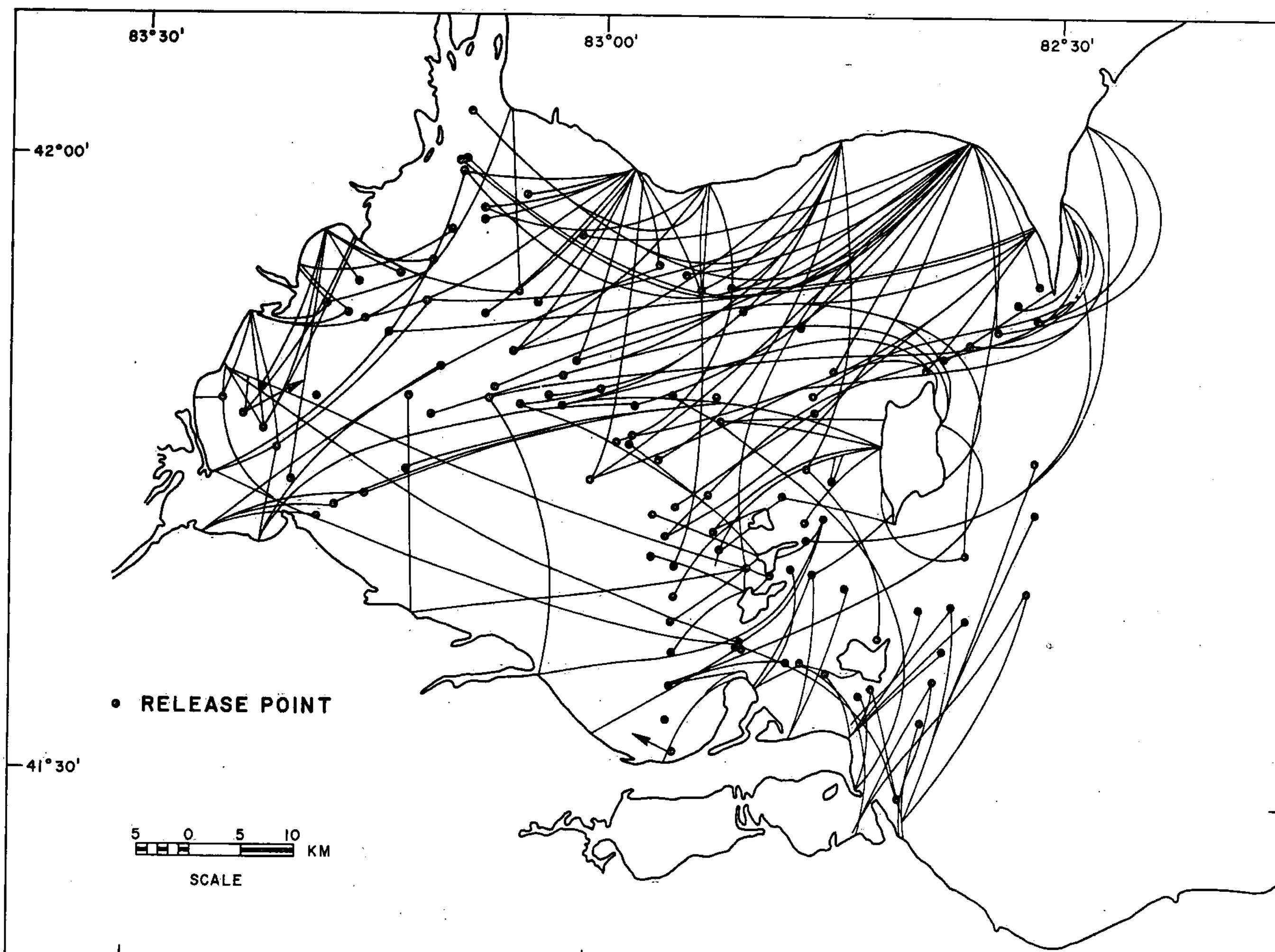


Figure 2. Drift card trajectories in the western basin of lake Erie (after Olson, 1950).

first to suggest a recirculation of Detroit River water on the Michigan and Colchester shores.

A most important contribution made by Olson was the estimation of the minimum drift speed of the surface current, and its relationship to the resultant wind between release and recovery times. Because of the multiple release of cards he was able to grade the data on the basis of both the number and the recovery time of the returns. For the best data he found that the drift speed was approximately 2 per cent of the resultant wind speed as measured at a shore station, plus a permanent drift of 3 km per day. He accounted for a portion of the set on the basis of the eastward hydraulic flow in the region.

After a careful analysis of drift object and resultant wind bearings, Olson concluded that on the average his drift cards travelled in a direction 20° to the left of the resultant wind. He pointed out that this result was not in agreement with the Ekman theory, nor with the fact that the eastward drift should deflect the northward trajectories to the right. Theoretically derived vertical profiles of current, based on the Ekman theory for the open waters of the western basin, are presented in Figure 21.

(4) Verber in an intensive study of the inter-island channels in 1951 and 1952, used a large number of drift cards (3,500), drogues, and a current meter. His investigations confirmed the gyral motion around Pelee Island (Verber, 1953, 1955). He considered the action of the longitudinal open lake seiche to be instrumental in the forcing of this gyral motion. Verber's analysis confirmed earlier observations that there is direct correlation between wind movement and surface flow, and that most of the basin water exits through the Pelee Passage. He noted that drift cards averaged about 15 cm/sec., a figure which agrees with his drogue and current meter results.

(5) The United States Bureau of Commercial Fisheries, in a recent study, has reported on the action of winds from various quarters on the distribution of drift cards. That study indicated that southerly winds result in flow being directed to the north shore and to Pelee Passage, while westerly and northwesterly winds cause patterns similar to the average pattern, with the Detroit River water reaching deep into the basin. Northeast winds are responsible for surface currents towards the west shore, with a simultaneous flow out of the Pelee Passage.

(6) The Lake Erie Program Office of the Federal Water Pollution Control Administration (FWPCA) embarked on an extensive observational program in Lake Erie in 1964. While the major portion of the study has been directed to the central and eastern basins, this agency has advanced the body of knowledge of the western area as well.

A self-recording, current metering station was established by FWPCA in Pelee Passage during the period August to October, 1965. The flow regime at this station is markedly bimodal about a northwest to southeast direction. Southeast flow predominates at a depth of 10 m. Apparently the currents of the Passage in proximity to the bottom, are not unlike those at the surface at this time of year. A current meter northeast of Cedar Point, during the summer of 1965, is reported to have indicated a dominant movement northwestward.

About one dozen returns of sea-bed drifters released by FWPCA (Hartley, 1968) suggest that a bottom current flows out of the western basin between Scot Point and South Bass Island, and that the clockwise gyre around Pelee Island extends to the bottom depths. The scant evidence from surface drift objects does not support the existence of this flow at the surface. Courses taken by surface drift objects in studies other than Olson's are depicted in Figure 3.

DIFFUSION EXPERIMENTS

Contaminants are dispersed in a body of water by two processes; by advection, and by turbulent diffusion. Because of the importance of turbulent diffusion in the dispersal of pollutants, all studies of diffusion in Lake Erie have been incorporated in this report.

(1) Dye diffusion experiments in 1963, conducted by Csanady (1964) within 2.1 km of the Colchester shore, are among the few reported works yielding a quantitative measure of the effective redistribution of contaminants in both the vertical and horizontal directions by turbulent mixing processes. Values derived for absolute vertical eddy diffusivity (7 cm^2/s) are in agreement with those given by Bowden (1965) for the Mersey estuary, but are somewhat higher than values obtained in Lake Huron and under similar conditions by Csanady. On the other hand, the coefficients of relative horizontal eddy diffusion are somewhat less than the values given for Lake Huron (700 - 2600 cm^2/s). Csanady attributed this to the relatively high vertical diffusivity in Lake Erie, to the shallowness of the bottom, and to the lack of strong temperature stratification.

During one of 8 trials, a barrier or "floor" to vertical diffusion developed at an intermediate depth. The effective vertical migration of pollutants was halted at this level while the horizontal spread was accelerated. A further phenomenon was noted; the horizontal transport of con-

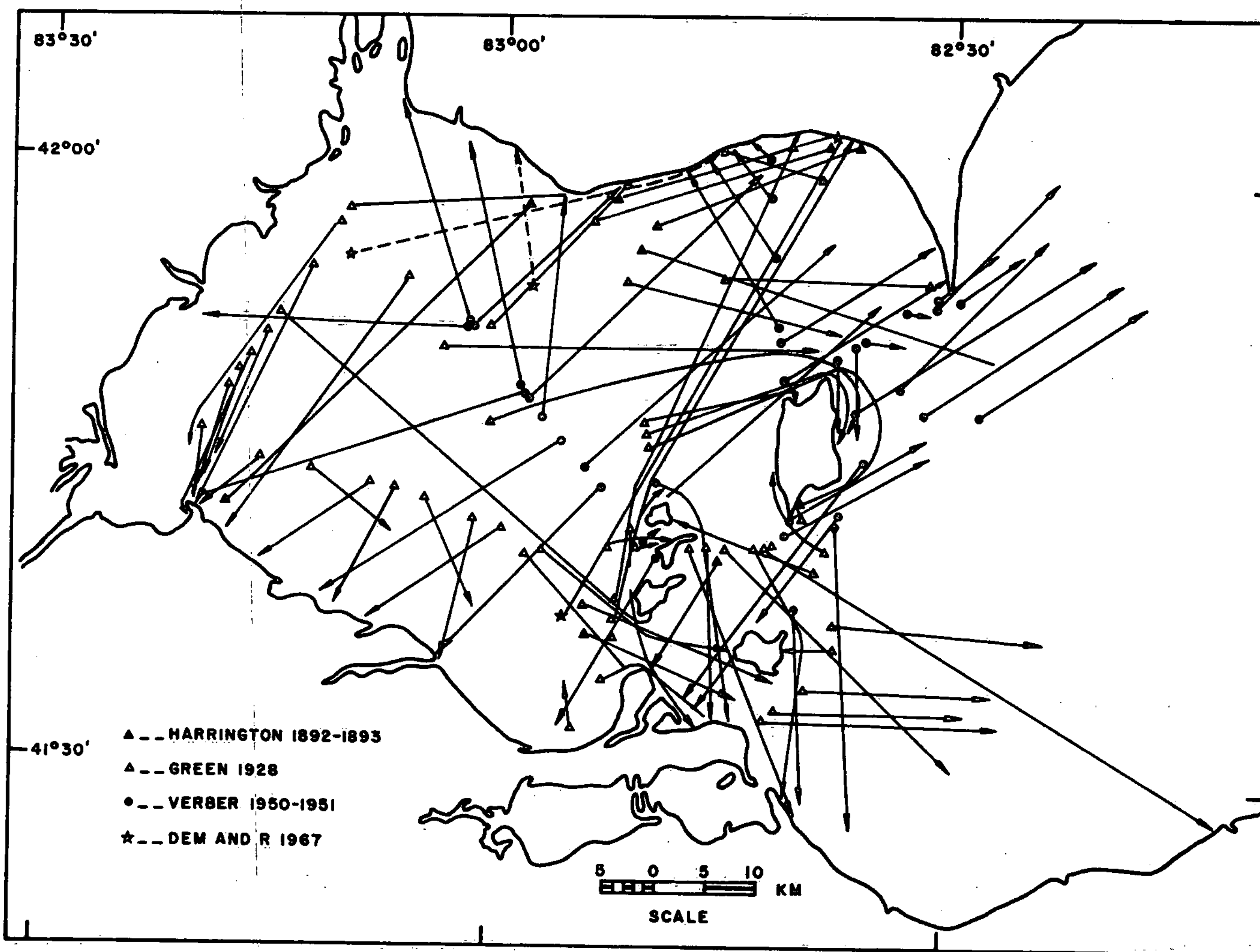


Figure 3. Drift object trajectories in the western basin of Lake Erie (from studies 1892-1967).

taminants was increased by the meandering, or the constant veering or backing of currents, beyond that which is usual for steady currents. Therefore, Csanady's values for the relative horizontal diffusivity may be considered as the lower limits for turbulent mixing processes in the basin.

(2) At a station 7 km southwest of Colchester, Okubo and Farlow (1967) deduced estimates of "absolute diffusion" coefficients in the horizontal direction. By considering the displacements of groups of drogues at successive intervals of time, they derived values which were one order of magnitude higher than the relative diffusion measurements of Csanady.

INDIRECT STUDIES

Under certain conditions it is possible to measure the combined effects of advection by the mean current distribution, and of turbulent diffusion on the dispersal of pollutants within a body of water by the synoptic measurement of water properties.

The mapping of distinct water masses in the western basin of Lake Erie has been frustrated for several reasons. It is of prime importance that the data used for mapping be reasonably close to synoptic; alternatively, the time taken for the survey must be nearly simultaneous, in order that the distribution does not change appreciably during the period of the survey. Not only must the data be synoptic, but a sizeable amount of data is customarily needed to define separate and distinct water masses. Furthermore, the parameters chosen for mapping must be conservative in nature and have distinguishable gradients of concentration level within the lake. Practical considerations in the area of interest are the restriction of navigation in certain areas, and the need for vessels of shallow draft with which to conduct the survey. For the reason outlined, there have been only two serious attempts to infer water mass movement from detailed water chemistry observations.

(1) In the summer of 1963, O'Leary (Detroit River Program Office, FWPCA), traced the courses taken by patches of dye released at 20 stations in the vicinity of the Detroit River. The assumption of synopticity was verified at repeated stations to hold over the course of the working day. Presumably, the dominating influence of the Detroit River validates the synoptic assumption in this area.

The results are presented as a series of charts of current directions, each under the influence of wind from different octants (O'Leary, 1966). Throughout all classes of wind direction, the Detroit River flow was distinguishable for a distance extending about 10 km into the lake proper. The direction of the flow was deflected to a small degree in the direction of the wind prevailing at the time of the experiment. Under the action of northeast winds, a small component of the flow was directed across the International Boundary to United States waters, while southerly, southwesterly, and westerly winds caused the opposite to occur.

A recirculation of surface water along the Michigan shore was experienced for all winds except those from the northwest, north and northeast, with the principal occurrence being effected by southerly winds. A similar, though weaker return flow along the Colchester shore was observed during easterly and southeasterly winds.

(2) Water sampling surveys conducted on single occasions in the summers of 1963 and 1964 are reported by (Hartley, Herdendorf and Keller, 1966) to have fulfilled the above mentionned requisites for the synoptic mapping of mass movement of water in the western basin. For the requirement of conservation, Hartley feels that conductivity is the most suitable parameter, and that water temperature at an intermediate depth is a secondary choice.

On the basis of two extremely detailed surveys, he concluded that the main flow of the Detroit River was felt as far southeastwards as the Ohio shore. Movements of water from the Maumee River, eastward along the southern shoreline and, subsequently, northward along the west side of Bass Island, were indicated. Thus the dominant basin outflow occurs through the Pelee Passage.

SUMMARY OF FINDINGS ON CIRCULATION AND DIFFUSION IN THE WESTERN BASIN

A tabulation of the findings presented here is based on a limited amount of field work undertaken by the Lakes Division, CCIW, and on some theoretical considerations, but in the main, is distilled from a search of the voluminous literature on the subject. A chart of the pattern of circulation derived from the available data, is presented in Figure 4.

(1) In consideration of theoretically derived profiles of current velocity (see Figure 21), and a small number of observations of current close to the bottom, the current decreases from its surface value to zero at the bottom, while remaining in a constant direction throughout the vertical column of water. The exception to this idealized current structure is when winds, imposed at the surface, produce a surface current, and continuity considerations demand a counterflow at depth. In most instances, the surface current distribution given will be representative of the vertically integrated basin circulation.

(2) The currents of the entire region are typically unsteady both in direction and in speed. Studies of the trajectories of drifting objects have shown that the currents in the western basin outside of the immediate influence of the Detroit River, are correlated with the direction and intensity of the antecedent and instantaneous winds, and with the fluctuations in water level known as seiches. The circulation, as presented here, is an idealized system resulting when the transient movements have been averaged out. It is emphasized that deviation from the mean flow is to be expected at any specific time.

(3) The principal flow of water into the basin is through the Detroit River. The influence of this river flow predominates well out into the lake proper in a southeastward direction and is the dominating influence in the western half of the basin. Occasionally the Detroit River flow is detectable as far south as the Ohio shore.

(4) A system of recirculation, which is dependent upon the wind direction, is known to develop along the Michigan and Colchester shores.

(5) Flow near the Ohio shore is directed parallel to the shoreline in an eastward direction, except in the Bass Island region where it is deflected to the north.

(6) The dominant basin outflow occurs via the Pelee Passage. In the open Passage the main body of current is directed to the southeast.

(7) A clockwise rotation of the shoreward water about Pelee Island has been confirmed by a number of investigators. There is evidence that this gyre extends to the bottom.

(8) Water movements in the inter-island region exhibit a degree of randomness to the extent that persistent directions cannot be ascertained. Wind-produced drift currents and slope currents associated with longitudinal seiche activity interacting with the irregular bottom and shoreline topography of the region are considered to be responsible for these erratic currents.

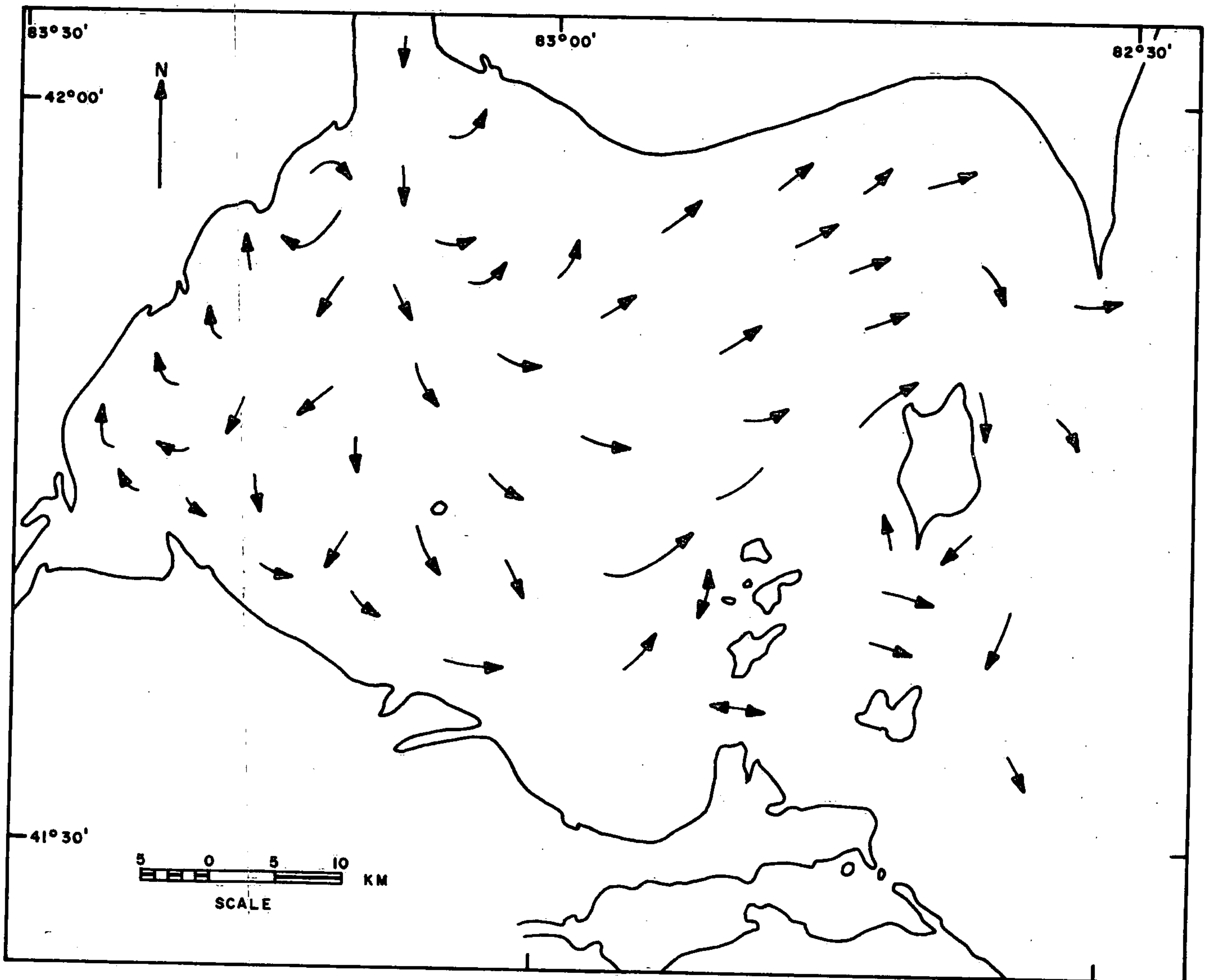


Figure 4. Direction of mean surface flow in the western end of Lake Erie as deduced from drift card studies 1892-1967.

(9) From the meagre evidence it is concluded that the circulation pattern is not differentiated into various seasonal regimes. It is conjectured that circulation during periods of winter ice cover is similar in direction to that of the summer with the possible exception of the Pelee Passage.

(10) Turbulent eddy diffusion is seen to be a property of the flow regime. Mixing in a vertical direction may be relatively higher in the western basin than in other areas in the Great Lakes while mixing in the horizontal direction is weaker in the western basin than in other areas.

Water Circulation in the Central Basin of Lake Erie

Although water currents in the central basin have attracted less interest than those in the western end of the lake, the task of synthesizing the description of the circulation in the central basin has been none the easier. This region is suitable but not ideal for the utilization of self-recording current meters at moored stations. During the years 1963 and 1964, the Great Lakes-Illinois River Basins Project of the Federal Water Pollution Control Administration collected a large amount of information from moored current meters in the central and eastern portions of the lake. The ensuing synopsis of the circulation of these regions is primarily based on an analysis of these data undertaken by the author. It is noteworthy that the analysis is the first to rely solely on data which have been corrected for an instrumental malfunction known as film blurring which had, heretofore, caused a number of errors in the direction readings of the currents.

Upon analysis of the current meter data and other available data, it became evident that the midlake flow regimen of the central basin is a superposition of three distinct regimes. Unlike the situation found in the western basin where the permanent flow is nearly constant in direction throughout the entire column of water, the mean currents of the central basin are skewed in depth. Most appropriate for the discussion of the circulation are the three classifications; surface circulation, intermediate circulation, and bottom circulation.

DIRECT CIRCULATION STUDIES

Surface Regime

Since most surface current observations taken in the central basin are relevant to a thin layer of water at the surface, the flow referred to hereafter as the surface circulation is considered to be the movement occurring in the upper metre of the water column after the variability in time has been sifted out. Data on the surface water movements are limited to three studies, none of which is as extensive as the studies conducted in the western basin. Nonetheless, the data are sufficient to define the general characteristics of the surface circulation in the basin.

(1) One of the few published works describing the surface circulation of central Lake Erie, is that conducted by Harrington (1895) during the navigation seasons of 1893 and 1894. The general course of bottles released in the central basin was eastward along the longitudinal axis of the lake. The tendency for a majority of strandings to occur to the right of the axis or along the southern shoreline, was noted. Because the demarcation between north stranding- and south stranding objects lies well to the north of the longitudinal midline of the lake, Harrington concluded that the main eastward surface current is much closer to the southern shore than to the northern coast.

(2) A limited number of observations of surface currents at a few locations in central Lake Erie were taken in 1928 by Green by means of a drifting pole. The observations, reported by Fish (1960), are too scattered in both time and space, as well as too few in number, to allow conclusions to be drawn.

(3) The United States Fish and Wildlife Service, Bureau of Commercial Fisheries, released drifting bottles in the western portion of the area of interest in May and August of 1958. The results of the study are reported by Powers *et al* (1960), who found that strandings of drift objects coincided well with those of Harrington's study.

(4) More recently, the Bureau of Commercial Fisheries experimented with drogues set at a shallow depth. As relayed by Hartley (personal communication), in nearly all cases the drogues indicated an eastward flow in the midlake. Drogue movements also show that the main influx into the central basin, via Pelee Passage, is directed southwards in the basin to its point of impingement along the Ohio shoreline between Sandusky and Lorain.

Summary of Findings on Surface Circulation

Evidence pertaining to the surface circulation is far from being complete. Two dominant features of the general circulation are presented as follows, and in a graphical form in Figure 5. For a discussion of possible subsidiary surface flows, the reader is referred to Powers *et al* (1960).

(1) Surface flow within the lake proper is directed eastwards and to the right of the longitudinal axis of the lake except in the western portion where the influence of the Pelee Passage inflow is predominant.

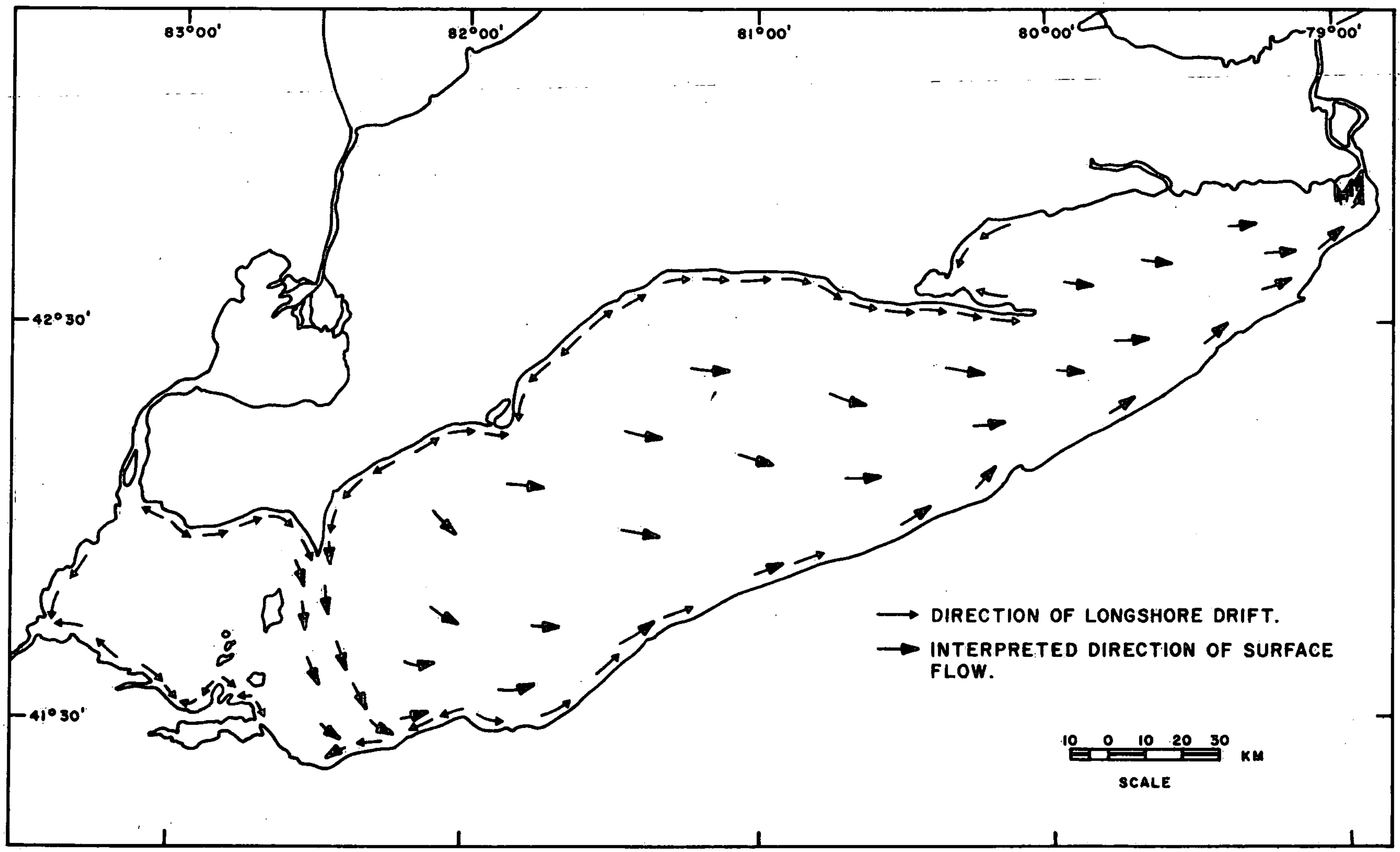


Figure 5. The permanent surface circulation of the central and eastern basins of Lake Erie.

(2) The principal influx to the central basin is expressed in the surface current regime in the extreme western portion of the central basin. This inflow is maintained as a coherent stream which proceeds in a southward direction to its point of impingement along the Ohio shoreline.

(3) Because of the lack of factual information on the surface circulation in the central region of Lake Erie, it is necessary to consider the more exhaustive surveys undertaken in the western basin and some theoretically derived calculations described in a later section of this report in order to arrive at the following conclusions:

a) Surface currents are typically erratic in time. Among other factors this variability is correlated with antecedent and actual winds.

b) The surface circulation derives a certain degree of permanence from the prevailing direction of the surface wind over the lake. The orientation of the basin with its longitudinal axis essentially parallel to the prevailing southwest winds, makes this effect especially important.

c) The resultant surface drift may be four times as rapid as the drift at intermediate depths. Thus, a large amount of the horizontal transport can be effected in the relatively thin surface flowage.

(4) While nearly all of the experimental evidence is relevant to summer conditions, it is unlikely that the surface pattern of circulation is altered appreciably with season. The prevalence of north and northwest winds during winter months is expected to cause the surface currents to run in a more southerly direction in winter.

Bottom Regime

Currents within 20 cm of the bottom are one of the least investigated aspects of water movement studies conducted in the Great Lakes. This is due, in part, to the fact that currents immediately above the bottom are generally too weak to be registered by the current metering instrumentation available at the present time. The success of a study of bottom currents in the central basin of Lake Erie can be attributed to a drifting device known as a sea-bed drifter which, in turn, owes much to the commercial fishery and the gently sloping bottom topography extant in the area for its recovery. As is the case with surface drift objects, the inference of water movement is clouded by uncertainties in the time and path travelled between release and recovery points, and results are customarily only qualitative in nature.

A large quantity of sea-bed drifters was released by FWPCA in the summer of 1965, in a pattern which, while covering the central basin, was weighted in favour of the inshore waters along the southern shoreline. Recovery positions of approximately 50 objects have been supplied to the author by Hartley of FWPCA. The system of bottom flow, as constructed from these data by the author, is presented in Figure 5.

From the trajectories undertaken by the drifters, it is evident that bottom circulation can be divided into two distinct regimes, the open lake flow and the nearshore flow. Drifters beaching on the shoreline nearest to the release point were predominantly displaced to the east, whereas those released in the vicinity of the American shore and arriving at destinations on the opposite shore, experienced a westward travel. No objects travelled across the lake from north to south.

It can be stated with some degree of assurance that the nearshore bottom flow is more rapid than the open lake flow. Although they travelled less distance than those traversing the lake, objects travelling to the northwest were resident in the lake for periods of one year or longer, while those remaining in the nearshore bottom flow beached much sooner.

An elaboration of the above mentioned interpretation is given by Hartley (1968) who feels that the absence of cross-lake returns during the first summer of immersion indicates that in the bottom layer there is no net transport during the period of summer stratification, although a to-and-fro movement may exist. Based on considerations of horizontal continuity, Hartley inferred that a closed or gyral bottom circulation exists in the western portion of the basin. Since continuity can be satisfied by vertical circulation at the boundaries, the interpretation given in Figure 6 is also valid. Hartley (personal communication) and the author agree there is strong evidence that materials originating on the American side of the International Boundary can be transported to the Canadian side of Lake Erie in a narrow zone adjacent to the bottom.

Surveys of water temperatures conducted by the Department of Energy, Mines and Resources have shown the existence of a number of episodes of substantially lower water temperatures occurring in a zone extending along the shore between Pointe aux Pins and Port Stanley and, on a more restricted basis, on the southern shoreline of the central basin throughout the period of vertical stratification of density. The occurrence of "upwelling" of bottom waters near a coastline, due to the offshore transport of surface water, is indicated by a lowering of the surface water temperatures near the shore (Figure 18). The presence of upwelling confirms that the bottom flow is not

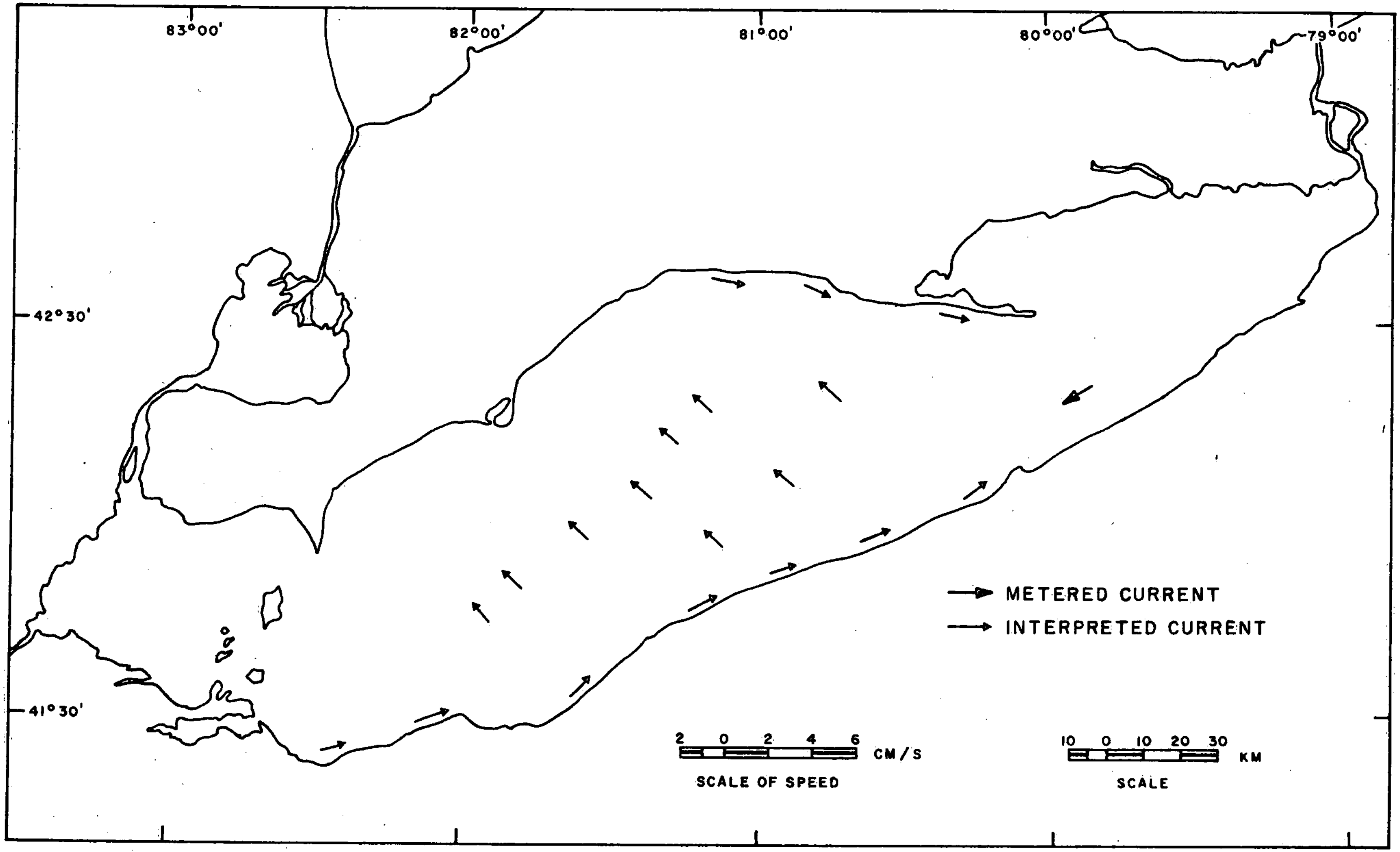


Figure 6. The permanent bottom currents in the central and eastern basins of Lake Erie.

devoid of movement during the period of summer stratification.

In summary, the circulation in a layer of water adjacent to the bottom is counter to that at the surface in the open lake. The bottom flow contributes a much smaller fraction to the total transport than does the surface current. A nearshore bottom current is directed eastwards along the northern and southern coasts of the central basin.

Intermediate Depth Regime

Data on transport between the depths of 10 and 15 metres have been collected with moored current meters by FWPCA and the Department of Energy, Mines and Resources. Henceforth, the circulation contained in this range of depth will be known as the intermediate or subsurface flow. The writer is indebted to those of FWPCA who have made voluminous amounts of metered current data available to him in the format of monthly current-speed histograms.

Since a current meter yields a large number of numerical readings sequenced in time, such data are suitable for quantitative treatment.

In brief, the following statistical analyses were undertaken on the metered current data. The mean speed over a monthly period, or longer, was computed. The individual current vectors were summed vectorially and divided by the number of samples, producing a quantity known as the resultant current vector. A test of whether this resultant current had components which were significantly different from zero on a 95 per cent confidence basis, was performed. Finally, the 25, 50, and 75 per cent probability contours for a current reading were computed. For example, the 75 per cent contour gives the range of speeds and directions into which the current readings should fall three quarters of the time.

It was found that a series of readings, when averaged vectorially over a month-long period, generally reduced to a resultant current vector which is significantly different from zero on a 95 per cent level of confidence. Moreover, at a specific location, the resultant flow remained roughly constant from one month to the next. In this report, therefore, currents averaged over periods of from one to six months will be referred to as the permanent flow. The permanent flow of the central basin is typically between 20 per cent and 30 per cent of the average speed.

A chart of the bathymetry of the lake and the locations and numbers of current metering stations operated by the Governments of Canada and the United States is provided in Figure 7. Figure 8 is a plot of the direction and magnitude of the permanent flow vectors. At locations where the flow is differentiated into a separate winter regime, the vectors are identified with respect to season. An interpolation of the circulation in areas not covered by direct measurements is shown by light arrows.

The reader is referred to Appendix I which is an atlas of monthly current vectors and average speeds for all data available at the time of writing.

At first sight, the accumulation of an extensive series of numerical data would seem to simplify the task of interpreting the intermediate circulation pattern. However, the existence of secondary flows, such as local and seasonal current systems which with less direct techniques were impossible to detect, alters and, in some instances, obscures the underlying circulation. As a denser network of stations would be required to determine the contributions of these auxiliary flows, an attempt is made here to present only the essential features of intermediate regimen.

Open Lake Flow

The permanent flow vectors indicate that the intermediate regime in the open lake is one of a diffuse flow aligned in a westward direction parallel to the longitudinal axis of the lake. The resultant current vector ranges from 1 to 3 cm/sec, while the average speeds fall into the interval from 7 to 10 cm/sec. Although rare, speeds in excess of 54 cm/sec, have been measured in the open lake. At stations 8 and 9, where currents at two levels were observed, the deeper flow is slightly weaker and is skewed by a small angle in a clockwise direction. At station 88, a current meter operated during the summer period of 1967 by the Department of Energy, Mines and Resources corroborated the above findings of FWPCA in the open lake.

On the basis of measured values of the permanent flow at intermediate depths, and a theoretically derived profile of current, the magnitudes of the surface and bottom drift can be predicted. The surface drift is estimated to have an order of magnitude of 10 cm/sec and the bottom flow, 0.6 cm/sec.

Unexpectedly, there is little differentiation of the open lake flow by season. A meter situated at mooring number 6 at a depth of 10 m yielded a resultant current almost identical for the periods from May to September, 1963, and from October, 1963 to March, 1964.

Nearshore Regions

Water movements at mid-depths in the western portion of the central basin are directed to the southwest, a

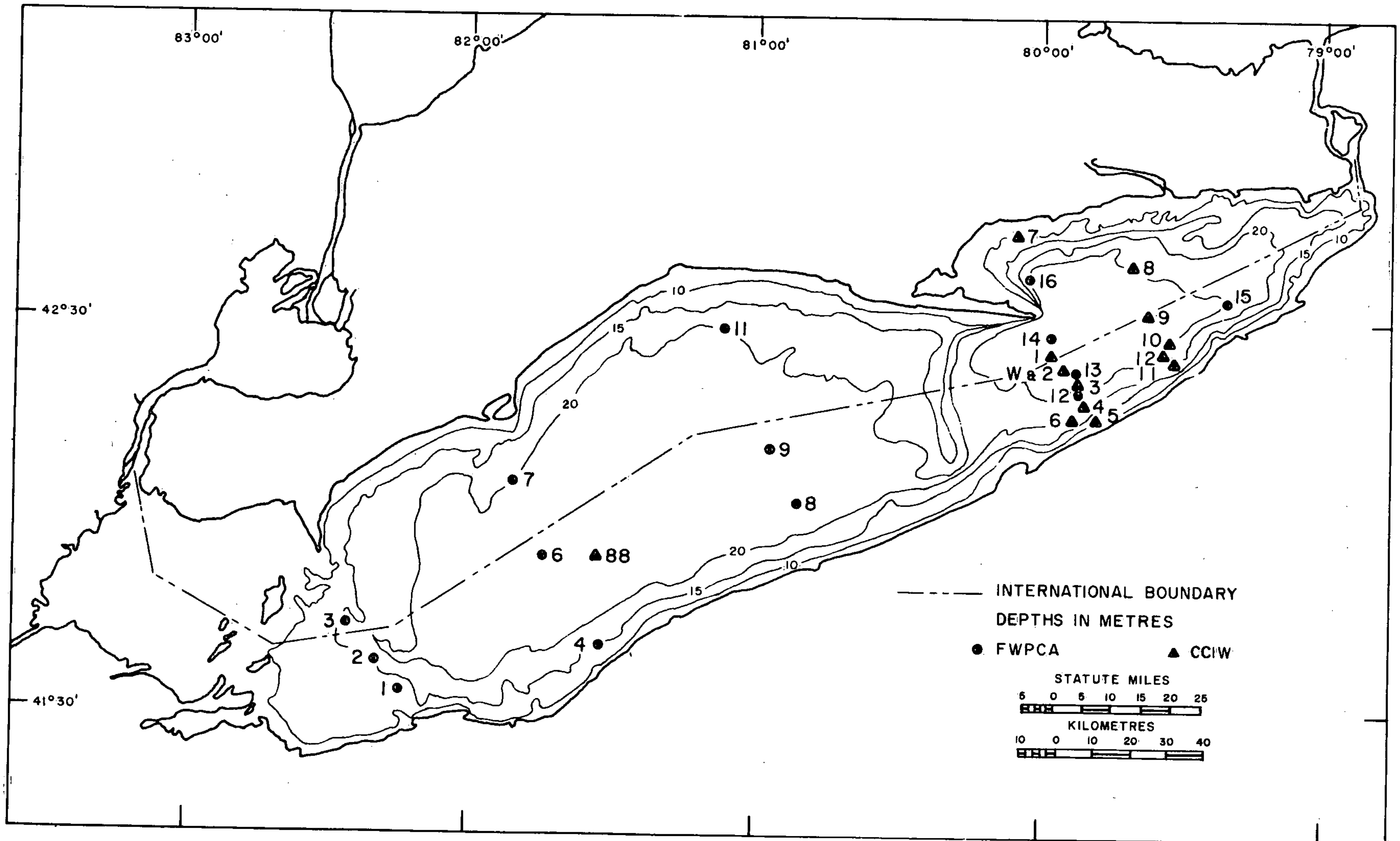


Figure 7. Bathymetric chart and metering station positions, Lake Erie.

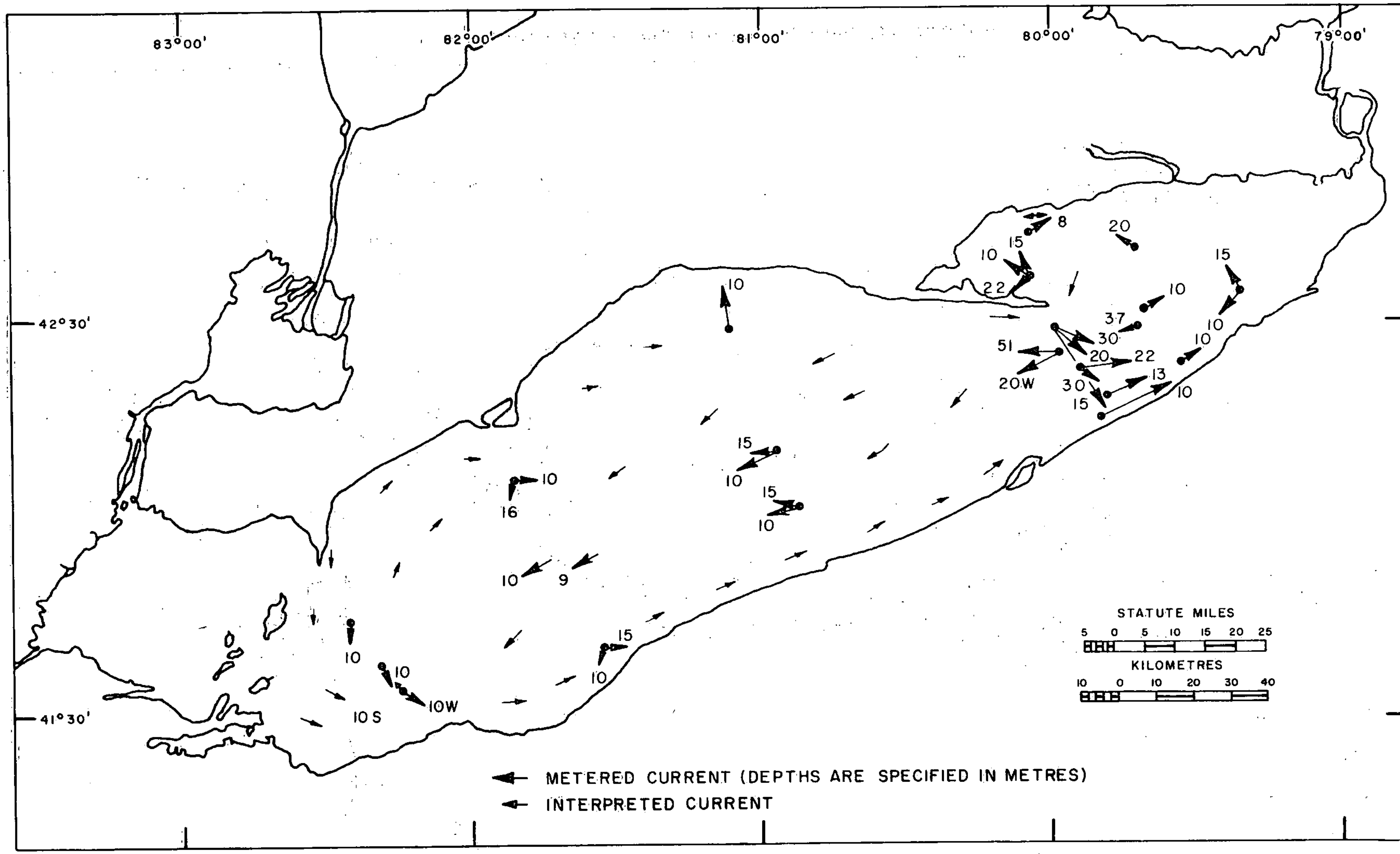


Figure 8. The permanent circulation at intermediate depth in the central and eastern basis of Lake Erie.

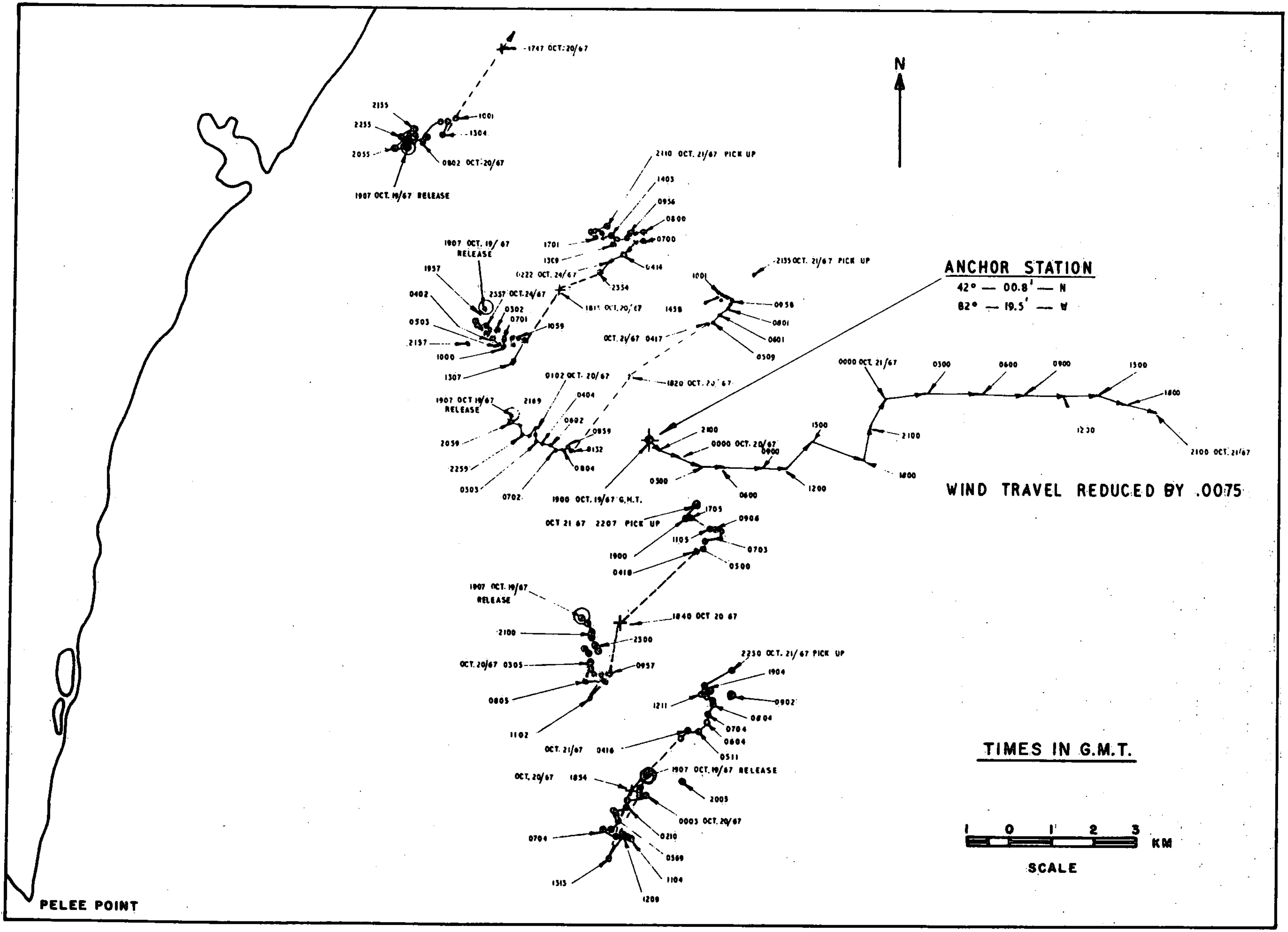


Figure 9. Drogue studies, Oct. 19-21, 1967, Lake Erie.

condition which also applies to the surface circulation. A factor which complicates this generalization is seen at station number 1 during the summer period when a minute counter-flow develops. Unfortunately, the influence of this subsidiary current on the regional flow cannot be ascertained for lack of horizontal control.

The currents near the southern and northern coastlines are less well known than those of the open lake. The presence of a clockwise loop of flow conforming to the semi-enclosed embayment formed between Pointe aux Pins and Pelee Point, and representing a portion of the return flow in the midlake, is somewhat conjectural. The southward movement at a station to the south of Pointe aux Pins on the northern shore tends to support this hypothesis. A tracking of drogues conducted in the fall of 1967 by the Department of Energy, Mines and Resources, demonstrates (Figure 9) the conformity of nearshore currents to the configuration of the shoreline, but does not confirm or deny the proposed gyral motion.

A resultant current which seemingly impinges on the shoreline adjacent to the Port Stanley area is indicated at station 11. This resultant current is the vectorial average of a bimodal distribution of current directions, a distribution composed principally of northwest and northeast currents.

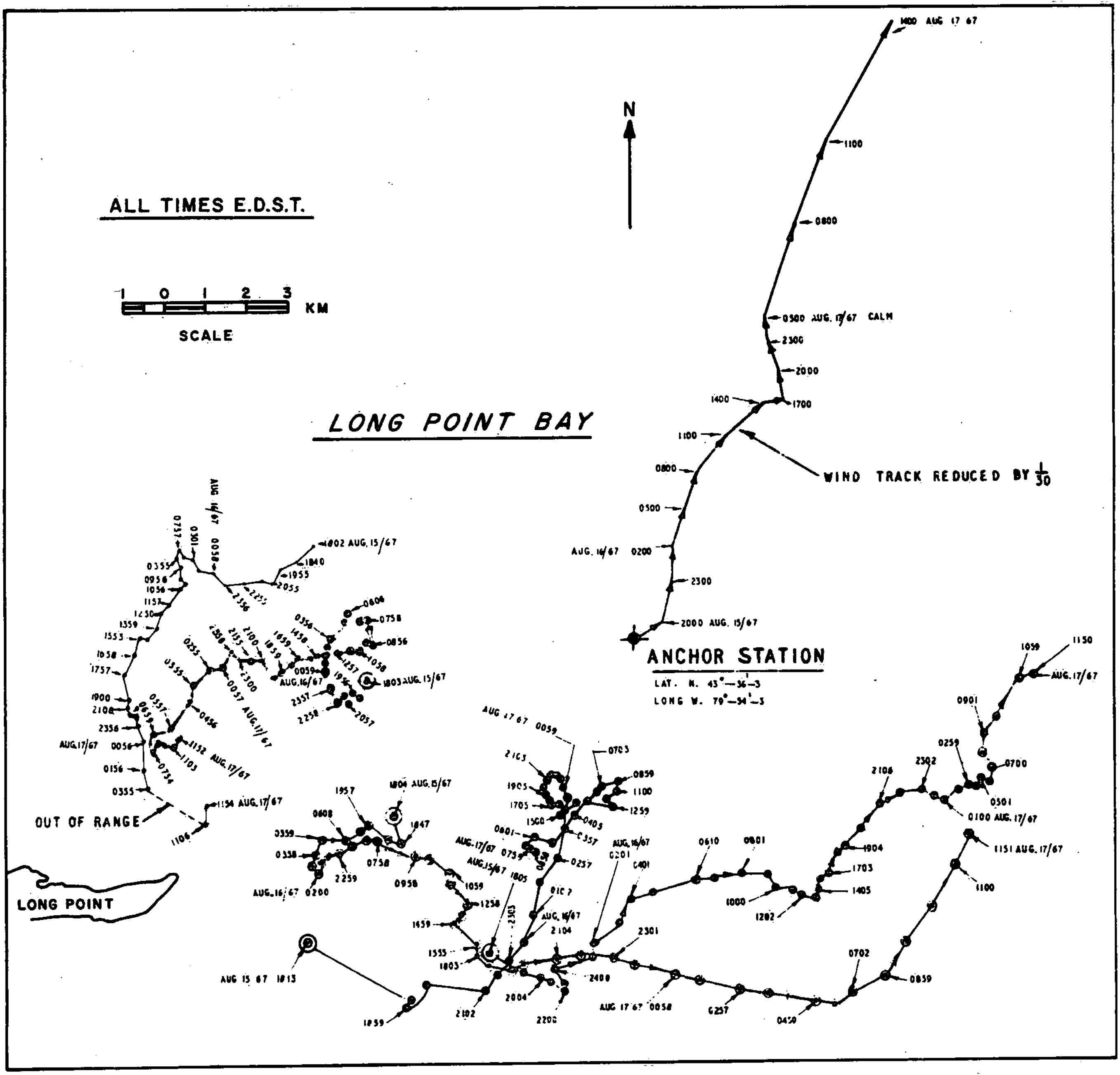


Figure 10. Drogue studies, Aug. 15-17, 1967, Lake Erie.

Inspection of Figure 7 reveals that the isobath in the neighbourhood of the station changes radically in direction at the station location. An alternate interpretation is that currents in this region conform closely to the direction of the upstream bottom contours, and that they are equally divided between westward and eastward movements.

Although at a considerable distance (10 km) from the southern perimeter of the central basin, apparently station 4 is sufficiently close to the shoreline to be influenced by the shoreline topography. Noticeable at the 10 and 15 m levels is the absence of current components which are perpendicular to the local isobaths, or shoreline configuration. Hence, the distribution of currents is markedly bimodal about the longshore direction. During both summer and winter, the preponderance of flow is to the east at a depth of 15 m, while preference for westward or eastward flow at a depth of 10 m is equal during the months of October and November. The mean speeds at this station are of the same magnitude as those in the open lake. Therefore, there is no suggestion of an increase in speed or the coastal jet phenomenon (Csanady, 1967) during either summer or winter as the shoreline is approached.

In conclusion, a conception of the permanent open lake regime emerges which is one of a wind-produced surface flow balanced by motion at intermediate and bottom depths. Near the shorelines, the system of flow is complicated by the vertical circulation that must exist at the boundary.

DIFFUSION STUDIES

(1) Dye studies along the southern shoreline of the central basin during the summer of 1965 were conducted by FWPCA in connection with the measurement of current. No estimates of the coefficients of turbulent mixing were attempted.

(2) As far as is known the only direct experimental estimates of the coefficient of eddy diffusivity are given by Okubo and Farlow (1967); on two occasions in 1964, they used an extensive array of drogues 2.4 km from the shore at Cleveland, Ohio. By repeatedly measuring the time behaviour of the areal spreading of the drogue pattern from their initial positions, they found an effective horizontal diffusivity of 3.3×10^4 cm^2/sec, a value which was an order of magnitude larger than that obtained in Csanady's (1964) work. This finding they have accounted for by the fact that their observations have included the effects of the very large eddies which probably are causing the meandering of dye plumes that Csanady observed. Moreover, because the study is purely a two-dimensional experiment, their estimates should be regarded as a lower limit for mixing in a lake.

INDIRECT STUDIES

(1) The computation of dynamic topography from observations of temperature at various depths presupposes that observations are obtained over the course of a synoptic period. Assuming synopticity and a level of no motion at a depth of 20 m, Powers *et al* (1960) deduced the circulation pattern in the central basin for a period of stratification in June, 1929. From this analysis, it was concluded that the flow is weak and variable in the northern half of the lake while an eastward flow is discernible in the southern half of the lake.

(2) In an accounting of the distribution of some major ions and trace elements in the central basin of Lake Erie, Weiler and Chawla (1968) refer to charts of the conductivity of lake waters which are thought to be representative of the summer distributions. A tongue-like intrusion of low-conductance water directed southeastwards from Pelee Passage conforms to the pattern of circulation in the western extent of the central basin as deduced from current measurements.

Water Circulation in the Eastern Basin of Lake Erie

The climatology of circulation found in the eastern basin of Lake Erie remains the least documented of the three regions to date. As in the preceding discussions, the substantiation of the system of flow has relied almost entirely upon the acquisition of historical records of data. In particular, metered current data collected in connection with a comprehensive lake study by FWPCA have been most helpful in the preparation of the following synopsis of the circulation.

An interpretation of the essential features of the permanent basin flow is offered. Such factors as the paucity of factual information, the irregularity of the shoreline configuration, the manifestations of sloping bottom topography, and the presence of a vertical stratification of density through a large portion of the year complicate the analysis. Reminiscent of the water movement of the central basin, the prevalent pattern of flow can be considered as a composite of three fundamental regimes, surface, subsurface, and bottom flow.

DIRECT CIRCULATION STUDIES

Surface Regime

(1) Drift bottles and drift cards released in the central basin in the aforementioned studies by Harrington and the United States Bureau of Commercial Fisheries, arrived on the southern shore of the eastern basin in great numbers.

Only a few were stranded on the northern shoreline of the eastern basin east of Long Point. As elsewhere, the relatively greater portion of northward to southward drifting objects is indicative of an eastwardly aligned, cross-lake flow of surface waters.

(2) In 1928, Green surveyed the speeds and directions of the surface currents in an area south of Long Point, using a drift pole as described previously (Fish, 1960). On nearly all of a limited number of occasions, he reported a rather rapid movement to the east; these currents rarely exceeded speeds of 25 cm/sec.

(3) In the fall of 1949, surface currents in the eastern end of Lake Erie and in the Niagara River were studied by United States field staff of the International Joint Commission, who released some 540 small wooden surface floats at six points located about one-half mile from the Canadian and American shores of Lake Erie (International Joint Commission Report, 1951). From the returns, numbering nearly 400, it was found that the many floats placed in Canadian waters remained in coves along the Canadian shore for several weeks. Of the floats placed in American waters, some were found on the Canadian shores, others turned up in the Buffalo Harbour area, while the largest proportion entered the Niagara River. The influence of the main flow toward the river was observed, particularly on floats placed along the Canadian shore about 6 km from the river inlet.

(4) A further study of the surface circulation in the eastern basin of Lake Erie was continued during the summers of 1967 and 1968 by the Canada Centre For Inland Waters, also using drifters. All tracks of cards recovered, the dates of release and recovery, and the direction of the average wind vectors of any cases where the time between release and recovery is relatively short, are presented in Figures 11, 12, 13 and 14.

The characteristic eastward movement is confirmed in this more detailed study. A summary of the deflection of the card tracks from the direction of the resultant vector wind is contained in Figure 15. On an overall basis, the tracks are directed about 20° to the right of the resultant wind, although the evidence suggests that this angle varies from time to time by as much as 30 degrees. Because of the uncertainties of the drift object technique, the speed of surface drift will on the average be underestimated. The largest surface drift speed observed was 18 cm/sec for three cards released from mooring 9 on July 18, 1968. During the travel time of these objects, the resultant wind speed was 2.5 m/sec, or 14 times greater than that of the surface current. A portion of this high surface speed may be accounted for by a permanent eastward drift.

Summary of Findings on Surface Circulation

(1) The areal pattern of the surface flow in the open-lake portion of the eastern basin, depicted in Figure 4, is not inconsistent with the pattern deduced in the central basin from similar evidence, that is, of an orientated drift

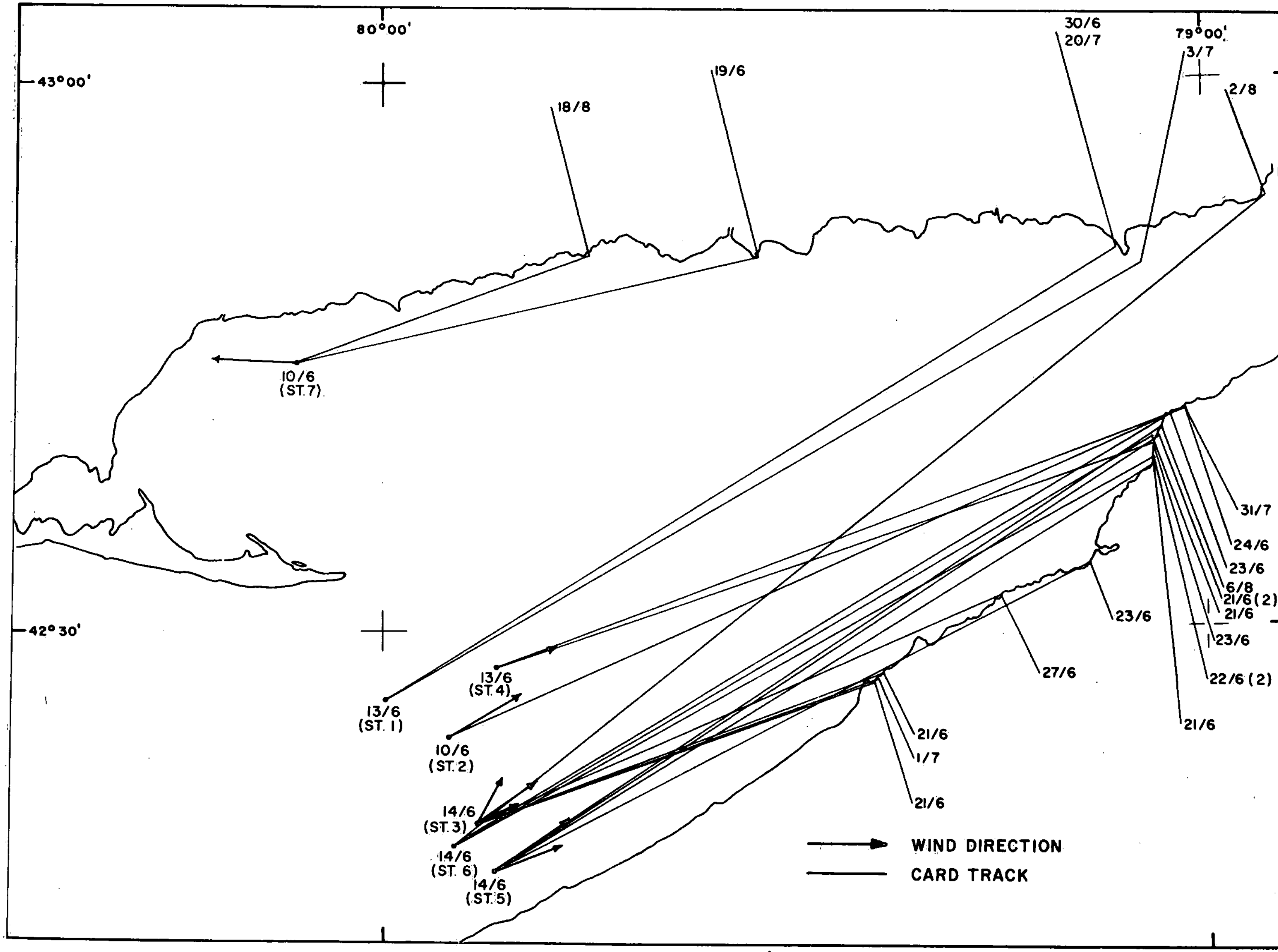


Figure 11. Drift object tracks, eastern Lake Erie June 10-14, 1968.

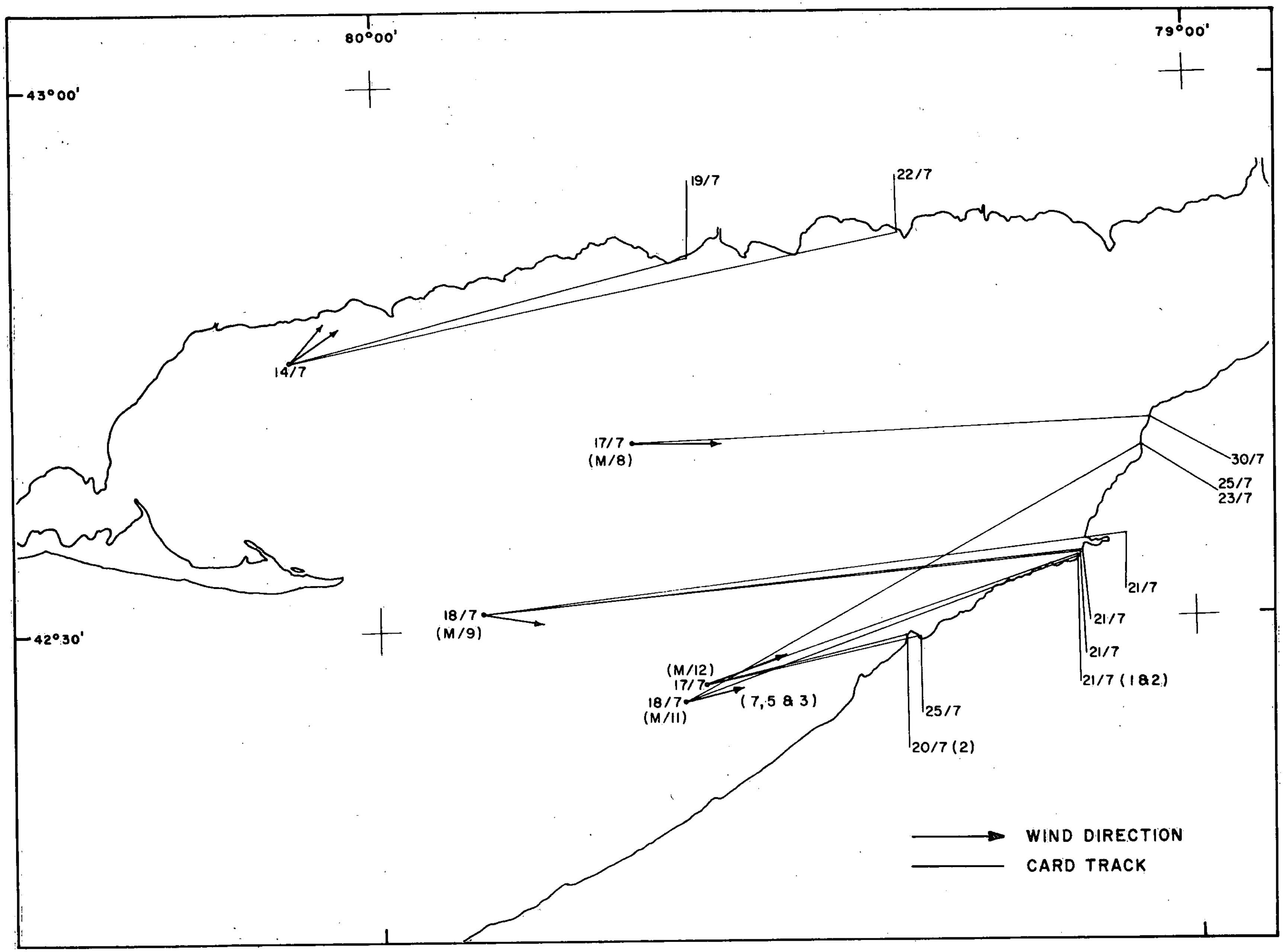


Figure 12. Drift object tracks, eastern Lake Erie July 14-18, 1968.

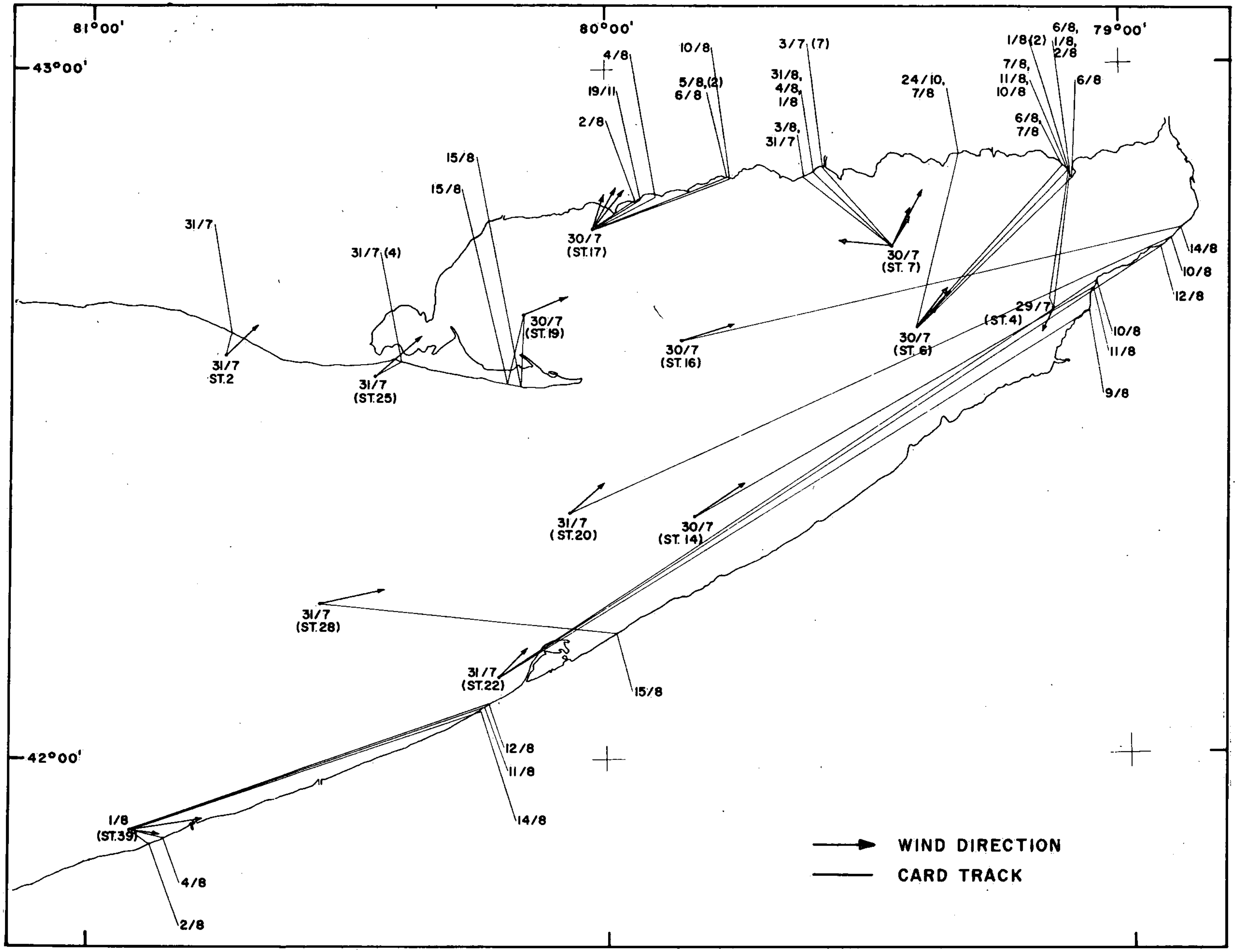


Figure 13. Drift object tracks, eastern Lake Erie July 29-Aug. 1, 1968.

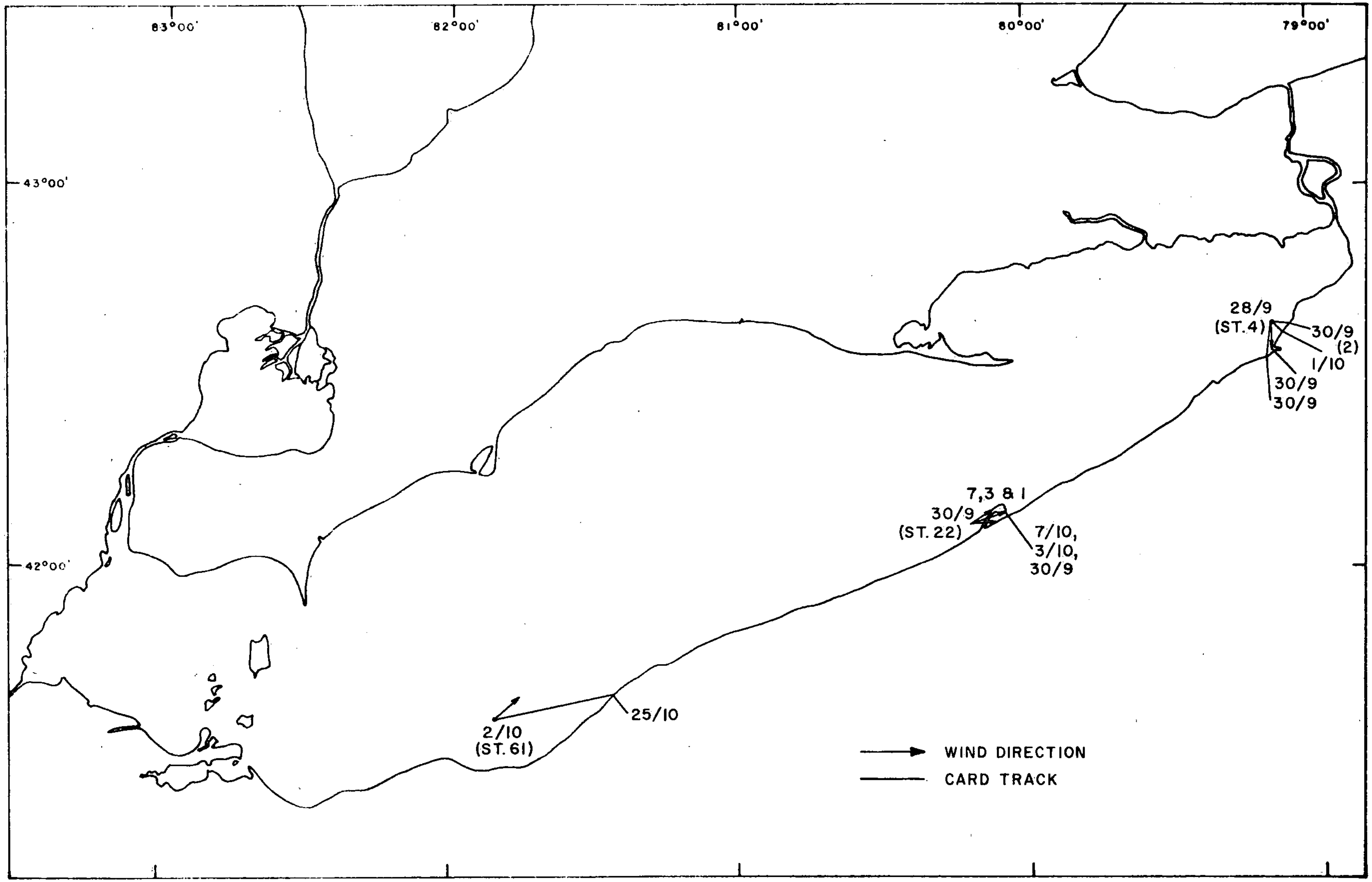


Figure 14. Drift object tracks, eastern Lake Erie Sept. 28-Oct. 2, 1968.

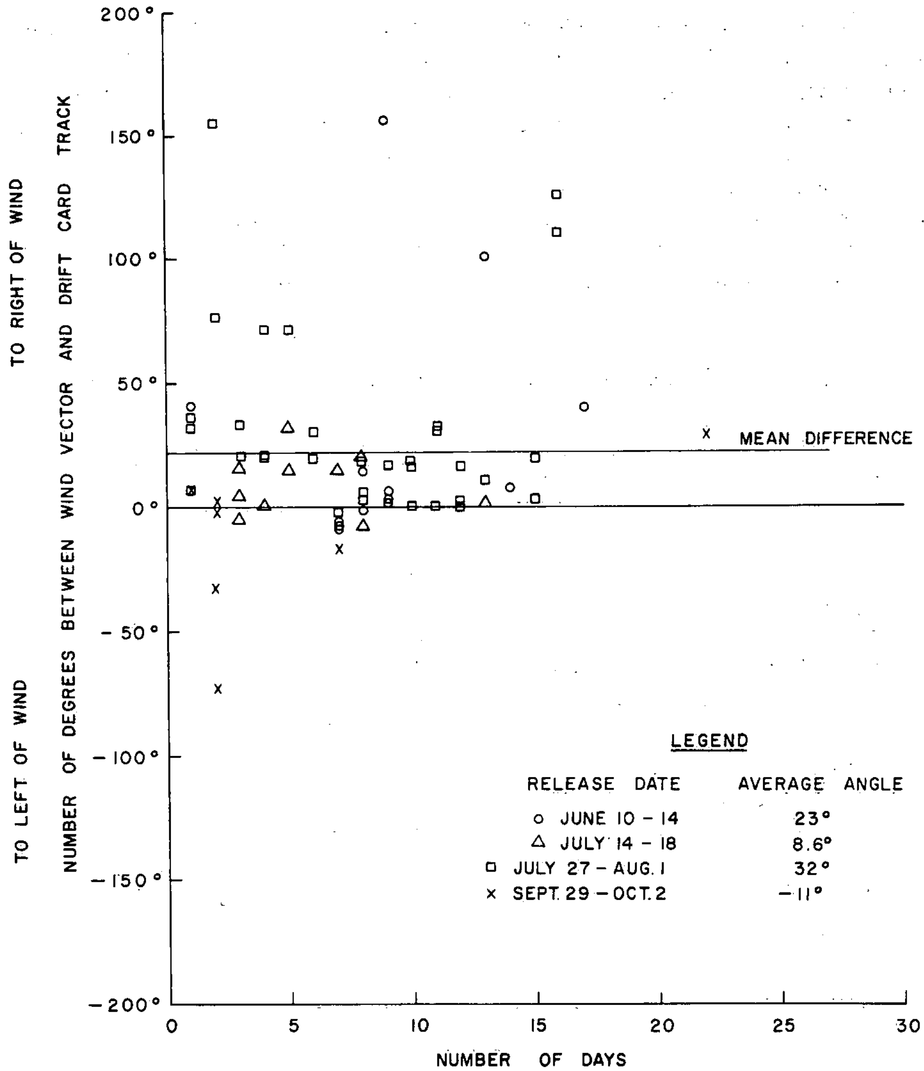


Figure 15. Angle between wind vector and drift card tracks versus number of days between release and recovery.

along the longitudinal axis of the lake with a proclivity for rightward deflection from this line.

(2) It is expected that surface currents are highly erratic in time and that they derive their variability from the vagaries of the surface wind. An exception to this occurs within 6 km of the head of the Niagara River where hydraulic currents overrule. There, the current regime is unidirectional in the downstream direction and fluctuates in velocity in response to the winds and lake setup.

(3) The preponderance of drifters released in American waters which were found in the Niagara River, attests to the fact that the principal portion of river flow is drawn from American waters.

(4) Surface currents are mainly wind-driven and therefore may be predicted from a knowledge of the surface wind over the lake.

Bottom Regime

(1) Fluctuating horizontal displacements in the bottom waters surrounding the "Deep Hole" of the eastern basin in the summers of 1928 and 1929, have been remarked upon by Green (Fish, 1960). He concluded that forcing by winds of a duration of two to three days, is instrumental in displacing the compensating waters near the bottom at a slow rate in a direction opposing that of the wind.

(2) At station 12, a current meter operated by FWPCA between May and October of 1964 (Figure 7) yielded metered data on currents in proximity to the bottom. At this location the flow was in a westward direction. Unlike other currents which are related to the slope of the bottom (for example, the currents at station 4), the distribution of current direction is essentially unimodal. The average speed of 5.9 cm/sec, and the permanent or resultant speed of 0.8 cm/sec, are not greatly divergent from the values predicted for the bottom current in the central basin.

(3) The only remaining evidence on the behavior of the bottom currents in the eastern basin consists of the returns of three sea-bed drifters which were released in the central basin by FWPCA, and which arrived at destinations on the northern shoreline of the eastern basin. Thus, a system of cross-lake flow from south to north is suggested.

In conclusion, the bottom waters of the eastern basin, while relatively quiescent, are not devoid of movement during the summer period. The existence of steeper gradients at the bottom modify the simple system of cross-lake return flow existing in the relatively planar-bottomed central basin. It is probable that bottom currents have an alignment parallel to the local isobaths. During periods of stratification, the indirect action of winds through the intermediate mechanism of surface setup is seen as the principal driving force for the bottom flow.

Subsurface Regime

Open Lake Flow

For the deduction of the permanent subsurface circulation, use is made of the summer patterns of temperature in the eastern basin, in conjunction with the metered current data taken both by FWPCA and the Department of Energy, Mines and Resources.

Representative readings of water temperatures, taken bi-weekly from late spring to early fall in 1967 by the Department of Energy, Mines and Resources, are presented in the form of a contoured chart of the depth of the epilimnion (Figure 16) and a vertical cross-section (Figure 17). These charts show a doming of the cooler bottom waters in the centre of the basin in the summer. A strong counterclockwise gyre is inferred from this pattern. This supposition is supported by the currents at stations 13 and 14 (Figure 7), which would thus be located on the western perimeter of the summer gyre, and by the currents at stations 8 and 9 on its opposite side.

An augmentation of the mean speeds over that of the central basin occurs in the eastern basin along the line of minimum transect. The three stations 6, 8 and 9 of the central basin have mean speeds of 8.8 cm/sec, and resultant speeds of 2.1 cm/sec, whereas average speeds at stations 13 and 14 have values of 16.6 cm/sec, and permanent flows of 4.0 cm/sec.

At depths below 20 m, the general subsurface flow is directed westerly along the axis of the lake. Within 5 km from the southern shoreline of the eastern basin, the current predominates in a northeasterly direction parallel to the shoreline. Data from a single winter mooring indicate a subsurface circulation to the southwest.

Another curious feature relevant to the open lake regime occurred at station 14. At 15 m, both the mean speed and the resultant flow were twice the corresponding values at 10 and 30 m. Normally, such an occurrence would be suspected to be a manifestation of an instrumental malfunction. However, a similar situation was noted by Verber (1965), who compiled an average vertical profile of current speed for the deep water currents of Lake Michigan. In his study, Verber noted that the peaking of current speeds was associated with the depth of the thermocline.

A detailed examination by the author of the response of the ratios of speeds to progressive deepening of the thermocline did not reveal any direct relation between current speed and the depth of the thermocline.

Long Point Bay

Station 16, situated on Long Point Bay, experienced a current regime which, in some respects, was not dissimilar to that of station 11 in the central basin. While all possible current directions occurred, there was a tendency for the principal components of flow to be aligned in the direction of bottom contours. Notable is that this relation was not as strong in Long Point Bay as it was in the central basin.

Some preliminary findings of a survey of nearshore currents in the vicinity of Nanticoke, Ontario, were conducted by the Hydro-Electric Power Commission of Ontario (Ontario Hydro, 1968). A series of drogue tracking experiments which were conducted throughout the summer period of 1967 revealed that nearshore currents generally conformed to the shoreline configuration, and were often related to the wind at the time of the experiment. This bi-directional regime was divided almost equally between east-going and west-going cases. At station 7 (Figure 7) located some distance offshore from this site, data collected by the Department of Energy, Mines and Resources revealed that northeastward currents are favoured.

A multi-drogue experiment, depicted in Figure 10, was undertaken by the Department of Energy, Mines and

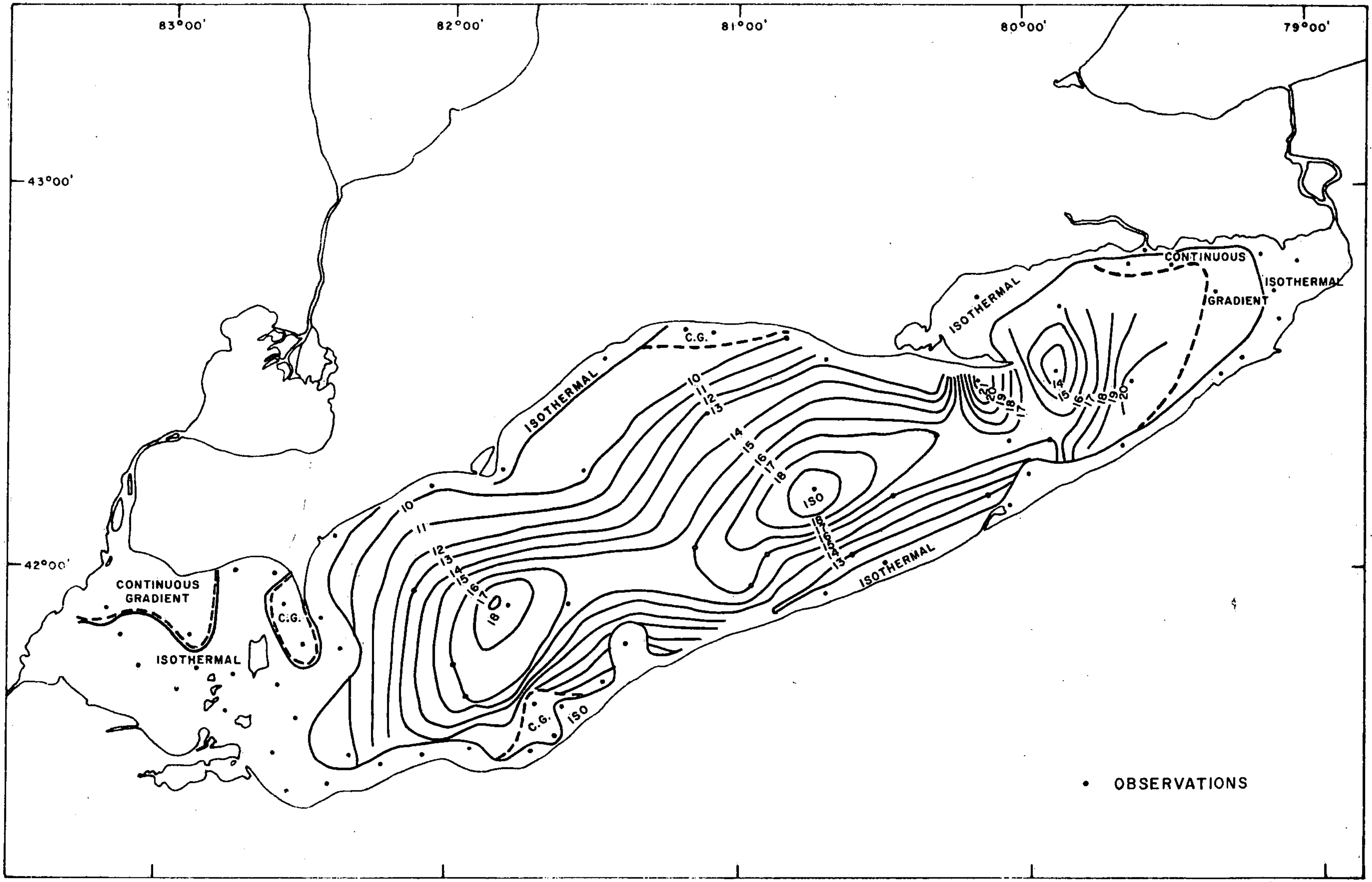


Figure 16. Depth of epilimnion, summer, Lake Erie.

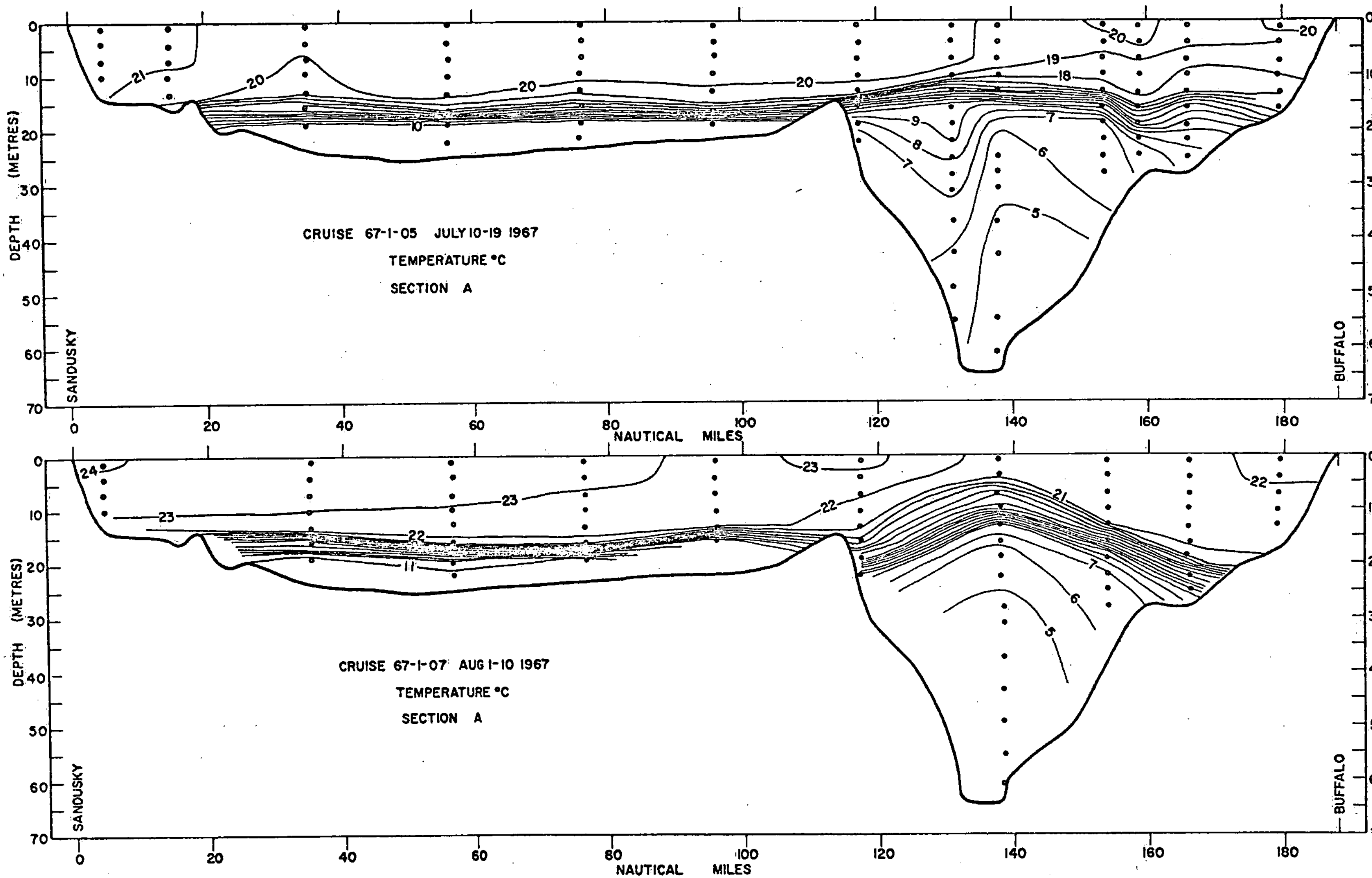


Figure 17. Temperature cross sections, Lake Erie.

Resources from 15 to 17 August, 1967. The drogues traced out winding paths, suggestive of the aforementioned meandering motions, especially in the less rapid regime of Long Point Bay. In spite of the spatial variability of the flow, the tracks within Long Point Bay are suggestive of the formation of a back eddy under the influence of a longshore current to the east, the prevailing current in this area.

Upwelling

Figure 18 illustrates a typical summer distribution of water temperatures at a depth of one meter. Along the northern and southern periphery of the basin, zones of lower temperature are indicated. Like the central basin, bottom waters are upwelled along both shorelines, a possible consequence of the prevailing gyral motion of basin waters. The number of episodes of upwelling along the north shoreline outweighed those along the southern shoreline.

In summary, the general pattern of circulation at intermediate depths has been deduced both from direct and indirect evidence. A counterclockwise rotation about the point of maximum depth appears to be the prevalent system of flow, at least during the period of stratification of density. Augmented flow in the deep waters of the basin, upwelling along the northern and southern coastlines, highly variable currents in Long Point Bay, and eastward flow along the southern shoreline, play significant roles in the overall formulation of the subsurface regimen of flow.

Diffusion Studies

Diffusion studies in the eastern basin of Lake Erie have been based solely on current meter measurements of the turbulent properties of the flow. These studies indicate that turbulent mixing is vigorous in the eastern basin of Lake Erie.

a) On the basis of nearshore current meter measurements in Long Point Bay, Palmer and Izatt (1969) arrived at diffusion coefficients using a number of assumptions on the nature of the local turbulence. They found that turbulent transfer is more intense parallel to the shoreline than it is in a normal direction. Nearshore transfer coefficients were of an order of 10^5 cm^2/sec parallel to the shore and of an order of 10^4 cm^2/sec laterally during the summer months and one order of magnitude greater in the winter months.

b) Large scale horizontal eddy diffusion coefficients were calculated at a depth of 20 m for a winter period at the station marked W in Figure 7. These coefficients were determined from current meter observations by Ertel's method of eddy mixing lengths outlined by Gezentsvei (1959). This method permits the effect of eddy scale size on the turbulent transfer to be examined. Coefficients were found to increase with scale size and, for the largest scale size employed, corresponding to averaging times of one day, the maximum effective coefficient had a magnitude of 5×10^6 cm^2/sec, a value of comparable magnitude to those obtained by Palmer and Izatt. The horizontal turbulent transfer in the open lake tends more closely to isotropy than the nearshore transport. This may be caused by the restrictions imposed on the flow by the presence of the shoreline.

CHAPTER 5

Phenomenology of Lake Circulation and Diffusion

Not only does theory provide a means for interpolation of observational data on currents between points of measurement, but it also serves as a deterministic basis for the forecasting of lake currents from easily measured shore-based factors such as wind strength and atmospheric pressure.

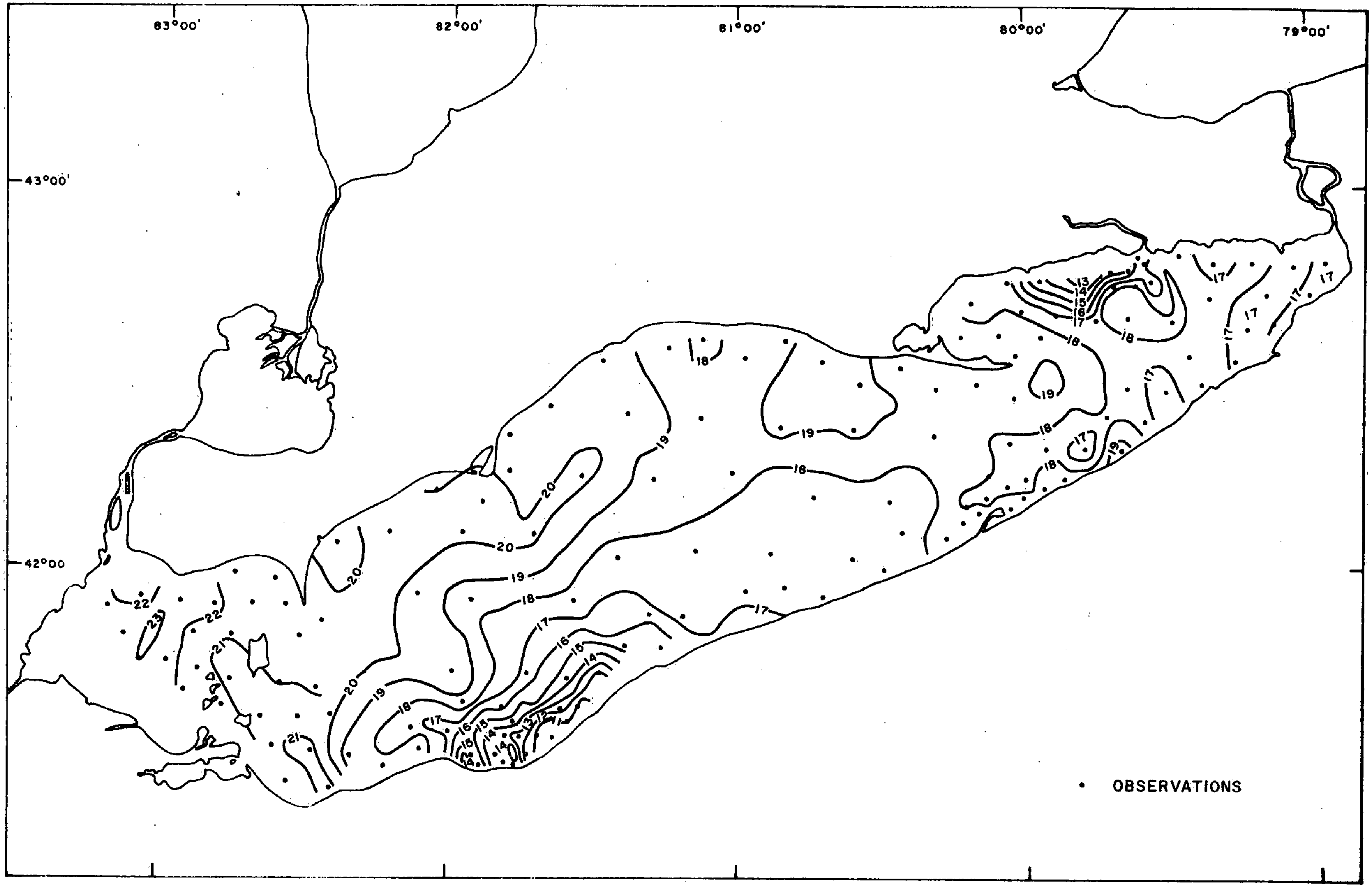


Figure 18. Temperature at depth of one metre, summer, Lake Erie.

LAKE CIRCULATION

Until the last several years, the theory of Great Lakes circulation has remained virtually unknown. In a recent book, Hutchinson (1957) in a survey of observation and theory of the Great Lakes circulation, stated that except perhaps along the western coasts of Lake Huron and in Georgian Bay, there is no clear evidence of any large scale geostrophic effect. Taken in the context that rotation of the earth is not an effective causitive agent of lake circulation, Hutchinson's conclusion has been disproved by recent theoretical and observational work.

Influences which ought to be accounted for in any theory of lake circulation are: the rotation of the earth; gravity; the slope of the water surface; the force of the wind and the atmospheric pressure; the friction between the water mass and lake boundaries; the stratification of density; and the influence of the lake boundaries, in particular, that of the bottom topography. Of necessity, in the analytical modelling of these complex factors, one is forced to consider only a few parameters at a time in each model.

Perhaps the most extensive analysis of the dynamics of Lake Erie has been accomplished by the numerical-hydrodynamical modelling technique of Platzman (1963). His dynamical equations account for the action of gravity, wind stress, the earth's rotation, a linearized bottom friction and the actual bottom- and shore-line configuration. Successive numerical integrations of his equations yield values of water levels and currents at six-hour intervals, based on an input of wind stress over the lake. A high degree of correlation between observed and computed lake setup was found, although verification of predicted currents has yet to be attempted. One of a number of distributions of currents supplied to the author by Platzman is shown in Figure 19.

A purely analytical solution of the time-invariant dynamical equations has been obtained by Birchfield (1967) for the case of a rotating circular model Great Lake with a parabolic profile of depth, homogeneous water mass, and a realistic parameterization of bottom friction under the action of various types of wind fields. His result (Figure 20) is applicable to the circulation produced by a uniform wind field and may be compared to the time-averaged current vectors presented in Figure 8. Distinguishable are a clockwise whirl on the upwind side of the lake, a counterclockwise whirl on the downwind side, an intensification of the currents on the inshore side of these gyres, and a diffuse circulation in the lake centre in a direction to the right of the wind.

A much simpler theoretical analysis of the vertical profile of currents in the central and western basins has been undertaken by the author, who assumed a constant surface wind stress, a representation of bottom stress identical to that used by Birchfield, and no net transport. Theoretically derived profiles are compared to those of Nomitsu and Takegami (1934) who assumed a different system of bottom friction (Figure 21). Agreement of both curves with observed intermediate currents and surface- and

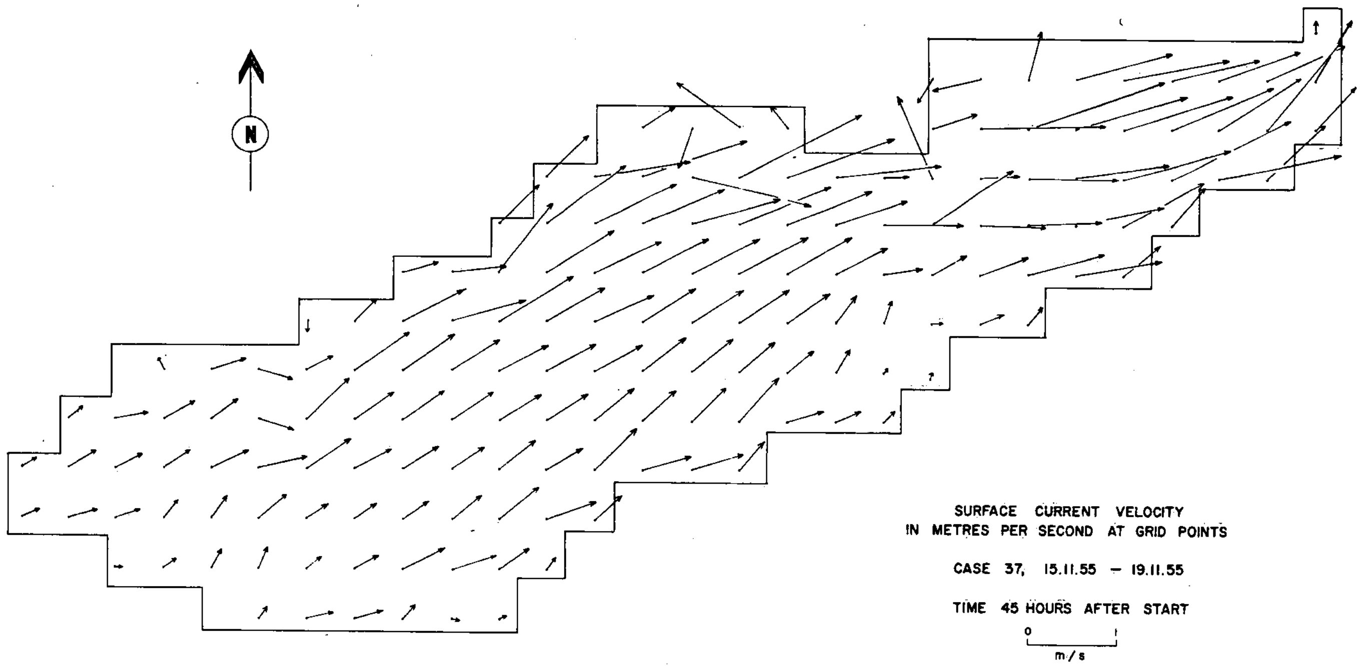
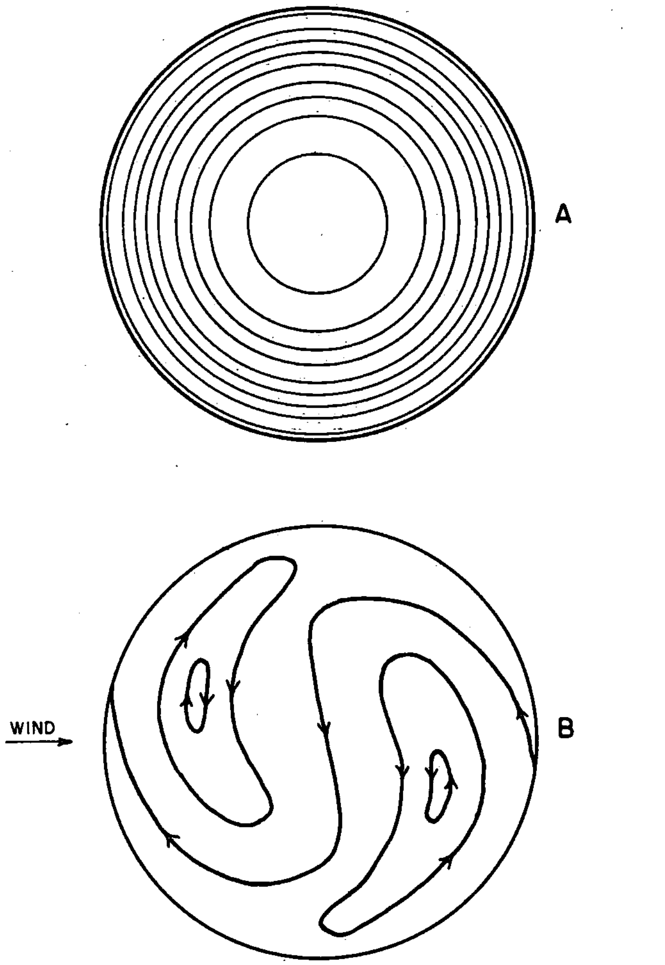


Figure 19. Predicted currents of dynamic model of Lake Erie



A. DEPTH CONTOURS IN MODEL GREAT LAKES BASIN

B. STREAM LINES FOR TOTAL TRANSPORT FOR CASE OF UNIFORM WIND STRESS (AFTER BIRCHFIELD 1967)

Figure 20. Model Great Lake.

bottom bearings for the case of a steady southwest wind is encouraging. Accordingly, the model has been used to predict the magnitudes of the steady surface and bottom currents and to interpolate between open lake stations.

Information on the circulation of Lake Erie has been obtained by rotating laboratory models. Rumer and Robson (1968) has demonstrated that, under rotation of the model, the Detroit River water is maintained as a relatively intense narrow stream along the southern shoreline of the Lake, except where it exits through Pelee Passage (Figure 22).

DIFFUSION

There are numerous, rather advanced, theoretical models of turbulent diffusion processes, all of which account for some of the observed features, but none of which explains all aspects of lake diffusion (Okubo, 1962). Critical observations will be needed to establish one theory over another. The theoretical difficulties arise from the inability to solve the diffusion equation under the very complex environmental conditions. Examples are flows sheared in the horizontal and vertical directions, and in flows in which vertical diffusion is barred by density discontinuities. A theory dealing with some of these aspects has been developed by Csanady (1966).

A simple theoretical model of the decay of the fundamental longitudinal surface seiche has yielded the value of the vertical eddy diffusivity used in the derivation of the vertical profile of currents.

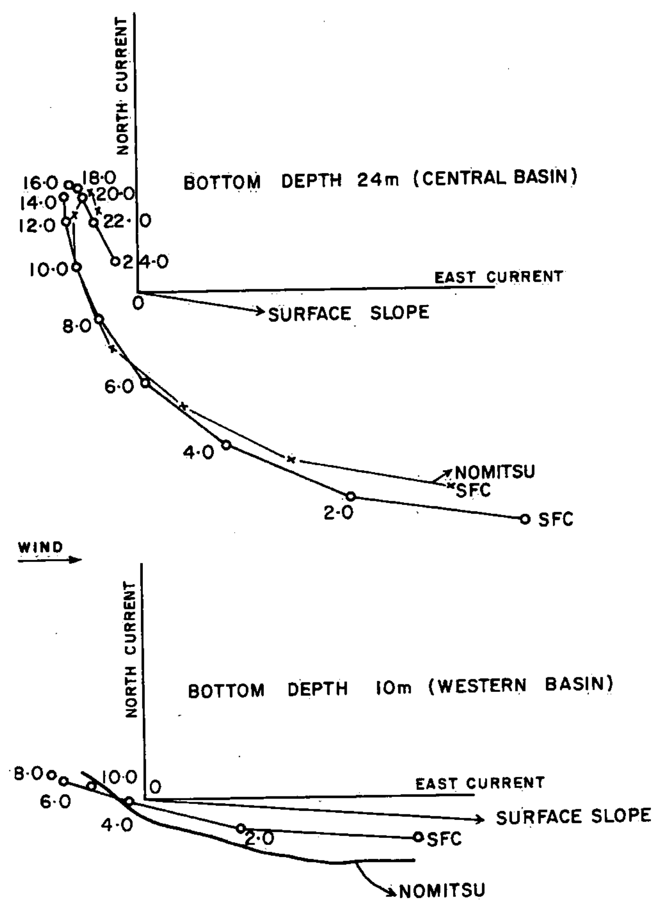


Figure 21. Vertical structure of wind-produced currents in two basins.

Discharge and Residence Time

Assuming that the discharge through Lake Erie is uniformly distributed (80 per cent is derived from the Detroit River flow), and that all water entering the lake is uncontaminated, one can estimate the time taken for self-purification of Lake Erie. At the average discharge rate of 5.6×10^6 l/sec (Rainey, 1967), approximately six years of continuous flow are required to reduce the levels of contamination to 10 per cent of the present levels. In the actual environment, the residence time is at least twice as large, since rotation of the lake causes a non-uniform discharge (Figure 22), and materials now deposited in bottom sediments may be released to the system. Quantitative estimates of residence time for the more realistic model are not known.

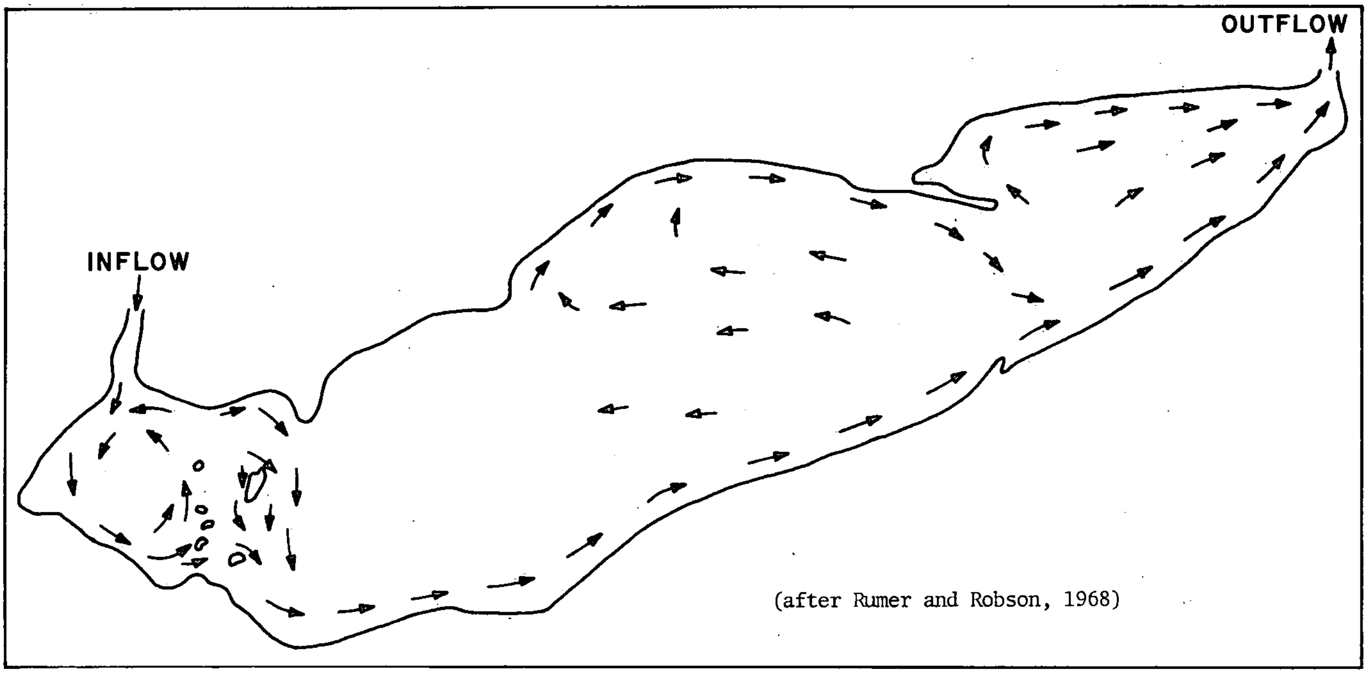


Figure 22. General circulation pattern in model lake without wind stress.

Time Variability of Water Movements

Up to this point the steady lake circulation has been discussed. Superimposed on the time-invariant lake circulation is a variable circulation which, in most instances, is much larger than the underlying steady one. As a result, the prediction of the movement of pollutants on a short term basis, say for periods less than one month, is virtually impossible from knowledge of the steady circulation alone. Several figures are provided to illustrate various aspects of the time-dependent circulation.

The trajectory that a particle of water initially at the current meter would be likely to follow if the current field is uniform in space is contained in Figure 23. Despite the general trend of currents in the direction of the average current vector, the conspicuous clockwise rotation of the current vectors causes the instantaneous current to range over all possible directions.

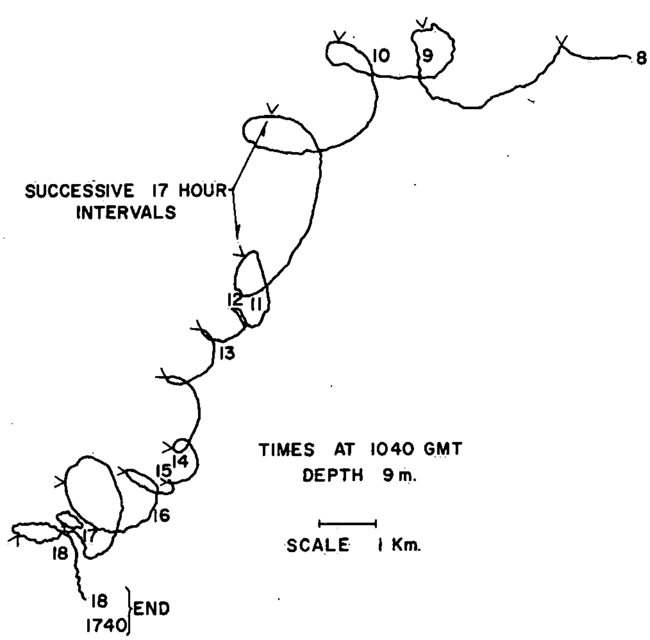


Figure 23. Progressive vector plot of current meter at station 88, Lake Erie.

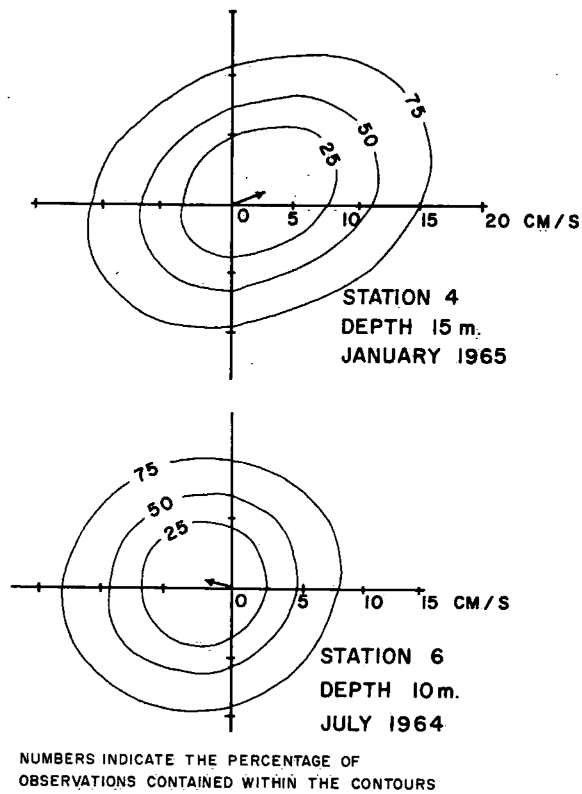


Figure 24. Representative monthly mean currents and vector variance cross-sections, Lake Erie.

Two typical monthly vector variance cross-sections demonstrate (Figure 24) how the variance of current meter observations is distributed about the monthly average current. Notable is the wide variability in direction of the flow, with only slight preference shown for currents in the mean direction of flow in both examples. The specific energies of the currents associated with the mean flow, and with various periodic components of the time-dependent circulation, are plotted in Figure 25 for metered current data taken during the summer in the central basin, and for data taken in the winter in the eastern basin of Lake Erie. The portion of the energy of the summer current field is concentrated about a period of approximately 18 hours (the local inertial period), a finding which is in agreement with the rotary motions shown in Figure 23. Time-dependent motions in winter are associated principally with wind tidal fluctuations of periods in the range 100 - 200 hours and to a lesser extent with the unimodal longitudinal surface seiche of a period of 14.7 hours.

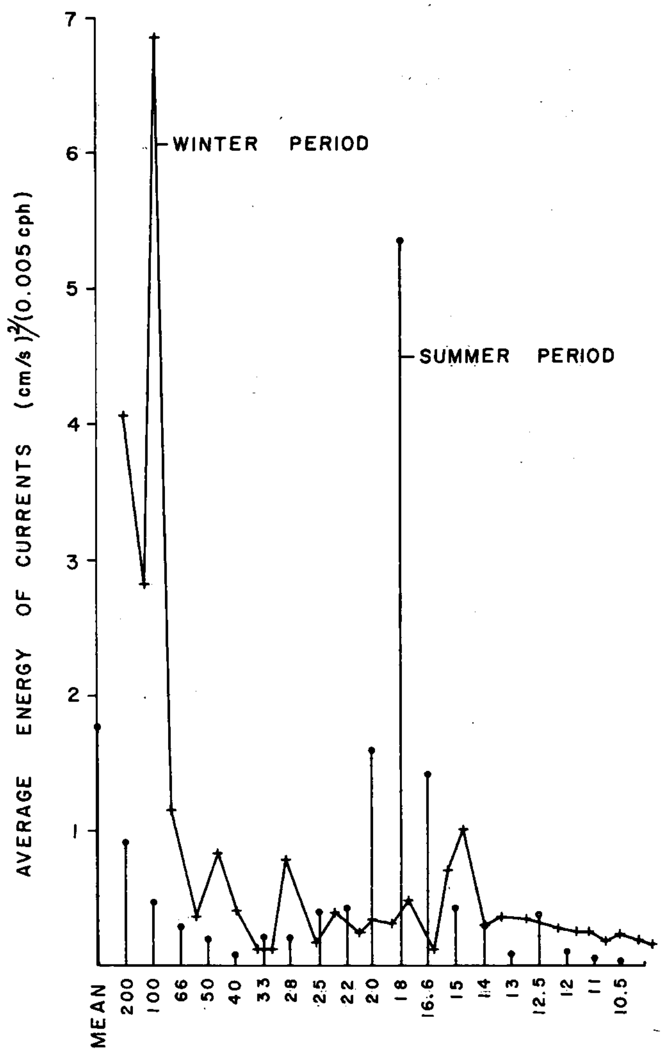


Figure 25. Average energy associated with the mean current and with various periods of the time-dependent circulation, Lake Erie.

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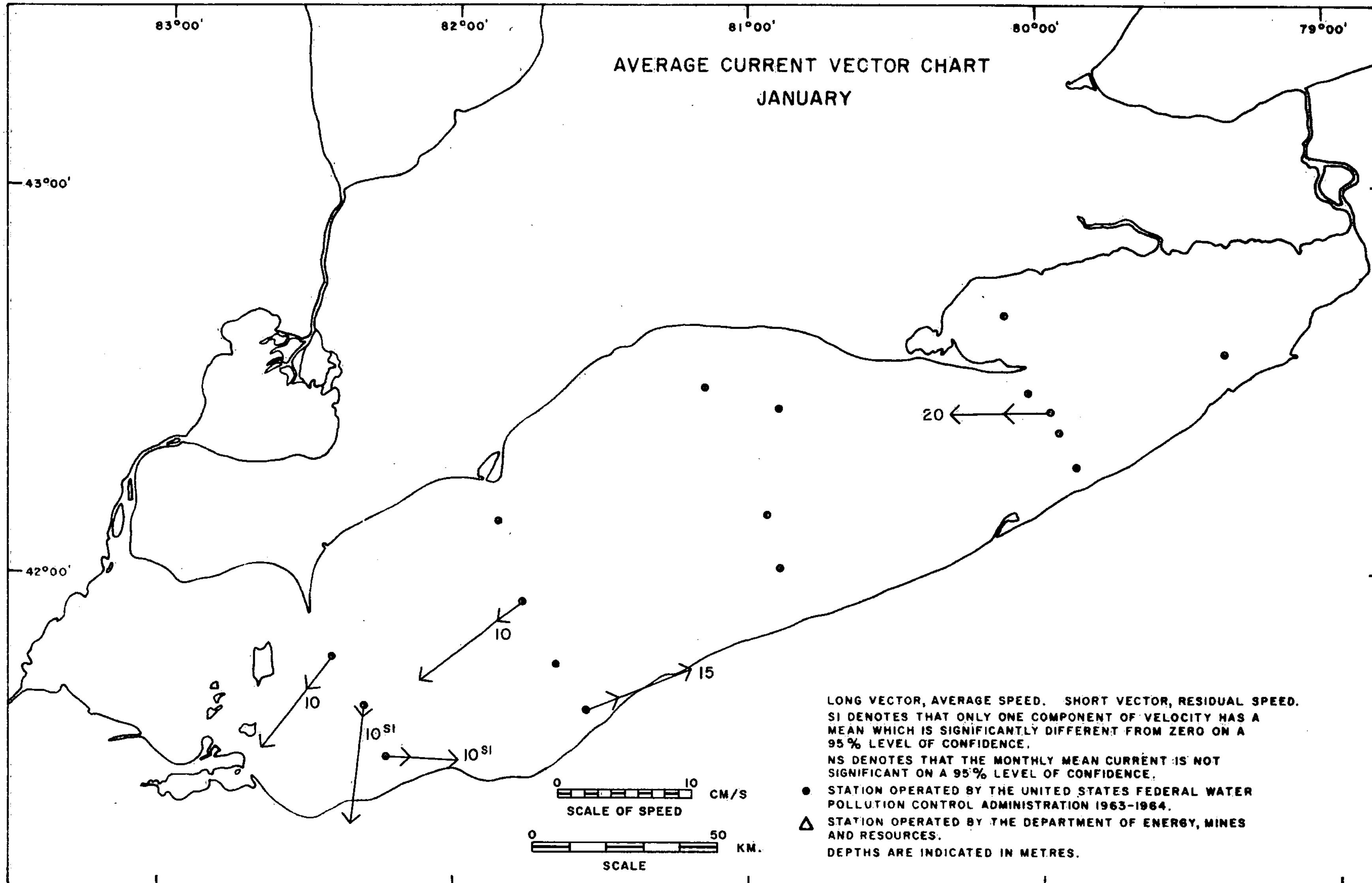
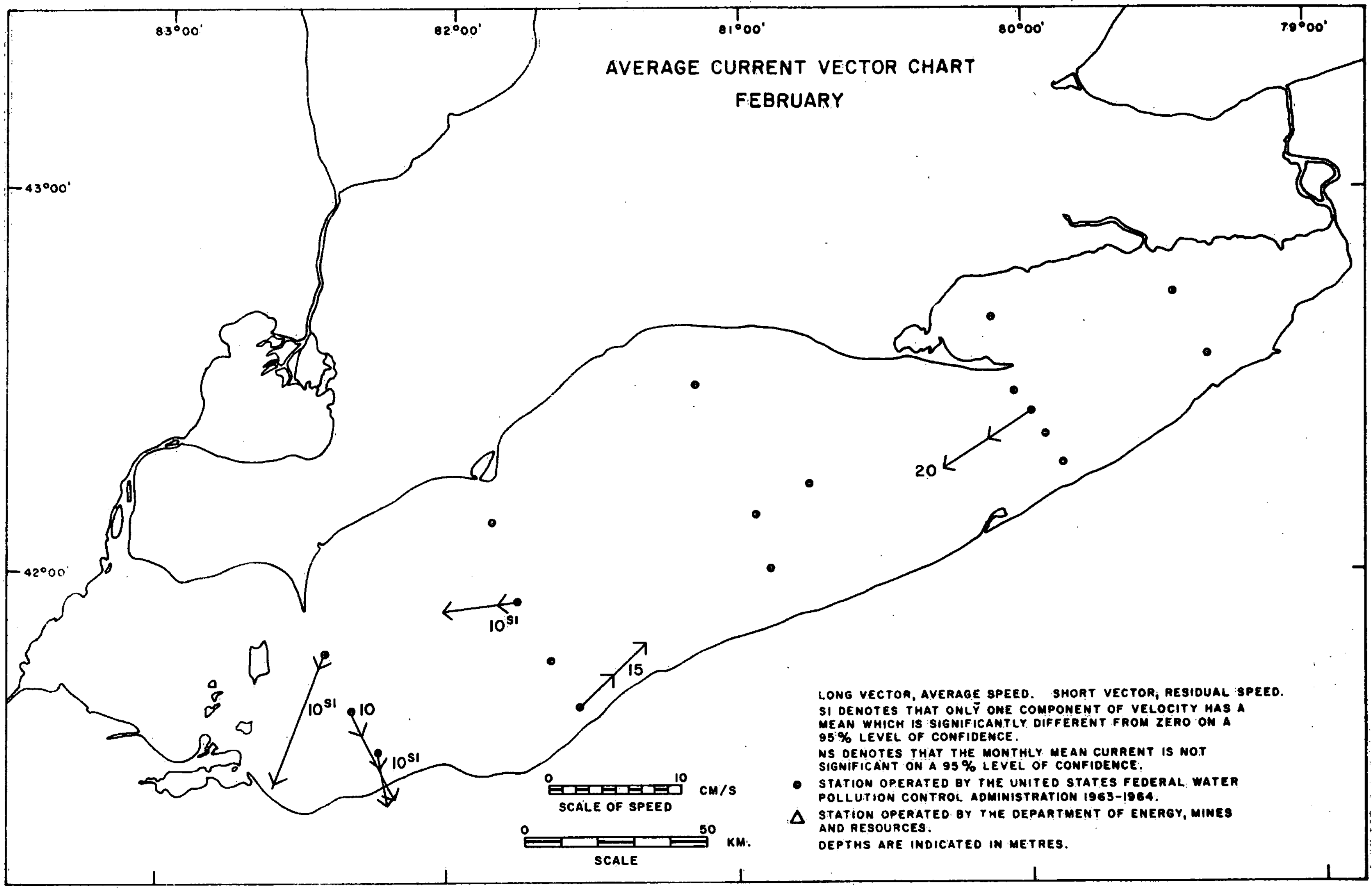
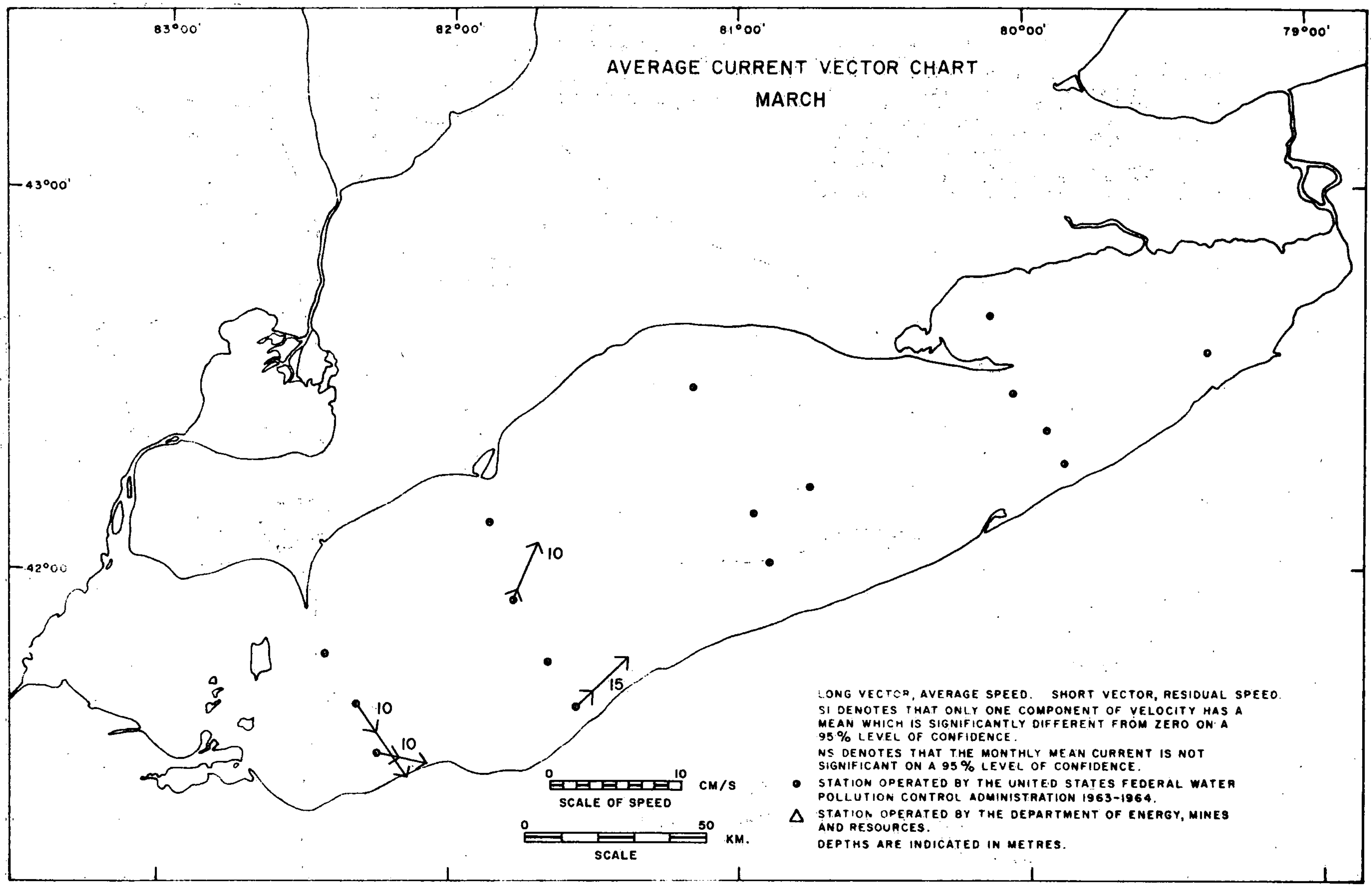
APPENDIX – MONTHLY AVERAGED CURRENTS, LAKE ERIE


AVERAGE CURRENT VECTOR CHART
JANUARY
83°00'
82°00'
81°00'
80°00'
79°00'
43°00'
42°00'
20
10
10
10 SI
10 SI
15
0
10
CM/S
SCALE OF SPEED
0
50
KM.
SCALE
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
NS DENOTES THAT THE MONTHLY MEAN CURRENT IS NOT SIGNIFICANT ON A 95% LEVEL OF CONFIDENCE.
● STATION OPERATED BY THE UNITED STATES FEDERAL WATER POLLUTION CONTROL ADMINISTRATION 1963-1964.
△ STATION OPERATED BY THE DEPARTMENT OF ENERGY, MINES AND RESOURCES.
DEPTHS ARE INDICATED IN METRES.


AVERAGE CURRENT VECTOR CHART
FEBRUARY
83°00'
82°00'
81°00'
80°00'
79°00'
43°00'
42°00'
20
15
10 SI
10
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
NS DENOTES THAT THE MONTHLY MEAN CURRENT IS NOT SIGNIFICANT ON A 95% LEVEL OF CONFIDENCE.
STATION OPERATED BY THE UNITED STATES FEDERAL WATER POLLUTION CONTROL ADMINISTRATION 1963-1964.
STATION OPERATED BY THE DEPARTMENT OF ENERGY, MINES AND RESOURCES.
DEPTHS ARE INDICATED IN METRES.
0
10
CM/S
SCALE OF SPEED
0
50
KM.
SCALE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MARCH
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81°00'
80°00'
79°00'
43°00'
42°00'
10
10
10
15
0
10
CM/S
SCALE OF SPEED
0
50
KM.
SCALE
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
NS DENOTES THAT THE MONTHLY MEAN CURRENT IS NOT SIGNIFICANT ON A 95% LEVEL OF CONFIDENCE.
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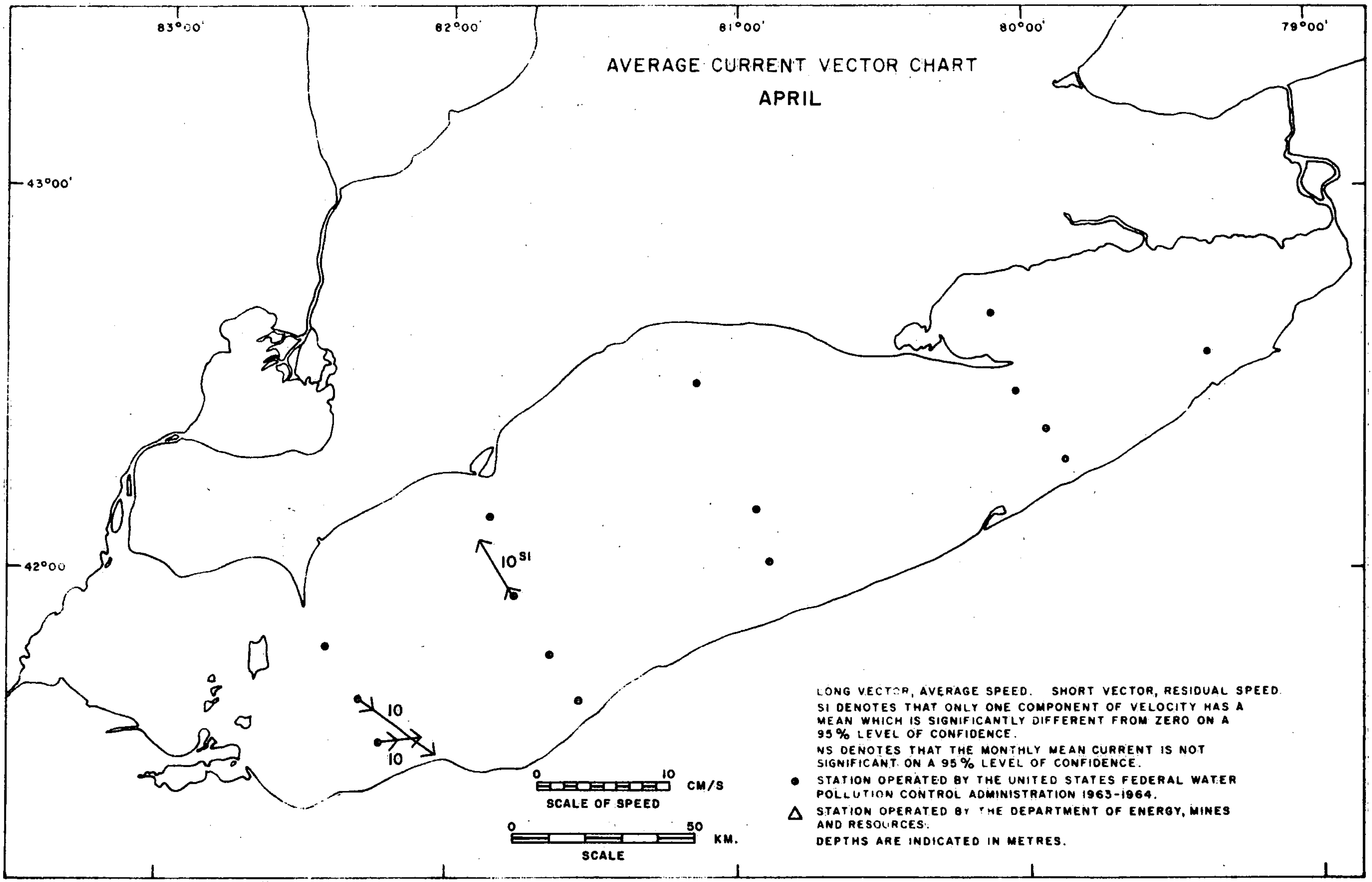
STATION OPERATED BY THE DEPARTMENT OF ENERGY, MINES AND RESOURCES.
DEPTHS ARE INDICATED IN METRES.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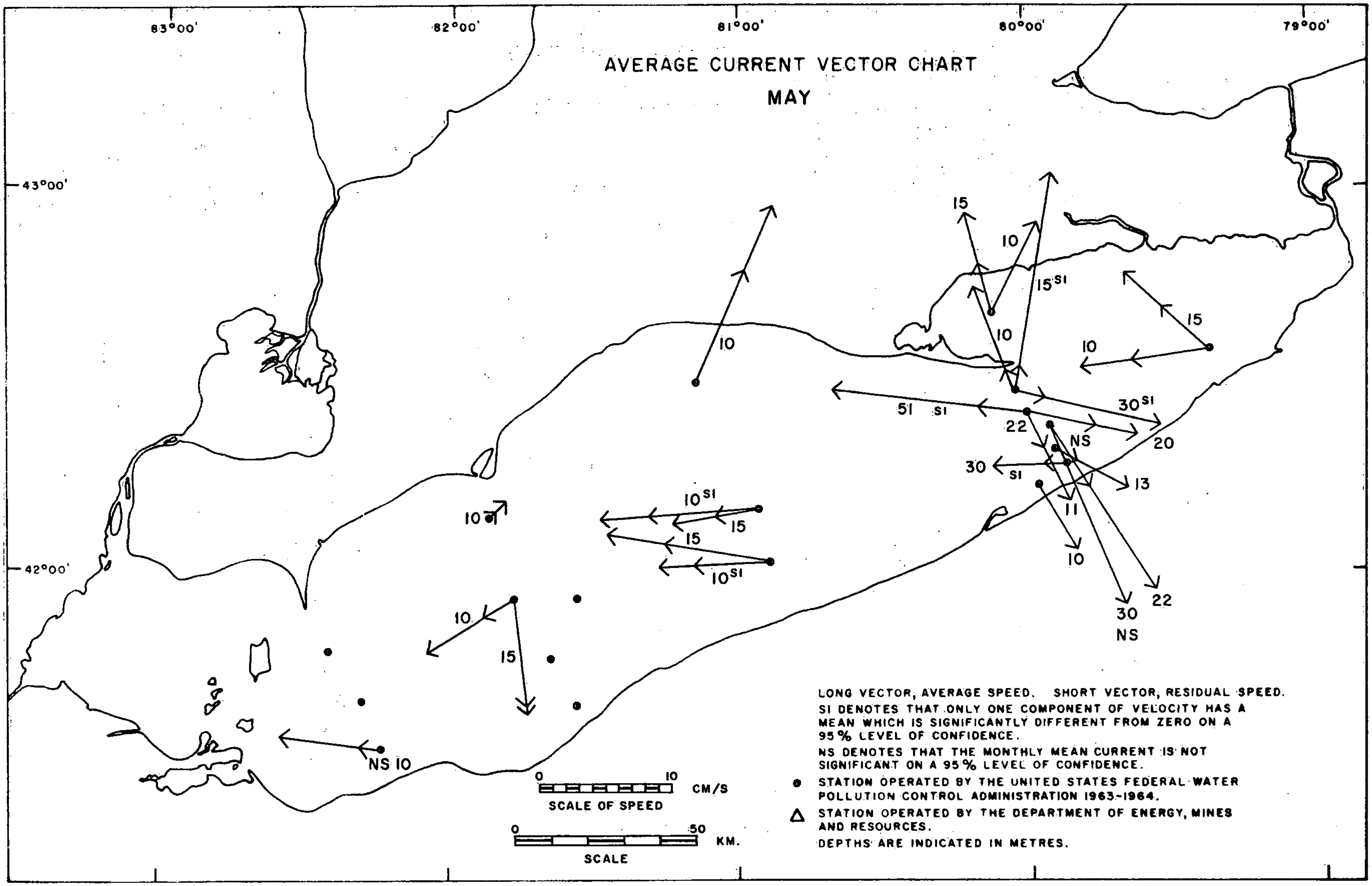
81°00'
80°00'
79°00'
43°00'
42°00
10 SI
10
10
0
10
CM/S
SCALE OF SPEED
0
50
KM.
SCALE
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
NS DENOTES THAT THE MONTHLY MEAN CURRENT IS NOT SIGNIFICANT ON A 95% LEVEL OF CONFIDENCE.
● STATION OPERATED BY THE UNITED STATES FEDERAL WATER POLLUTION CONTROL ADMINISTRATION 1963-1964.
△ STATION OPERATED BY THE DEPARTMENT OF ENERGY, MINES AND RESOURCES.
DEPTHS ARE INDICATED IN METRES.


AVERAGE CURRENT VECTOR CHART
MAY
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82°00'
81°00'
80°00'
79°00'
43°00'
42°00'
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
NS DENOTES THAT THE MONTHLY MEAN CURRENT IS NOT SIGNIFICANT ON A 95% LEVEL OF CONFIDENCE.
STATION OPERATED BY THE UNITED STATES FEDERAL WATER POLLUTION CONTROL ADMINISTRATION 1963-1964.
STATION OPERATED BY THE DEPARTMENT OF ENERGY, MINES AND RESOURCES.
DEPTHS ARE INDICATED IN METRES.
0 10 CM/S
SCALE OF SPEED
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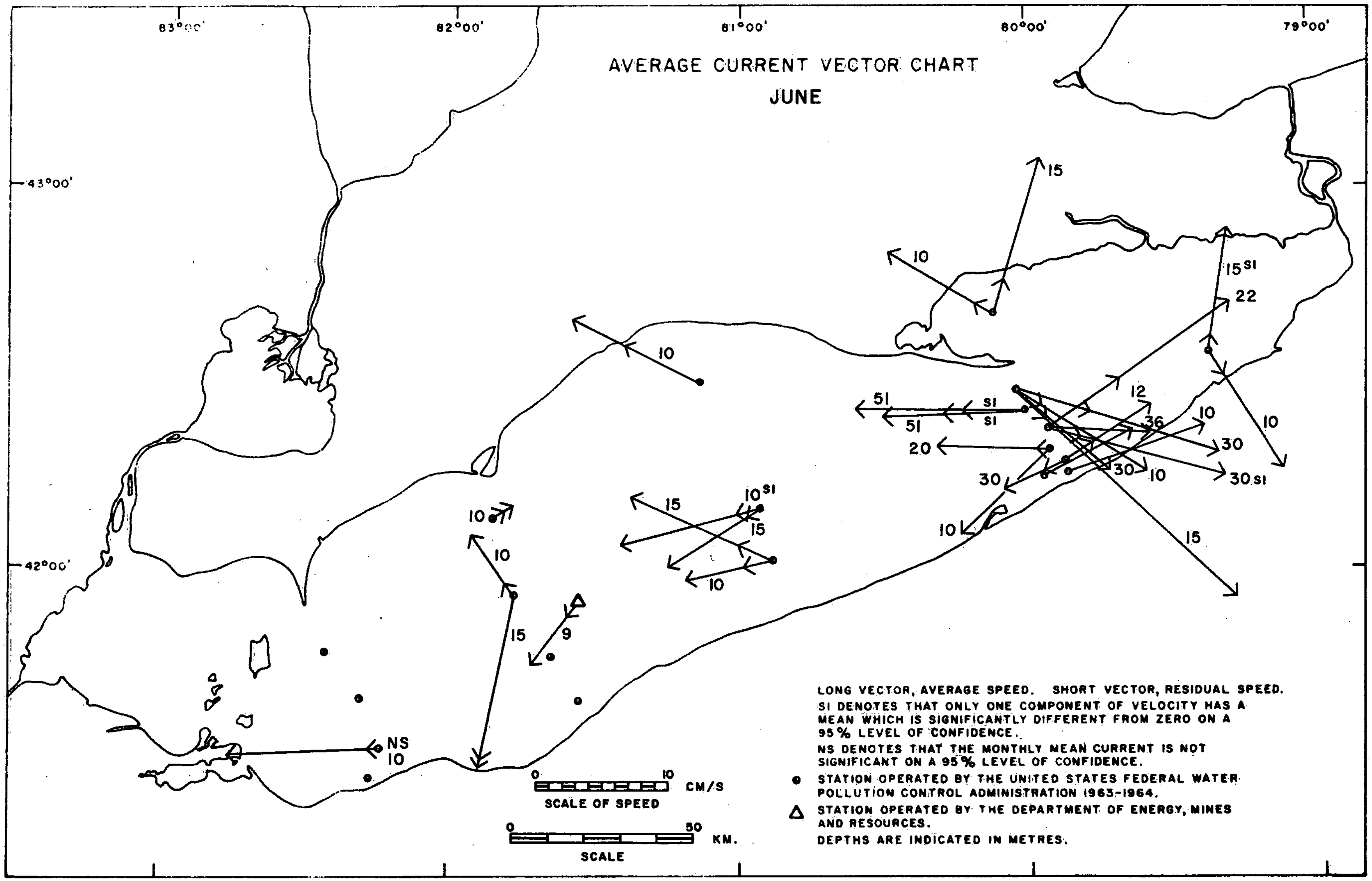
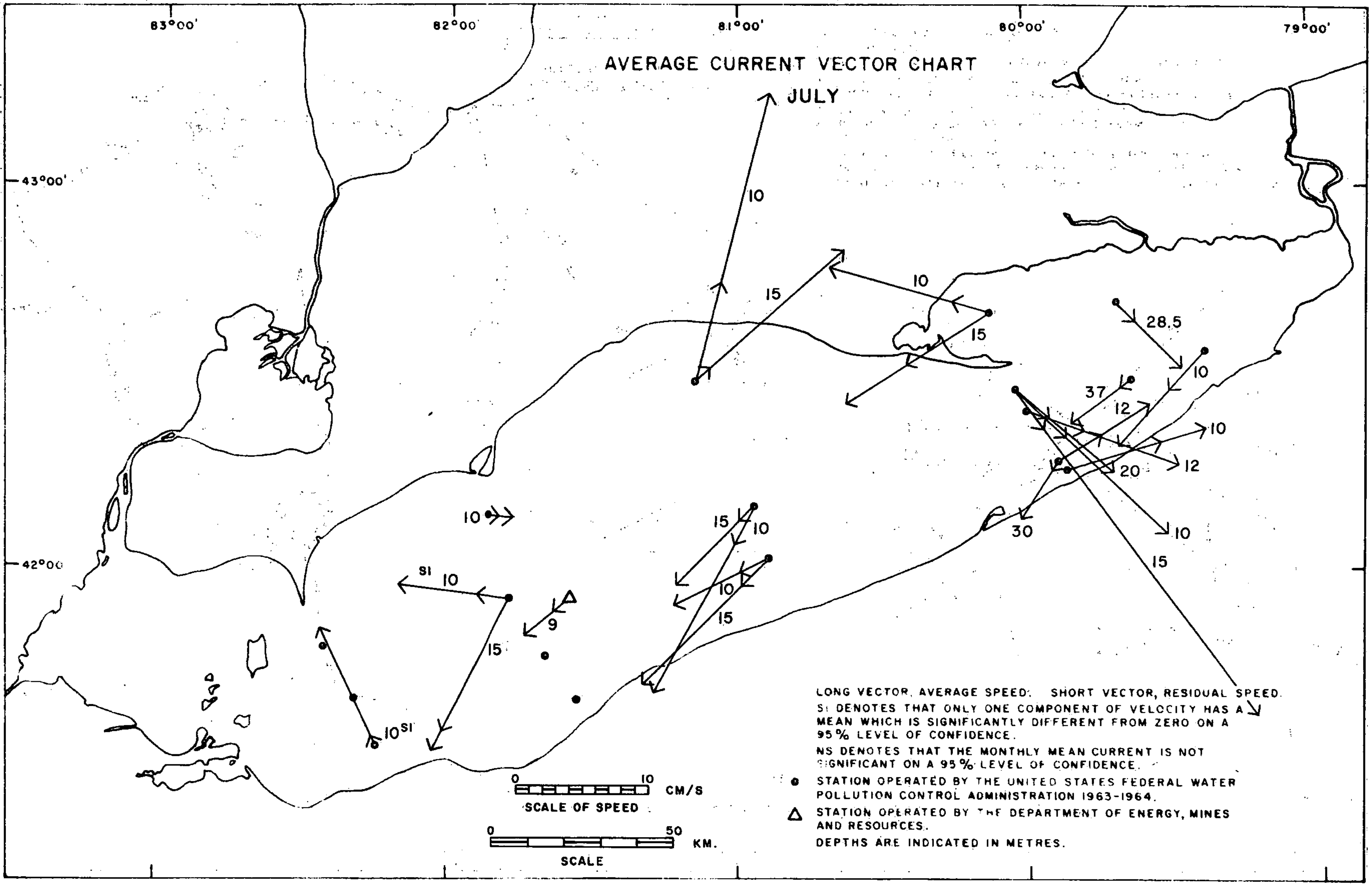
SCALE


AVERAGE CURRENT VECTOR CHART
JUNE
83°00'
82°00'
81°00'
80°00'
79°00'
43°00'
42°00'
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
NS DENOTES THAT THE MONTHLY MEAN CURRENT IS NOT SIGNIFICANT ON A 95% LEVEL OF CONFIDENCE.
STATION OPERATED BY THE UNITED STATES FEDERAL WATER POLLUTION CONTROL ADMINISTRATION 1963-1964.
STATION OPERATED BY THE DEPARTMENT OF ENERGY, MINES AND RESOURCES.
DEPTHS ARE INDICATED IN METRES.
0
10
CM/S
SCALE OF SPEED
0
50
KM.
SCALE


AVERAGE CURRENT VECTOR CHART
JULY
83°00'
82°00'
81°00'
80°00'
79°00'
43°00'
42°00'
LONG VECTOR, AVERAGE SPEED; SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
NS DENOTES THAT THE MONTHLY MEAN CURRENT IS NOT SIGNIFICANT ON A 95% LEVEL OF CONFIDENCE.
STATION OPERATED BY THE UNITED STATES FEDERAL WATER POLLUTION CONTROL ADMINISTRATION 1963-1964.
STATION OPERATED BY THE DEPARTMENT OF ENERGY, MINES AND RESOURCES.
DEPTHS ARE INDICATED IN METRES.
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CM/S
SCALE OF SPEED
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KM.
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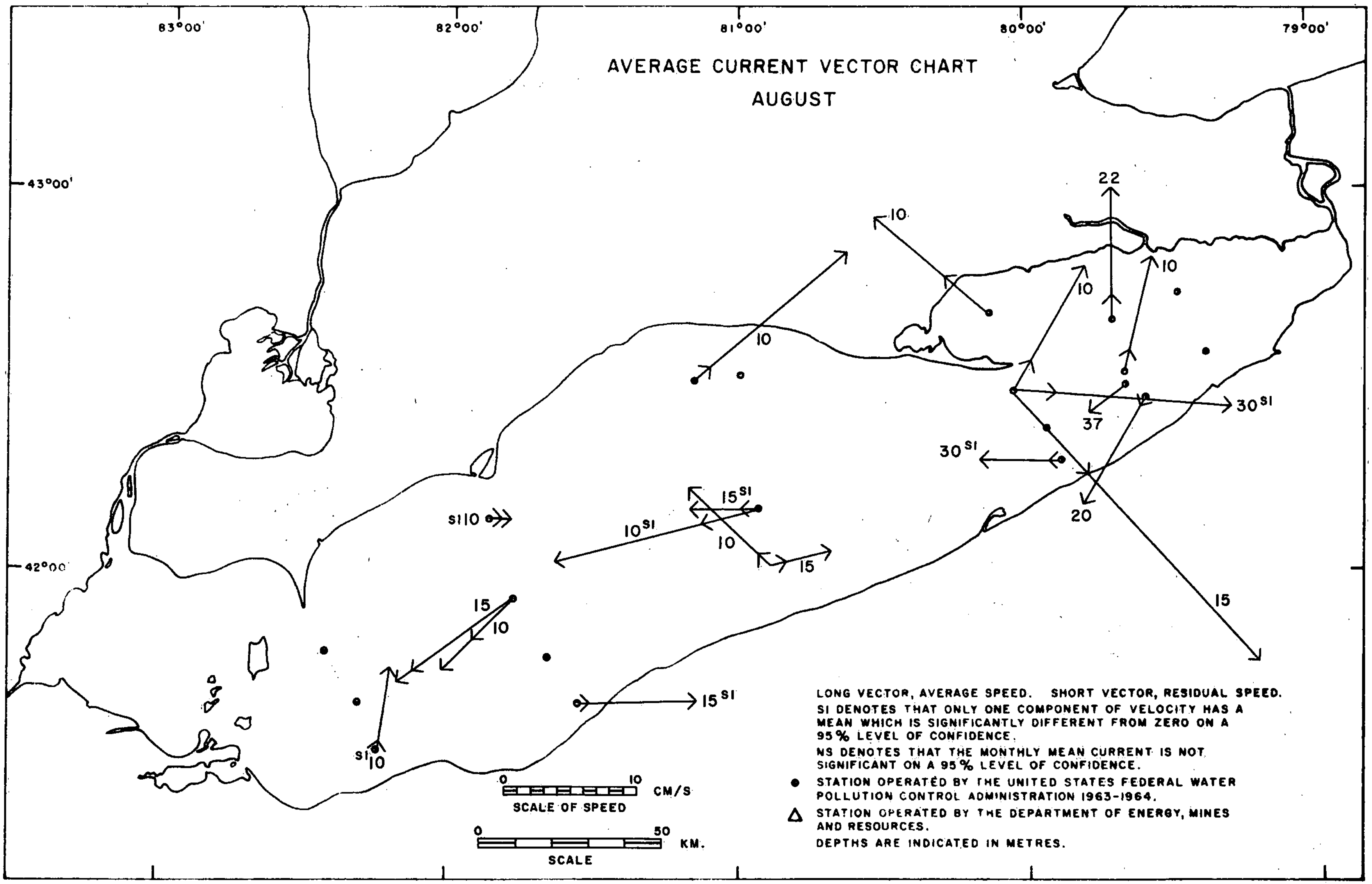
AVERAGE CURRENT VECTOR CHART
AUGUST
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80°00'
79°00'
43°00'
42°00'
22
10
10
10
10
37
30 SI
30 SI
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15 SI
10 SI
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SI 10
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SI 10
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CM/S
SCALE OF SPEED
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KM.
SCALE
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
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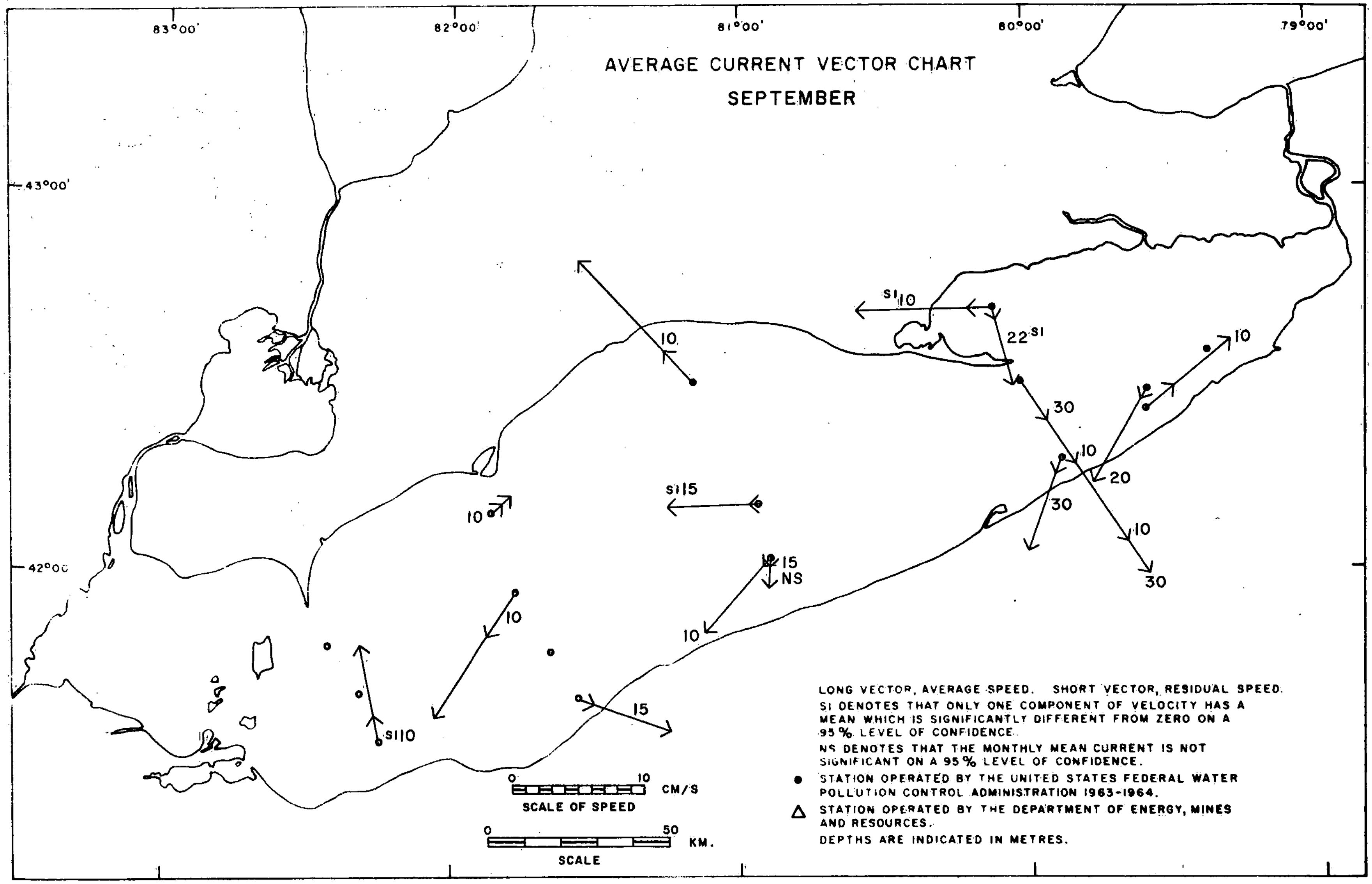
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SEPTEMBER
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81°00'
80°00'
79°00'
43°00'
42°00'
10
S1 10
22 S1
30
10
10
20
30
10
30
S1 15
10
15
NS
10
10
S1 10
15
0
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CM/S
SCALE OF SPEED
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KM.
SCALE
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
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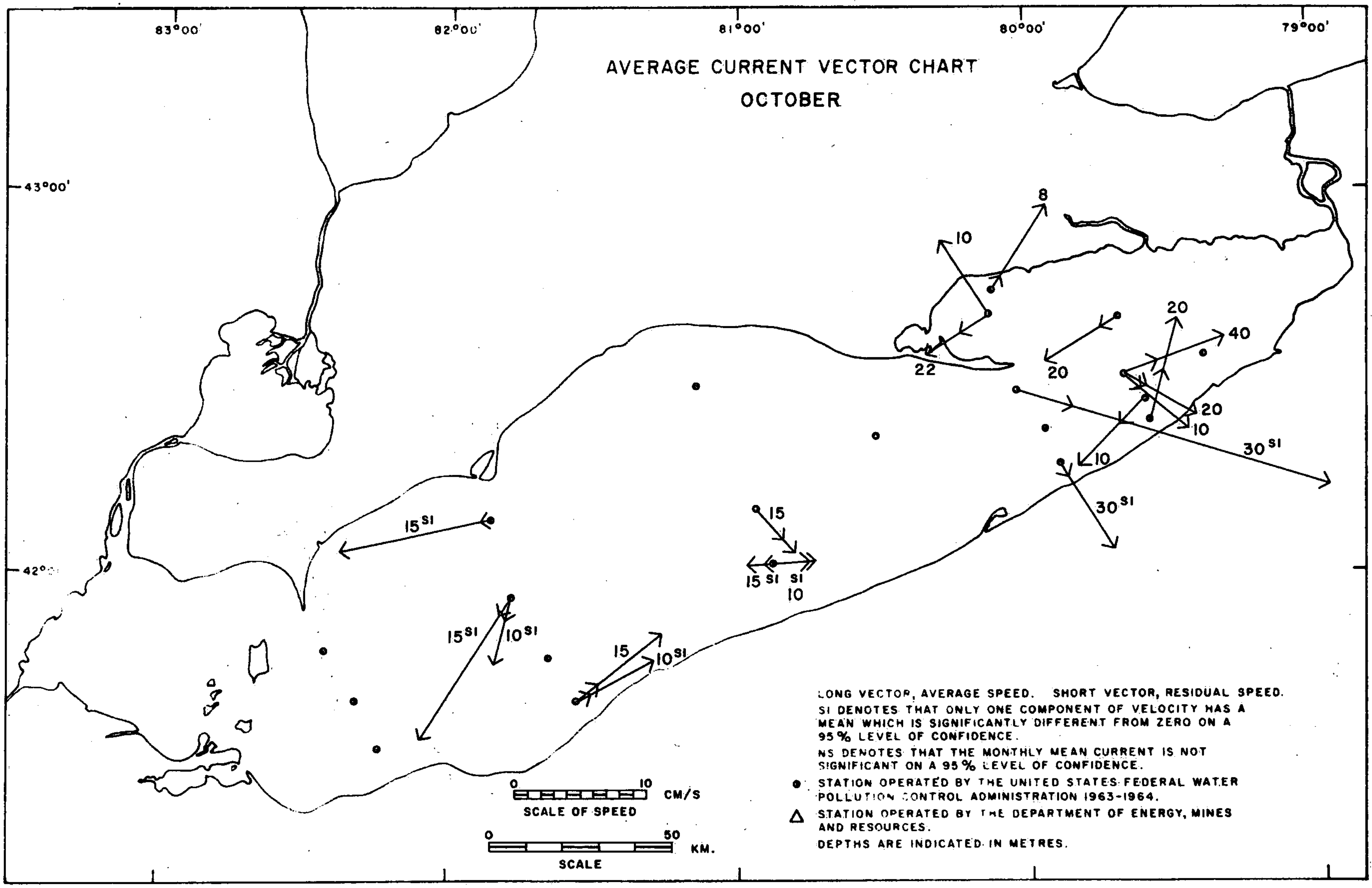

AVERAGE CURRENT VECTOR CHART
OCTOBER
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79°00'
43°00'
42°00'
8
10
22
20
20
40
20
10
30 SI
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SI
10
15 SI
10 SI
15
10 SI
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10
CM/S
SCALE OF SPEED
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KM.
SCALE
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
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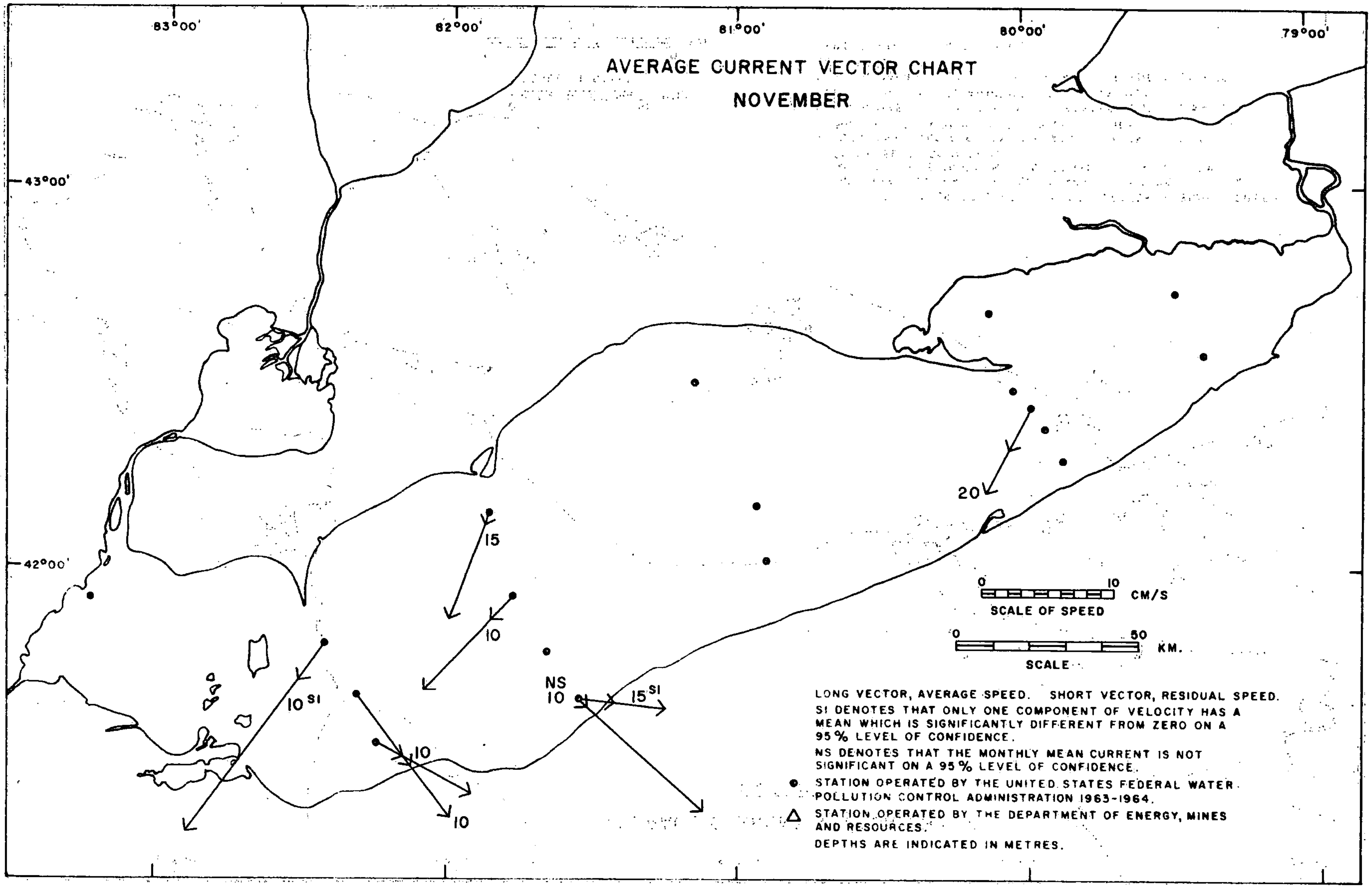
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15
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20
10 SI
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10
NS
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15 SI
0 10 CM/S
SCALE OF SPEED
0 50 KM.
SCALE
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
NS DENOTES THAT THE MONTHLY MEAN CURRENT IS NOT SIGNIFICANT ON A 95% LEVEL OF CONFIDENCE.
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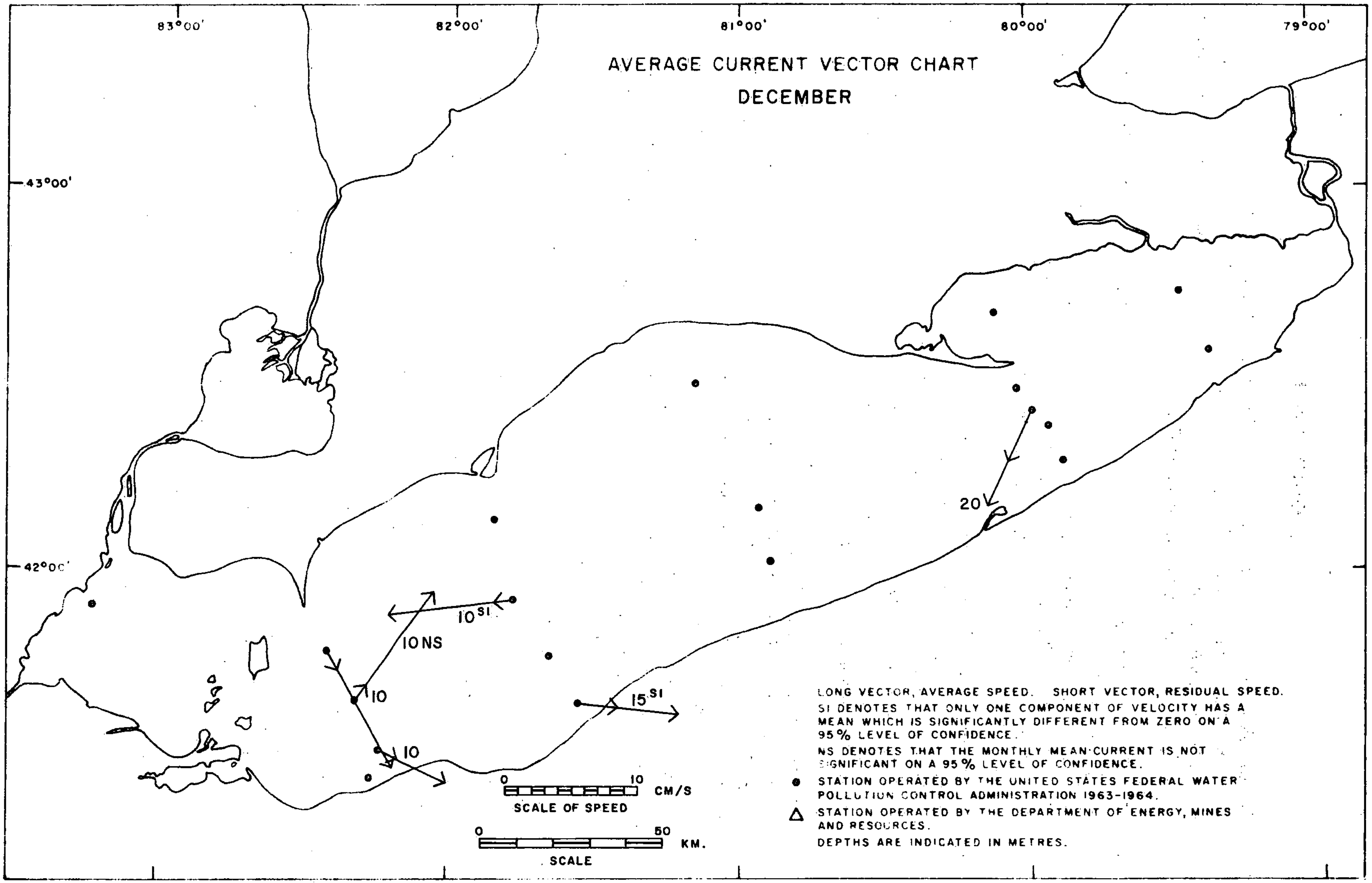
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DECEMBER
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80°00'
79°00'
43°00'
42°00'
10 SI
10 NS
10
10
15 SI
20
0 10 CM/S
SCALE OF SPEED
0 50 KM.
SCALE
LONG VECTOR, AVERAGE SPEED. SHORT VECTOR, RESIDUAL SPEED.
SI DENOTES THAT ONLY ONE COMPONENT OF VELOCITY HAS A MEAN WHICH IS SIGNIFICANTLY DIFFERENT FROM ZERO ON A 95% LEVEL OF CONFIDENCE.
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DEPTHS ARE INDICATED IN METRES.

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