

**TEMPERATURES AND CURRENTS
IN WESTERN LAKE ONTARIO
JUNE-NOVEMBER, 1984**

by

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EXECUTIVE SUMMARY

Due to the dense population and industrialization around the western shoreline of Lake Ontario, the local nearshore zone is affected by numerous effluent discharges while at the same time being heavily utilized as a source of drinking water. An important natural phenomenon influencing the response of the lake to these man-made stresses is the tendency of coastal currents to align themselves with the shoreline. As a consequence, contaminants injected into the shallow coastal waters move primarily back and forth along the shore rather than out into the open lake, thus tending to affect nearby water intakes. In view of the potential hazards of this situation, a field program was organized to study the physical and biochemical characteristics of the western basin of Lake Ontario. This report presents an analysis of the physical measurements to provide background information for studies of water quality and contaminants in this basin.

An array of continuous temperature recorders covered the nearshore zone from the west end of the lake to Cobourg, Ontario, a distance of about 160 km. Continuous current measurements were made with moored instruments. The field equipment was out in the lake from early June to the middle of November, 1984. This provided an opportunity to study the behaviour of the lake throughout the seasonal stratification cycle from late spring to autumn.

The temperature variations along the northwest shore of Lake Ontario were found to be strongly linked to the wind with winds from westerly directions causing upwelling and cooling and easterly winds inducing downwelling and warming of coastal waters. In general, similar temperature changes were seen to occur simultaneously along the whole array of instruments. On occasion, however, warmer water propagated along the shoreline from the eastern end of the measurement array all the way to the western tip of the lake. Currents were also highly correlated with the wind but with a pronounced preference for westward flow against the mean wind direction. Alongshore current speeds often exceeded 20 km/day and episodes between current reversals usually lasted from five to ten days, thus resulting in alongshore water displacements of more than 100 km over such periods. This means that the water quality in the entire nearshore zone is affected by effluents entering at any point along the shoreline.

RÉSUMÉ EXÉCUTIF

Étant donné la densité de population et d'industries le long du littoral ouest du lac Ontario, les eaux de la zone à proximité du rivage sont non seulement contaminées par un grand nombre d'effluents mais aussi largement utilisées pour la consommation. Un important phénomène se produit et modifie la réaction du lac à ces contraintes imposées par l'homme : les courants côtiers tendent en effet à se déplacer parallèlement à la rive. Par conséquent, les contaminants rejetés dans les eaux côtières peu profondes ne font que se déplacer parallèlement à la rive plutôt que d'être entraînés vers le large, ce qui peut résulter en une contamination des prises d'eau locales. Pour tenir compte des risques que peut poser cette situation, on a mis sur pied un programme d'étude sur le terrain des caractéristiques physiques et biochimiques du bassin ouest du lac Ontario. Le rapport présente une analyse des mesures physiques qui serviront de données de base pour étudier la qualité de l'eau de ce bassin et les contaminants qu'il contient.

Une batterie d'enregistreurs continus de température a été déployée dans la zone côtière depuis l'extrémité ouest du lac jusqu'à Cobourg (Ontario), soit sur une distance d'environ 160 km. Des instruments amarrés ont permis de prendre sans interruption des mesures de courants. L'étude sur le terrain s'est déroulée du début de juin jusqu'à la mi-novembre 1984. Il a ainsi été possible d'étudier le comportement du lac durant tout un cycle saisonnier de stratification, de la fin du printemps jusqu'à l'automne.

On a découvert que les variations de température le long de la rive nord-ouest du lac Ontario étaient fortement liées au vent. Il semble en effet que les vents qui soufflent de l'ouest causent des remontées et des refroidissements de l'eau alors que ceux qui viennent de l'est entraînent des descentes et des réchauffements des masses d'eau côtière. En général, tous les instruments de mesure ont enregistré simultanément des changements de température semblables. On a toutefois noté à certains moments que des eaux plus chaudes se propageaient le long du littoral à partir de l'extrémité est de la zone d'étude jusqu'à la pointe ouest du lac. Il semble également que la direction des courants soit fortement liée aux vents, mais que les courants vers l'ouest avaient fortement tendance à aller contre la direction moyenne du vent. La vitesse des courants côtiers dépassait fréquemment 20 km/jour et les intervalles entre les changements de direction des courants étaient généralement de cinq à dix jours. Au cours de ces périodes, les déplacements des eaux côtières ont donc pu porter sur une distance de plus de 100 km. Tout ceci signifie que la qualité des eaux de toute la zone côtière est affectée par les effluents qui se déversent dans le lac à n'importe quel endroit de la côte.

INTRODUCTION

The present study is an extension of the Lake Ontario study described by Simons and Schertzer (1985). While the earlier study dealt with measurements along the north shore and a central cross section of Lake Ontario during 1982 and 1983, the present study is concerned with observations in the western basin of Lake Ontario during 1984. The study was motivated by concerns about effects of effluent discharges on numerous drinking water intakes along the western shore of the lake.

Like the 1982/83 program, physical measurements during 1984 were coordinated with a biochemical surveillance program but this report describes only the physical measurements. Specific objectives of these measurements were to obtain detailed patterns of wind-induced upwelling and current reversals in the western basin and to compare them with similar phenomena observed along the north shore in 1982. Such knowledge is essential for studies of water quality and contaminants in the western basin of Lake Ontario.

FIELD PROGRAM

The 1984 program of physical measurements in Lake Ontario covered the five-month period from June 5 to November 14, 1984. The main component of the field experiment was an array of seven fixed

temperature profilers (FTP's) along the northwest shore of the lake. Each FTP recorded temperatures at 20 depths and time intervals of 20 minutes. Four FTP's extended to a depth of 20 m, two FTP's reached to 30 m and one to 36 m (Figure 1, top of Table 1). Currents were measured at time intervals of 20 minutes by seven Geodyne current meters in five moorings (Figure 1, bottom of Table 1). Wind records were obtained from routine weather observations at Toronto Island Airport. Satellite observations of surface water temperatures are available for clear days from the Atmospheric Environment Service.

The wind stress at the water surface was computed in the conventional way from the square of the wind speed with a drag coefficient of 1.2×10^{-3} . Wind stresses and currents were decomposed into alongshore and onshore components. Temperatures were averaged over 16 hours to eliminate near-inertial oscillations which tend to obscure day-to-day variations.

The periods of data return of FTP's and current meters are depicted in Figure 2. The data return of the FTP's is quite good between July 25 and September 22 but rather unsatisfactory before and after this period. For that reason, the data analysis and presentation in this report were divided into three periods: June 5 - July 24, July 25 - September 22, and September 23 - November 14. These dates are displayed in the centre of Figure 2.

OBSERVATIONS JUNE 5 - JULY 24 (SPRING/SUMMER)

Alongshore components of wind stress and currents from this period are presented in Figure 3. Available temperatures are shown in Figure 4 and selected satellite data in Figure 5. As discussed in the report by Simons and Schertzer (1985), the alongshore component of the wind stress is much more effective than the onshore component in exciting upwelling and currents in nearshore water and the alongshore component of the nearshore flow is generally much larger than the onshore component.

Figures 3 and 4 show that the major current reversals and upwelling events were directly related to wind impulses. A strong westward stress on June 23 depressed the 10-degree isotherm by more than 10 metres along the north shore. The subsequent wind reversals appeared to have relatively little effect but, after a period of calm weather, an eastward wind on July 7 resulted in strong upwelling and a current reversal to the east. However, the eastward currents lasted only two days (July 8-9). After July 10 the currents were persistently westward (Figure 3) and caused a gradual warming of nearshore water progressing from east to west along the north shore (Figures 4 and 5). Since the wind stress during this episode was directed to the east, the westward currents and downwelling cannot be explained by direct wind forcing but must be due to wave-like free

motions in the coastal zone. The dynamics of these phenomena are discussed in the report by Simons and Schertzer (1985).

OBSERVATIONS JULY 25 - SEPTEMBER 22 (SUMMER)

Wind stress and currents for this period are depicted in Figure 6, temperatures in Figures 7 and 8, and satellite data in Figure 9. The data return from the fixed temperature profilers during this period is fairly complete, thus allowing for a study of temperature variations along the whole northwest shore of Lake Ontario. To facilitate comparison of various stations, the results from the fourth station were entered in Figure 8 as well as Figure 7.

As seen in Figure 6, during the first ten days of this period calm weather prevailed and the nearshore water continued to flow to the west. As a result the warm water advanced farther and farther along the shore and eventually reached the western tip of the lake (top of Figure 7). A succession of eastward and westward wind impulses caused episodes of upwelling and downwelling, respectively, during August. An episode of particularly strong downwelling and westward currents was initiated by the westward wind stress of September 2. This was followed by two upwelling episodes during the remainder of this period.

The satellite pictures (Figure 9) illustrate the response of the whole lake to the wind reversals of this summer season. The

upwelling of cold water along the south shore on August 21 was due to the westward storm of August 19 (Figure 6) which caused downwelling at the north shore (Figures 7 and 8). The situation was reversed by the end of August after a period of eastward winds. On September 7 colder water was observed along both the north and south shores. This was apparently caused by the sequence of southshore upwelling on September 2 (northshore downwelling) followed by northshore upwelling on September 7 (Figure 7-8).

OBSERVATIONS SEPTEMBER 23 - NOVEMBER 14 (FALL)

Wind stress and currents for this period are presented in Figure 10, FTP data in Figure 11 and satellite data in Figure 12. Figure 10 shows that the currents attained large speeds in response to the strong wind impulses which commonly occur during the fall season. The wind-induced mixing together with the strong surface cooling seen in the satellite pictures (Figure 12) result in a deep upper mixed layer with temperatures close to 10°C (Figure 11). Thus, the major temperature changes occur below the measurement depths of the FTP's. Also, most of the FTP's stopped operating in September (Figure 2) and hence the output from the FTP array for this period is of rather limited use.

ALONGSHORE TEMPERATURE VARIATIONS

Inspection of the temperature data from the FTP's (Figures 4, 7, 8, 11) shows that pronounced upwelling and downwelling events generally occurred simultaneously at the seven FTP stations. On a few occasions, however, a change of temperature is seen to progress from east to west along the north shore. The former events are clearly associated with strong wind impulses while the latter are more likely to occur during periods of calm weather.

To illustrate this dual behaviour of the nearshore zone, Figure 13 presents a composite of parts of Figures 3-12 with significant wind, current and temperature events connected by heavy dashed lines. The events of June 22, July 7, September 2 and October 3 are typical examples of the class of wind-induced temperature and current variations. On the other hand, the period from July 10 to August 7 is clearly dominated by an event of the second class with downwelling progressing from east to west along the array of FTP's. This direction of propagation of warm water and the associated westward currents are against the prevailing eastward wind forcing during this period.

The contrast between these two types of events may be elucidated by constructing synoptic alongshore temperature distributions. This was done as follows. At each FTP station, daily-averaged temperatures were interpolated vertically to 1 metre

intervals. This was followed by horizontal interpolation at each level with due regard for the alongshore spacing of the stations (Figure 1). Daily-mean alongshore currents were then entered in the form of arrows at the measurement locations.

Figure 14 shows daily alongshore temperature distributions and currents for the last ten days of July. It is seen that this period is dominated by a westward propagating wave of warm water accompanied by persistent westward currents in the nearshore zone. For a discussion of the dynamics of this phenomenon, the reader is referred to Simons and Schertzer (1985). In this case the current speeds in the upper layer average out to about 13 km/day. This translates into an alongshore displacement of 130 km over a 10-day period which is comparable to the total alongshore distance covered by the array of FTP's (Figure 1). Assuming that currents of similar magnitude prevail along the whole north shore, it follows that during such an episode nearshore water originating from the Cobourg area may end up at the western tip of the lake. The satellite pictures of Figure 5 confirm that estimate of water mass displacements.

Figure 15 shows daily alongshore temperature distributions and currents for the first ten days of September. As shown in Figures 6 and 13, this period was dominated by a strong westward wind impulse on September 2. This wind moved the warm surface water from the open lake toward the northwest shore. Unlike the case illustrated in Figure 14, the downwelling in the present case was quite uniform along

the whole FTP array and the strong westward currents were directly driven by the wind. Also in this case, the duration of the downwelling was much shorter than in the previous case and the isotherms started to rise again by September 6. However, a resurgence of strong westward currents a few days later appeared to move warmer water back into the western basin by the end of this period. This situation is reminiscent of wind-induced thermocline movements at the downwind end of a small lake. In that case the response to wind consists of a downward displacement of the thermocline followed by internal seiches. However, a glance at Figure 6 shows that the lake during September was subjected to a series of quite strong wind impulses and hence it is unlikely that free oscillations could develop.

SUMMARY AND CONCLUSIONS

The temperature variations along the northwest shore of Lake Ontario were found to be strongly linked to the wind with winds from westerly directions causing upwelling and cooling and easterly winds inducing downwelling and warming of coastal waters. In general, similar temperature changes were seen to occur simultaneously along the whole array of instruments. On occasion, however, warmer water propagated along the shoreline from the eastern end of the measurement array all the way to the western tip of the lake. Currents were also

highly correlated with the wind but with a pronounced preference for westward flow against the mean wind direction. Alongshore current speeds often exceeded 20 km/day and episodes between current reversals usually lasted from five to ten days, thus resulting in alongshore water displacements of more than 100 km over such periods. This means that the water quality in the entire nearshore zone is affected by effluents entering at any point along the shoreline.

ACKNOWLEDGEMENTS

The field program was planned and coordinated by J.A. Bull, the data analysis was supervised by J.A. Bull and F. Chiocchio and the satellite data were provided by G. Irbe of the Atmospheric Environment Service.

REFERENCES

Simons, T.J. and W.M. Schertzer 1985. The circulation of Lake Ontario during the summer of 1982 and the winter of 1982/83. NWRI Contribution #85-26, 190 pp.

TABLE 1 Fixed Temperature Profilers and Current Meters, Lake Ontario, 1984

Station Number	Measurement Depth (m)	Sounding Depth (m)	Latitude (north)	Longitude (west)	Mooring Number
T1	0 - 21.3	24.3	43.16.03	79.37.28	32
T2	0 - 30.2	44.6	43.24.44	79.38.21	34
T3	0 - 20.2	29.4	43.33.15	79.30.16	30
T4	0 - 36.7	46.8	43.37.58	79.16.43	28
T5	0 - 30.2	36.1	43.48.42	79.51.49	29
T6	0 - 21.2	38.0	43.52.14	78.27.10	31
T7	0 - 19.8	32.0	43.55.56	78.02.50	33
C1,1	15	40.2	43.52.14	78.26.55	23
C1,2	17	40.2	43.52.14	78.12.55	23
C2	17	17.4	43.56.39	78.09.18	24
C3	18	18.5	43.56.35	78.08.48	25
C4,1	17	37.0	43.55.06	78.08.24	26
C4,2	35	37.0	43.55.06	78.08.24	26
C5	15	49.2	43.53.52	78.08.07	27

FIGURE LEGENDS

Figure 1 Location of fixed temperature profilers (FTP's) and current meters in western Lake Ontario, June 5 - November 14, 1984.

Figure 2 Periods of data return of instruments in Lake Ontario during 1984 field program. Dates in centre of figure refer to periods of data analysis and presentation in this report.

Figure 3 Alongshore components of wind stress and currents observed near Lake Ontario's north shore during 1984. Positive values represent eastward winds and currents.

Figure 4 Isotherm depths obtained from fixed temperature profilers along Lake Ontario's north shore during 1984.

Figure 5 Satellite observations of surface water temperatures in Lake Ontario during 1984.

Figure 6 Continuation of Figure 3.

Figure 7 Continuation of Figure 4.

Figure 8 Continuation of Figure 4.

Figure 9 Continuation of Figure 5.

Figure 10 Continuation of Figure 6.

Figure 11 Continuation of Figure 8.

Figure 12 Continuation of Figure 9.

Figure 13 Illustration of response of currents and temperature to wind, Lake Ontario, 1984.

Figure 14 Daily-averaged temperature distributions along northwest shore of Lake Ontario, July 22-31, 1984. Arrows denote daily-mean currents.

Figure 15 Same as Figure 14 but for September 1-10, 1984.

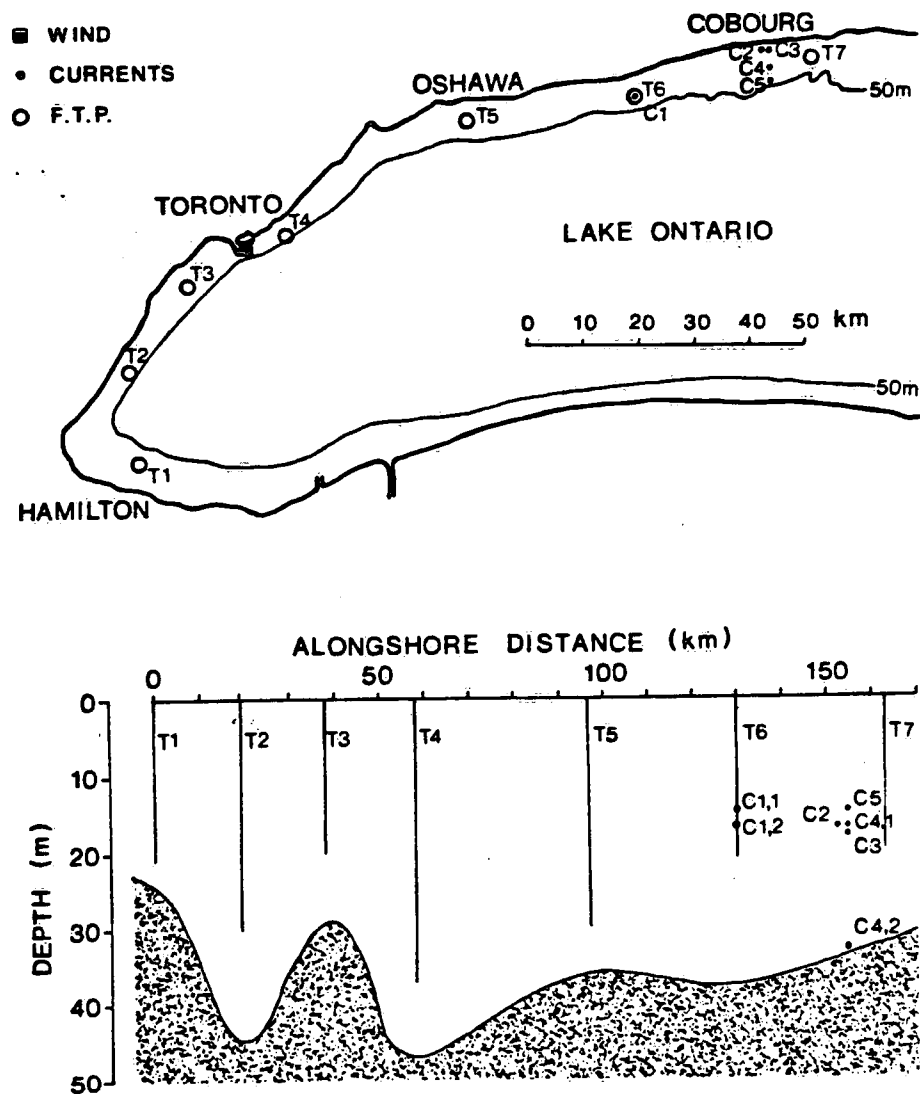


Figure 1 Location of fixed temperature profilers (FTP's) and current meters in western Lake Ontario, June 5 - November 14, 1984.

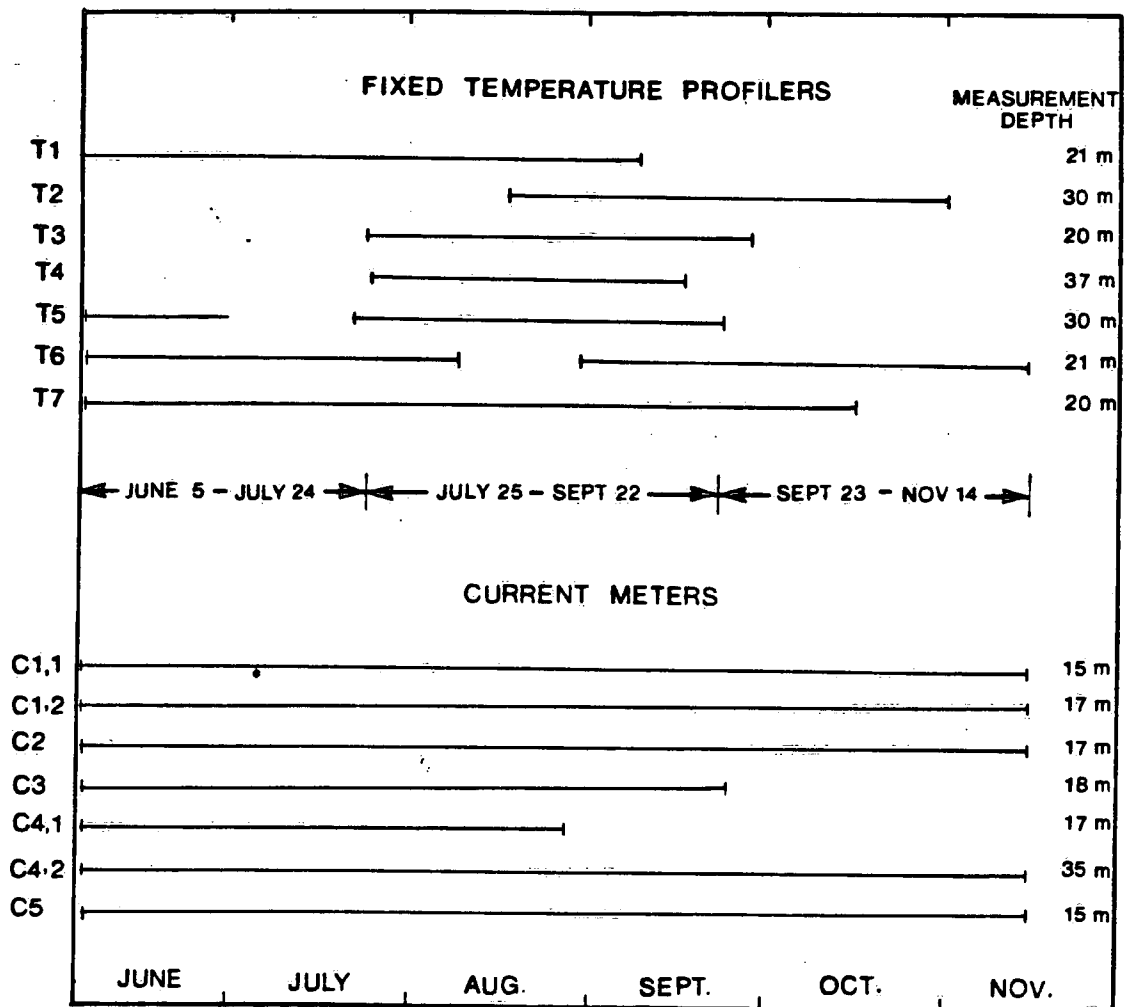


Figure 2 Periods of data return of instruments in Lake Ontario during 1984 field program. Dates in centre of figure refer to periods of data analysis and presentation in this report.

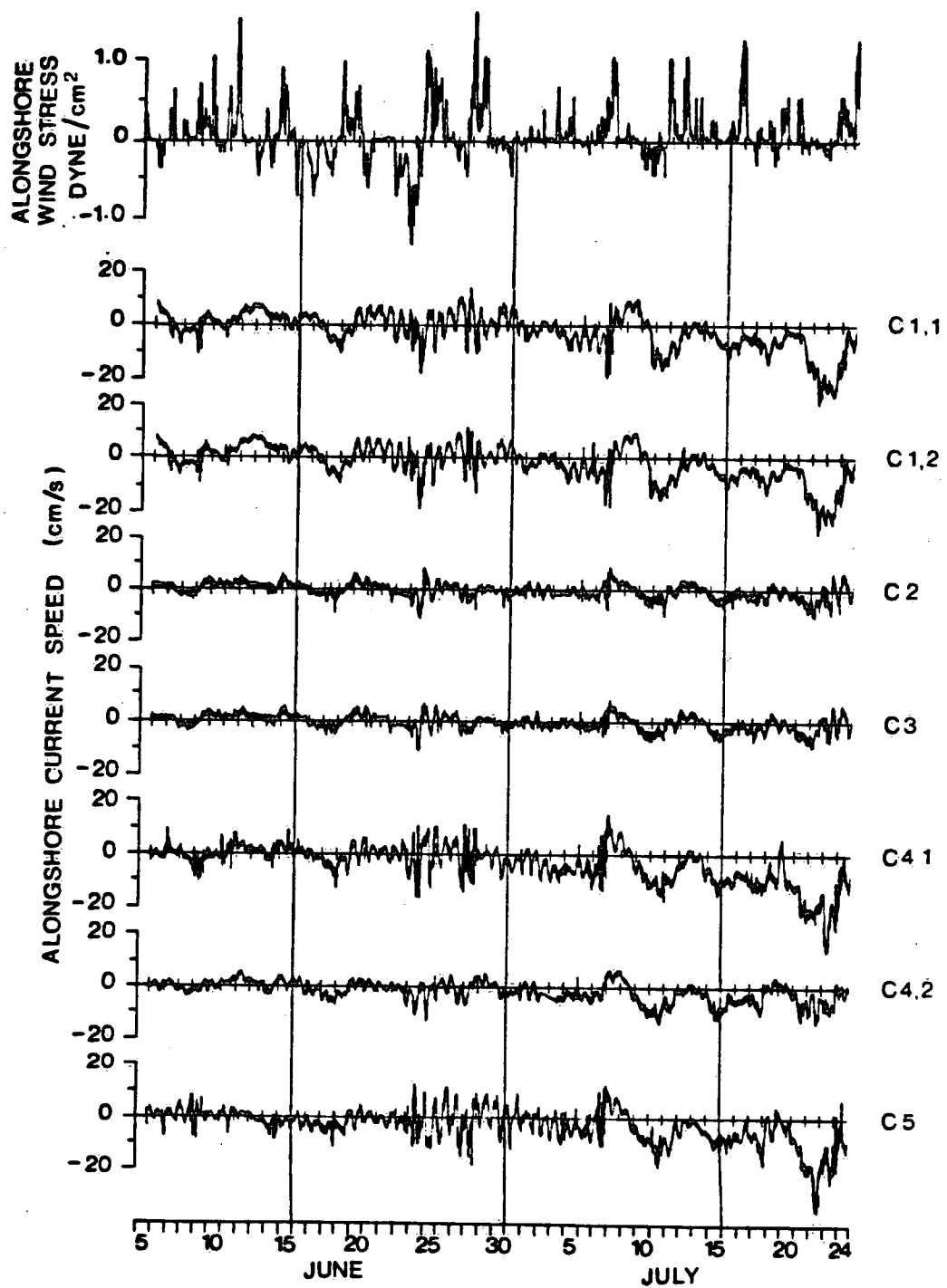


Figure 3 Alongshore components of wind stress and currents observed near Lake Ontario's north shore during 1984. Positive values represent eastward winds and currents.

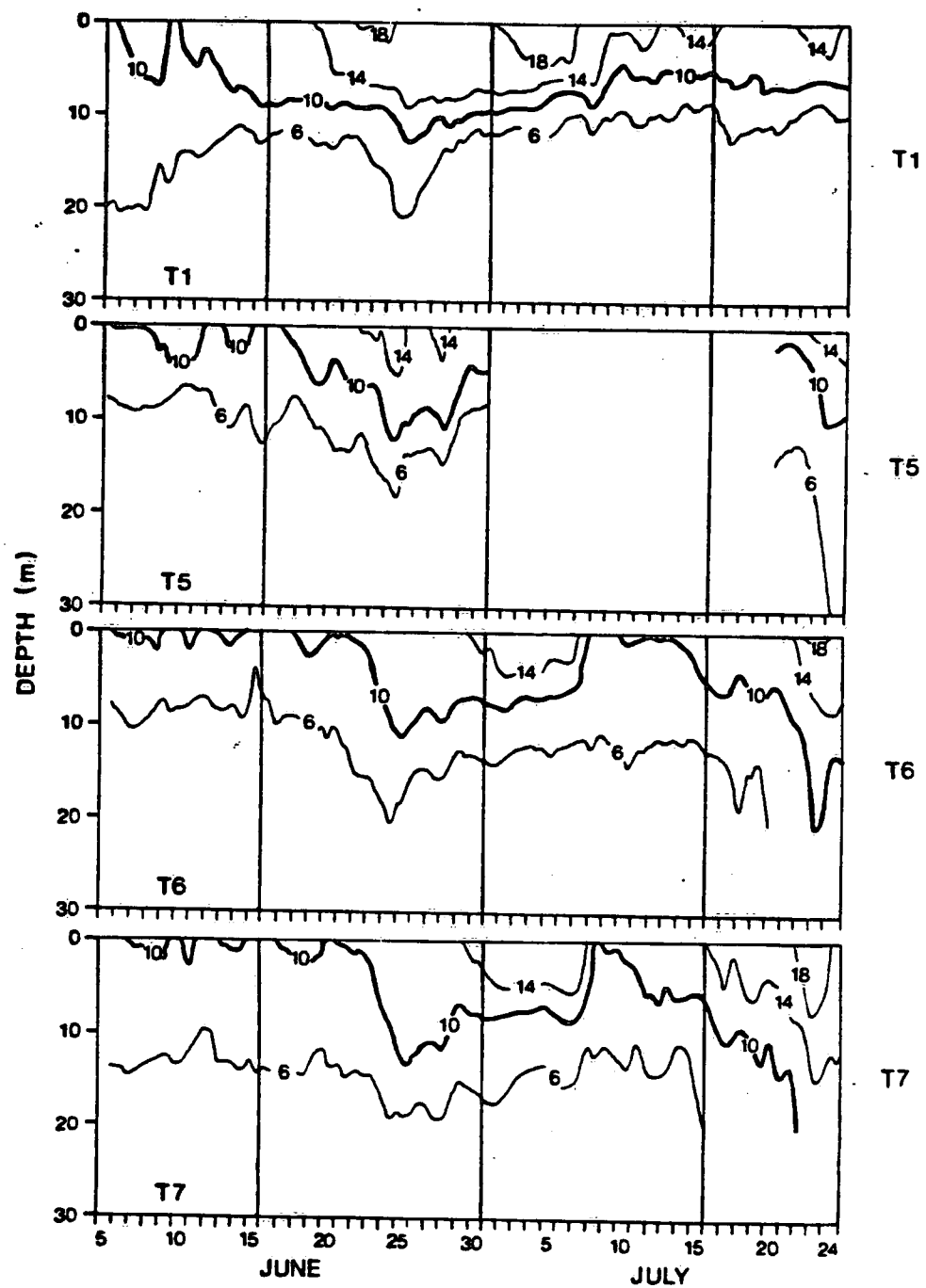
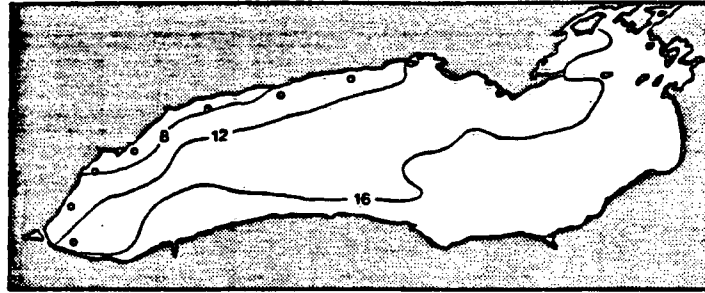
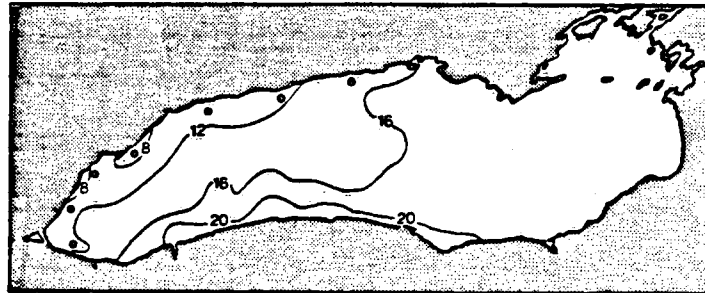


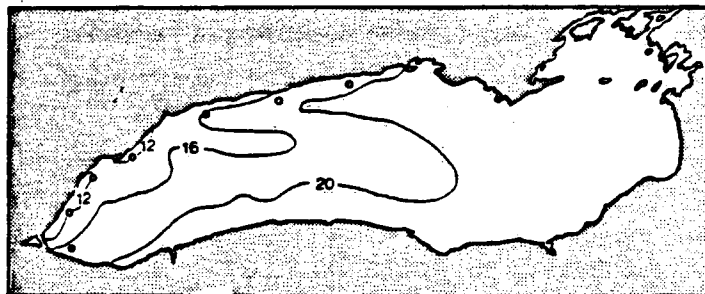
Figure 4 Isotherm depths obtained from fixed temperature profilers along Lake Ontario's north shore during 1984.



JULY 8, 1984 (1230 GMT)



JULY 19, 1984 (0930 GMT)



JULY 24, 1984 (2000 GMT)



JULY 28, 1984 (2100 GMT)

Figure 5 Satellite observations of surface water temperatures in Lake Ontario during 1984.

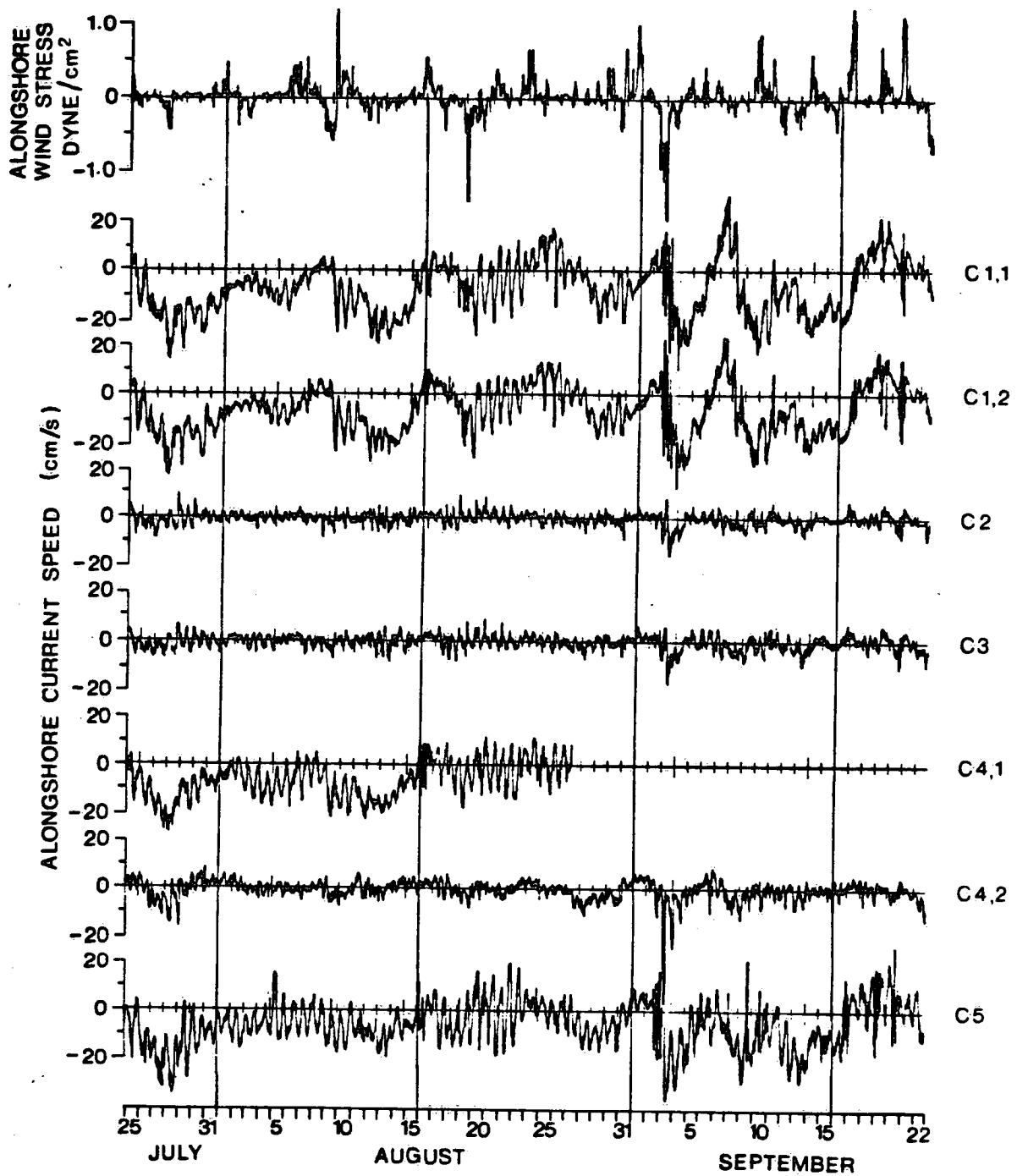


Figure 6 Continuation of Figure 3.

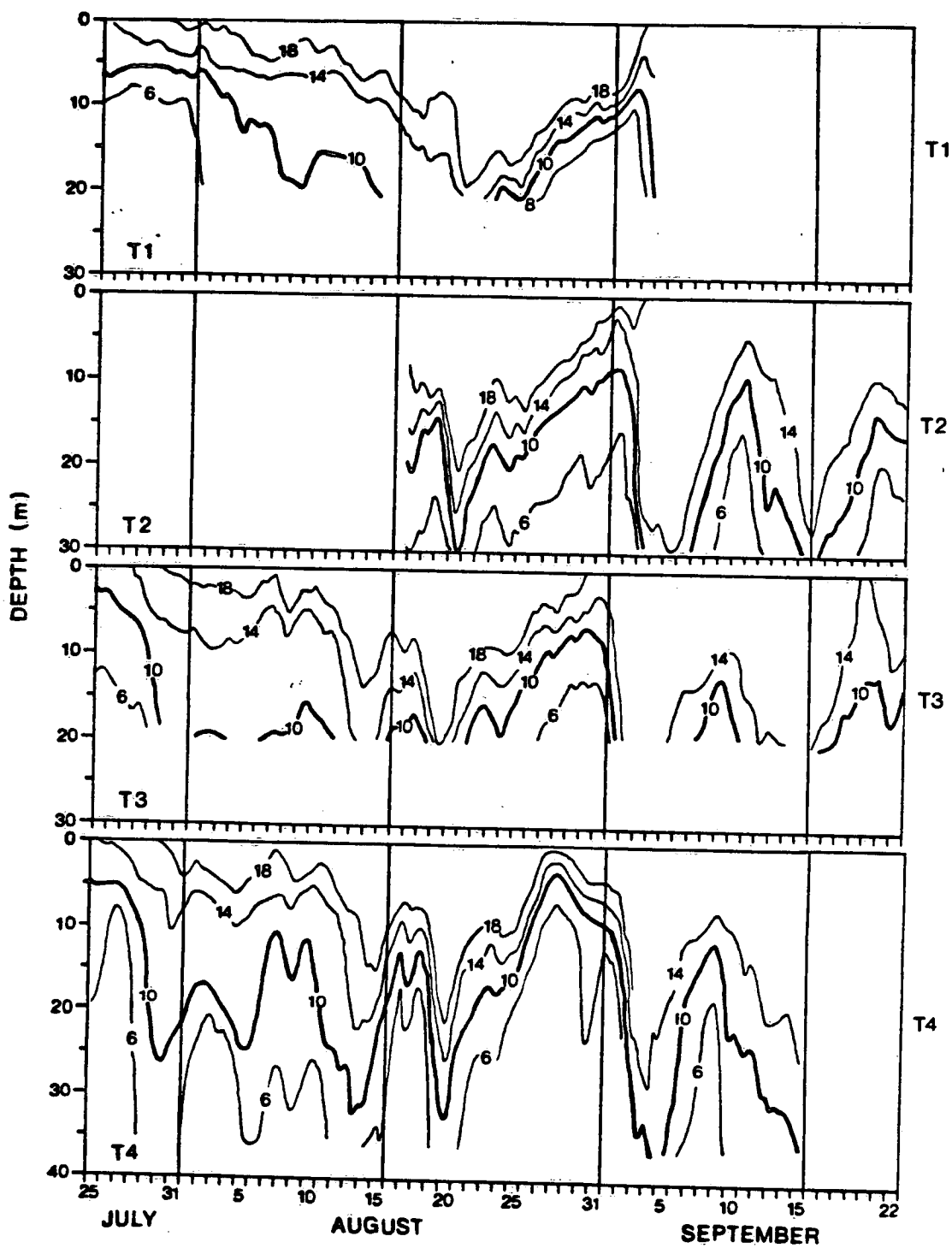


Figure 7 Continuation of Figure 4.

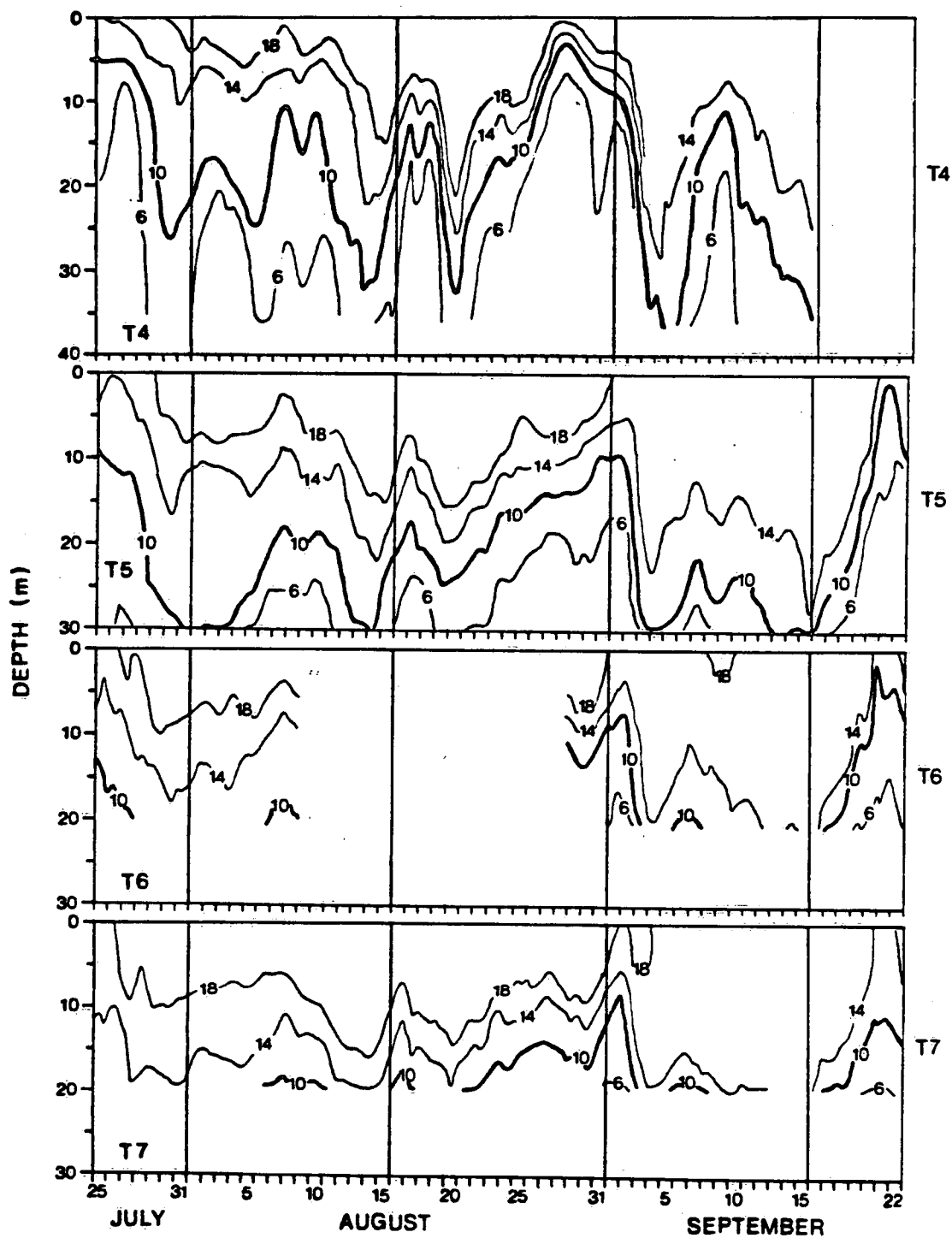
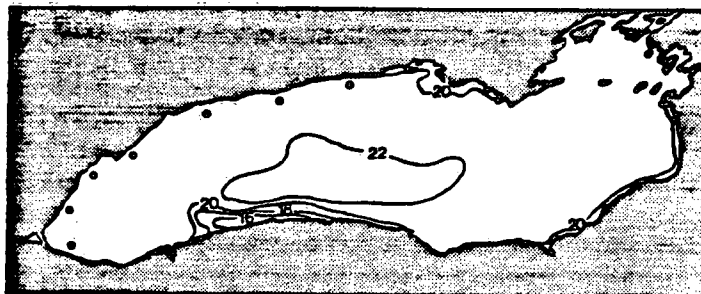


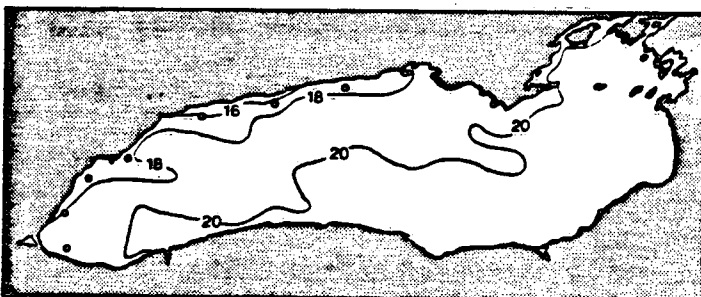
Figure 8 Continuation of Figure 4.



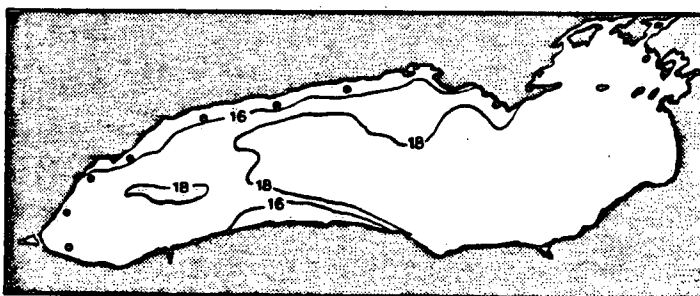
AUGUST 21, 1984 (0930 GMT)



AUGUST 24, 1984 (2030 GMT)



AUGUST 31, 1984 (1230 GMT)



SEPTEMBER 7, 1984 (0930 GMT)

Figure 9 Continuation of Figure 5.

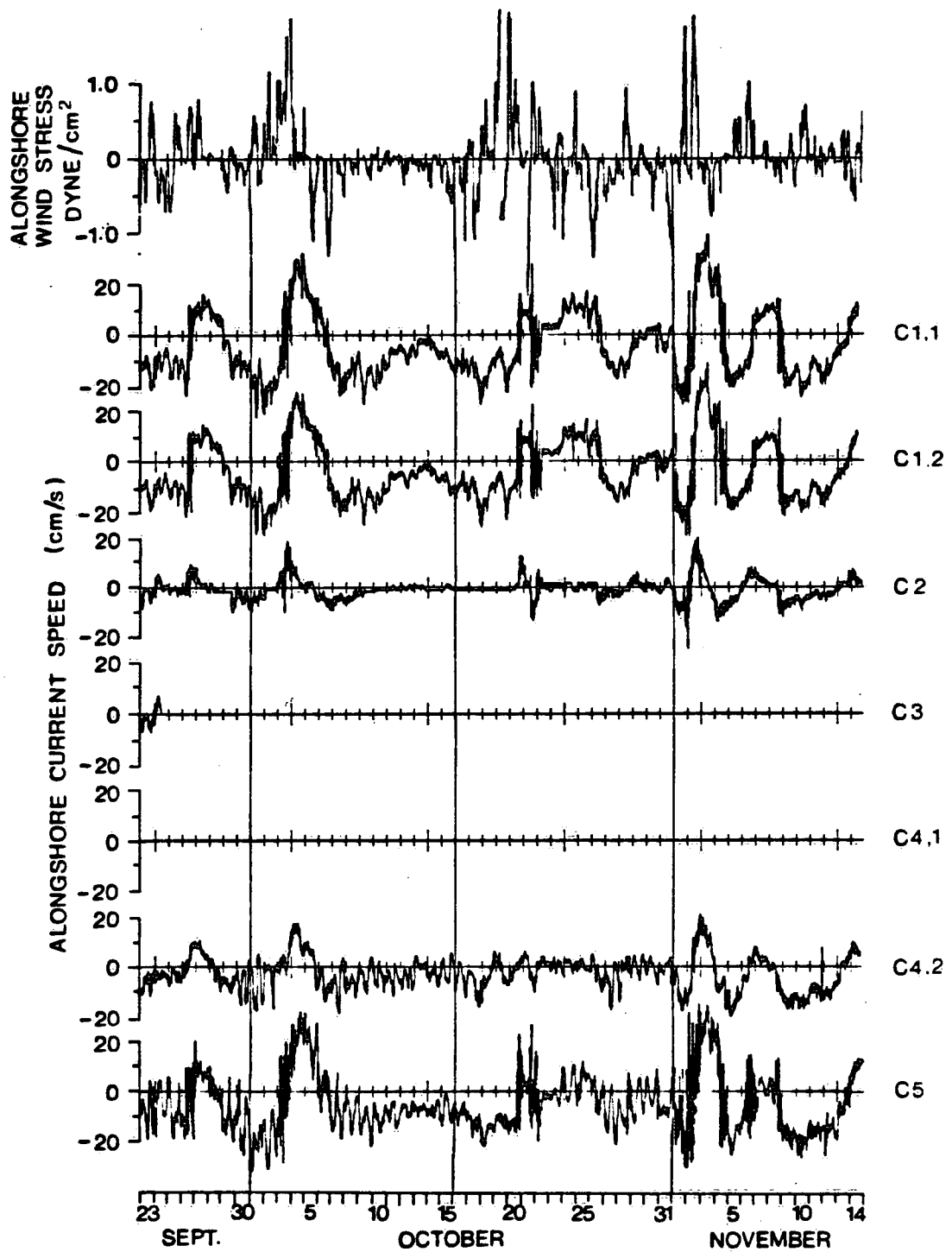


Figure 10 Continuation of Figure 6.

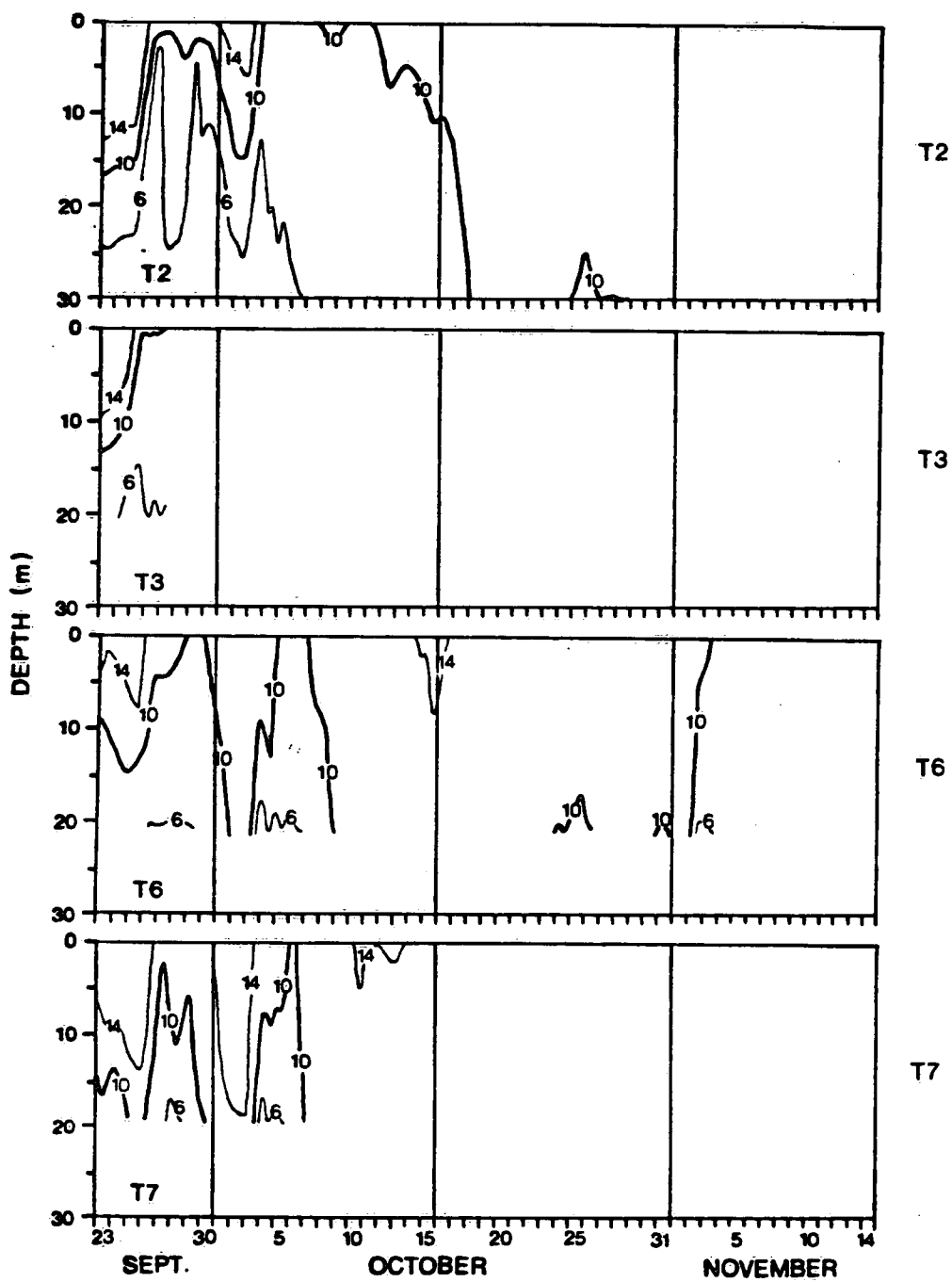
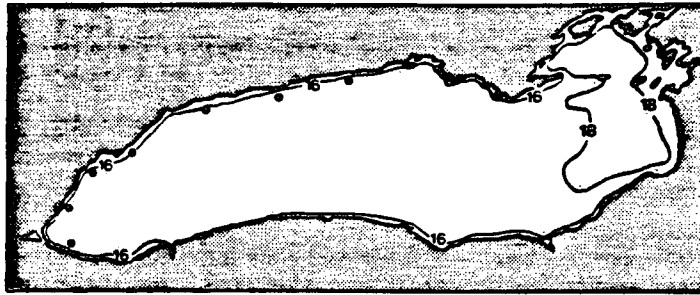
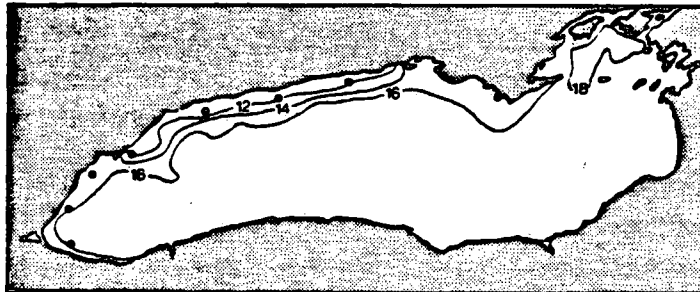


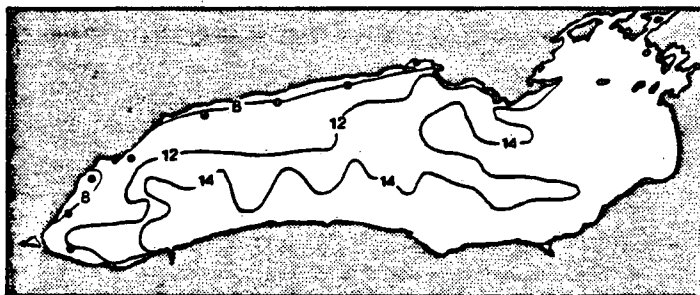
Figure 11 Continuation of Figure 8.



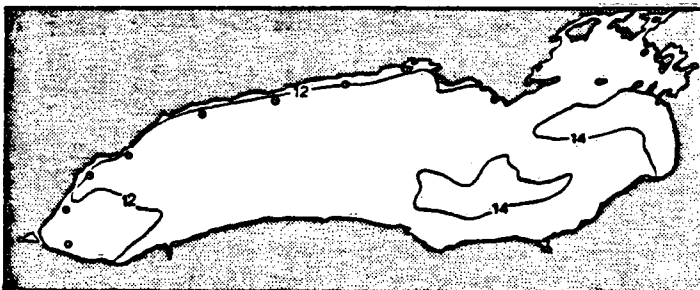
SEPTEMBER 17, 1984 (0900 GMT)



SEPTEMBER 21, 1984 (1230 GMT)



OCTOBER 6, 1984 (1308 GMT)



OCTOBER 29, 1984 (2345 GMT)

Figure 12 Continuation of Figure 9.

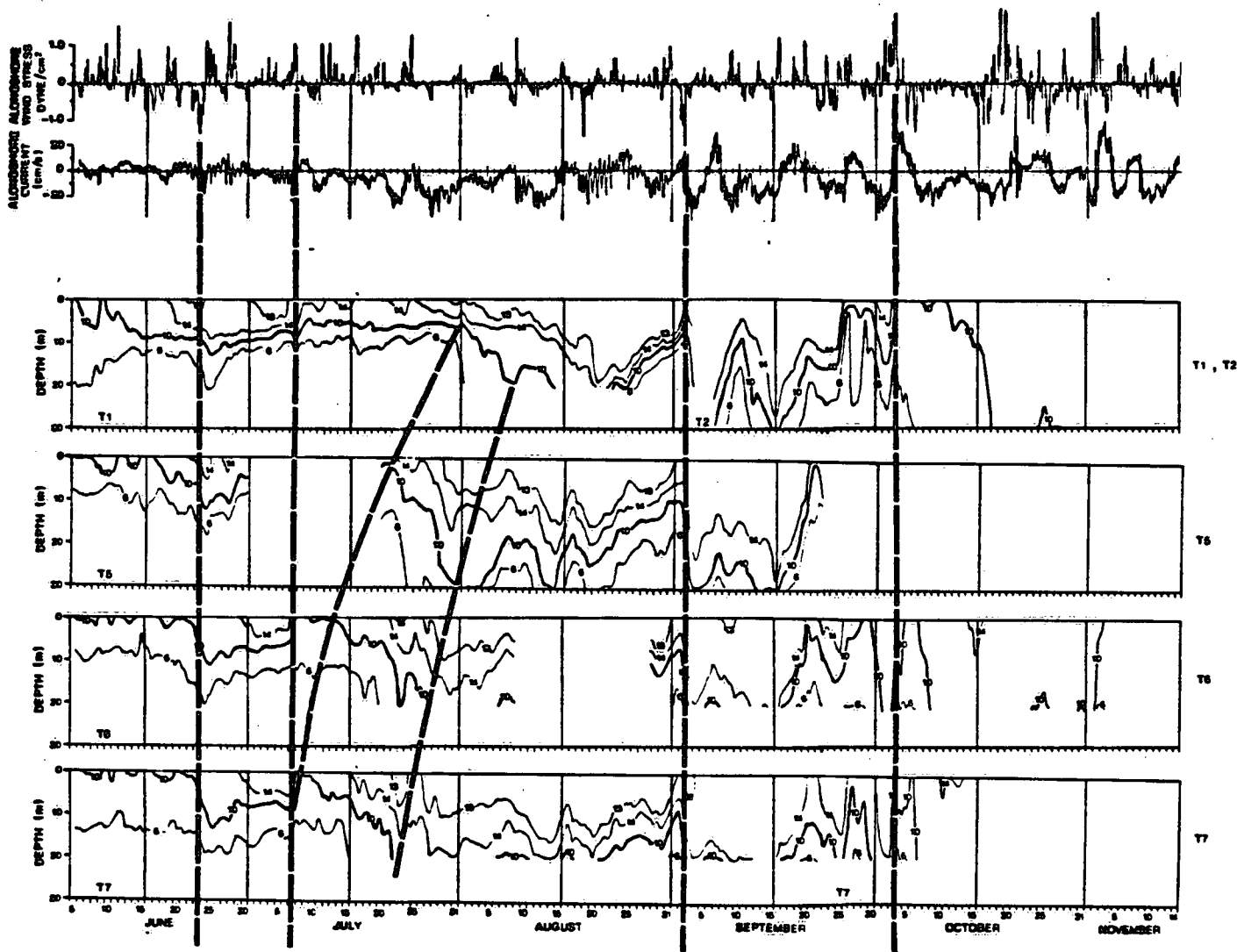


Figure 13 Illustration of response of currents and temperature to wind, Lake Ontario, 1984.

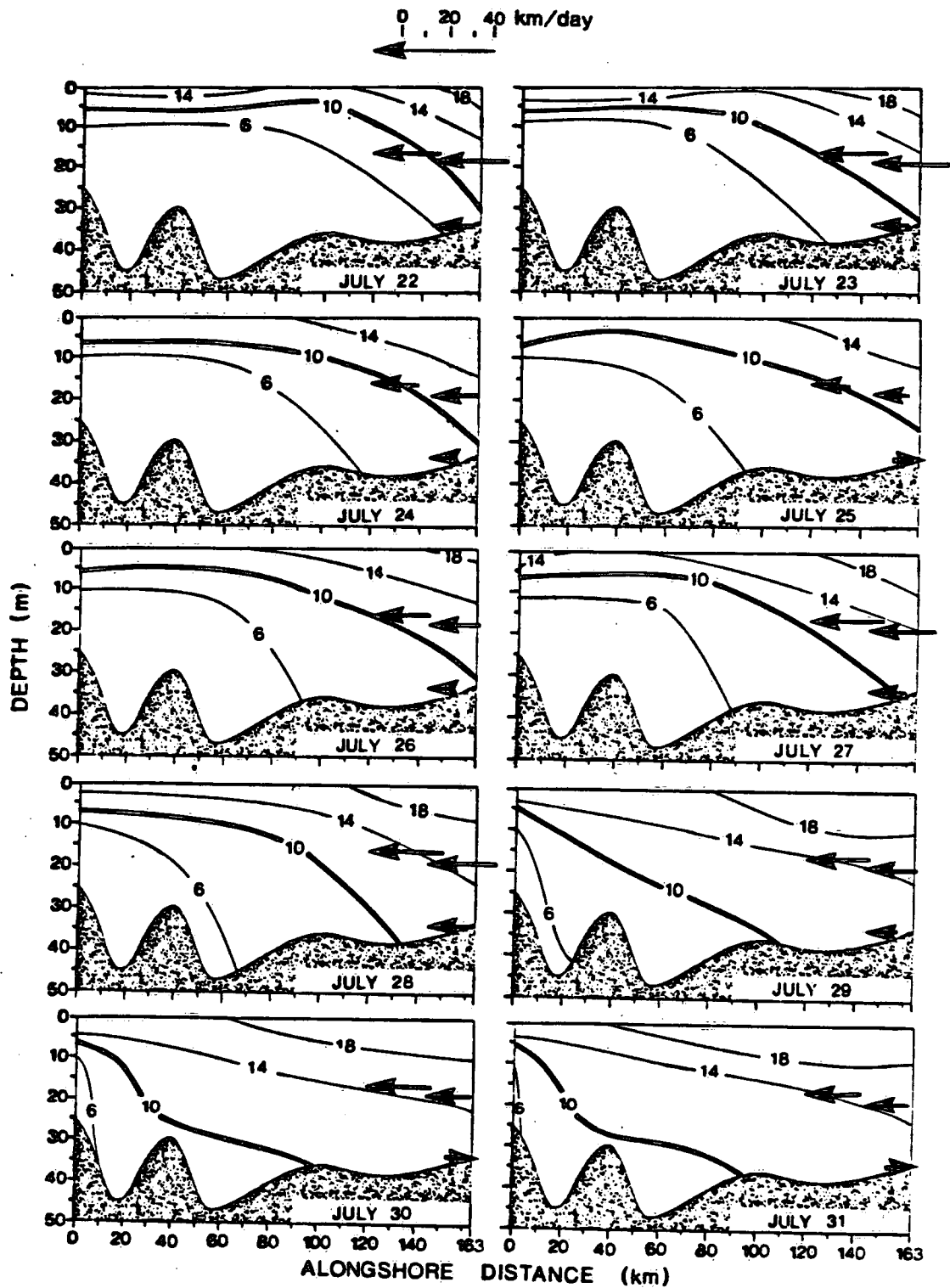


Figure 14 Daily-averaged temperature distributions along northwest shore of Lake Ontario, July 22-31, 1984. Arrows denote daily-mean currents.

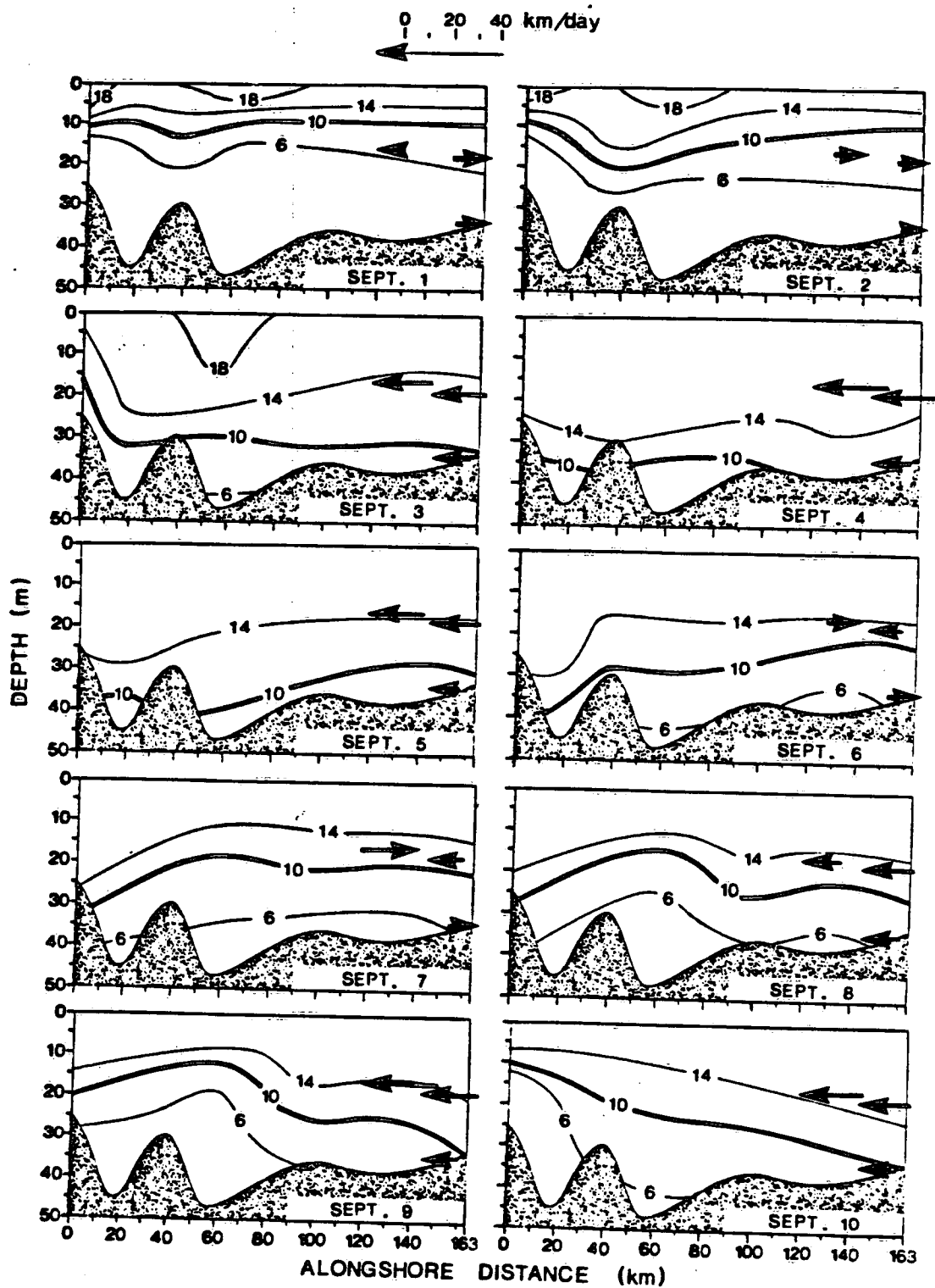


Figure 15 Same as Figure 14 but for September 1-10, 1984.