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STRATIFICATION, CURRENTS AND UPWELLING IN LAKE ONTARIO, SUMMER 1982

by

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EXECUTIVE SUMMARY

Established theories and ideas on eutrophication and biochemical activity in lakes are mostly based on research and experiments on small lakes. A basic property of such lakes is that nutrient and plankton concentrations are essentially uniform in the horizontal and, except for deep basins, also in the vertical. However, large lakes such as the Great Lakes are characterized by significant horizontal and vertical gradients of dissolved and suspended matter. The seasonal stratification progresses slowly from the shore zones toward deep water with the result that the nearshore waters may be fully stratified in early spring while the open lake may remain fully mixed until early summer. The study of large lakes is further complicated by wind-induced horizontal and vertical displacement of water masses. This is particularly so in the shore zones which are dominated by frequent occurrences of upwelling and downwelling and by rapid alongshore currents. Since the various water masses have different biological properties, field observations of nutrients and plankton populations cannot be analyzed fruitfully without detailed knowledge of the physical processes.

With the foregoing in mind, extensive physical measurements were carried out in conjunction with the Lake Ontario Nutrient Assessment Study (LONAS) during 1982. An unprecedented instrumental coverage of the lake was achieved by judicious planning and pooling of

all institutional resources. This permitted a detailed evaluation of cross-sectional as well as alongshore variations of the physical properties of the lake. The present paper describes the observed temperatures and circulation patterns with a view to facilitate analysis and interpretation of the chemical and biological measurements of the LONAS study. This description consists of two parts. First, on a seasonal time scale, the measurements illustrate the seasonal temperature cycle from the nearshore "thermal bar" stratification in May to lake-wide summer stratification in August and the associated variations of water movements in the lake. Second, on a day-to-day scale, the paper describes in detail the dynamic response of the lake for three episodes coinciding with biochemical LONAS cruises. In addition to the descriptive presentation of the data, the basic physics involved in the observed response of the lake to wind are explained and illustrated in a manner suitable for inter-disciplinary communication.

RÉSUMÉ ADMINISTRATIF

Les théories et les notions de l'heure sur les phénomènes d'eutrophisation et d'activité biochimique dans les lacs sont basées en grande partie sur la recherche et les expériences menées sur de petits lacs. Une des caractéristiques fondamentales de ces petites étendues d'eau est que la concentration de nutriants et de planctons y est, à toute fin pratique, uniforme au plan horizontal et, sauf dans le cas de cours d'eau profonds, au plan vertical. On remarque toutefois que dans les Grands lacs, il existe différents gradients de concentration de substances dissoutes et en suspension dans les plans horizontal et vertical. La stratification saisonnière progresse lentement des rivages vers le large, ce qui fait que les eaux de la zone côtière sont souvent totalement stratifiées au début du printemps alors que celles du large peuvent demeurer complètement mélangées jusqu'au début de l'été. L'étude des grandes étendues d'eau se complique d'autant plus lorsqu'on fait intervenir un autre paramètre, c'est-à-dire le déplacement horizontal et vertical de masses d'eau causé par le vent. Ce problème est plus particulier aux zones côtières, où les remontées et les descentes de masses d'eau ainsi que les courants côtiers rapides sont fréquents. Puisque les propriétés biologiques des masses d'eau varient énormément, on comprend que sans connaissances approfondies des processus physiques, il est difficile d'analyser avec succès les données récoltées au cours d'observations de nutriants et de planctons.

C'est pour résoudre ces difficultés que nous avons entrepris en 1982 un programme exhaustif de mesures physiques en collaboration avec l'équipe d'évaluation des éléments nutritifs du lac Ontario. Grâce à une planification rigoureuse et à une mise en commun des ressources disponibles, nous avons déployé dans le lac Ontario un réseau d'instruments d'une ampleur sans précédent. Les résultats obtenus ont permis de procéder à une évaluation minutieuse des variations des propriétés physiques du lac en fonction des coupes transversales et de la zone côtière. Ce rapport, qui décrit les différences de température et de circulation observées, se veut un outil qui facilitera l'analyse et l'interprétation des données chimiques et biologiques recueillies par l'équipe d'évaluation des éléments nutritifs du lac Ontario. La description comprend deux volets. Le premier est basé sur une échelle saisonnière; il présente des mesures du cycle saisonnier de température prises de mai jusqu'en août, tout d'abord dans les couches de la "barre thermique" côtière puis dans la stratification estivale de tout le lac, ainsi que les variations des mouvements d'eau dans le lac qui en résultent. Le second volet est basé sur une échelle quotidienne et décrit en détails l'état dynamique du lac tel qu'enregistré au cours de trois croisières d'études biochimiques de l'équipe d'évaluation des éléments nutritifs du lac Ontario. En plus de fournir une description des données, ce document apporte des explications sur les phénomènes physiques à la base de la réaction du lac au vent et présente des graphiques susceptibles de favoriser l'échange entre les spécialistes des diverses disciplines scientifiques concernées.

ABSTRACT

A description is presented of physical measurements carried out on Lake Ontario during the summer of 1982. Seasonal variations of stratification and circulation are illustrated by monthly averages of temperature and current distributions in a north-south cross section of the lake. Day-to-day variations of temperature and currents are presented for three periods coinciding with biochemical ship cruises along the same transect of the lake. A wind-induced upwelling event followed by alongshore propagation of a warm water wave is described and the dynamics involved are discussed.

RÉSUMÉ

Ce rapport décrit les mesures physiques prises dans le lac Ontario au cours de l'été 1982. Les données saisonnières sur les variations des couches et de la circulation de l'eau sont représentées par des moyennes mensuelles de distribution de températures et de courants dans une coupe transversale nord-sud du lac. On y présente également des données sur les variations quotidiennes de température et de courants durant trois périodes qui coïncident avec les trois croisières d'études biochimiques de l'équipe d'évaluation des éléments nutritifs du lac Ontario dans la même zone du lac. Le rapport présente en outre une description du phénomène de remontée causée par le vent, suivie de la propagation d'une vague d'eau tiède le long de la rive, ainsi qu'une discussion sur les mécanismes dynamiques en cause.

INTRODUCTION

Coinciding with the Lake Ontario Nutrient Assessment Study (LONAS), extensive physical measurements were carried out on Lake Ontario during a four-month period from early May to late August, 1982. Continuous time series of temperatures, currents and winds were obtained from eight fixed temperature profilers, forty self-recording current meters, four meteorological buoys on the lake and a number of shore-based meteorological stations. Most of the instruments were located in the LONAS cross section of Lake Ontario between Port Hope, Ontario, and Point Breeze, New York. Two coastal transects were established 30 km east and west of the main transect. The location of the transects and the network of meteorological stations are shown in the upper part of Fig. 1. The depth profile of the central section is shown in the lower part of Fig. 1 with current meters identified by black circles and fixed temperature profilers by solid vertical lines.

The purpose of the present paper is to provide a description of the stratification cycle and circulation patterns encountered in Lake Ontario during the spring and summer of 1982. In addition, detailed analyses of temperatures and currents will be presented for three periods coinciding with ship cruises along the LONAS transect. The periods are June 28-July 2, August 9-13 and August 23-27. Large day-to-day variations in currents as well as temperature will be shown to occur in the course of each cruise. In view of the pronounced spatial variations of temperatures and nutrients in large lakes, the currents transport different water masses into the measurement area which must be anticipated to have a significant impact on biochemical processes in these lakes.

SEASONAL STRATIFICATION AND CIRCULATION

The seasonal stratification cycle of a lake results from the combined effects of surface heating and wind. In early spring the water is colder than the temperature at maximum density (4°C) and hence surface heating leads to complete mixing of the vertical water column until the temperature approaches 4°C. In the shallow shore zones this warming is rapidly accomplished and followed by stratification with a "thermal bar" separating these zones from the fully-mixed open lake. As the statification spreads out over the whole lake, the intensity of wind-induced turbulence determines the level to which the surface heat is mixed down and hence the thermocline in the open lake tends to deepen during stormy periods. In the shore zones large thermocline displacements are caused by wind-induced surface currents normal to the shore which are compensated by return flow at lower levels and vertical motions at the shore.

The above elements of the seasonal stratification cycle are vividly illustrated in Fig. 2. The top of Fig. 2 shows the eastward component of the wind stress at the surface of Lake Ontario obtained in the usual way from the square of the measured wind. It is known from Ekman's work in the early 1900's that, due to the earth's rotation (Coriolis effect), the wind-driven surface transport tends to be to the right of the wind. Therefore, the eastward component of the wind stress is primarily responsible for upwelling along the north shore and downwelling along the south shore. The bottom of Fig. 2 shows the behavior of the 10°C isotherm measured by the fixed temperature profilers at the north-shore, mid-lake and south-shore, respectively. It is apparent that the deep-water stratification lags the nearshore stratification by more than a month and, once established, the thermocline depth in mid-lake remains more or less at the same level. At opposing shores, the thermoclines move in opposite directions and are clearly forced by the wind. An eastward wind causes southward surface drift and hence upwelling at the north shore and downwelling at the south shore; a westward wind has the opposite effect.

A suitable display of temperature and current variations may be obtained by interpolating all available observations in the LONAS cross section of Lake Ontario. As shown in the lower part of Fig. 1, temperature observations for this transect are available from four fixed temperature profilers each providing continuous records at 20 depths. In addition, continuous time series of temperature are available from 24 current meters in this cross section. These observations were interpolated by the following procedure. First, vertical temperature profiles were constructed at the location of each current meter mooring by adopting the shape of the profile measured by an adjacent temperature profiler and shifting this profile up or down to match the temperatures measured by the current meters. A total of 10 vertical temperature profiles was thus obtained for the cross section. Next, temperatures were interpolated horizontally between temperature profiles at vertical intervals of 1 m between the surface and 30 m.

Monthly averaged temperatures obtained by this procedure are presented in the upper half of Fig. 3. The temperature distribution in May was clearly dominated by the thermal bar at the shallow north shore. The thermal bar at the much deeper south shore did not develop until the end of May. In June, the stratification in the shore zones increased gradually but the open lake remained colder than 4°C and hence continued to be fully mixed between the surface and the bottom. In July, the stratification in this section of the lake was fully established with the thermocline sloping upward toward the north shore and downward toward the south shore. This was partly a remnant of the thermal bar episode and partly the result of generally eastward winds (see top of Fig. 2) which, as noted earlier, tend to cause a drift of warm surface waters to the south. During August the average temperature distribution remained nearly the same but it will be seen in the following that strong day-to-day variations were induced by wind events.

The currents were interpolated in the same manner as the temperatures. Although no continuous vertical profiles of currents were measured, they may be inferred from the temperature profiles. In the absence of stratification, currents are vertically uniform and the same holds true below the thermocline during the stratified season. Between the thermocline and the surface vertical variations of currents may also be expected to be relatively small and hence the major shearing currents are concentrated around the thermocline. Thus, when the thermocline depth exceeds 10 m, the upper current meter provides an estimate of the epilimnion current while the bottom current meter measures the hypolimnion current. The transition from upper to lower layer current may be taken to match the temperature profile. Once the vertical current profile has been established for each mooring, horizontal interpolation is readily accomplished.

The lower half of Fig. 3 shows monthly averages of the component of the current normal to the LONAS transect. The units are km/day and positive values represent eastward currents, negative currents run westward. The total flow of water through a cross section of a closed lake must vanish when averaged over periods of a few days or longer. For Lake Ontario the total transport should be equal to the average flow from the Niagara to the St. Lawrence River. If the results of Fig. 3 are averaged over the whole period of the experiment, the total transport is 10^4 m^3/s to the east which compares favourably with the Niagara discharge of 7 x 10^3 m^3/s. Similar eastward transports are found for the months of June and August. However, the net transport for July is two-to-three times as large while the net transport during May is westward. Fortunately, these errors can be most likely attributed to inaccuracies in the deep lake currents which are too small to be accurately observed but make significant contributions to the total water transport because of the large water depths.

The most interesting aspects of Fig. 3 are the persistent boundary currents near the two shores. Along the south shore the water flows from west to east with surface velocities of 5-10 km/day. On the north shore the water flows from east to west. The boundary currents can be traced back to the thermal bar episode which is known to be associated with counterclockwise circulation around the perimeter of the lake. Although affected by a few summer storms, the currents appear to persist throughout the season.

SHORT-TERM VARIATIONS OF TEMPERATURE AND CURRENTS

Detailed descriptions of temperature and currents will be presented for three periods coinciding with biochemical cruises: June 29-July 2, August 10-13 and August 24-27. The overall temperature distributions in Lake Ontario during these periods are illustrated in Fig. 4. During the first period, the deep-lake station was just-getting stratified and winds from westerly directions resulted in upwelling of cold water at the north shore. The second period was dominated by three days of strong winds from the west again causing upwelling along the whole north shore. By the time of the third period, the cold north shore water had drifted into the western basin due to dynamical processes discussed later in this paper.

Day-to-day variations of temperature and currents for each period are shown in Figs. 5-7. The upper part of each figure presents temperature distributions for the LONAS cross section. These results were obtained by the same procedure used for the monthly averages of Fig. 3. The lower part of each figure shows daily averaged currents through the LONAS cross section. To facilitate comparison with the temperature distributions, the current meter positions are shown by black circles in the temperature maps.

In the course of the first period an eastward wind started blowing over the lake (see top of Fig. 2). The initial effect of such a wind is to move water to the east end of the lake such that the surface will slope down against the wind. The subsequent currents result from the counteracting effects of wind and surface slope. The surface slope creates a pressure gradient which is not affected by the depth of a water column. However, the wind stress is much more effective in moving shallow water than deep water. Since, as noted earlier, the total transport through a cross section of a closed lake must vanish, the net result of these opposing forces is that the shallow nearshore water moves in the direction of the wind while the mid-lake water returns against the wind. This explains the generation of eastward currents along both shores (Fig. 5). Near the north shore the currents were weaker and more uniform than at the south shore. The reason is that the north-shore stratification was weakened by upwelling and hence the wind forcing could be mixed down to accelerate the whole water column. By contrast, the south-shore water was strongly stratified and the wind moved only the relatively thin upper layer. In addition, the surface currents are seen to be more southward than the bottom currents. This agrees with the aforementioned Ekman theory which predicts surface drift to the right of the wind resulting in upwelling at the north shore and downwelling at the south shore.

During the second episode the wind blew again to the east and hence the lake reacted in the same way as before. However, in this case the wind stopped in the middle of the four-day period and, consequently, the thermocline started returning to its original position. This was particularly noticeable on the south shore. Near the north shore a broad band of eastward currents was observed on August 11 but the speeds decreased rapidly after the storm and the currents reversed themselves two days later. At the south shore strong eastward currents were generated which again were confined to the wedge of warm water. At the peak of the storm the thermocline was depressed below the level of the bottom current meter in the mooring adjacent to the south shore. This explains the large dashed arrows pointing to the east in that location.

The final episode was affected by two wind events, a short but strong westward wind impulse on August 25 followed by eastward winds on August 26. At first glance this sequence of events might seem to explain the initial downwelling and westward flow along the north shore and the subsequent upwelling and current reversal. However, it will be shown presently that these events were caused primarily by the passage of a warm water wave. Indeed, near the south shore the wind seemed to have little effect and a strong eastward current persisted throughout this episode.

To investigate the north-shore temperature and current variations in more detail, use was made of observations in the coastal transects 30 km east and west of the main transect (Fig. 1). Alongshore distributions of temperature were obtained by the same interpolation procedure used for the cross-sectional distributions. Figure 8 presents daily alongshore temperature patterns at a distance of 5 km from the north shore for August 20-27. The vertical line in the centre of each figure represents the intersection with the LONAS cross section, the left side coincides with the coastal transect to the west and the right side with the transect to the east. Daily values of observed currents are shown by arrows. The results show a wave of warm water progressing from east to west along the north shore and being accompanied by strong westward surface currents. The dynamics involved in this event will be discussed below.

DYNAMICS OF COASTAL UPWELLING

The theory of wind-induced upwelling in large lakes contains two basic elements. The first element concerns the forcing of coastal upwelling by local winds. According to Ekman theory, the wind causes a 10-20 m deep surface layer to move to the right of the wind due to the Coriolis force of the earth's rotation. Therefore, an alongshore wind tends to generate a surface current normal to the coast. In order to maintain a mass balance in the coastal zone, the surface drift must be offset by a return current at lower levels and the two are joined together by vertical motion at the coast. Thus, a wind blowing along the shore with the land on the left causes upwelling and a wind blowing in opposite direction causes downwelling. It has been shown by Charney (1955) that, in presence of stratification, thermocline displacements due to upwelling or downwelling decrease rapidly with offshore distance such that coastal upwelling or downwelling affects only a strip of a few km adjacent to the shore.

The second element of the theory of coastal upwelling deals with the way a pattern of upwelling and downwelling, once established by the wind, propagates around the lake. From the foregoing it follows that a uniform wind blowing over a lake causes upwelling at the shore to the left of the wind and downwelling at the shore to the right but has little or no effect at the upwind and downwind shores where the alongshore component of the wind vanishes. By unfolding the whole shoreline of the lake into a straight shore it is easy to visualize that the wind-induced thermocline excursions display a wave-like variation along the shore with wavelength equal to the perimeter of the lake. A thermocline wave of this type which, as noted above, is confined to a narrow strip near the coast, is known as an internal Kelvin wave. Such waves move with the speed of gravity waves on the interface between layers of fluid of different density but due to the Coriolis force of the earth's rotation they remain trapped at the shore and propagate with their right shoulder to the shore (in the Northern hemisphere); that is, counterclockwise around the Great Lakes. This alongshore propagation of warm and cold water after major upwelling events was first observed in Lake Michigan by Mortimer (1963) and a theoretical discussion for idealized lakes was presented by Csanady (1968). This Kelvin-wave mechanism is responsible for the wave propagation seen in Fig. 8.

From the foregoing it follows that upwelling at a given location depends not only on local wind forcing but also on the history of wind-induced upwelling at other points around the lake because these disturbances may eventually propagate into the region of interest. On this basis, a workable theory of wind-induced upwelling in large lakes was developed in the early seventies by Bennett (1973), Bennett and Lindstrom (1977), Csanady and Scott (1974), Gill and Clarke (1974), and Clarke (1977). This theory will now be used to explain observed thermocline movements at the north shore of Lake Ontario after the storm of August 9-11, 1982.

The first step is to compute the alongshore component of the wind stress at regular intervals around the shore since it is this component which drives the upwelling or downwelling. Given the wind, the alongshore component for each shoreline interval follows from the local orientation of the shoreline relative to the wind direction. By way of illustration, the mean wind stress for the August 9-11 storm is shown by the arrow at the centre of Lake Ontario in Fig. 9 and a few alongshore stress components are shown by arrows at selected shore locations. The actual calculations were carried out at 5-km intervals along the shore. The middle of Fig. 9 shows the same information after the shoreline has been unfolded into a straight line, starting from the west end of the lake and proceeding in clockwise direction around the perimeter. Note that the arrows along the south shore now point to the left because the shore lies to the right of the local wind direction. The bottom of Fig. 9 presents the resulting thermocline excursions at the shore measured relative to the thermocline level before the storm. These excursions are proportional to the alongshore stress component integrated over the duration of the storm. According to theory, the proportionality factor is $C/(\varepsilon gh)$ where C is the internal wave speed, ε is the density difference across the thermocline, g is the earth's gravity and h is the mean thermocline depth. Based on Fig. 2, estimated values are ε=0.0015 and h=12 m, while the empirical model of Bennett and Lindstrom (1977) for Lake Ontario suggests C=20 km/day. The average stress for the three-day storm period is 0.054 N/m^2 and thus the theoretical thermocline excursion during the storm is 18.3 m. This compares favourably with the observations in Port Hope and Point Breeze (Fig. 2).

The next step of the calculation is to move the thermocline wave along the shoreline such that the shore is to the right of the direction of propagation. Thus the wave moves to the left in Fig. 9 as indicated by the open arrows. With the above propagation speed of 20 km/day, the wave front would reach Port Hope by August 19, a little earlier than indicated by the observations of Fig. 8. However, a number of additional effects will modify the shape of the wave as it propagates along the shore. In the first place, allowance must be made for a gradual damping of wave amplitude due to bottom and shoreline irregularities and mixing across the thermocline. Secondly, although the storm of August 9-11 accounts for most of the subsequent thermocline movements, each of the following wind events make a similar, but smaller, contribution. Therefore, the above procedure must be repeated for each wind event and the results must be added. Since effects of past winds are gradually damped out, the result at any given time depends primarily on the more recent wind events. Finally, as shown by Bennett (1973), nonlinear effects cause the warm water wave to steepen into a warm front.

To conclude this discussion, a few words may be added regarding the currents associated with wind-induced thermocline movements. According to the above upwelling model, the thermocline excursions are accompanied by alongshore currents in a narrow coastal strip. Above the thermocline the currents run with the shore on their left in upwelling zones and with the shore on their right in downwelling areas. Thus the surface water flows in the same direction as the wind arrows shown in Fig. 9. As the wave moves to the left, so does the current pattern. Thus the eastward currents induced by the wind on the north shore will turn to the west as the warm water approaches. The current meter observations of Fig. 8 show the expected strong westward surface currents following the passage of the warm front.

ACKNOWLEDGEMENTS

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FIGURE LEGENDS

Fig. 1 Location of current meters, fixed temperature profilers and meteorological stations in Lake Ontario, summer 1982.

Fig. 2 Eastward component of wind stress and depth of 10° isotherm in Lake Ontario, summer 1982.

Fig. 3 Monthly averaged distributions of temperature (above) and currents (below) in the cross section of Lake Ontario between Port Hope, Ontario and Point Breeze, New York. Vertical lines in temperature graphs identify the five LONAS stations 401-405.

Fig. 4 Satellite observations of surface water temperatures in Lake Ontario. Black circles show the five LONAS stations.

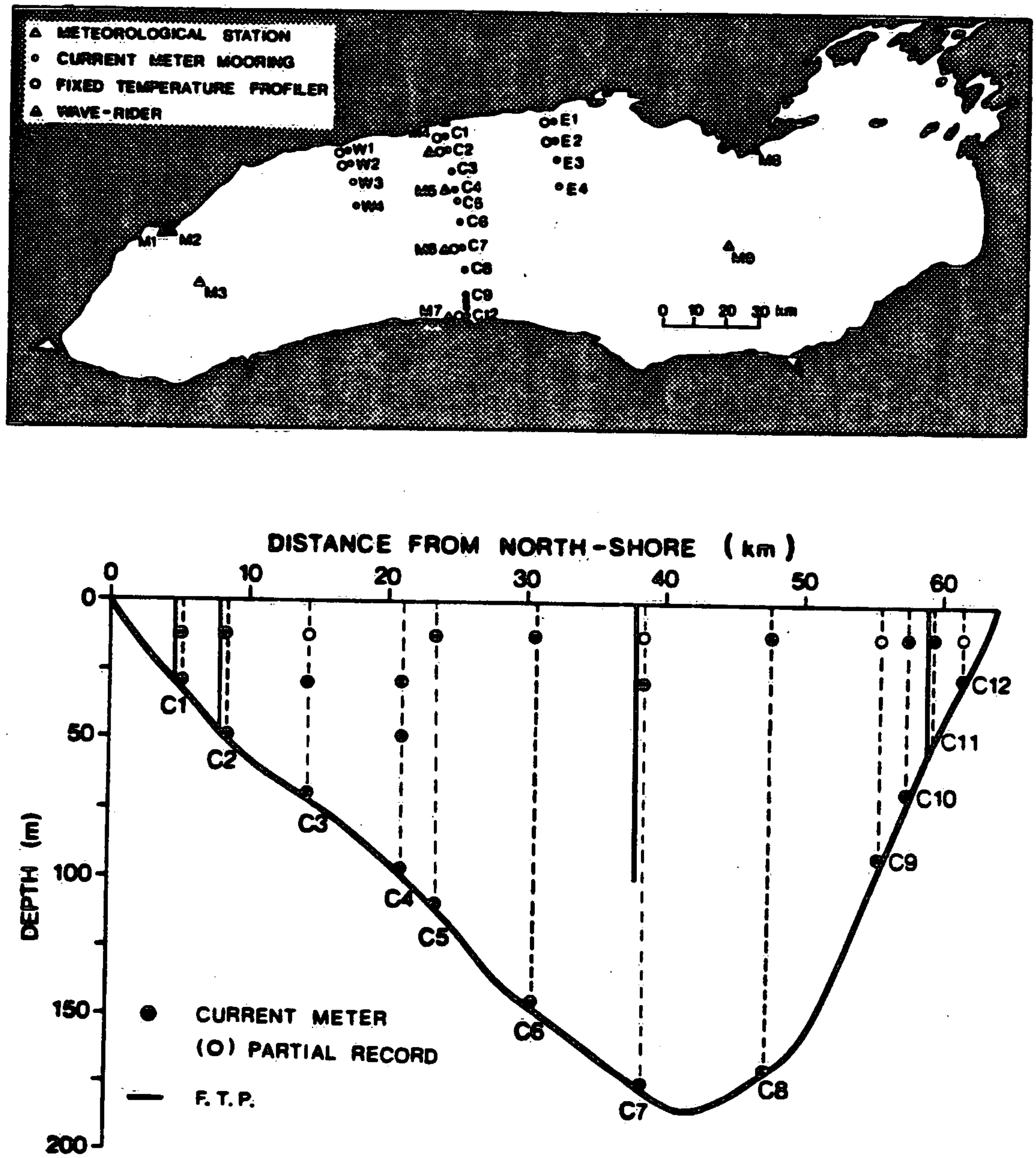
Fig. 5 Daily temperatures (above) and currents (below) in the Lake Ontario cross section between Port Hope, Ontario and Point Breeze, New York, June 29-July 2, 1982. Vertical lines in temperature graphs identify the LONAS stations. Black circles in current graphs show locations of Port Hope and Point Breeze.

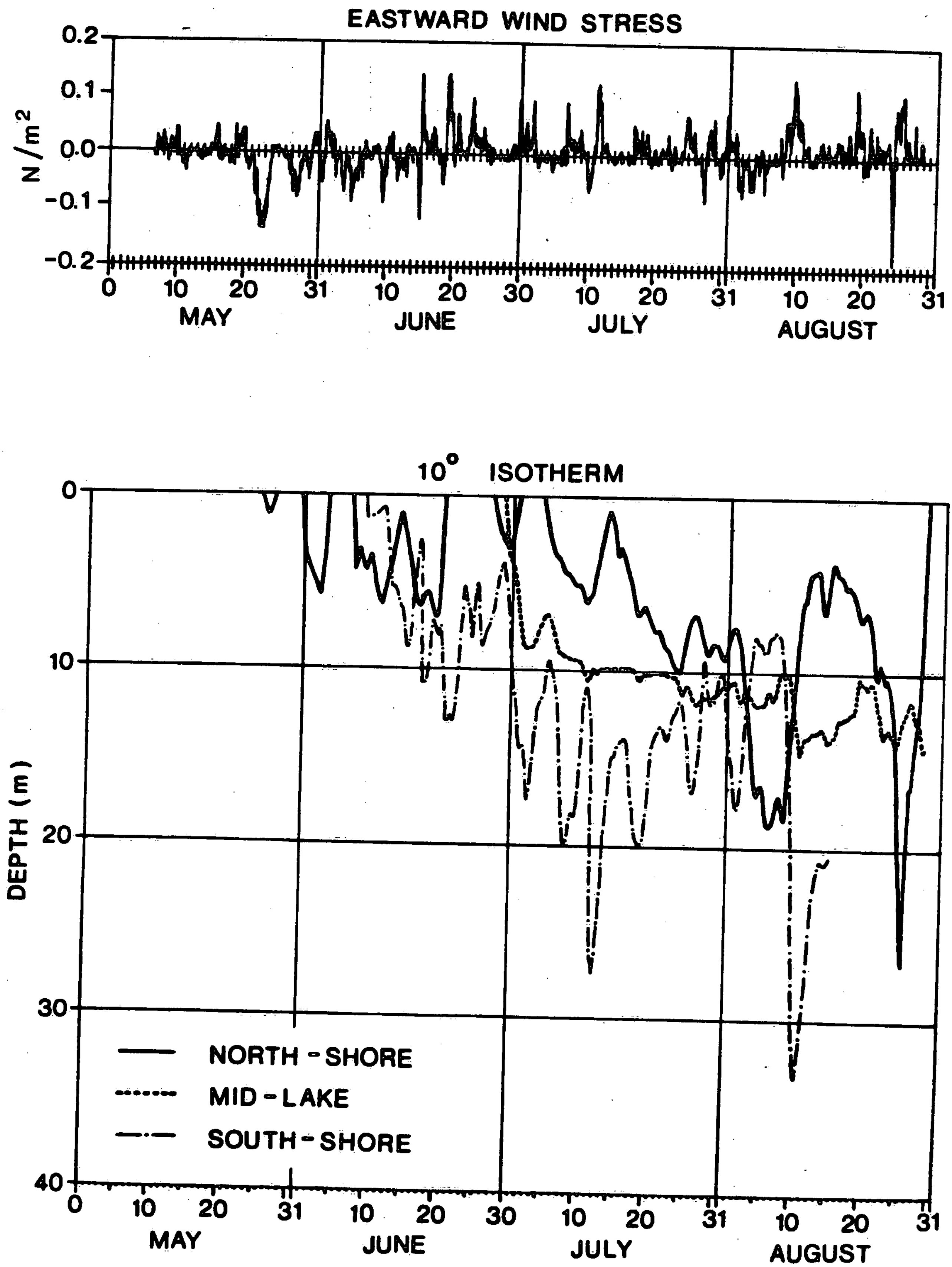
Fig. 6 Daily temperatures (above) and currents (below) in the Lake Ontario cross section between Port Hope, Ontario and Point Breeze, New York, August 10-13, 1982.

Fig. 7 Daily temperatures (above) and currents (below) in the Lake Ontario cross section between Port Hope, Ontario and Point Breeze, New York, August 24-27, 1982.

Fig. 8 Daily values of alongshore temperature variations 5 km off the north shore of Lake Ontario, August 20-27, 1982.

Fig. 9 Alongshore component of wind stress during storm of August 9-11, 1982 and resulting thermocline excursions computed from a simple upwelling model.


METEOROLOGICAL STATION
CURRENT METER MOORING
FIXED TEMPERATURE PROFILER
WAVE-RIDER
DISTANCE FROM NORTH-SHORE (km)
DEPTH (m)
CURRENT METER
(O) PARTIAL RECORD
F. T. P.
C1
C2
C3
C4
C5
C6
C7
C8
C9
C10
C11
C12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0.2
0.1
0.0
-0.1
-0.2
N/m²
0
10
20
31
10
20
30
10
20
31
10
20
31
MAY
JUNE
JULY
AUGUST
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0
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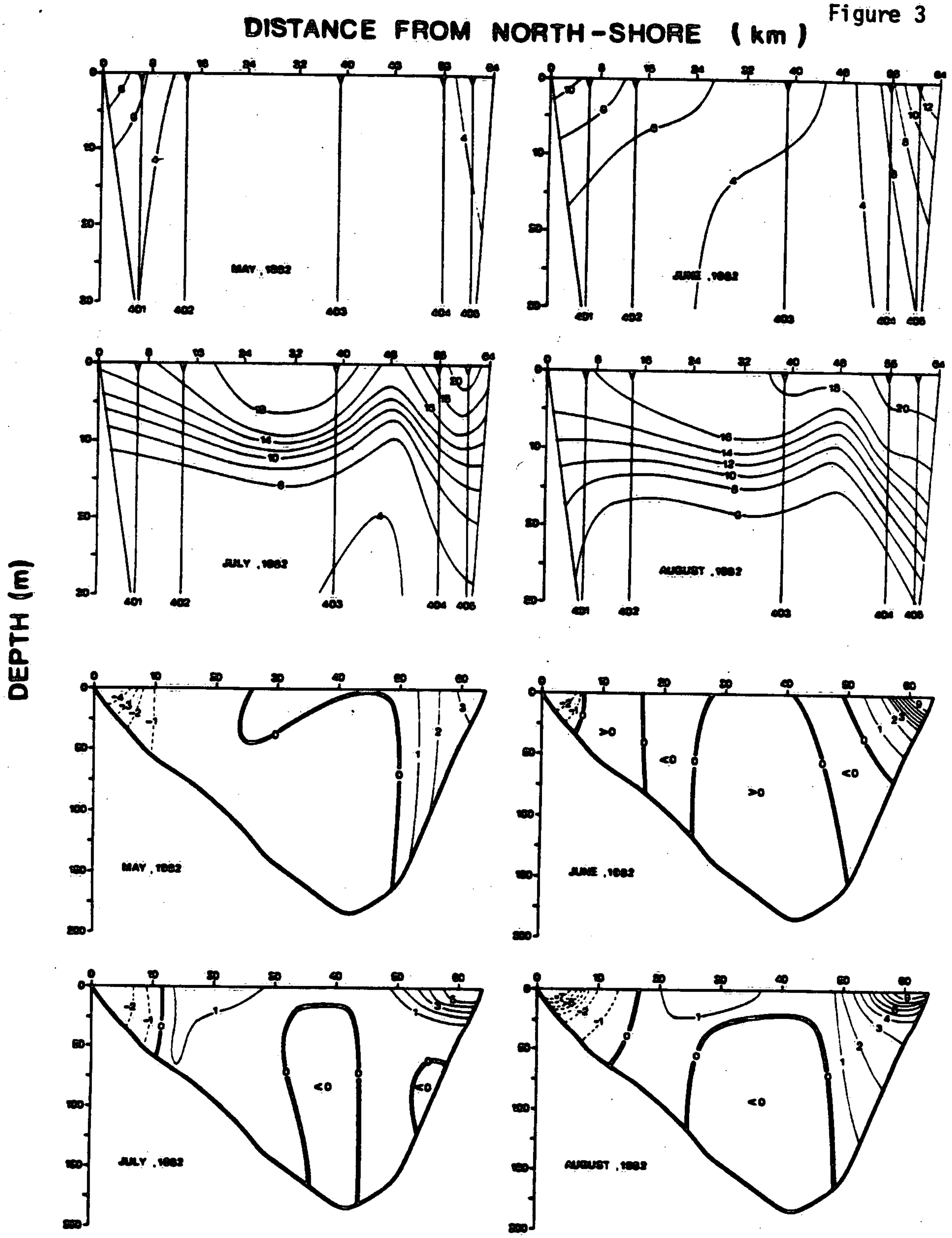
30
40
DEPTH (m)
NORTH-SHORE
MID-LAKE
SOUTH-SHORE


DISTANCE FROM NORTH-SHORE (km)
DEPTH (m)
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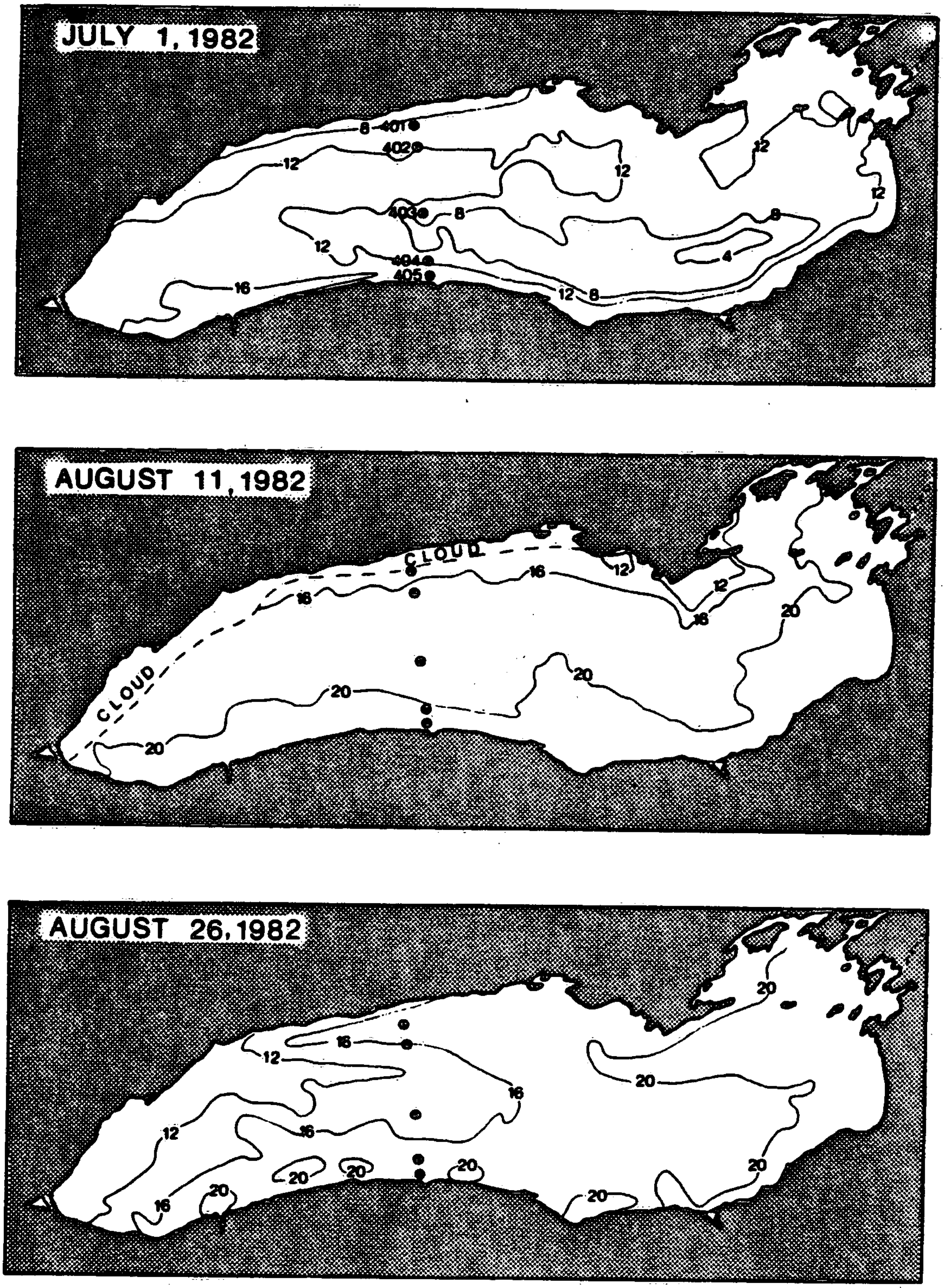
JUNE, 1982
JULY, 1982
AUGUST, 1982
401
402
403
404
405
>0
<0

Figure 4



JULY 1, 1982
401
402
403
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405
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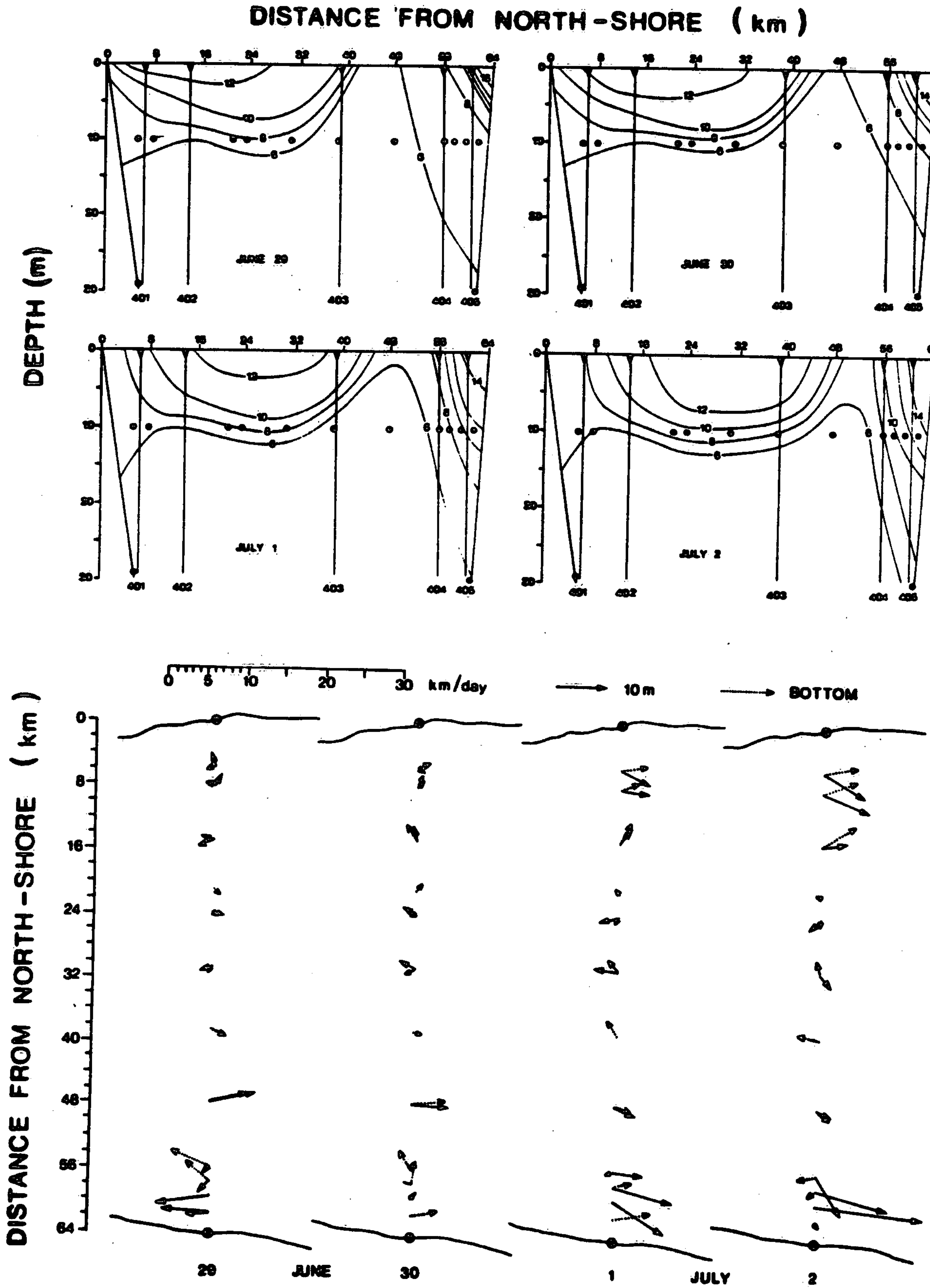
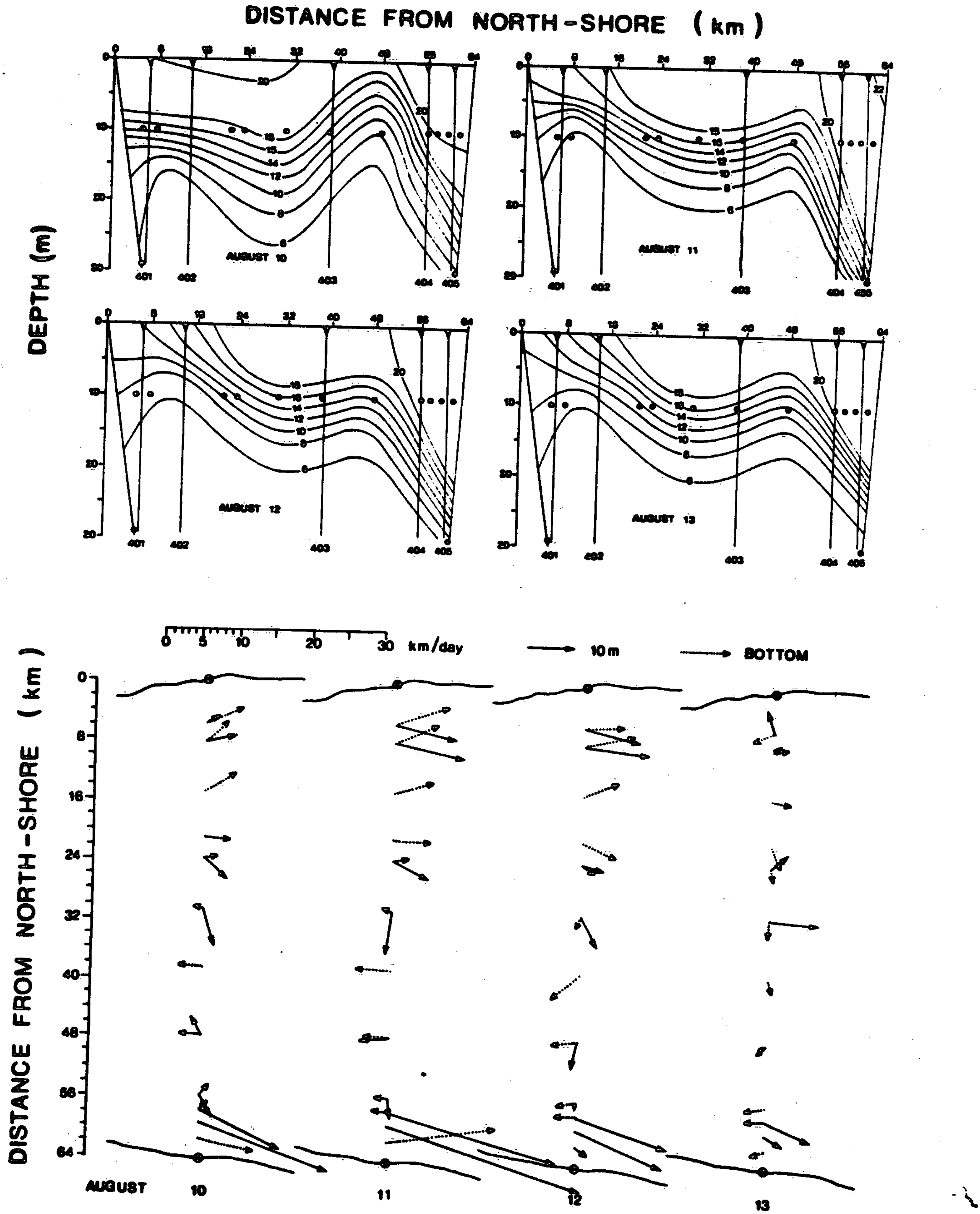
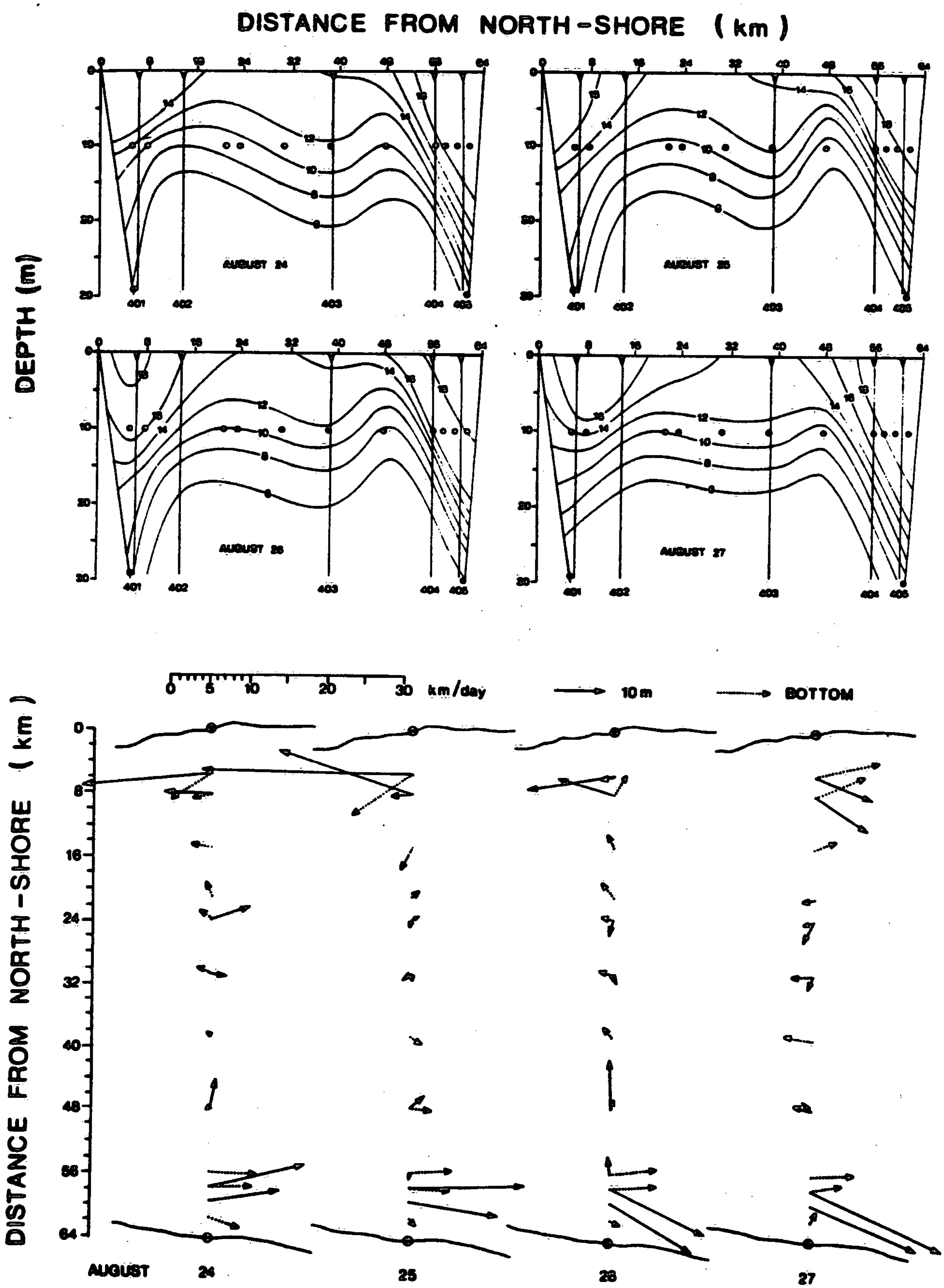
AUGUST 11, 1982
CLOUD
CLOUD
12
16
20
AUGUST 26, 1982
12
16
20

Figure 5



DISTANCE FROM NORTH-SHORE (km)
DEPTH (m)
JUNE 29
JUNE 30
JULY 1
JULY 2
401
402
403
404
405
km/day
10 m
BOTTOM
DISTANCE FROM NORTH-SHORE (km)
29
JUNE
30
1
JULY
2


DISTANCE FROM NORTH-SHORE (km)
DEPTH (m)
AUGUST 10
AUGUST 11
AUGUST 12
AUGUST 13
401
402
403
404
405
km/day
10 m
BOTTOM
DISTANCE FROM NORTH-SHORE (km)
AUGUST
10
11
12
13


DISTANCE FROM NORTH-SHORE (km)
DEPTH (m)
AUGUST 24
AUGUST 25
AUGUST 26
AUGUST 27
401
402
403
404
405
km/day
10 m
BOTTOM
DISTANCE FROM NORTH-SHORE (km)
AUGUST
24
25
26
27

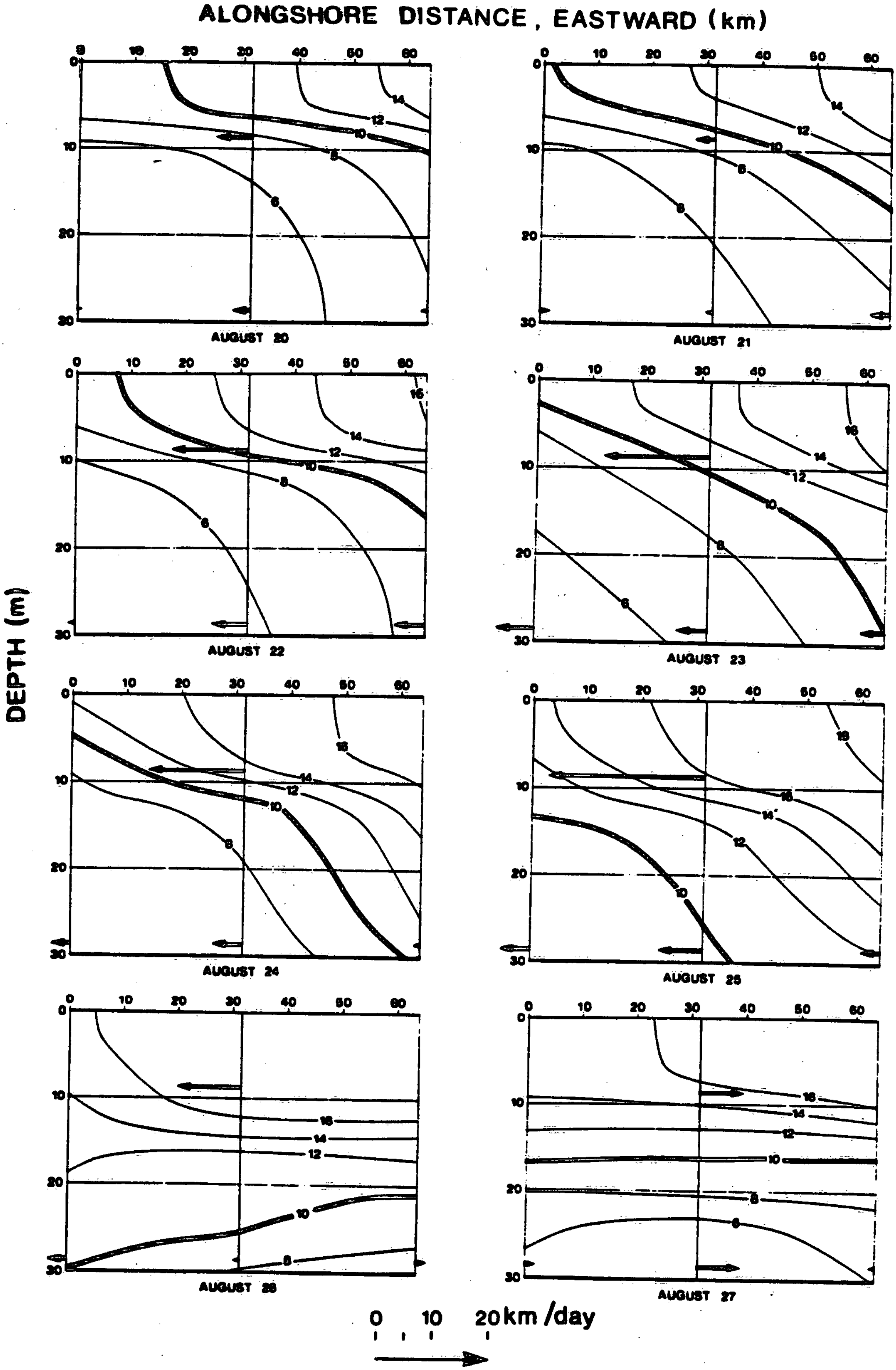
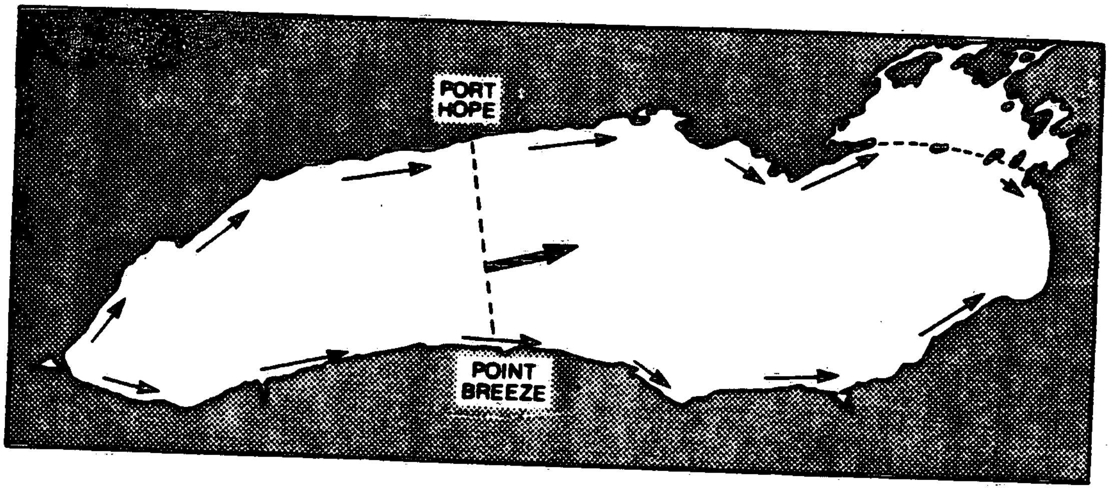
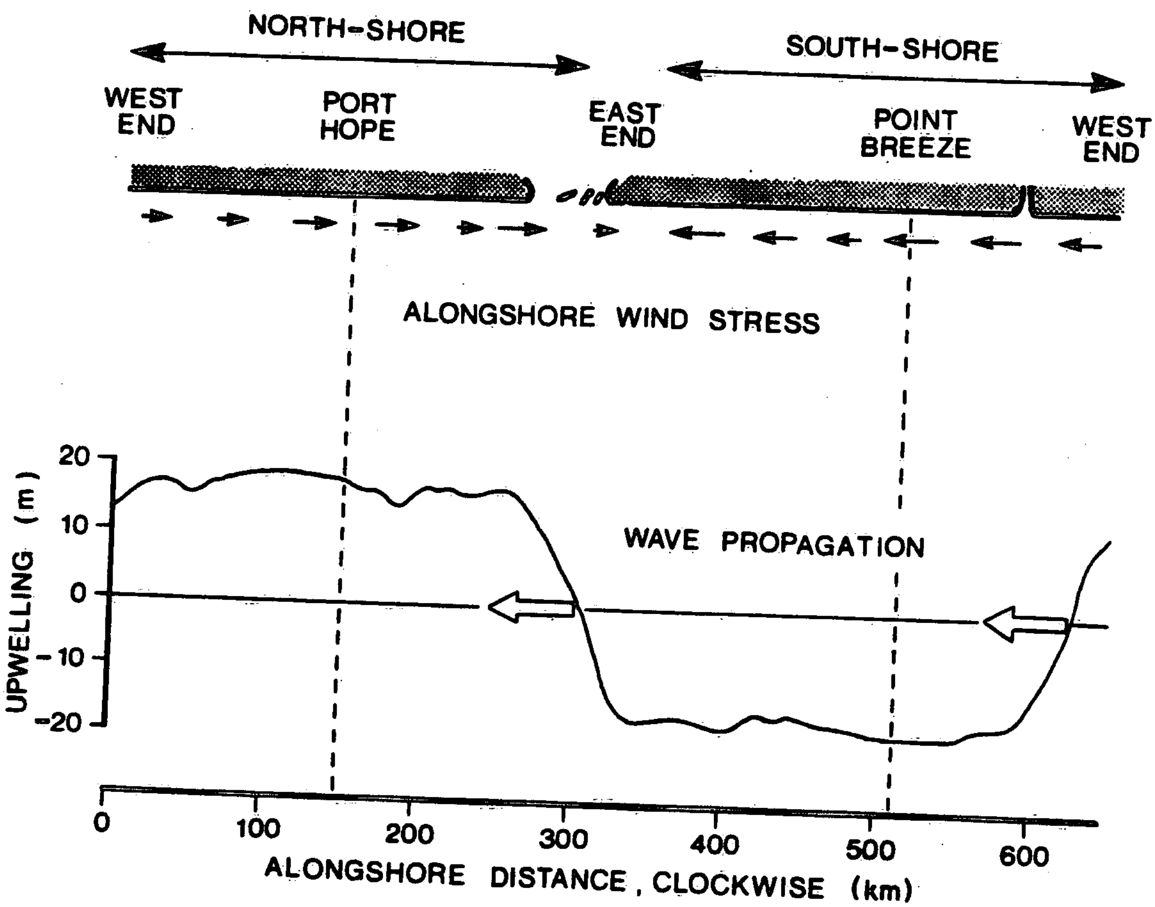

ALONGSHORE DISTANCE, EASTWARD (km)
DEPTH (m)
AUGUST 20
AUGUST 21
AUGUST 22
AUGUST 23
AUGUST 24
AUGUST 25
AUGUST 26
AUGUST 27
0 10 20 km /day

Figure 9


PORT HOPE
POINT BREEZE


NORTH-SHORE
SOUTH-SHORE
WEST END
PORT HOPE
EAST END
POINT BREEZE
WEST END
ALONGSHORE WIND STRESS
WAVE PROPAGATION
UPWELLING (m)
20
10
0
-10
-20
0
100
200
300
400
500
600
ALONGSHORE DISTANCE, CLOCKWISE (km)