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Comparative description of the thermal features of
Lake Ladoga and Lake Ontario with particular
reference to nearshore water quality

By:

G. Rodgers, M. Naumenko, C. Murthy

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**COMPARATIVE DESCRIPTION OF THE THERMAL FEATURES OF
LAKE LADOGA AND LAKE ONTARIO WITH PARTICULAR
REFERENCE TO NEARSHORE WATER QUALITY**

G.K. Rodgers¹, M.A. Naumenko² and C.R. Murthy¹

¹ National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario L7R 4A6
Canada

² Institute for Lake Research
Russian Academy of Sciences
St. Petersburg 196199
Russia

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MANAGEMENT PERSPECTIVE

Lakes Ontario and Ladoga are both large deep dimictic lakes of the north temperate zone. A descriptive comparison has permitted an overview of where there are similarities in the physical processes that could allow some economy in the research that might be undertaken in one lake to the benefit of both.

In general terms, the larger scale processes, such as the annual heating cycle and general stratification, are quite similar with the exception of the degree of ice cover and its effects on mixing - Lake Ladoga has a much more extensive ice cover.

Nearshore processes of flow and mixing call for the development of more site-specific coastal limnological climatology, although the general types of features that require elaboration in each area can be established ahead of time.

This work has been carried out as part of the Canada/Russia Cooperative Agreement on Water Quality.

ABSTRACT

Lakes Ladoga and Ontario have comparable depths and areas, and several parallel studies of their thermal characteristics permit useful comparisons. The principal contrasts reflect largely the climate, the shape of the lake, the depth distribution and, to some extent, the hydraulic regime of the lakes. Differences in the central latitude (45°N - Lake Ontario; 61°N - Lake Ladoga) give rise to greater ice cover and a reduced range in heat content change in Lake Ladoga. Both lakes are dimictic, giving rise to vernal thermal fronts (thermal bars) with characteristics that are very similar with respect to the influence of depth changes and thermal stratification. The patterns of upwelling and coastal regimes are affected in a similar fashion.

TABLE OF CONTENTS

	Page
1.0 INTRODUCTION	1
2.0 THE PHYSICAL GEOGRAPHY OF LAKE ONTARIO AND LAKE LADOGA	2
2.1 Geology	2
2.2 Lake Basin Morphometry	2
2.3 Watersheds and Their Hydrological Characteristics	9
2.4 Water Levels	14
2.5 Climate and Ice Cover	15
3.0 LAKE PHYSICS	21
3.1 Seasonal Thermal Regime of Large Lakes	23
3.1.1 Temperature Cross-Sections	29
3.2 Annual Heat Budgets	43
3.3 The Vernal Thermal Front (Thermal Bar)	44
3.4 Autumnal Thermal Front	56
3.5 Coastal Current Regime (Seasonal)	57
3.6 Coastal Upwelling	58
4.0 SUMMARY	64
5.0 ACKNOWLEDGEMENTS	65
6.0 REFERENCES	65

LIST OF TABLES

- Table 1: Morphometric characteristics of Lake Ladoga and its regions**
- Table 2: Dimensions of the Great Lakes**
- Table 3: Dimensions of lakes in the Ladoga Basin**
- Table 4: Water budget of Lake Ontario**
- Table 5: Hydrological characteristics of major river inflows into Lake Ladoga**
- Table 6: Effect of fetch, wind speed, and atmospheric stability on lake/land ratios (Phillips and Irbe, 1978)**
- Table 7: List of surveys in Lake Ladoga**

PLATE AND FIGURES

- Plate 1: Great Lakes of North America thermal infra-red image of the surface temperature for Lake Ontario, the northeast corner of Lake Erie and inland lakes, 22 June, 1978. (NASA AEM-A. LANDSAT-1: Bright white areas denote higher temperatures. Black central areas of Lake Ontario have surface temperatures less than 4°C.)
- Figure 1: Depth and volume distribution for Lake Ontario.
1(a) Hypsometric curve.
1(b) Cumulative volume by depth.
- Figure 2: Bottom topography of Lake Ladoga.
- Figure 3: Bottom topography of Lake Ontario.
- Figure 4: Great Lakes - St. Lawrence River Basin: watershed and elevation profile (from Environment Canada and U.S. Army Corps of Engineers).
- Figure 5: Neva River tributary basin: watershed and elevation profile.
- Figure 6: Long-term average monthly surface water temperature and land air temperature near the shore for Lake Ontario (from Rodgers and Anderson, 1961).
- Figure 7: Seasonal variation of air and dew-point temperature difference (air over land versus air over lake) for Lake Ontario (from Phillips and Irbe, 1978).
- Figure 8: Seasonal variation of the ratio, R_w , of the wind over the lake to the wind over land for Lake Ontario (from Phillips and Irbe, 1978).
- Figure 9: Maximum 1983 ice cover compared to normal maximum ice cover for the Great Lakes (Assel *et al.*, 1985).
- Figure 10: The thermal regime of Lake Ladoga.
- Figure 11: Lake Ladoga air-water temperature differences.
- Figure 12: Average temperature of Lake Ontario (whole lake volume) and the temperature of the upper 10 m during the International Field Year for the Great Lakes (IFYGL) (from Boyce *et al.*, 1977).

- Figure 13: Temperatures in 1959 at the R.C. Harris water treatment plant intake, Toronto (from Rodgers and Anderson, 1963).
- Figure 14: Lake Ladoga showing the location of temperature transects.
- Figure 15: Temperature transects in Lake Ladoga for the ice-free period (April to November).
- Figure 16: Surface temperatures and temperature structure in Lake Ontario through spring and summer, 1959.
- Figure 17: Lake Ontario thermal structure through fall and early winter.
- Figure 18: Lake Ontario thermal structure in winter.
- Figure 19: Weekly averages of energy balance terms (from Pinsak and Rodgers, 1981).
- Figure 20: Surface temperatures - Lake Ladoga at the beginning of June.
- Figure 21: Vertical distribution of temperature, density and Brunt-Väisälä frequency in a transect crossing, and perpendicular to the vernal thermal front (thermal bar) in Lake Ladoga's eastern sector.
- Figure 22: Progressive vector diagram for currents at the 5-m depth as the thermal front passes - N^2 and R_i were calculated for the 4 to 6 m and 5 to 10 m depth layers, respectively.
- Figure 23: The position of the vernal thermal front for dates from May 10 to July 1, for several years, for Lake Ladoga (H is the mean depth at the 4°C surface temperature isotherm).
- Figure 24: The data of disappearance of the 4°C surface temperature isotherm as a function of the late winter temperatures of the deep core of Lake Ontario (from Rodgers, 1987).
- Figure 25: Progressive vector diagram of coastal currents, northshore, Lake Ontario.
- Figure 26: Coastal boundary layer characteristics, northshore, Lake Ontario.
- Figure 27: Coastal upwelling and coastal jet characteristics, northshore, Lake Ontario.
- Figure 28: Coastal upwelling and alongshore counterclockwise propagation of Kelvin waves, northshore, Lake Ontario.

1.0 INTRODUCTION

Over the past four decades there have been major developments in the understanding of the limnology of large lakes of the northern temperate zone. Intensive studies have centred on Lake Ontario in the Great Lakes of North America and in Lake Ladoga in northern Europe. Through various means there has been regular comparisons of the results of physical limnological studies in these two lakes - lakes which are ostensibly similar in size, maximum depth and climate zone.

It is an appropriate time to consolidate our understanding of such lakes through a comparative limnological analysis, as an aid to decision makers in both Canada and Russia and as a preliminary to further investigations that might benefit both countries.

Under the auspices of the Canada-Russia Cooperative Agreement on Water Quality, authors from both countries have collaborated in the development of this report which focusses on the physical processes that affect the movement, transport and mixing of water masses that are found near the shore or injected at the shores of these lakes.

Both of these lakes are subject to anthropogenic stresses as a result of agricultural, industrial and urban development while serving as a water supply for millions of people. Understanding the balance that must be struck between these potentially conflicting beneficial uses will call for good scientific understanding of the natural forces at work in these lakes.

2.0 THE PHYSICAL GEOGRAPHY OF LAKE ONTARIO AND LAKE LADOGA

2.1 Geology

Lake Ladoga is the largest lake in Europe, situated at the periphery of the Baltic Crystalline Shield and centred about 61°N latitude and 31°E longitude. Lake Ontario is the smallest of the Great Lakes downstream of the much larger Lakes Erie, Huron, Michigan and Superior. It is centred on 43°31'N and 78°E and its complete basin is situated in palaeozoic rock just south of the Precambrian Shield. The outlet control of Lake Ontario in the St. Lawrence River is a ridge of undifferentiated metamorphic rock of the Precambrian about 74 to 75 m above sea level. The outlet of Lake Ladoga is the Neva River which lies in sedimentary rock at an elevation only just above sea level.

Both basins were subject to major glaciation that receded about 10,000 to 12,000 years B.P. The direction of glacial movement and the hardness of the underlying bedrock and soils resulted in markedly different topography and orientation for these two lake basins.

2.2 Lake Basin Morphometry

Lake Ontario is, for the largest portion, ellipsoidal in shape with a central deep and a slight sill (160 m deep) about mid-lake separating a 185 m deep basin to the west from a 244 m deep basin to the east. The axis of the lake is nearly east-west and the ratio of length to width is about 9:2. The outlet basin of the lake in the north-east is a 20 to 30 m deep shelf area with several large and small islands. The major embayments (at the level of Lake Ontario) are Hamilton Harbour at the west end, Toronto Harbour and Presquid Bay on the north shore

and the Bay of Quinte that drains into the north side of the outlet basin. Sodus Bay is another on the south shore. Altogether these embayments constitute a very small percentage of the area of the lake.

The major axis of Lake Ladoga is the lake along a line about 25 degrees west of north with the ratio of the long to short axes of 7:4. Bottom relief in the northern part of the lake is more complicated than the south due to the underlying geological structure. In this northern area there are both deeps (including the deepest location in the whole lake) and shallows. Ninety percent of the 500 islands in the lake are found in the north. In the southern part of the lake, the bottom is gently sloping with depths typically between 10 and 50 m.

The bottom of Lake Ladoga has been classified according to the hypsometric curve, the depth histogram, and volume. It was divided into six regions and named (Table 1) as follows:

- 1 - nearshore shallow region
- 2 - transitional region
- 3 - shelf region
- 4 - slope region
- 5 - deep water region
- 6 - deeps

Bottom relief in lakes affects the distribution of bottom sediments, the distribution of bottom organisms, horizontal temperature differences and circulation within the lake.

Nearshore shallow areas are particularly vulnerable to the effects of wastewater discharges and industrial, agriculture or urban development. Closed embayments such as Hamilton Harbour or the Bay of Quinte on Lake Ontario or

the fjord-like bays near Sortavala, Taskela and Pitaranta in Lake Ladoga, are particularly vulnerable. Open embayments where there can be active exchange with the open waters of the main body of the lake are less vulnerable. Examples include the Volkhov and Soir Bays, Petrokrepost Bay and the Priozersk areas of Lake Ladoga, or the Rochester embayment on the south shore of Lake Ontario.

TABLE 1: Morphometric characteristics of Lake Ladoga and its regions

Region	Depth Range m	Volume km ³	%	Area km ²	%	Mean Depth m
1	0 - 18	46.6	5.6	5572	31.2	8.4
2	18 - 50	153.2	18.3	4675	26.1	32.8
3	50 - 70	224.1	26.8	3810	21.3	58.8
4	70 - 100	145.3	17.3	1751	9.8	83.0
5	100 - 140	177.7	21.2	1513	8.5	117.4
6	>140	90.5	10.8	560	3.1	161.6
Whole Lake	0 - 230	837.5	100	17,891	100	46.9

The nearshore shallow region occupies approximately one-third of the area of Lake Ladoga and 5.6% of the volume. It is particularly vulnerable to water quality problems, especially where industrial or agricultural discharges into the lake do not undergo rapid dilution.

Comparable figures for Lake Ontario (i.e., for depths less than 18 m) are 14% of the area and 18.5% of the volume with an average depth of 9 m. The contrast between these two lakes is most marked in this regard (see Figure 1).

Differences in depth and exposure to the open lake must both be taken into account when analyzing the processes affecting anthropogenic eutrophication or the impact of toxic chemicals in wastewater discharges or in river inputs.

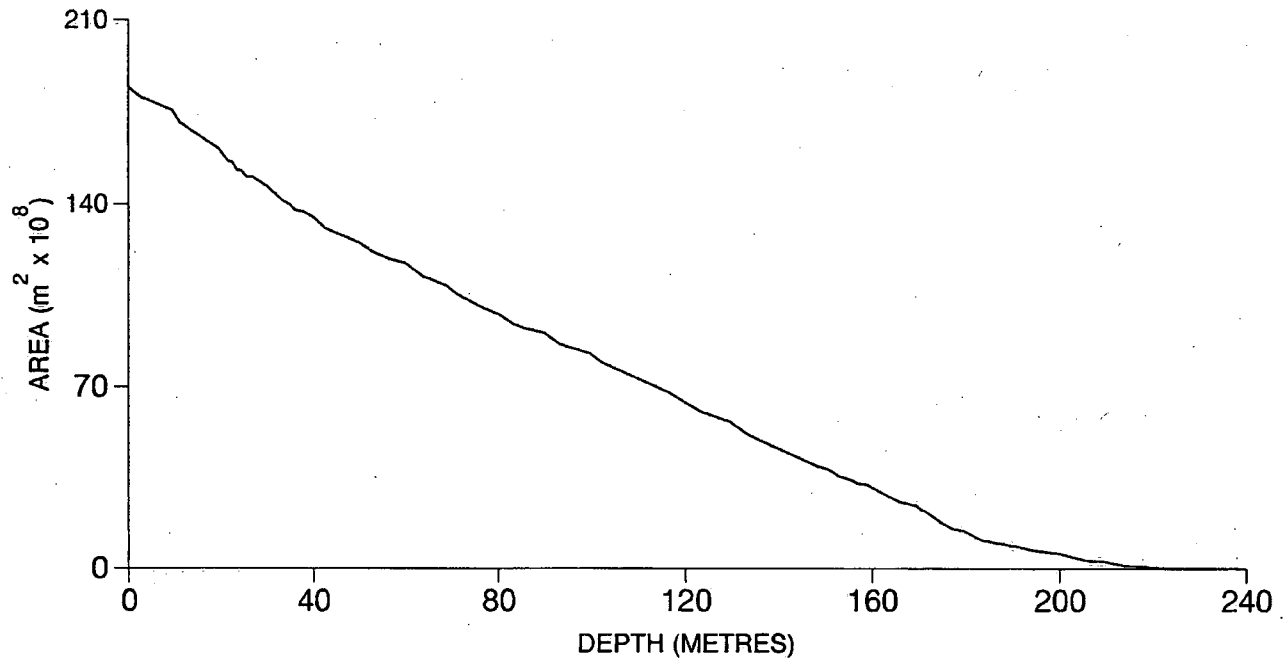


Figure 1a Hypsometric Curve

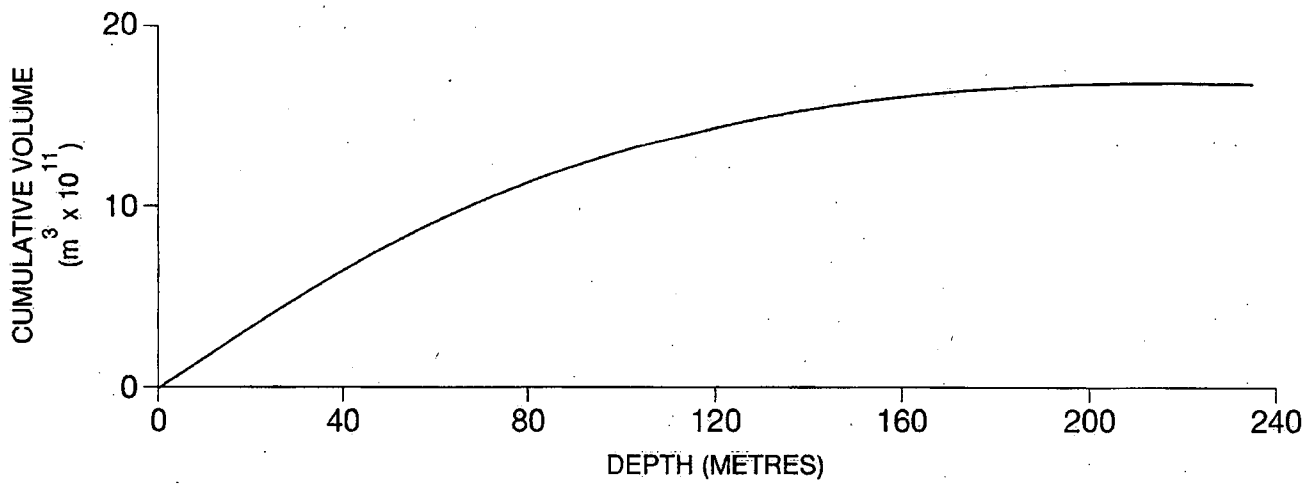


Figure 1b Cumulative Volume by Depth

Figure 1 Depth and Volume Distributions for Lake Ontario

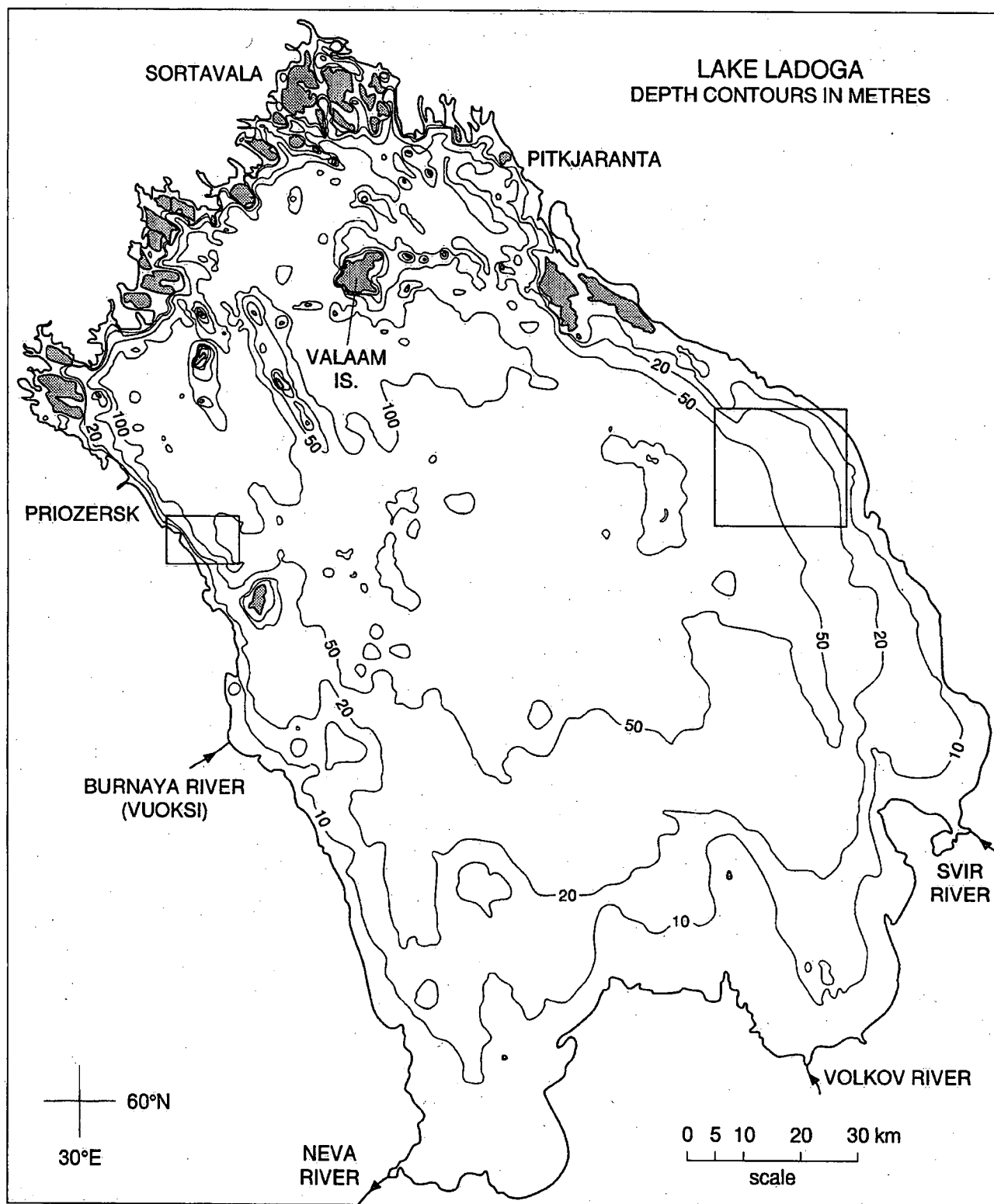


Figure 2 Bottom Topography of Lake Ladoga

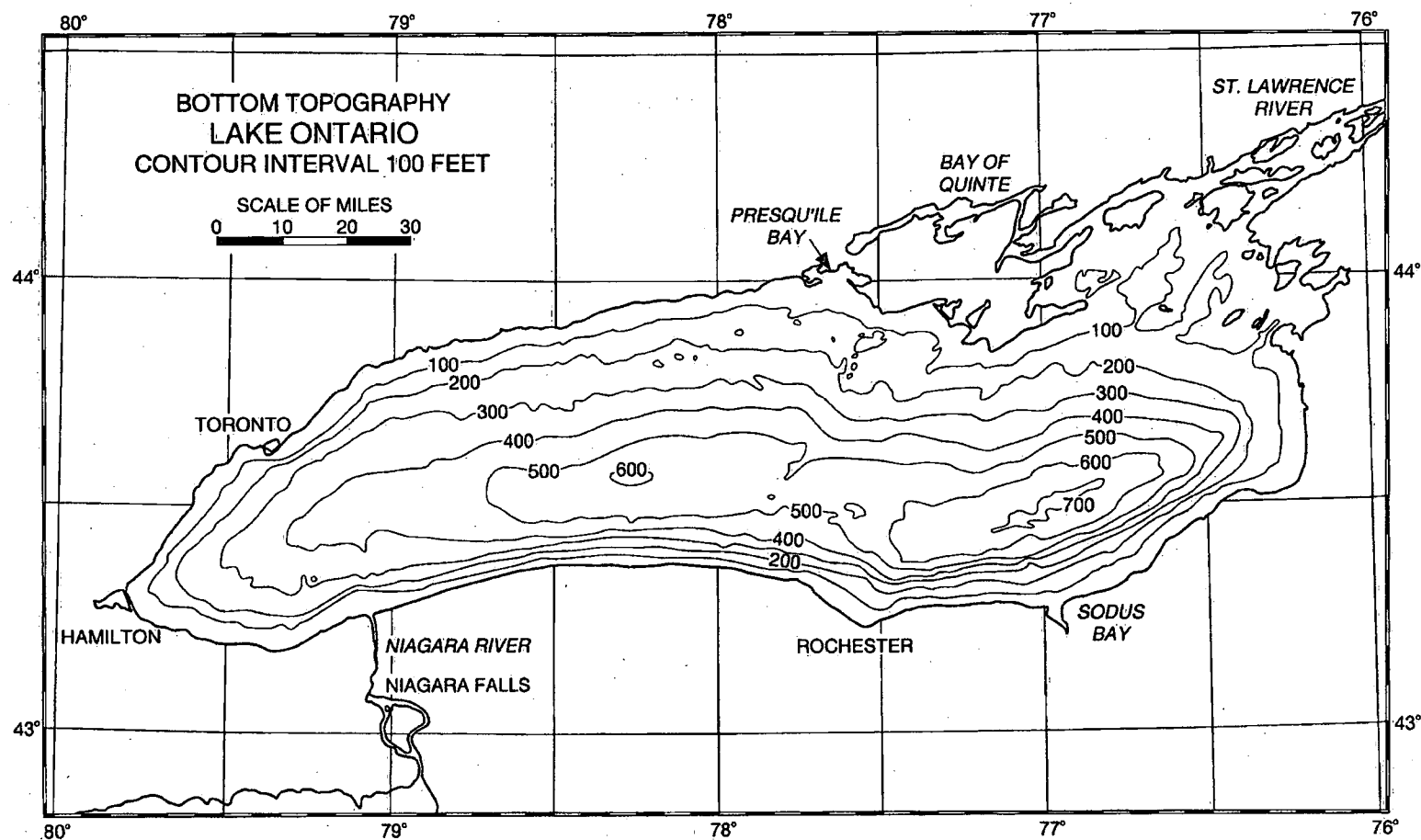


Figure 3 Bottom Topography of Lake Ontario

Details of the water depths can be found in Figures 2 and 3, and a summary of hydrometric data is in Tables 2 and 3.

TABLE 2: Dimensions of the Great Lakes

	Area Mi ² (Km ²)	Volume Mi ³ (Km ³)	<u>Shoreline Length</u>		<u>Water Depth</u>	
			Mainland Miles (Km)	Island Miles (Km)	Average Feet (Metres)	Maximum Feet (Metres)
Lake Superior	31,700 (82,100)	2,900 (12,100)	1,730 (2,780)	997 (1,600)	483 (147)	1,330 (405)
St. Marys River	(230)	89	(153)	95 (244)	152	
Lake Michigan	22,300 (57,800)	1,180 (4,920)	1,400 (2,250)	238 (383)	279 (85)	923 (281)
Lake Huron	23,000 (59,600)	850 (3,540)	1,850 (2,970)	1,980 (3,180)	195 (59)	750 (229)
St. Clair River	21 (55)		58 (93)	5 (8)		
Lake St. Clair	430 (1,110)		130 (210)	127 (204)		21 (6)
Detroit River	39 (100)		60 (96)	72 (116)		
Lake Erie	9,910 (25,700)	116 (484)	799 (1,290)	72 (116)	62 (19)	210 (64)
Niagara River	23 (60)		69 (110)	37 (60)		
Lake Ontario	7,340 (19,000)	393 (1,640)	634 (1,020)	78 (125)	283 (87)	802 (244)

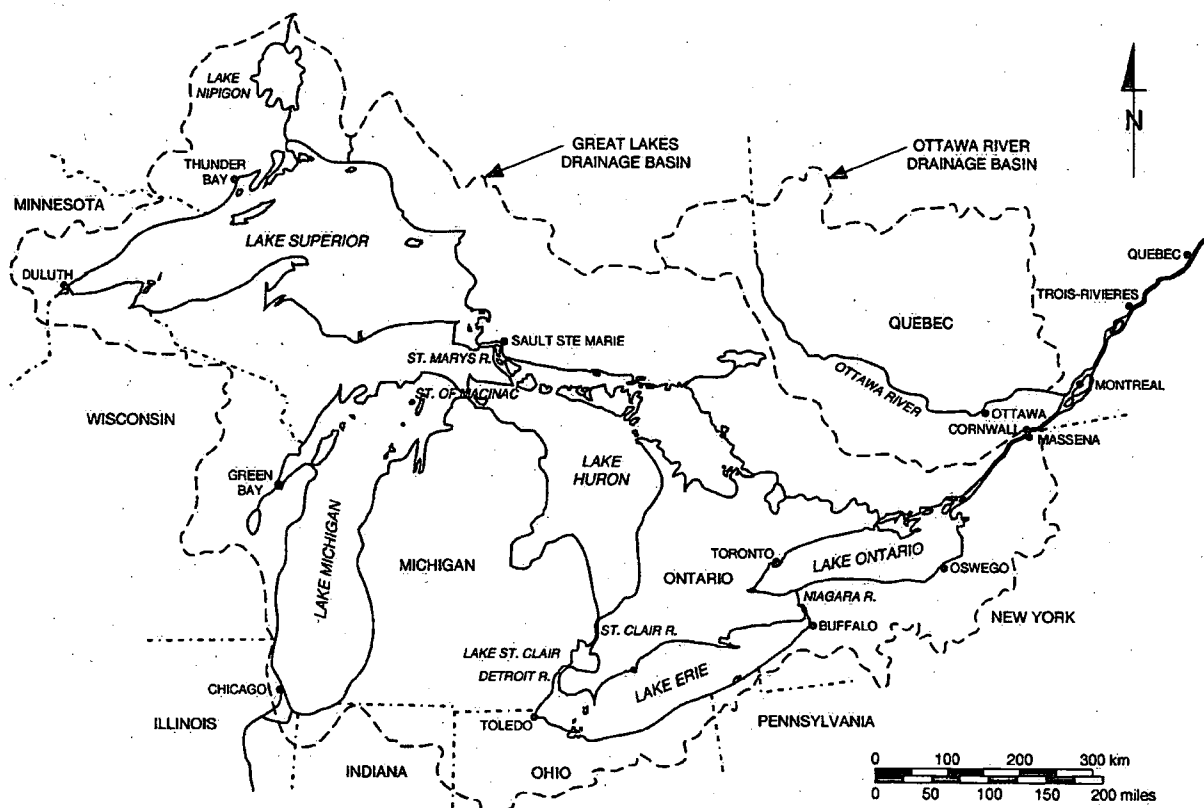
TABLE 3: Dimensions of lakes in the Ladoga Basin

	<u>Area</u> Mi ² (Km ²)	<u>Volume</u> Mi ³ (Km ³)	<u>Water Depth</u>	
			<u>Average</u> Feet (Metres)	<u>Maximum</u> Feet (Metres)
Lake Ladoga	6,800 (17,700)	200 (837)	154 (47)	755 (230)
Onega Lake	3,700 (9,690)	70 (291)	99 (30)	394 (120)
Saimaa Lake	1,700 (4,380)	15 (61)	46 (14)	269 (182)
Ilmen Lake	460 (1,200)	1 (3.5)	6.6 (2)	36 (11)

2.3 Watersheds and Their Hydrological Characteristics

Lake Ontario is in the downstream end of the chain of large lakes that form the Great Lakes of North America. Consequently the water exiting Lake Ontario is derived from the complete basin of the system. This area, including lake surfaces, is 765,990 km² (see Figure 4). Thirty-two percent of this area is open lake water. Since annual average evaporation from the lake surfaces approximately equals the precipitation falling on their surfaces, the yield for flow through the lakes, on an annual basis, is the runoff from the land surface.

The approximate water balance of Lake Ontario is dominated, therefore, by the outflow from Lake Erie through the Niagara River which constitutes about 80% of the total inflow. Table 4 provides the annual average water budget for Lake Ontario.



LAKE SURFACE ELEVATIONS AT CHART DATUM
(INTERNATIONAL GREAT LAKES DATUM, 1995)

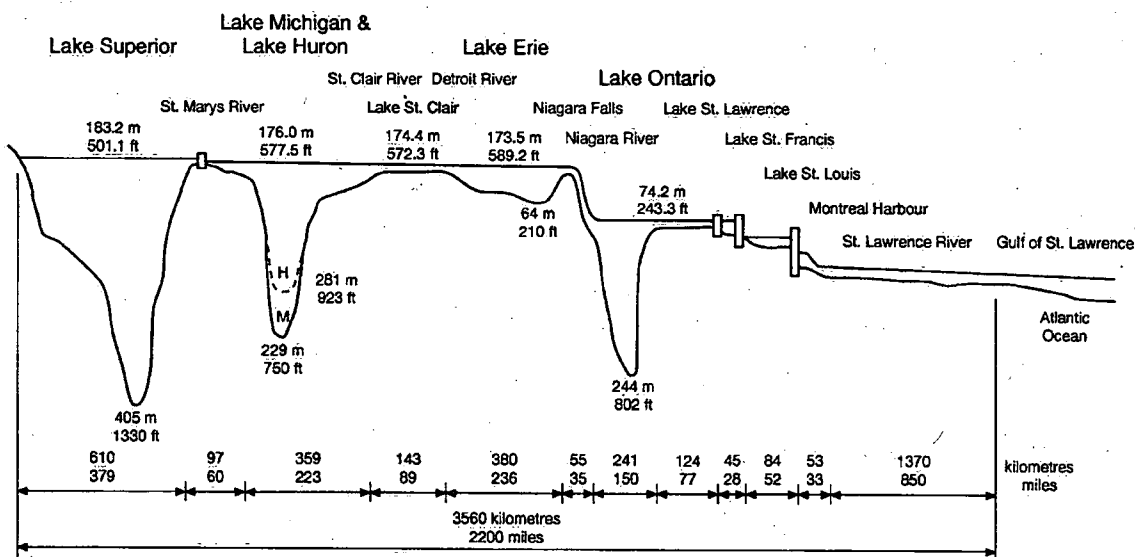


Figure 4 Great Lakes - St. Lawrence River Basin: Watershed And Elevation Profile (from Environment Canada and the U.S. Army Corps of Engineers)

TABLE 4: Water budget of Lake Ontario

<u>GAIN</u>	Niagara River	5,800 m ³ /sec from Lake Erie
	Welland River	200 m ³ /sec from Lake Erie
	Runoff to lake from its own watershed	900 m ³ /sec
	Precipitation on to lake surface	500 m ³ /sec
<u>LOSS</u>	Evaporation from lake surface	400 m ³ /sec
	St. Lawrence River outflow	7,100 m ³ /sec

The watershed of Lake Ladoga is 258,000 km² located in both Russia and Finland. The four secondary watersheds within this system are as follows:

Lake Ladoga itself:	28,400 km ²
Lake Onega and Svir River:	83,200 km ²
Lake Ilmen and Volkhov River:	80,200 km ²
Lake Saimaa and Vuoksi River:	66,700 km ²

(see Figure 5)

River discharge (96%) and atmospheric precipitation (14%) are the principal inflow components of the water balance. The outflow consists of the discharge into the Neva River (92%) and evaporation (8%). The largest rivers draining to Lake Ladoga are the Vuoksi, the Svir, the Volkhov, the Syas, the Pasha, the Oyat, and the Olonka. The first three of these rivers provide 86% of total inflow to the lake (see Table 5 and Figure 5).

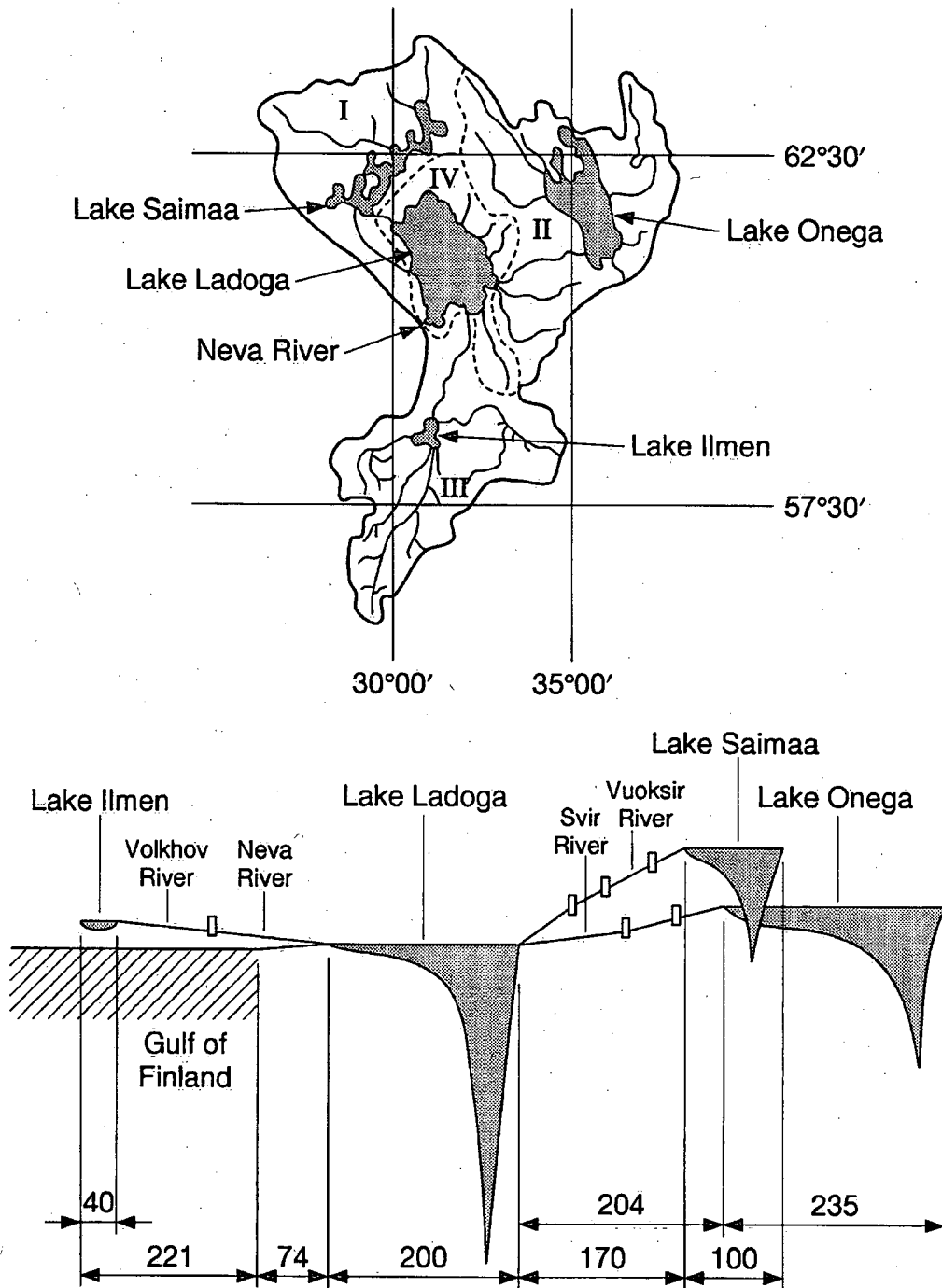


Figure 5 The Neva River Tributary Basin: Watershed and elevation profile (distances in km)

TABLE 5: Hydrological characteristics of major river inflows into Lake Ladoga

	Annual Total Input km ³	Mean Annual Input Rate m ³ /sec	Maximum Turbidity g/m ³	Electrical Conductivity μs/cm
Svir	20.2	756	12	50
Volkhov	15.8	475	18	100-150 - 230
Burnay (Vuoksi)	19.2	608	5	60
Neva River (outflow)	75.5	2400		

In Lake Ladoga the maximum inflow occurs in May or June. In Lake Ontario the maximum inflow is also in May or June when Lake Erie water levels (and hence Niagara River flows) are typically at their highest and evaporation from the surface of Lake Ontario is nearly zero (Bruce and Rodgers, 1962).

In both lakes, the outflow comprises a small fraction of the total volume of the lake. In the case of Lake Ladoga, the coefficient of water exchange is 0.088 giving an overall lake residence time of approximately 12 years. For Lake Ontario, the coefficient of water exchange is 0.133 and the overall residence time is 7.5 years. The latter figures contrast with the residence times for Lakes Erie (2.5 years) and Superior (165 years) in the Great Lake system.

These average flushing times are indicative of the time response of these lakes to discharge into the lakes of conservative pollutants such as salts. The response of these lakes to climatic variations in such things as runoff volume will be damped by the longer periods of flushing time.

The mean annual flushing rates, while being indicative of the overall time response of the lake to inputs, is just an average. One cannot necessarily apply this figure to individual discharges to a lake. For example, a discharge that is

close to the outflow channel may be carried in lake currents directly to the outflow without the discharge being mixed significantly throughout the lake. Each individual discharge or river influent has to be assessed based on its site-specific situation. See Chapter 3 for some of the flow characteristics that can affect this process.

2.4 Water Levels

Water level variations in both Lakes Ontario and Ladoga are only partly natural because of artificial water level and flow regulation. Dams designed for power production upstream of Lake Ladoga reduce the natural annual variation of river flow and hence the range of water levels in the lake. In the case of Lake Ontario, the principal regulation structure is downstream of the lake and the lake level and (consequently) St. Lawrence River flows are regulated to optimize navigational needs and power production (priority given to navigation) while making best efforts to avoid flooding of key areas downstream at the same time as mitigating erosion on Lake Ontario shorelines. Since this regulatory regime came into effect in 1960, the low levels have been slightly higher than natural levels would have been in drought periods, and high levels have been reduced from what would have been naturally high water levels by significant amounts of the order of 0.5 m.

Average annual or seasonal water level variation in Lake Ladoga is 0.7 m, and in Lake Ontario is 0.5 m. In both lakes the highest level occurs in June. The lowest levels (monthly means) are found in December in Lake Ontario and in January in Lake Ladoga. These are typical annual cycles. But it should be kept in mind that the range of extremes can be much larger. For example, in Lake Ontario in over 80 years of historical records, the maximum mean monthly level (1975) exceeds the minimum mean monthly value (1934) by 1.4 m. This indicates

the presence of major variations in the flushing characteristics of a single lake - a climatic effect that may not be economically feasible to eliminate with dams, control structures or channelization.

Instantaneous water levels can have an even larger range due to seiches and surface wave radiation during high wind storms. This situation has major implications for shore protection and avoidance of short-term flooding and erosion.

2.5 Climate and Ice Cover

Lake Ladoga is situated in a moderate climatic zone. The climate is affected by the interaction of the warm Atlantic Ocean air mass and cold air from the Arctic.

The mean annual net solar radiation for Lake Ladoga equals 39 kilocalories/cm² (1.63×10^9 J/m²). The difference between the northern part and the southern is about 18%. About 67% of the total annual input of solar radiation occurs during the most intensive heating period from May to August, with a maximum in June for the whole lake and a maximum in May for the southern part.

The annual amplitude of solar radiation is 14 to 15×10^3 cal cm⁻².

Mean monthly cloudiness varies from month-to-month in the range of 0.4 to 0.9. Minimum cloudiness is in June and July. It should be noted that in the ice-free period, cloudiness is less in the central part compared to near-shore regions. For Lake Ladoga, annual sunshine duration is approximately 1620 to 1720 hours. Up to 64% of this sunshine occurs during four months (May to August).

Lake Ontario is set in a primarily continental climate zone. But, being further south, being itself a deep lake with a large heat capacity, and being in a part of the continent where there are other large deep lakes, the climate is markedly moderated. This is partly reflected in the air temperature and water temperature regime shown in Figure 6. A plot comparable to that for Lake Ladoga (Figures 10 and 11), has been drawn up based on data collected from ships and buoys. During the International Field Year for the Great Lakes (IFYGL) greater detail was obtained (see Figure 12 and Phillips and Irbe, 1978). The mean annual air temperature as an average over the whole lake was 3.2°C for the period from 1961 to 1987. Mean differences between water temperature and air temperature indicate the direction of heat exchange through the surface for the free-ice period (Figure 7). From May to August the water gets most of its heat from the atmosphere but the heat content at any particular point in the lake depends on the depth distribution and the position of the thermal bar (see Section 3.3).

Perhaps more significant for the analysis of specific is the situation incidents where one might have to take into account wind speed, wind fetch and air mass stability over the lakes. For example, the ratio of wind speed over water to wind over land (monthly trends) is shown for Lake Ontario in Figure 8. Wind speeds over these lakes are comparable. But as one combines these fetch, wind strength and stability factors, one finds weaker winds in the northern area of Lake Ladoga where large areas are shielded by offshore islands. And there are large differences in wind regimes of both lakes when large differences in surface water temperature exist such as during the period of the spring thermal front (thermal bar) or during major upwellings along upwind shores. The characteristics of the air masses over Lake Ontario for these different effects have been described for the IFYGL (1972 to 1973) (see Table 6). Estimates of evaporation, sensible heat exchange and wind stress upon the lake surface are dependent on these conditions.

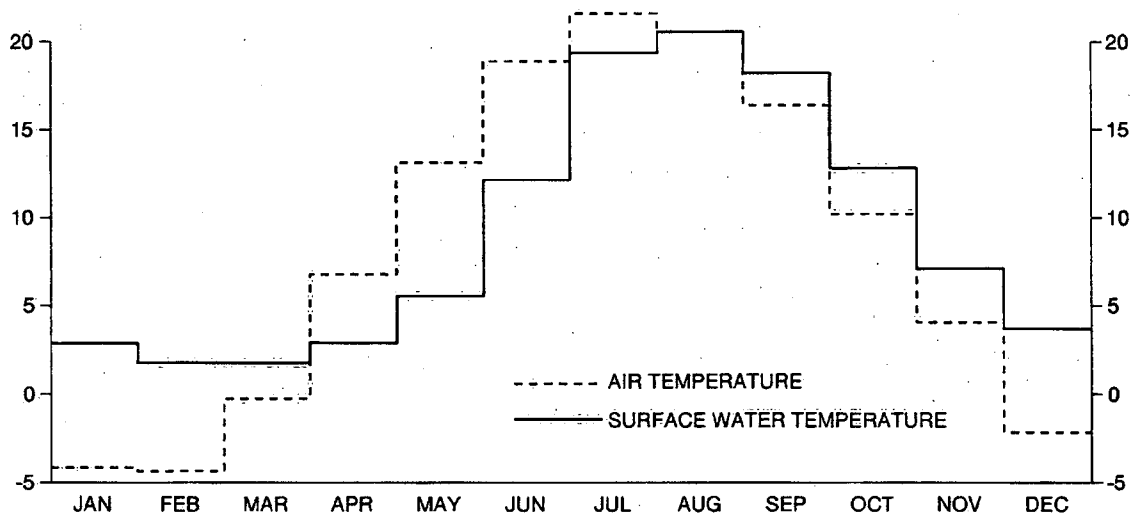


Figure 6 Long-term average monthly surface water temperature and land air temperature near the shore for Lake Ontario. (from Rodgers and Anderson, 1961)

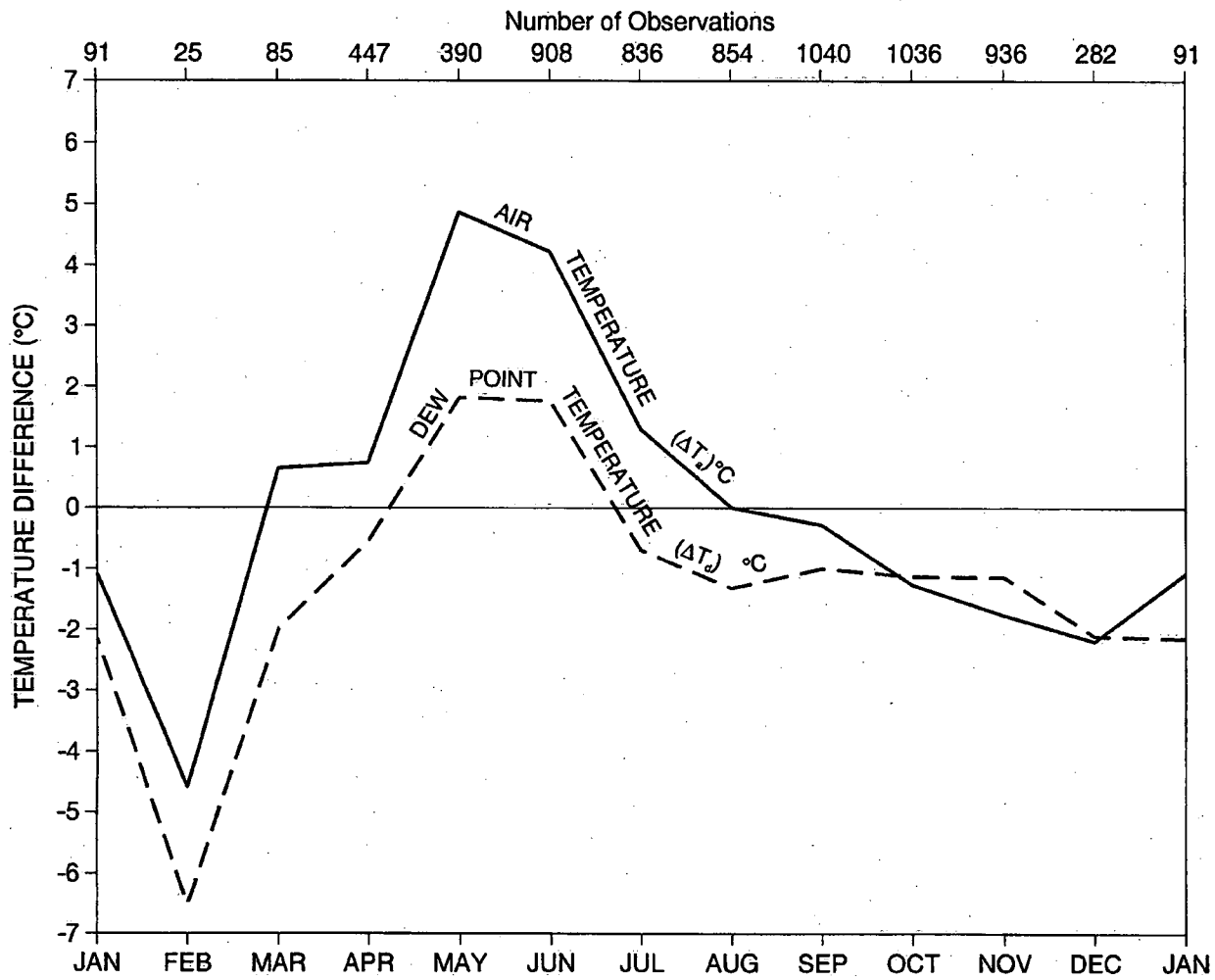


Figure 7. Seasonal variation of air and dew point temperature differences (air over land vs. air over lake) for Lake Ontario. (from Phillips and Irbe, 1978)

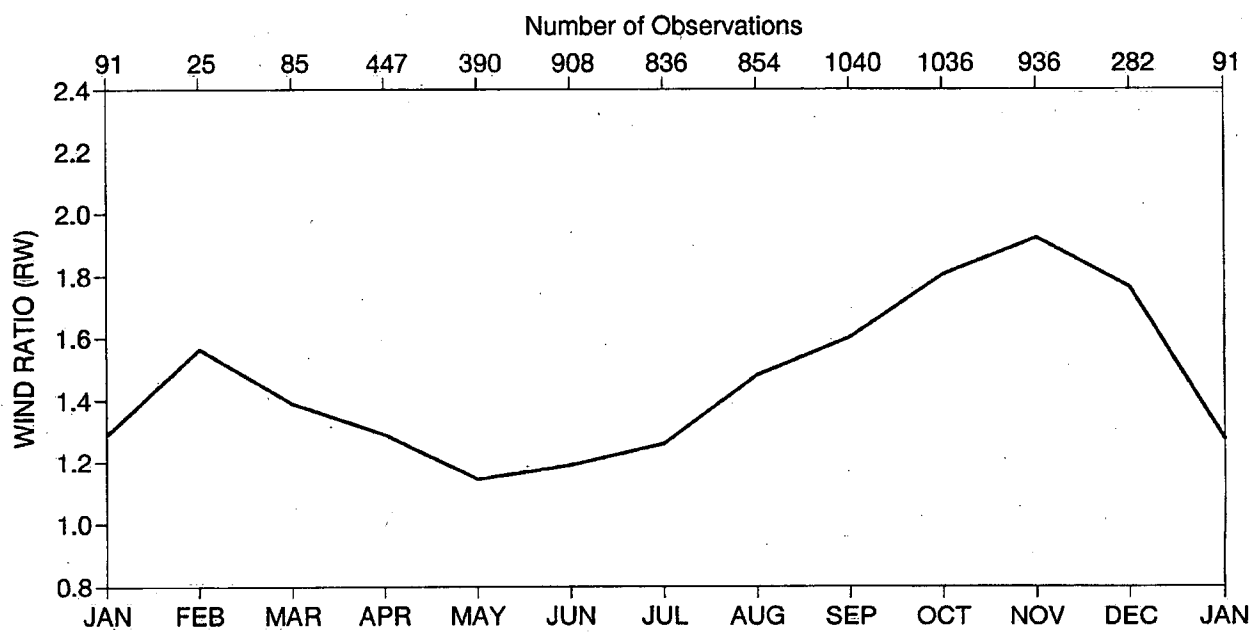


Figure 8 Seasonal variation of the ratio, RW, of the wind over the lake to the wind over land for Lake Ontario. (from Phillips and Irbe, 1978)

TABLE 6: Effect of fetch, wind speed, and atmospheric stability on lake/land ratios (Phillips and Irbe, 1978)

Effect of Fetch Fetch (km)						
Ratio	0 to 11	12 to 26	27 to 45	46 to 75	≥76	All Fetches
R_w	1.37	1.45	1.49	1.58	1.66	1.53
ΔT_a	0.43	0.06	0.37	0.74	1.30	0.48
ΔT_d	-0.74	-0.56	-0.59	-0.42	-0.63	-0.56

Effect of Wind Speed Wind Speed (m s^{-1})						
Ratio	<2.1	2.1 to 4.0	4.1 to 6.0	6.1 to 8.0	8.1 to 10.0	≥10.1 A I I Speeds
R_w	2.64	1.56	1.27	1.03	1.01	0.96 1.53
ΔT_a	-1.14	0.33	0.59	1.85	1.79	0.02 0.48
ΔT_d	-0.77	-0.41	-0.55	-0.53	-0.56	-1.25 -0.56

Effect of Stability (All Fetches and Speeds)			
	R_w	ΔT_a	ΔT_d
Very stable	1.15	8.78	4.38
Stable	1.10	3.74	0.50
Neutral	1.47	-0.17	-1.07
Unstable	1.96	-2.81	-1.62
Very Unstable	2.38	-5.26	-3.18

Note: The stability classes are given by the following:

	$T_a - T_w$ °C
Very stable	>10.4
Stable	3.5 to 10.4
Neutral	-3.4 to 3.4
Unstable	-10.4 to -3.5
Very unstable	<-10.4

Finally, a good measure of climate in the temperate zone is the degree of ice cover that is usually found on a lake. It is here that the more northern latitude of Lake Ladoga stands out. Freezing of Lake Ladoga starts in December. The lake is completely covered by ice usually by mid-February, although it does depend on weather conditions to some extent. Mean ice thickness in March is 50 to 60 cm at the same time as the minimum water temperature is reached (0.6°C). The ice has usually disappeared by May 10th.

Much less ice cover is found in Lake Ontario. In fact, its ice cover is the least of all the Great Lakes. Ice cover usually forms first in harbours and bays. Typically the shore areas and the northeast outlet basin have an ice cover by the end of January. The mid-lake area remains relatively free of ice, although broken ice and slush ice are often found drifting with the wind and current.

Normally, the maximum ice cover for Lake Ontario is 24% by the latter half of February; is reduced to 10% by mid-March, and is virtually ice-free by April 15 (Assel *et al.*, 1985). In a mild winter, the maximum would be about 10% covered (i.e., 1983 as documented by Assel *et al.* 1985). Normal ice cover and 1983 winter ice covers are shown in Figure 9 for comparison for all of the Great Lakes. Ice thickness measurements are less meaningful in situations for such open waters since there is much ice movement and rafting of ice. The shallower, protected embayments have average thicknesses of 30 cm for bays with depths over 15 m, to 50 cm for bays less than 5 m deep (Bolsenga *et al.*, 1988).

3.0 LAKE PHYSICS

We now turn to consideration of how the lakes respond to the heating and cooling processes, hydraulic flows and wind stress. We begin with the annual cycle of the thermal regime and the quantification of the heat balance. This is

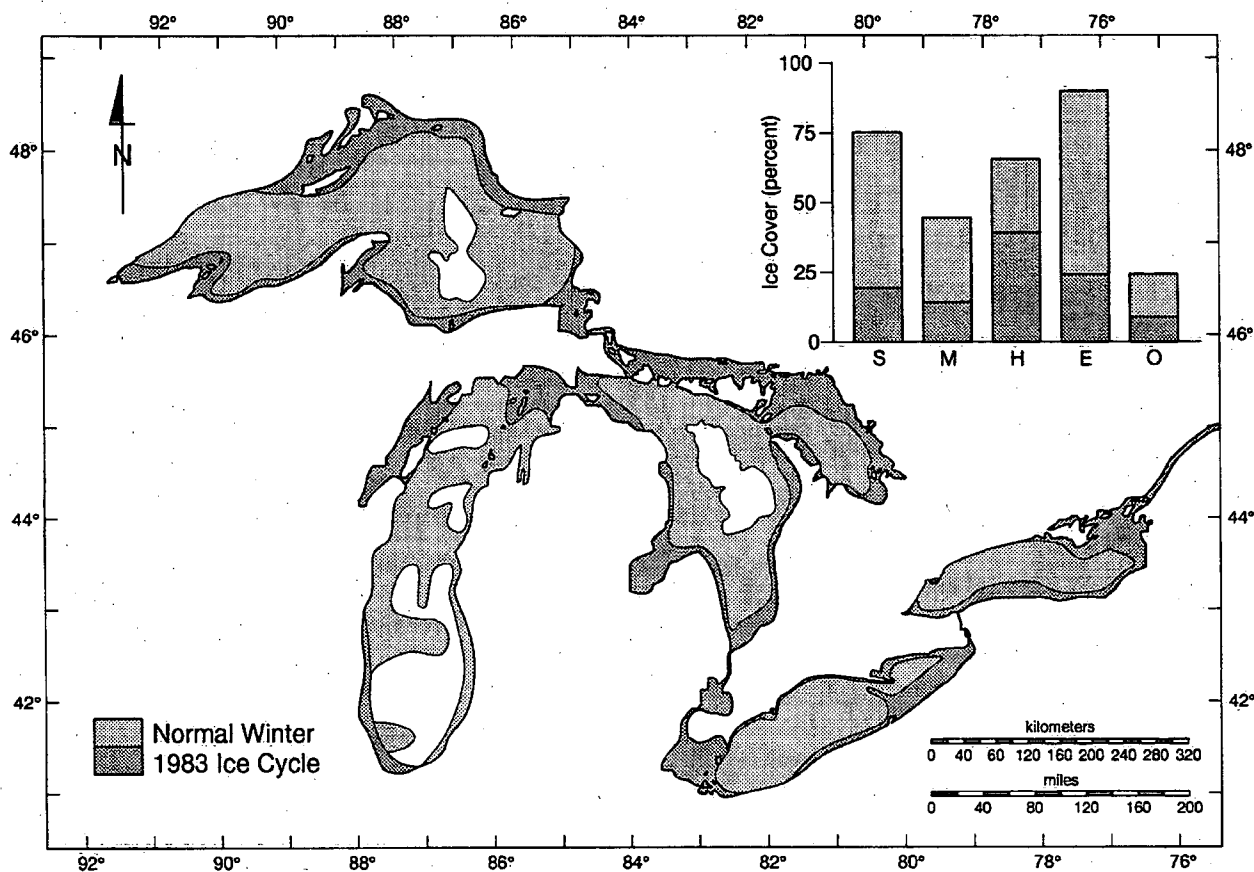


Figure 9 Estimated maximum ice cover for 1983 compared to normal maximum ice cover modified from Assel, *et al.* (1983). Maximum ice cover in 1983 occurred the first half of February; it normally occurs the second half of the month. Normal and 1983 estimated seasonal maximum ice covers are: Lake Superior 75% (21% in 1983), Lake Michigan 45% (17% in 1983), Lake Huron 68% (36% in 1983), Lake Erie 90% (25% in 1983) and Lake Ontario 24% (10% or less in 1983). (from Assel, *et al.* 1983)

followed by an examination of phenomena particularly relevant to conditions near the shore - namely, thermal fronts (vernal and autumnal), upwelling, and shore-constrained wind currents.

3.1 Seasonal Thermal Regime of Large Lakes

The heating and cooling of these lakes in a temperate zone gives rise to their designation as dimictic lakes. That is, the lakes go through two periods in their seasonal cycle where virtually the whole water column undergoes vertical mixing. These seasons are spring and fall. The mixing periods centre around the times when lake surface temperatures are close to the temperature of maximum density (approximately 4°C at 1 atmosphere).

This classical, and somewhat simplified picture of the pattern of the thermal regime applies quite well to smaller lakes at these same latitudes. But there are some important complexities that are manifested in these large, deep lakes. The first is that the time at which top-to-bottom mixing takes place, in spring especially, is different depending on the depth of water at a particular location in the lake, or the proximity of an area to heated or warmer discharges such as industrial discharges or rivers.

The second feature is that a large lake that is usually free of ice cover in winter will often be nearly fully vertically mixed all winter so that a winter 'inverse' thermocline is small or non-existent. Thus, the nearly complete vertical mixing period persists from the time the thermocline breaks down in fall until it begins to reform in late spring.

Finally, the concept of a 'dimictic' lake centres around the temperature of maximum density, implying that density effects due to temperature are the primary

key to the situation. This temperature range is, however, the range in which the rate of change of density with respect to temperature is least (particularly from 0°C to 8°C) and in which active mixing precludes development of large temperature differences. In this situation, density differences due to differences in total dissolved solids (salinity) are more significant. This is especially true close to shores, in embayments, or where water sources are markedly different in salinity due to industrial effluent, road salt use, or due to naturally occurring salt deposits that affect water salinity in inflowing streams.

Some of the features noted in the introduction to this chapter are illustrated in the description of the seasonal thermal regimes that arise from the heating and cooling processes (see Section 3.2 - wind mixing and lake depth).

The thermal regime of large Russian lakes (Lake Ladoga and Lake Onega) have been described by A. Tikhomirov (1959, 1982) and by K. Kondratyev (1988). The thermal regime of Lake Ontario has been examined by G.K. Rodgers (1965, 1966, 1968, 1987), G.K. Rodgers with K. Sato (1970). W. Schertzer *et al.* (1987) and F. Boyce *et al.* (1977, 1989) have addressed Lake Ontario and the Great Lakes system as a whole.

The mean monthly values for surface temperature (T_s) of Lake Ladoga, the temperature of the whole water body (T_l) and the main inflows (t_{in}) are shown in Figure 10. The minimum of the temperature of the whole water body occurs in March when the lake is solidly covered with ice. In the beginning of May, when the mean temperature T_l reaches 1.5°C and equals T_s , the thermal bar associated with the 4-degree isotherm appears in the shallowest southern part of the lake. Surface temperature increases faster than T_l and in the first half of July the 4-degree isotherm disappears from the Lake Ladoga water surface. In Figure 10, spring and fall thermal bar periods are illustrated. In the heating period, the temperature of inflows are always higher than surface water temperatures and

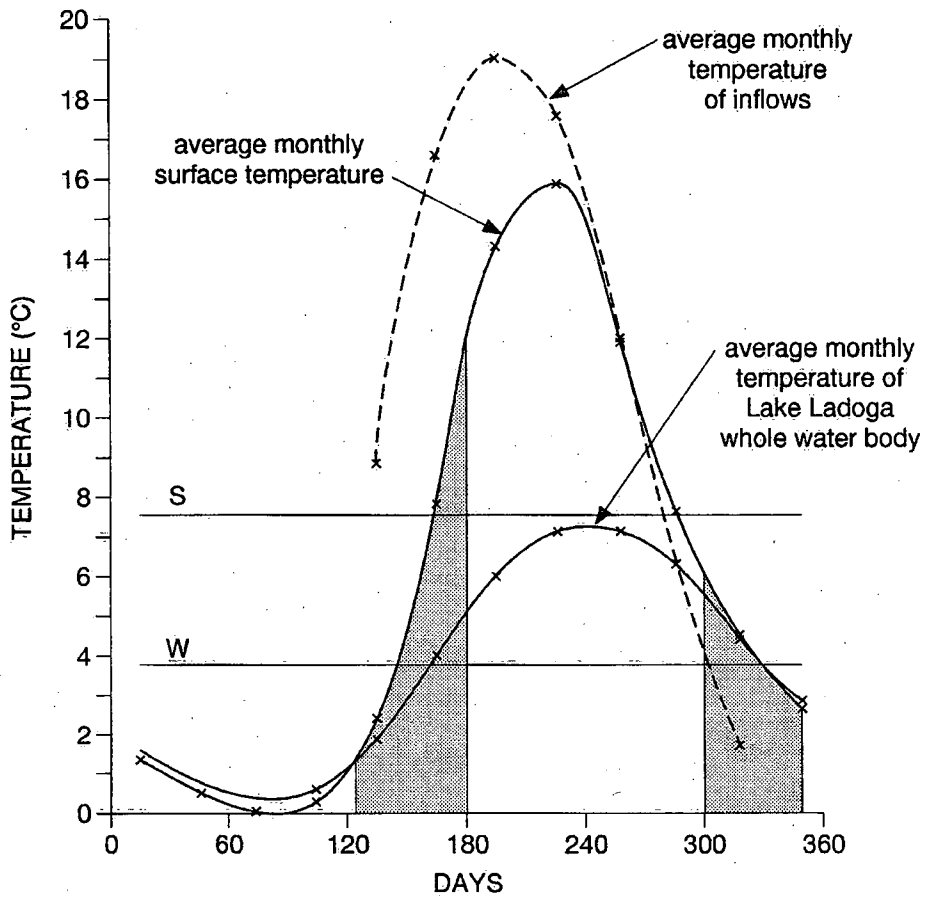


Figure 10 The thermal régime of Lake Ladoga (data from A. Tikhomirov, N. Smirnova and M. Veselova)

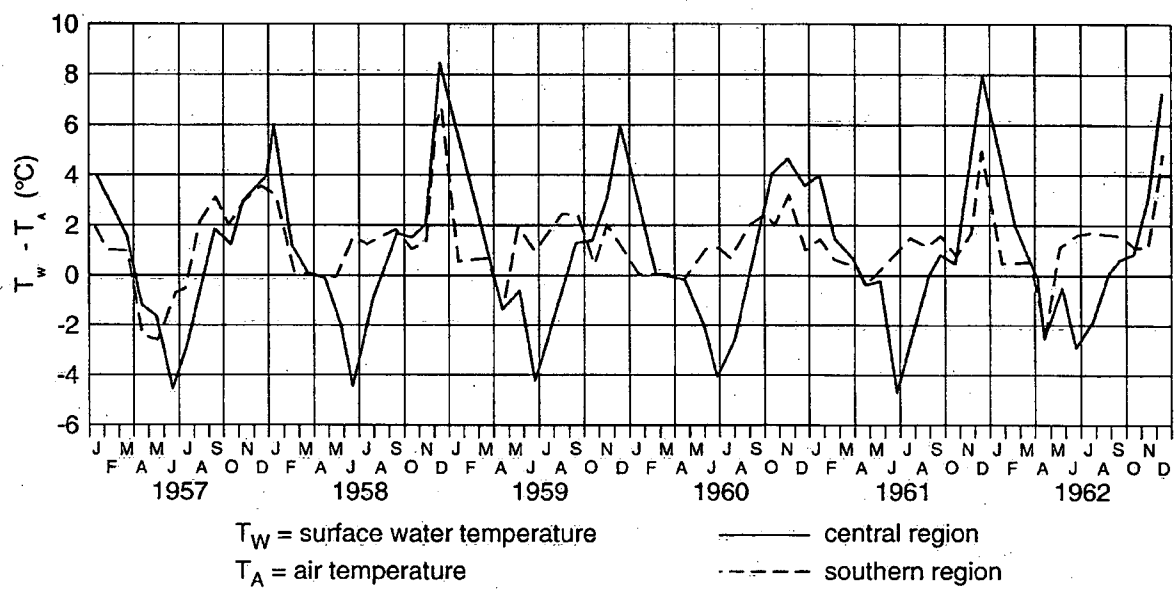


Figure 11 Lake Ladoga water-air temperature differences.

temperature contrasts due to river inflows are somewhat suppressed in July and August. The distribution of suspended matter in the nearshore areas are mainly the result of river plumes.

The maximum of the mean monthly surface temperatures is in August (16°C), while the maximum T_z equals 7.2°C in July and August.

In September, the cooling of the whole lake is intensive. Increasing wind speeds result in the surface temperature becoming equal to the temperature of inflows. Surface spatial contrasts disappear at 11°C.

The fall thermal bar (see Section 3.4) arises at the end of October and in the beginning of November. The duration of this period is the same as spring thermal bar (see shaded area), however, horizontal temperature gradients are rather small (see Figure 10). During the spring heating period, the mean surface temperature changes from 1.5 to 10.5 to 11°C (at least), whereas in the fall, the thermal zone period surface temperature is decreasing only from 6.5 to 1.5°C. Horizontal temperature gradients are small in this fall period and there are generally no significant density gradients because water temperatures are within 4°C of the temperature of maximum density (i.e., from 0 to 8°C).

Lake Ontario has a similar seasonal pattern that can be illustrated with data from the International Field Year for the Great Lakes IFYGL (1972 to 73). In Figure 12, the average whole lake temperature, and the temperature of the top 10 m, are plotted on a weekly basis. The maximum and minimum whole lake temperatures are 7.5 and 1.5°C, respectively, and this represents an equivalent heat transfer of 10×10^{18} calories (Boyce *et al.*, 1977). These temperatures are just slightly higher than those for Lake Ladoga.

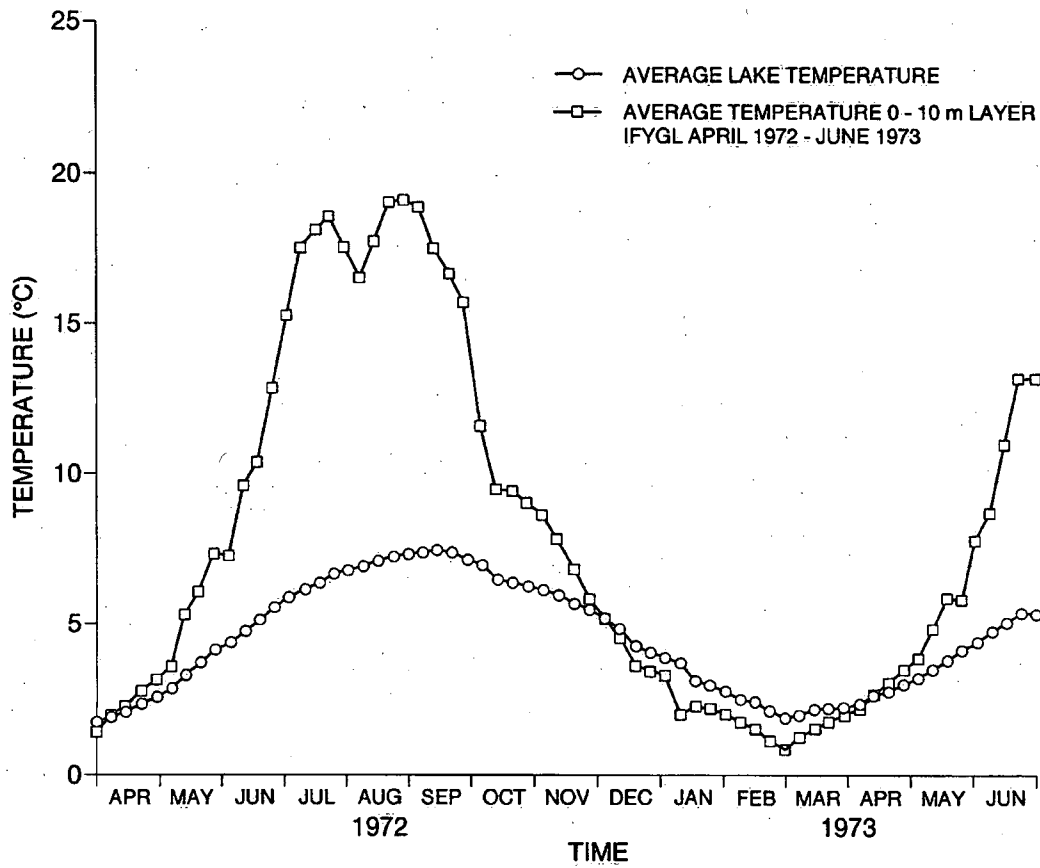


Figure 12 Average temperature of Lake Ontario (whole lake volume) and temperature of the upper 10 m during the International Field Year for the Great Lakes (IFYGL). (from Boyce, et al, 1977)

The seasonal spatial pattern of surface temperature changes (which are obscured in the average temperatures) are, in general, the same as for Lake Ladoga. The differences relate principally to the different depth patterns in these lakes. The main body of Lake Ontario is primarily an ellipse with steeper offshore depth gradients on the south shore than on the north shore. The progress of spring thermal stratification is closely related to depth (Rodgers, 1966) and therefore the thermal bar, especially in the first few weeks, is very close to the south shore, but progresses at least twice as quickly towards the centre of the lake from the north shore. There are many meanders in these boundaries, as the infrared imagery for Lake Ontario at this time of year clearly show (Plate 1).

In summer, the major features are a strong thermocline, internal waves of several types, and upwelling that can flood beaches with metalimnetic waters of temperatures of 7 to 16°C. Daily data from water supply intakes illustrate these occurrences well (see Figure 13).

The autumnal thermal bar is a much less dramatic feature than the spring thermal bar and horizontal temperature gradients are far smaller (Rodgers and Anderson, 1963).

3.1.1 Temperature Cross-Sections

Water depth has a major influence on the annual temperature cycle. The main features of this cycle are described here in temperature sections and maps. Data have been taken from publications by A. Tikhomirov (1982) for Lake Ladoga, and from Rodgers and Anderson (1963) or Saylor *et al.* (1981).

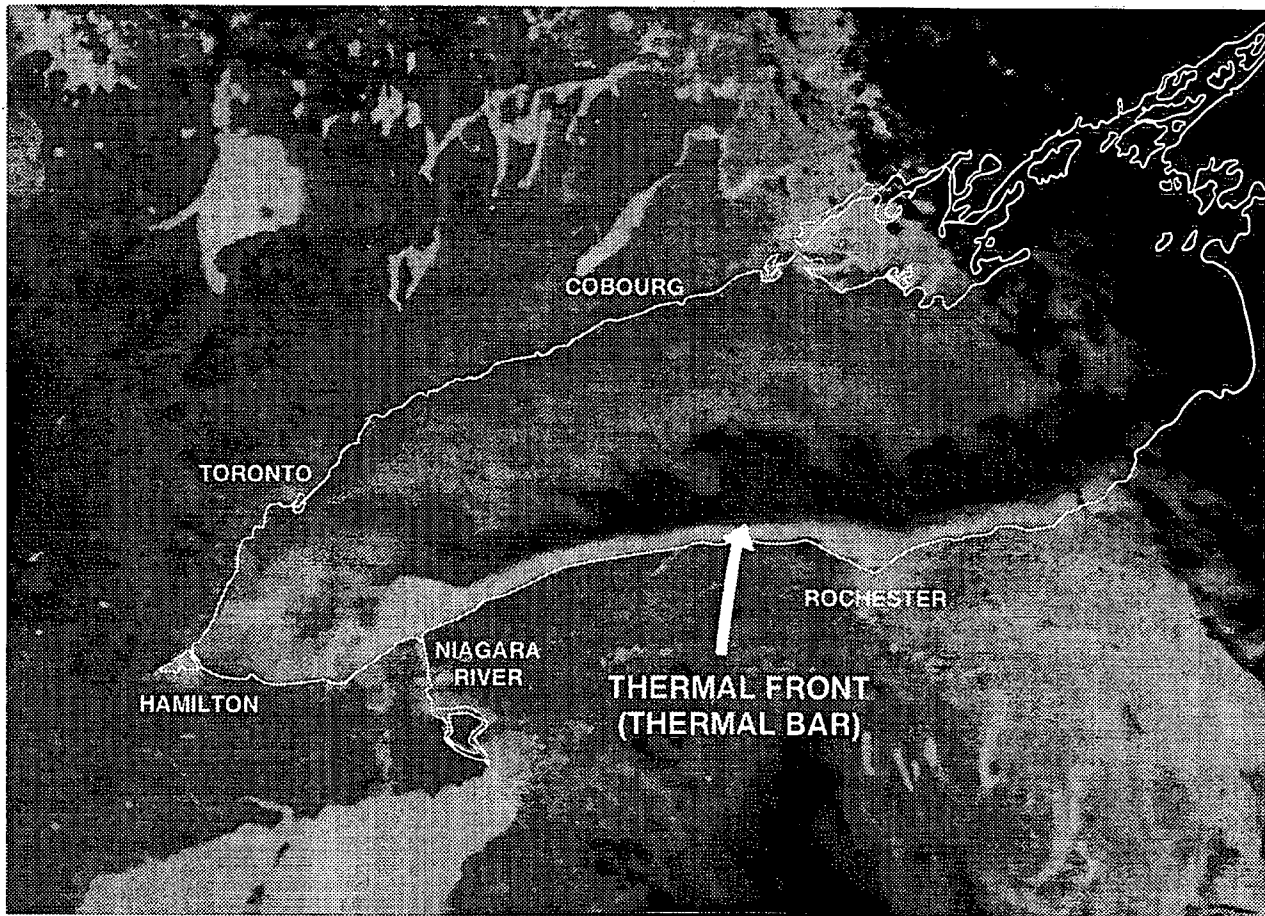


Plate I Thermal infra-red image of the surface temperature for Lake Ontario, June 22, 1978. (NASA AEM-A LANDSAT-I: Bright white areas denote higher temperatures. Black central areas have some surface temperatures less than 4°C.)

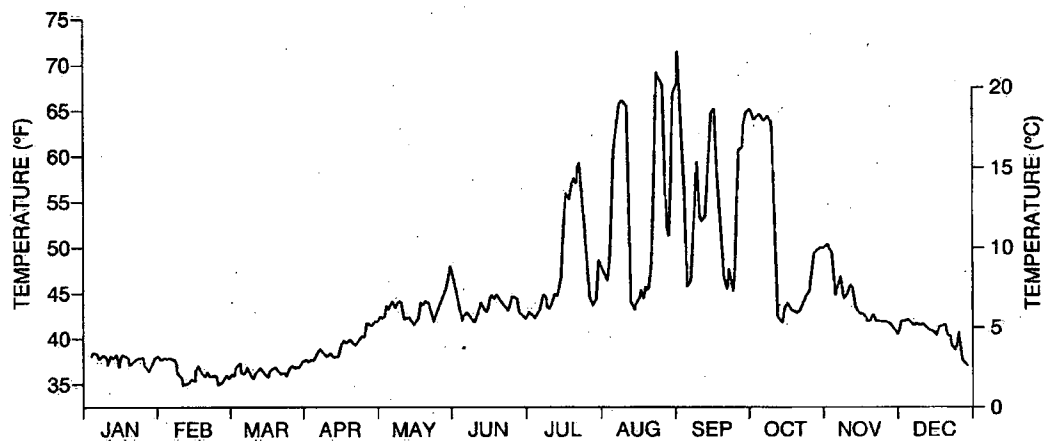


Figure 13 Temperature in 1959 at the R. C. Harris water treatment plant intake, Toronto. (from Rodgers and Anderson, 1963)

In Lake Ladoga major temperature surveys were undertaken between 1959 and 1962. The surveys are tabulated below (Table 7) and the cross-sections shown in Figures 14 and 15.

TABLE 7: List of surveys in Lake Ladoga

Date		Transect Number in Figure 14	Letter in Figure 15
April	24-25 1960	1	A
May	13 1962	2	B
May	29 1962	3	C
June	15-16 1962	4	D
June	7 1962	3	E
June	24-25 1962	2	F
July	14 1962	5	G
July	13 1962	3	H
July	12-11 1961	2	J
July	26-28 1960	2	K
July	23-24 1962	2	L
August	14-14 1960	2	I
July	8-9 6	1960	2
			M
August	16-17 1962	2	N
September	1 1962	4	O
September	3-4 1962	3	P
September	18-19 1962	4	Q
September	19-20 1962	6	R
October	3-5 1962	2	S
October	28 1959	2	T
October	28 1959	northern shore	U
October	29 1959	northern shore	V
November	16-19 1962	2	W

The water temperature under the ice from the surface to 200 m increases from 0.3 to 2.7°C in the deepest part of Lake Ladoga. The isotherms are practically parallel with each other and there is no reason for baroclinic current in this period (Figure 12a).

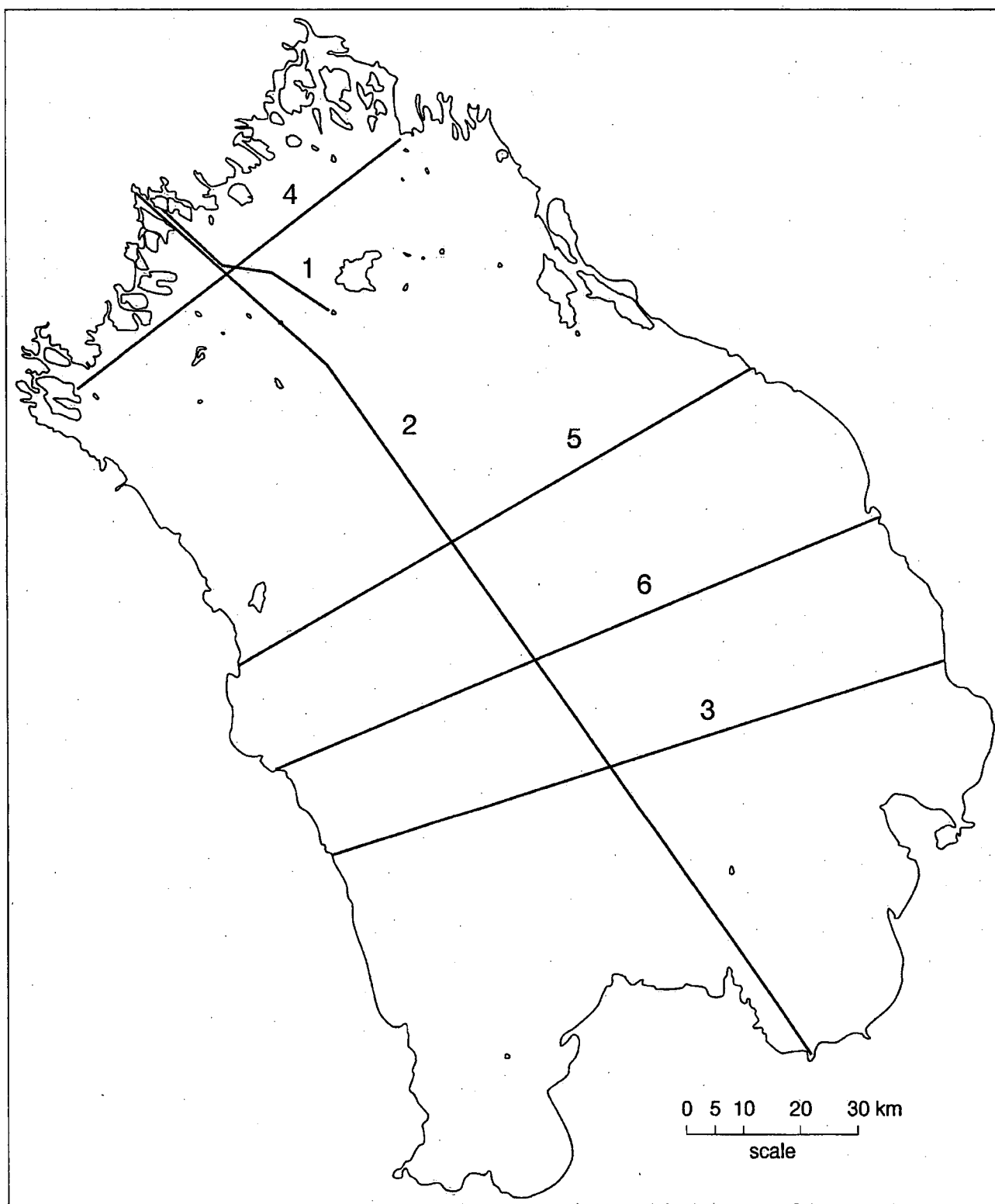


Figure 14 Lake Ladoga showing the location of temperature transects

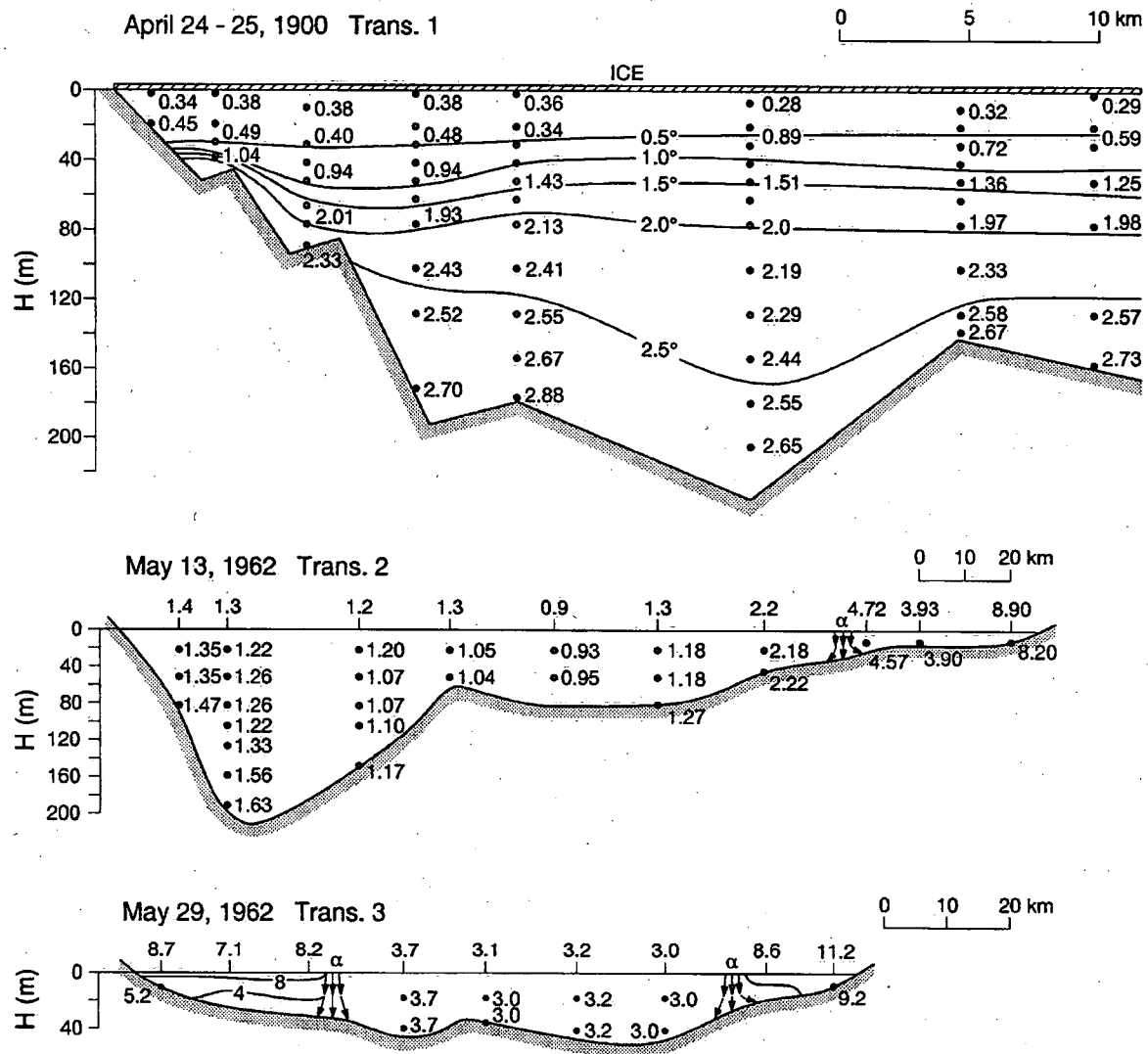


Figure 15 Temperature transects in Lake Ladoga for the ice-free period from April to November.

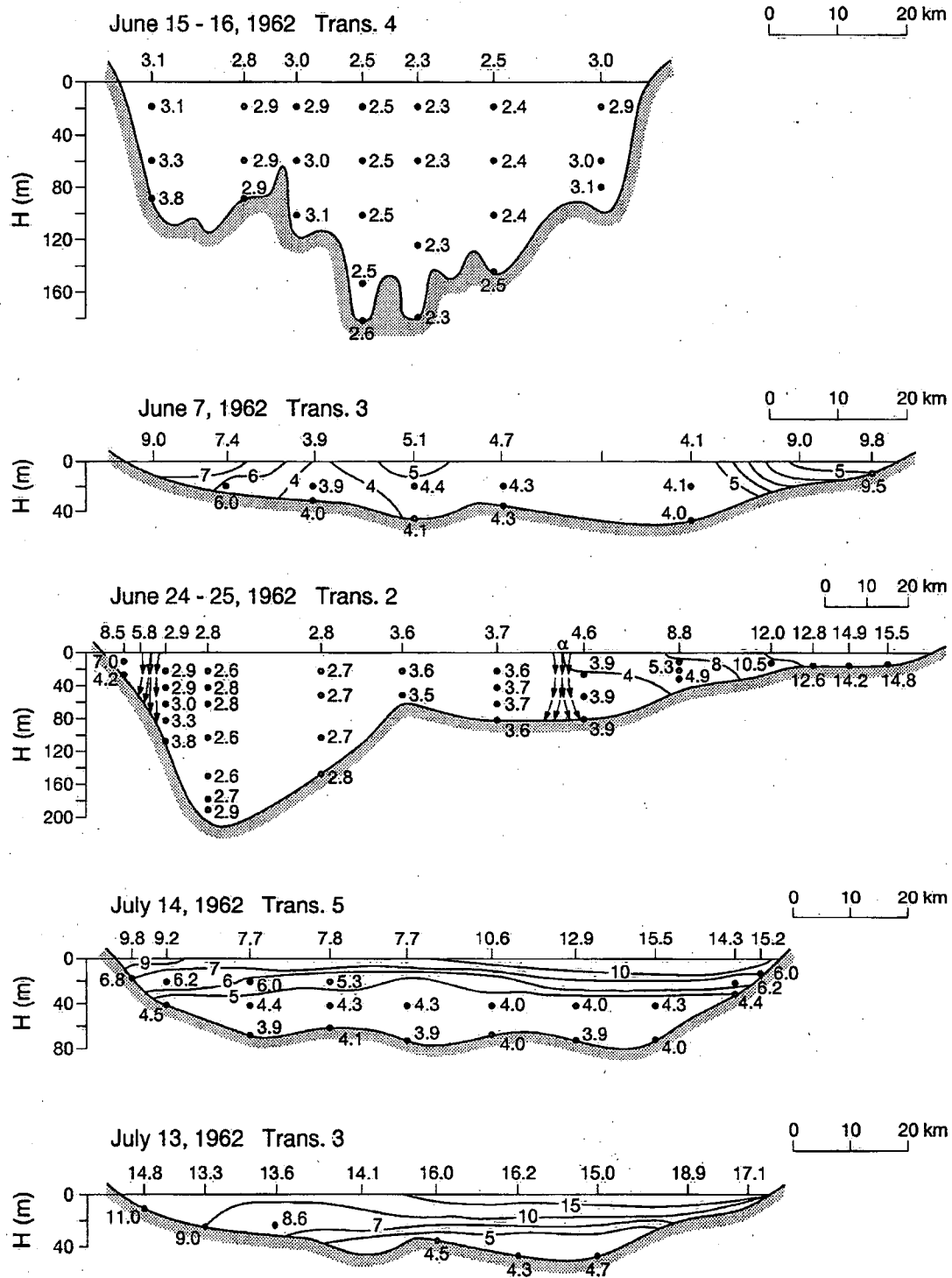


Figure 15 cont'd

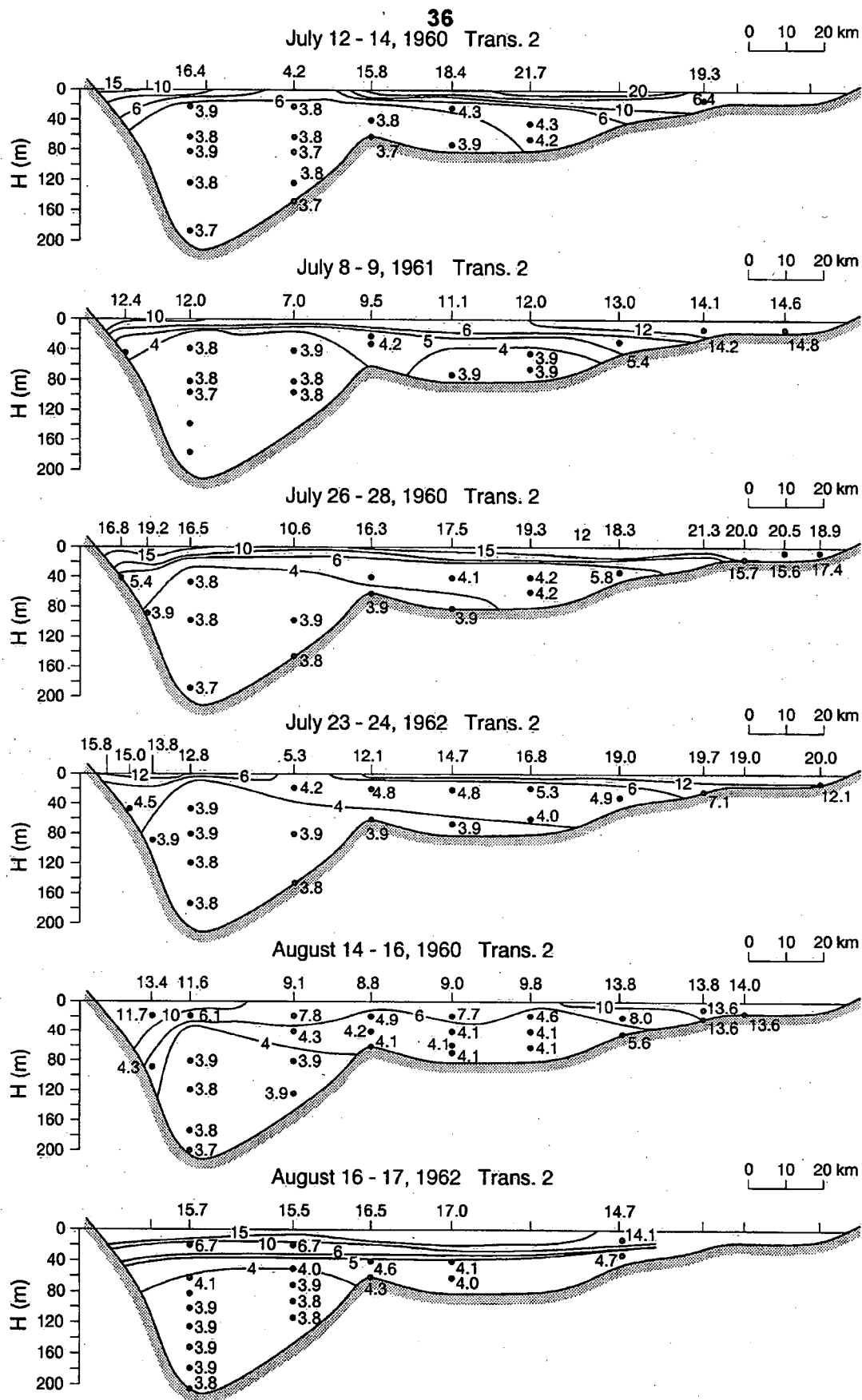


Figure 15 cont'd

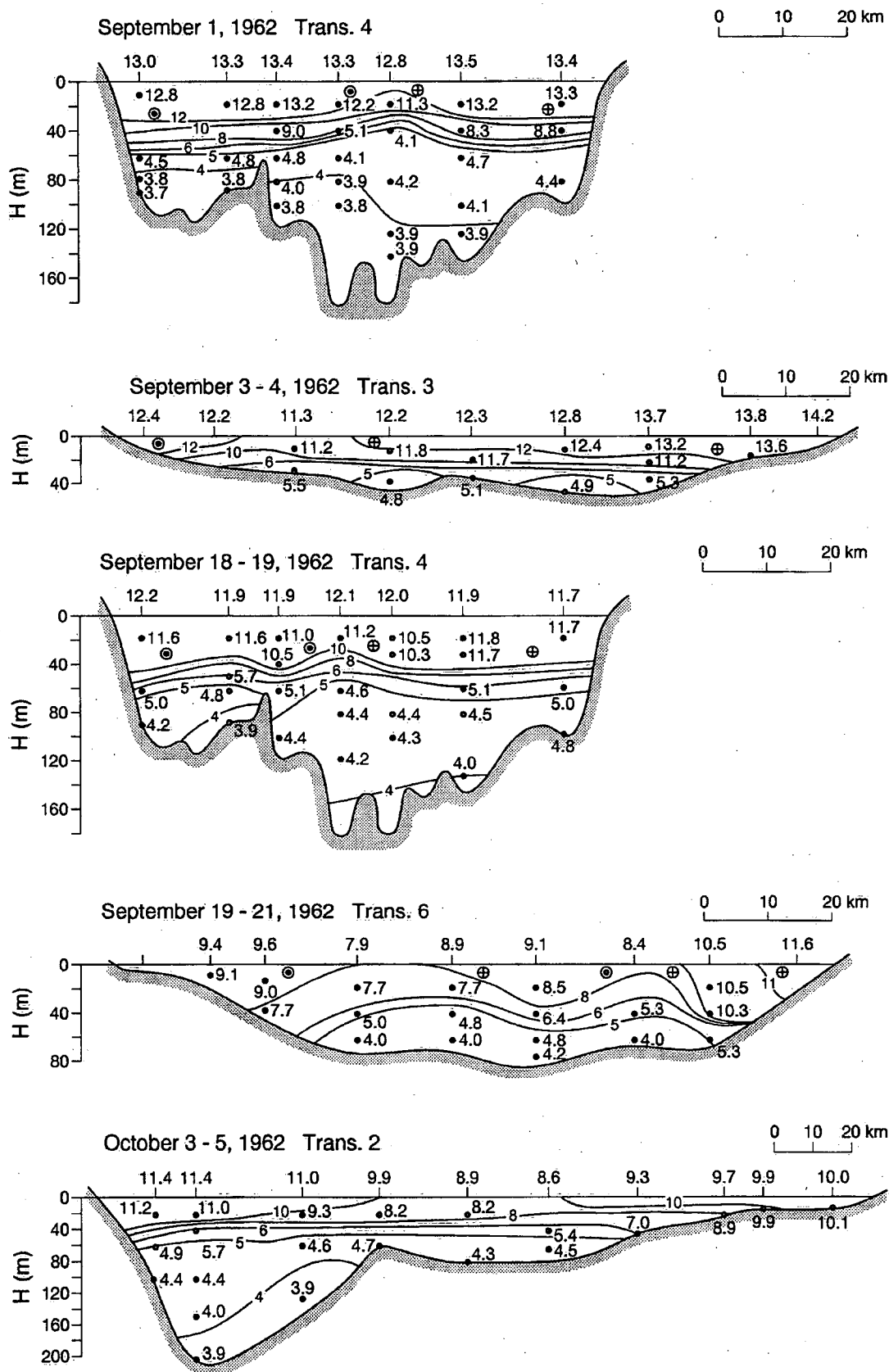


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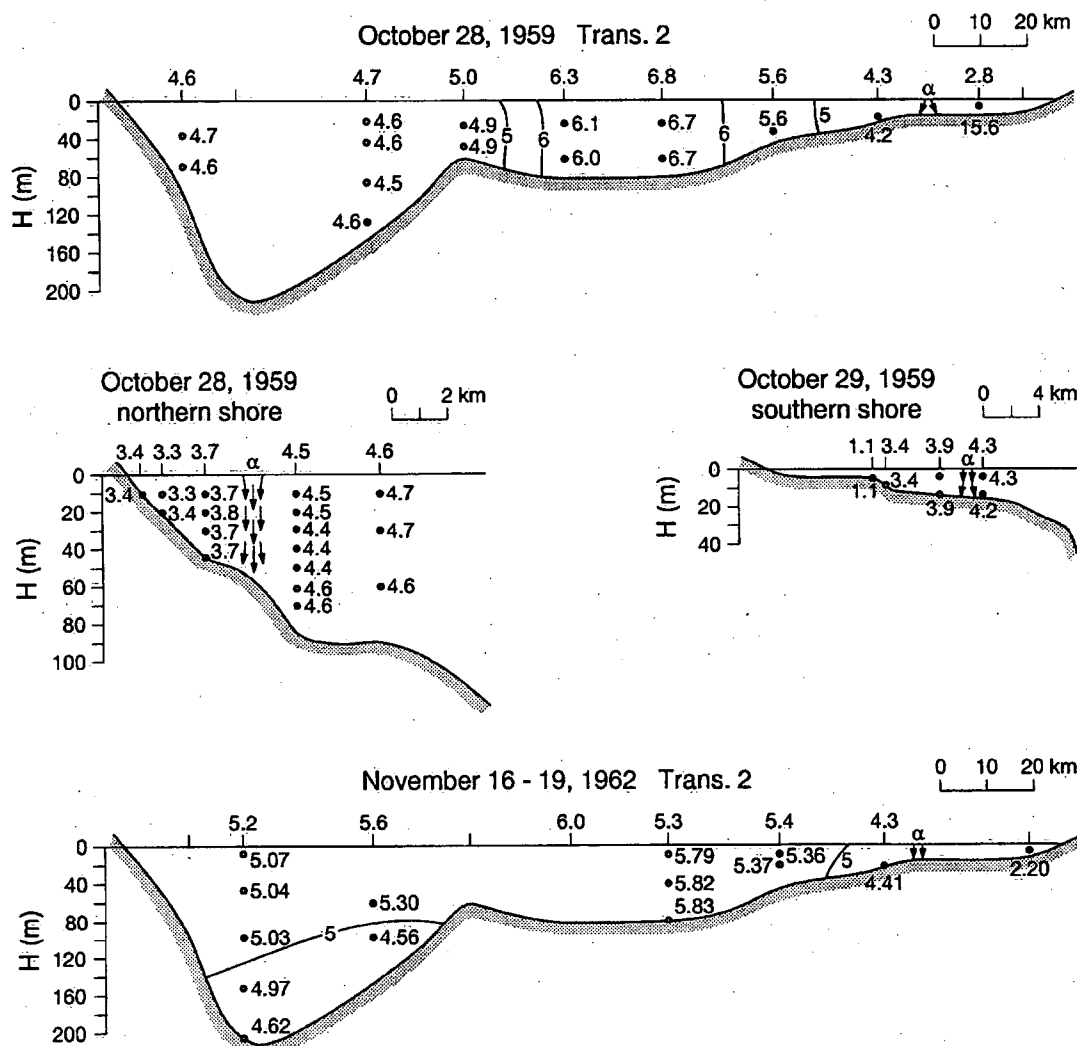


Figure 15 cont'd

The spring warming is responsible for faster heating of the shallowest parts of the lake. In mid-May, thermal fronts usually are present. Southern nearshore waters are stably stratified. The central and northern waters are still isothermal.

When the 4°C isotherm reaches regions with depths of 50 to 60 m, a secondary thermal front appears in the central part. The secondary front is related to the slowing and deepening of the 4°C front where the bottom slope steepens very abruptly. Shoreward of the 5°C surface isotherm, there are large horizontal temperature gradients.

In July, the thermocline forms in the central part of Lake Ladoga. When the wind forces increase and the cooling period begins at the end of August, an upper quasi-homogeneous layer appears. The thickness of this layer increases up to 40 m at the end of September. The southern shallow waters are fully mixed at this time.

The fall thermal front is formed when the shallower regions are in the range of the temperature of maximum density. In the cooling period, the horizontal frontal temperature gradients are smaller than in the heating period, especially in the northern regions.

The shallow regions bounded by the front cool more quickly. That is why, in the second half of December, about one-third of the lake can be covered with ice.

Starting with the spring period, the pattern of thermal structure development for Lake Ontario is described with surface temperature maps and maps of the depth of particular isotherms that illustrate the internal thermal structure (Figures 16 to 18).

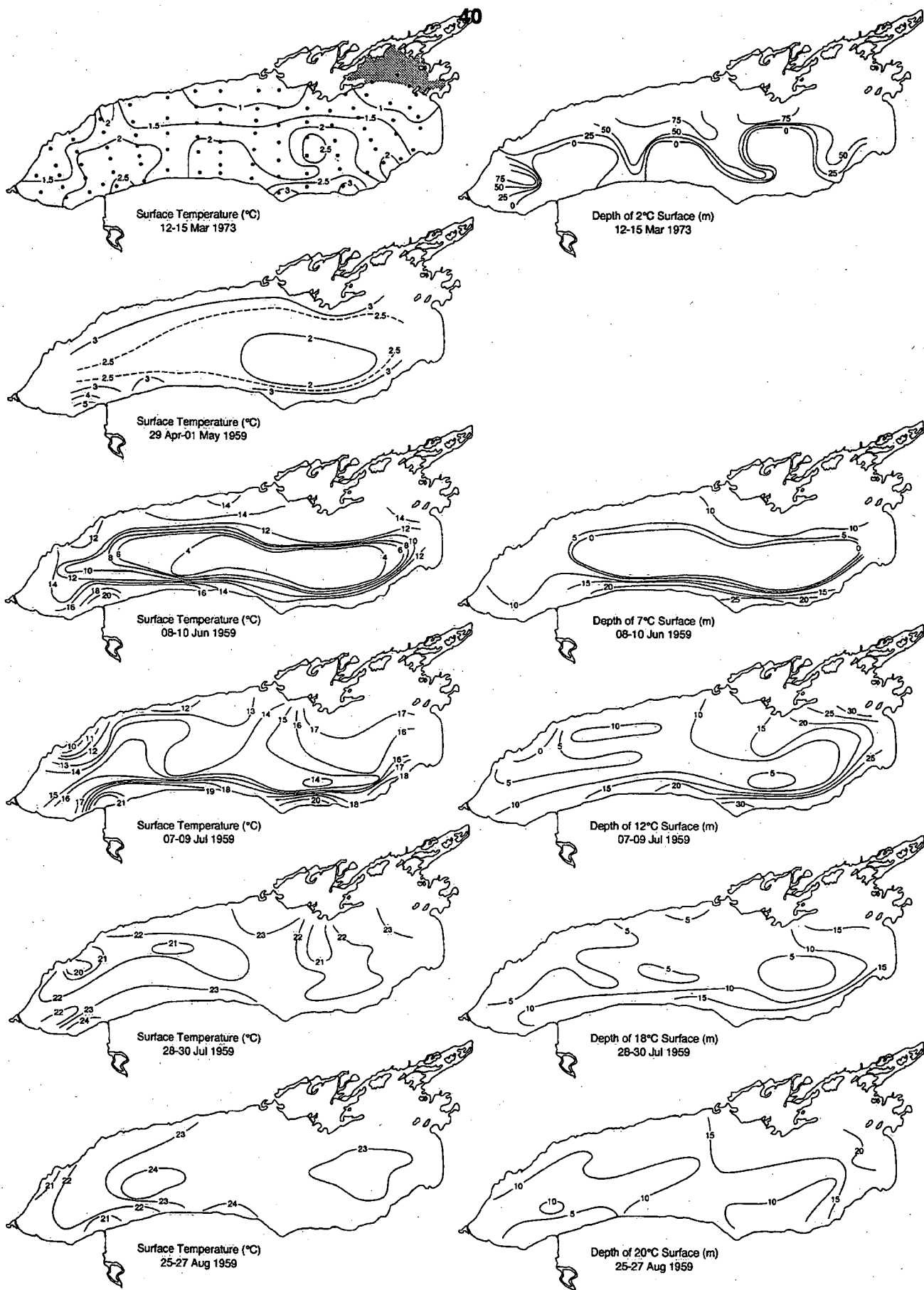


Figure 16 Surface temperatures and temperature structure in Lake Ontario through spring and summer.

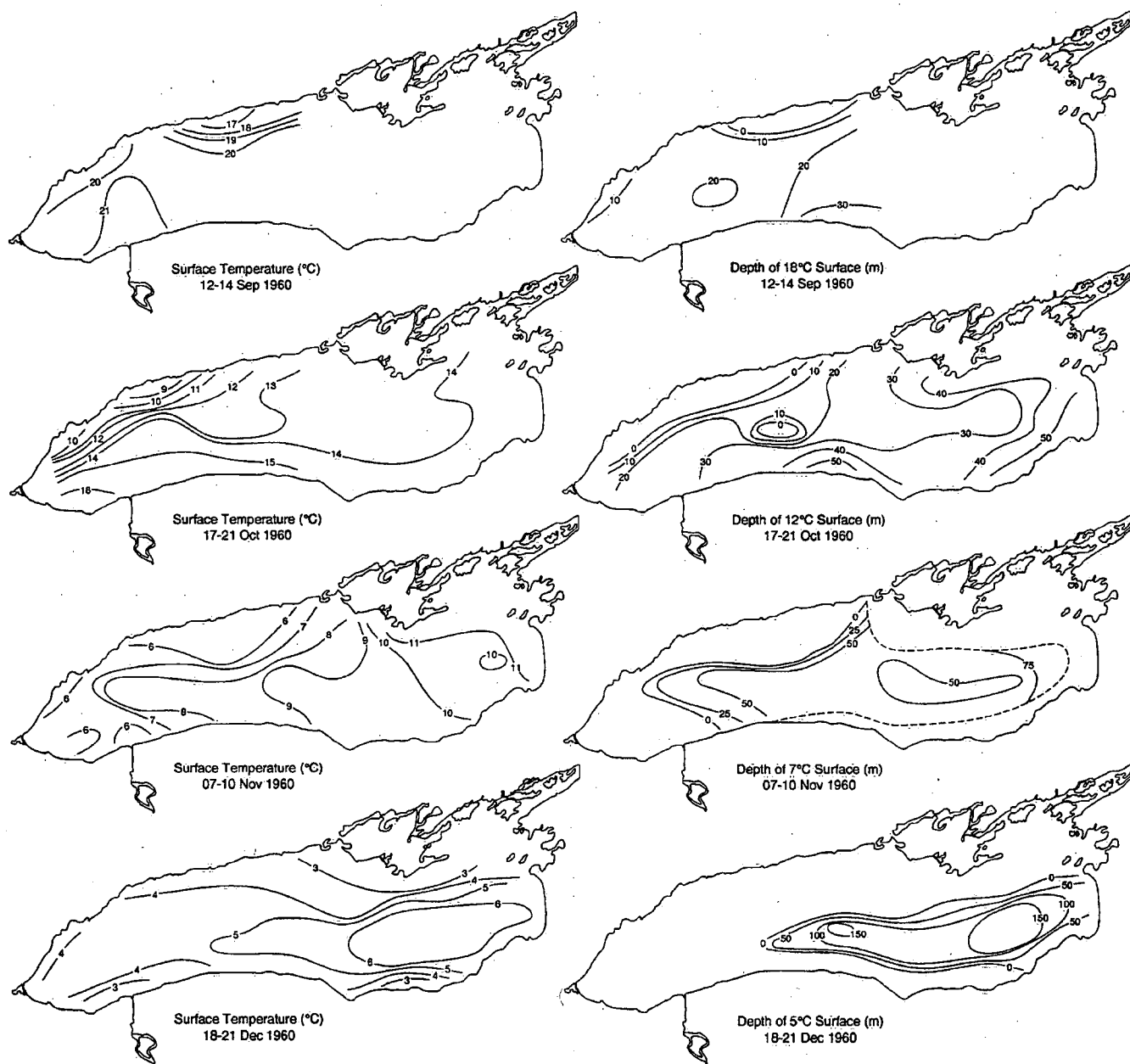


Figure 17 Lake Ontario thermal structure through fall and early winter.

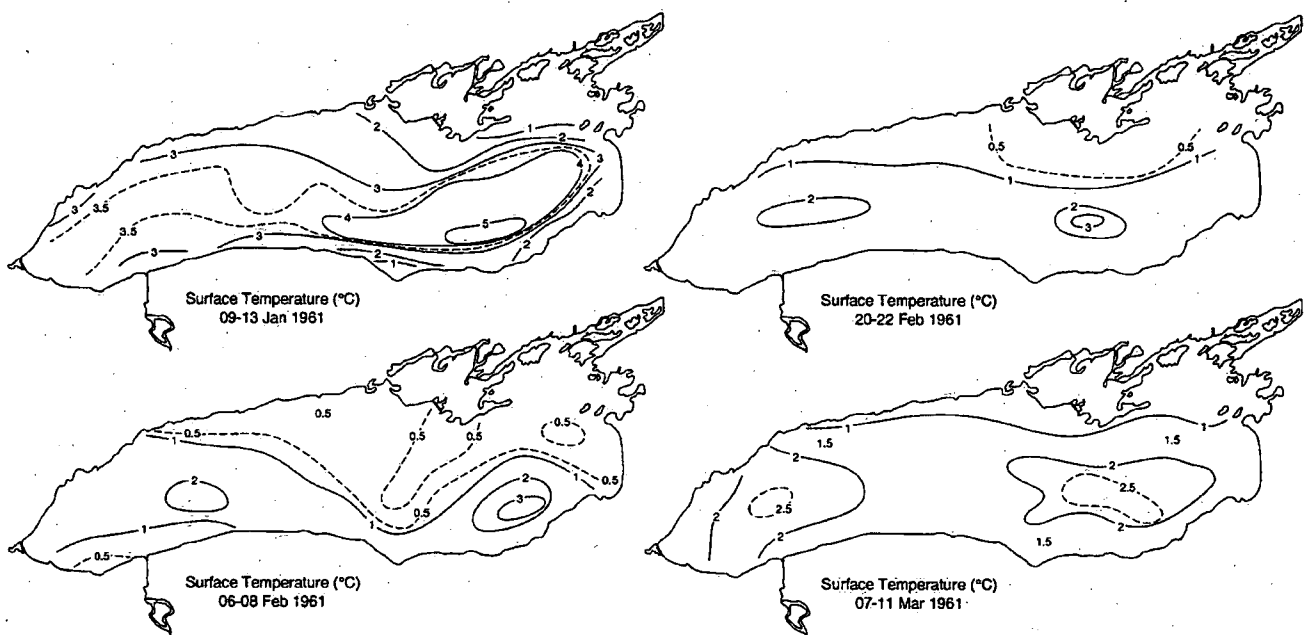


Figure 18 Surface temperatures and temperature structure for Lake Ontario in winter.

The late winter condition is typically one where the complete lake is less than 4°C with slightly warmer water in the deepest part of the lake. Sometimes there is slight thermal stratification at depths of 100 m or more where temperatures are 0.5°C or so higher than the upper layers.

The thermal bar forms around the shores in late April, particularly where there are major warmed inflows. Surface isotherms tend generally to reflect depth contour patterns through into June until the 4°C surface isotherm disappears.

Summer stratification is complete in July and internal waves, internal seiches or upwelling/downwelling can be observed depending on the winds during the few days prior to the survey.

In the fall, the surface cools and the thermocline deepens. The smaller density difference between epilimnion and hypolimnion gives rise to even larger tilts in the thermocline and dampens thermocline 'recovery' following major wind storms.

The fall/winter thermal bar (or 4°C surface isotherm) is often present in December and persists through into January.

The coldest temperatures are found usually in February or early March. Ice cover in the lake is seldom extensive, and usually consists of floating broken slush or pan ice.

3.2 Annual Heat Budgets

The energy balance for Lake Ontario has been the subject of two major examinations (Rodgers and Anderson, 1961; Pinsak and Rodgers, 1981). The latter reference is an analysis of weekly ship surveys and ancillary meteorological

observations during the International Field Year for the Great Lakes (IFYGL - 1972/73). The results of the IFYGL Study are shown in Figure 19, where ΔQ_l is the change in heat content of the lake, Q_e is the evaporative flux, Q_h the 'sensible' heat transfer, Q_n is the net radiation flux (solar and long-wave), Q_v is the advective component and Q_f is the latent heat associated with the formation and melting of ice. Evaporation corresponds well, on average, with estimates made by other techniques such as water balance or use of mass-transfer equations with over-lake meteorological data. Net radiation dominates the heat budget from April to September. Evaporation and sensible heat loss predominate during the fall and winter.

3.3 The Vernal Thermal Front (Thermal Bar)

The spring thermal frontal zone, called by the name "thermal bar" by F. Forel (1895), is a major thermal front and water circulation feature for both Lake Ontario and Lake Ladoga. The thermal front forms on the shoreward side of the 4°C surface temperature isotherm (the temperature of maximum density) and it separates a thermally stratified shoreward water mass from a central zone in the lake that is freely convecting. Heating at the surface in combination with the heat capacity of the water column (essentially the depth) with limited onshore-offshore water exchange (partly a depth and boundary 'friction' effect) generates this situation. Tikhomirov (1959, 1963, 1982) and Rodgers (1963, 1965, 1966, 1968 and 1970) have described phenomenon for Lake Ladoga and Lake Ontario, respectively.

The frontal zone, which can be as abrupt as 200 or 300 m wide, or as broad as 4 km, moves from shore to the centre of the lake, marking the gradual development of summer stratification. This means that thermal stratification in the

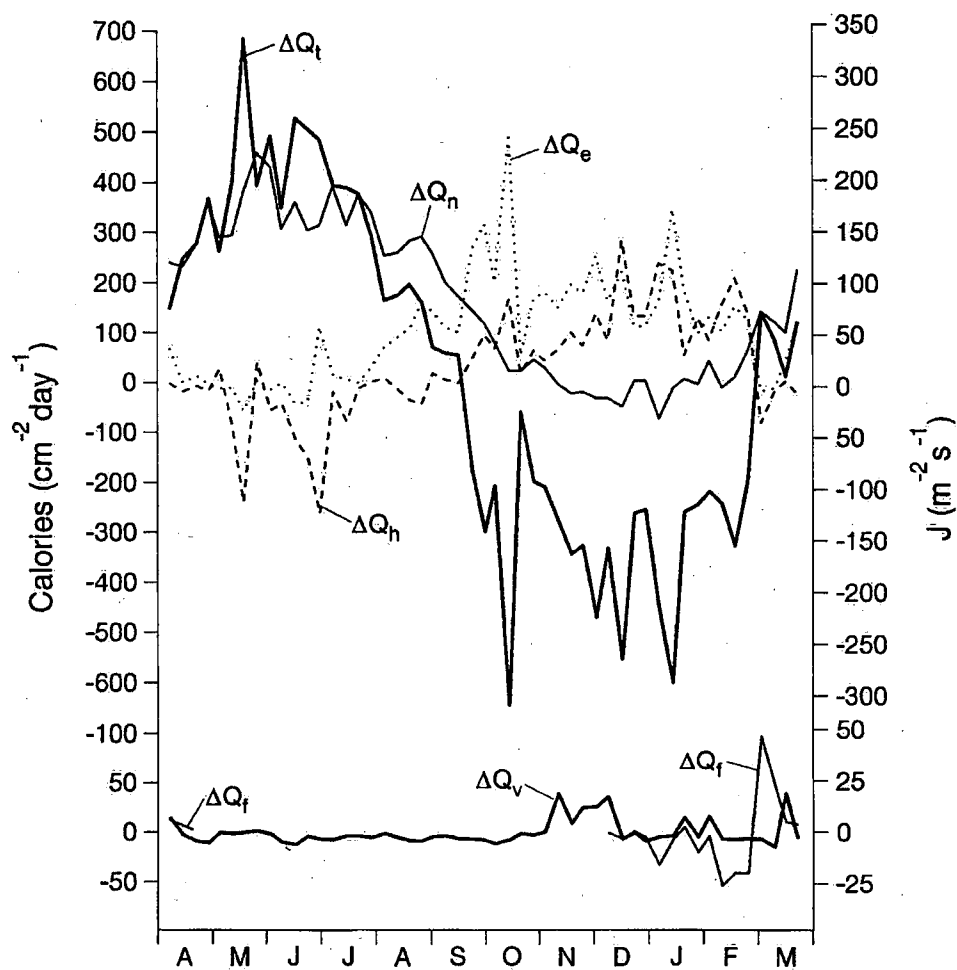


Figure 19 Weekly averages of energy balance terms. (from Pinsak and Rodgers, 1981)

deepest (or central) waters of these lakes lags stratification in nearshore waters by up to six weeks.

Observational programs encompassing temperature, currents and optical properties have been carried out in both lakes over the past 30 years. Some studies have concentrated on lakewide implications of the phenomenon, others have focussed research on a detailed study of particular shore segments.

The frontal zone is characterized by anisotropic horizontal exchange of water and of substances contained in them. Horizontal temperature gradients have been observed as large as $7^{\circ}/\text{km}$ in Lake Ladoga in the larger scale of observations. Details showing up in towed thermistor records on crossings of the thermal bar (perpendicular to the front) indicate much fine structure on the scale of 100 m or less (Rodgers, 1968). Generally, the sharper temperature gradients are formed where surface temperatures are 6 to 8°C , rather than directly at the 4°C isotherm.

The frontal zone is also characterized by vertical motion (primarily downward) and by quite marked gradients in water clarity (Rodgers, 1968) - with clear colder waters and more turbid warmer waters - and in biological characteristics. While differences in algae concentrations are evident, there have also been suggestions that salmonoid movements are also conditioned by the presence of the thermal bar (fishermen often fish the boundary between the water masses). The natural die-off of alewife in spring combined with the convergence in surface currents at the front results in major accumulations of rows of dead fish, along with any other floating debris - especially at the early stages of the formation of the thermal front when it is within 5 to 15 km from shore.

Other surface water quality conditions are also different on either side of the frontal zone (Rodgers, 1965, and many others) reflecting, usually, the

characteristically higher concentrations of suspended and dissolved material in spring runoff. It is not clear that this is uniquely a thermal bar phenomenon, but the thermal bar circulation enhances the appearance of such onshore-offshore gradients.

Finally, under moderate winds, the thermal front is clearly evident in many areas by virtue of differences in surface roughness due to waves. The colder waters can be glassy smooth while nearshore waters are choppy - no doubt the result of a more stable cold air mass directly over the colder lake water surface.

All of these features have major implications for the circulation regime of such large lakes and the water quality that results from it.

Temperature Gradients and the Variability of Currents

The charts noted above have documented the typical distributions of surface temperature for Lakes Ladoga and Ontario during the period of the vernal thermal bar. The thermal bar or front, separates two zones of the lake. On the shoreward side is a stratified zone, and towards the centre of the lake there is little stratification. The two zones are separated by greater horizontal temperature gradients in the upper layers of the lake that are in relatively narrow frontal zones. An example for Lake Ladoga is shown in Figure 20.

Based on data from anchored instrument chains and temperature cross-sections, there seem to be two general states of the frontal zone. One is a relatively weak front with the surface temperature increasing linearly with distance from the front; the second is a sharply pronounced front with a non-linear relation with distance from the front (hyperbolic or logarithmic). The width of the frontal zone depends on this horizontal temperature distribution and this width, in turn, is

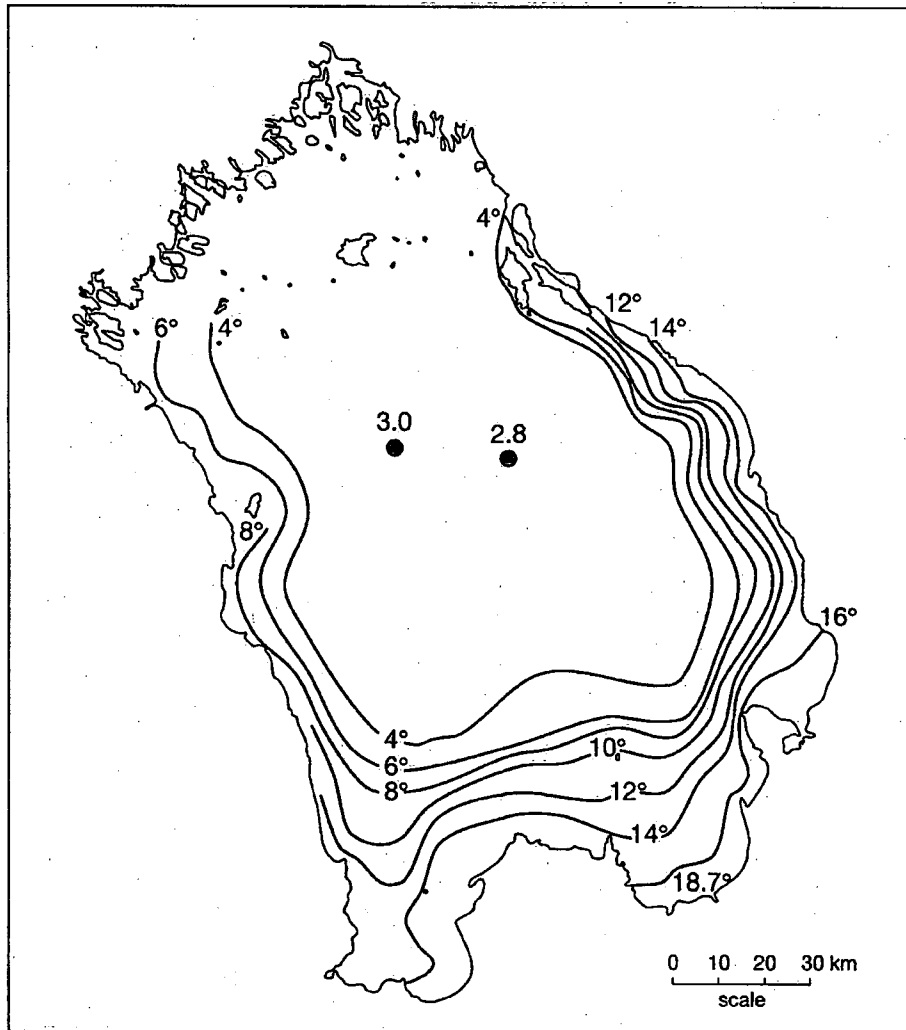


Figure 20 Surface temperature (°C) distribution in Lake Ladoga at the beginning of June.

found to be inversely correlated with water column depth at the location of the front (Naumenko, 1989).

The main spatial scales of variability in the frontal zone can be compared with the Rossby radius of deformation, within which geostrophic equilibrium takes place. For both Lake Ladoga and Lake Ontario this scale is about 3 to 5 km. It is at these scales that non-stationary ageostrophic disturbances are seen in the form of internal waves and coastal jets. In Figure 21 the temperatures, density and Brunt-Väisälä frequency are plotted for a shore-to-midlake section across the thermal front. At this point, there are the greatest horizontal and vertical density gradients, and conditions should give rise to currents parallel to the shore, under geostrophic assumptions.

The inclination of the maximum density surface towards the shallower part of the lake is about 10^3 (which approximates the bottom slope in the opposite direction). The frontal inclination, however, can depend on its stage of development, as well as upon depth. There is convergence in the frontal zone (with downwelling at the surface) and divergence in the lowest layers.

Measurements of temperature and current were carried out from an anchored vessel during a two- to three-day period. The ship was anchored in the offshore, colder, isothermal zone in anticipation of the passage of the thermal front as it moved offshore. Observations were made in winds less than 2.5 m/s. Figure 22 shows the change in speed and direction of the current as the temperature passed through 4°C (the temperature of maximum density) at 5 m depth. Both the Richardson number and the Brunt-Väisälä frequency increased during this period as well.

Other aspects of the change in the current regime are reflected in a "steadiness" factor defined as the ratio of the vector-averaged velocity to the mean

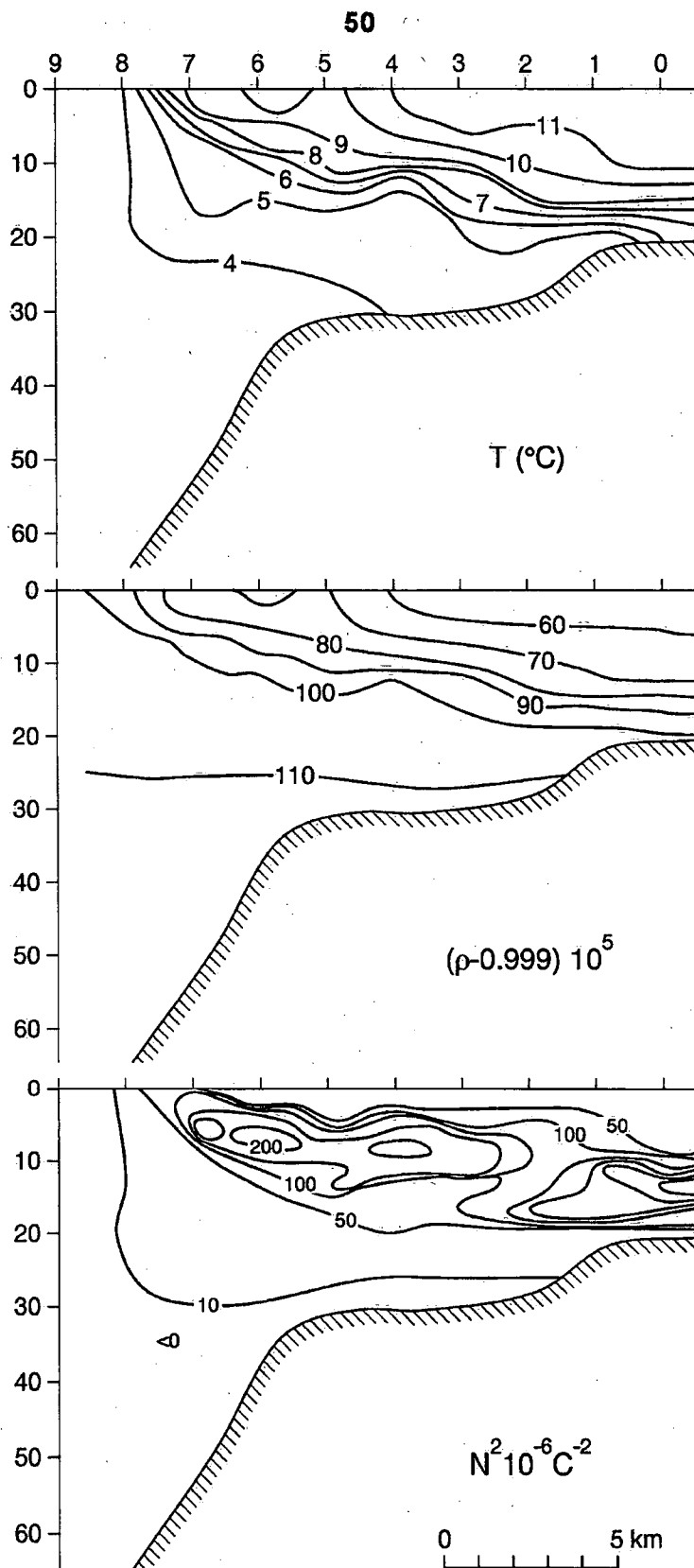


Figure 21 Vertical distribution of temperature, density and the Brunt-Väisälä frequency in a transect perpendicular to the vernal thermal front (thermal bar).

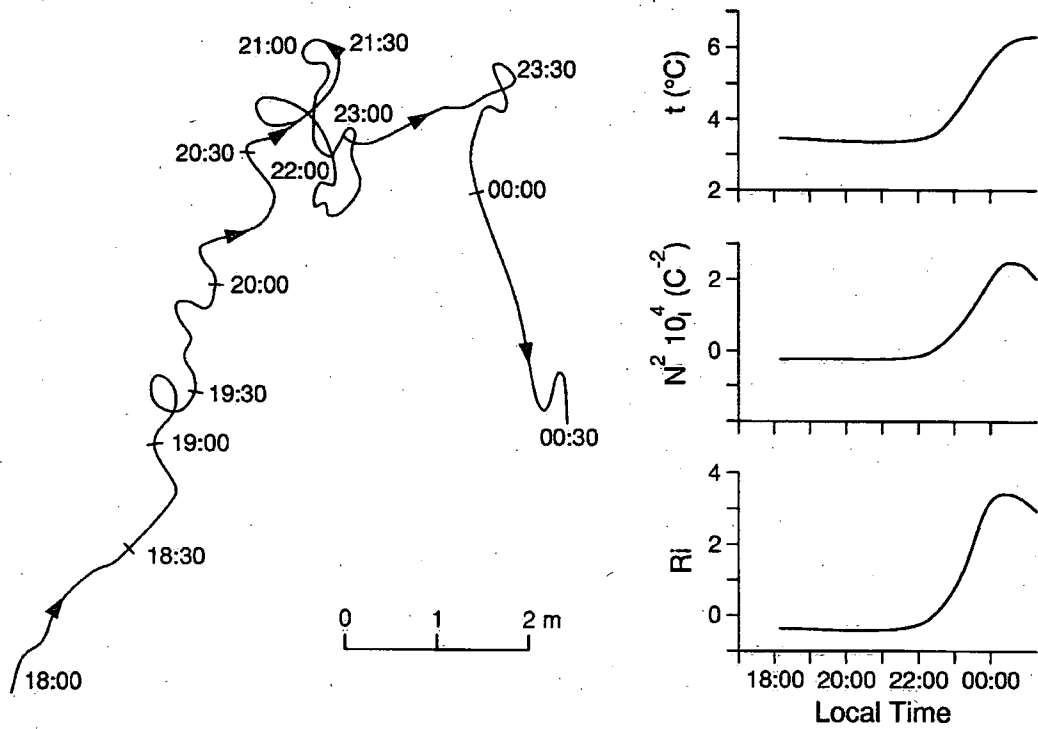


Figure 22 Lake Ladoga progressive vector diagram of coastal currents at a depth of 5 m when the thermal front passes. Observations were taken near western shore of Lake Ladoga. N^2 and Ri have been calculated for the 4-6 m and 6-10 m layers, respectively.

speed (steady flow is defined as a ratio of 100%). Before the front passed, this ratio was high at 70 to 95%. This decreased by 20% in a few hours as the front approached.

The passage of the front was characterized by a sharp increase in speed pulsations both along and across the plane of the front. The intensity of these pulsations, defined as the ratio of the standard deviation of speed, to the mean value of net vector speed was 4 to 20. Typically, this ratio is less than 1 outside the frontal zone. Speed pulsation energy increases first at the surface and only follows this pattern at greater depths several hours later.

Continuity considerations applied to a network of horizontal velocity measurements suggest that the vertical velocities in the frontal zone were of the order of 10^{-3} to 10^{-2} cm/s (Naumenko, 1989).

The Displacement and Speed of the Vernal Thermal Front

In Lake Ladoga the period during which the thermal bar moves from the shore to its disappearance lasts 7 to 8 weeks from mid-May to the beginning of July. The duration in Lake Ontario is perhaps 4 to 6 weeks beginning in April or early May and lasting typically until mid-June or even early July, in extreme years. The speed of frontal movement determines the time of onset of thermal stratification at any particular point in the lake.

In the case of Lake Ladoga, an empirical relation for the thermal bar movement (TM) has been developed based on a 30-year record:

$$TM = H - aD + bD^2$$

where H = depth (in metres) at which the 4°C surface isotherm is found;
 D = the number of days after April 20;
 a = 0.0776; and
 b = 0.0237.

The correlation coefficient is 0.9483. This is a quantitative expression of the control of depth on the progress of the thermal front.

For Lake Ladoga, the front moves rapidly in the southern shallow part of the lake and very slowly in the northern deep part. In the final states of its existence, the frontal zone movement accelerates (Figure 23).

For Lake Ontario, a slightly different analysis has been presented (Rodgers, 1987) where the date of disappearance of the thermal bar from the lake surface has been correlated with the average temperature of the water from the surface to a depth of 100 m in the deepest part of the lake on April 1st. Since Lake Ontario is often not frozen completely over every winter, the initial heat content of the lake is a controlling factor (see Figure 24). The implication is that the rate of heating in spring is fairly constant from year-to-year. This was subject to scrutiny in other studies (Sato and Rodgers, 1970) and found to have some validity. More critical analyses would have to take account of these differences in heating rates from year-to-year.

By the 1st of June, the stratified area of Lake Ladoga is 51% of the total and encompasses 60% of its volume. On June 20, these figures are 86% and 90%, respectively.

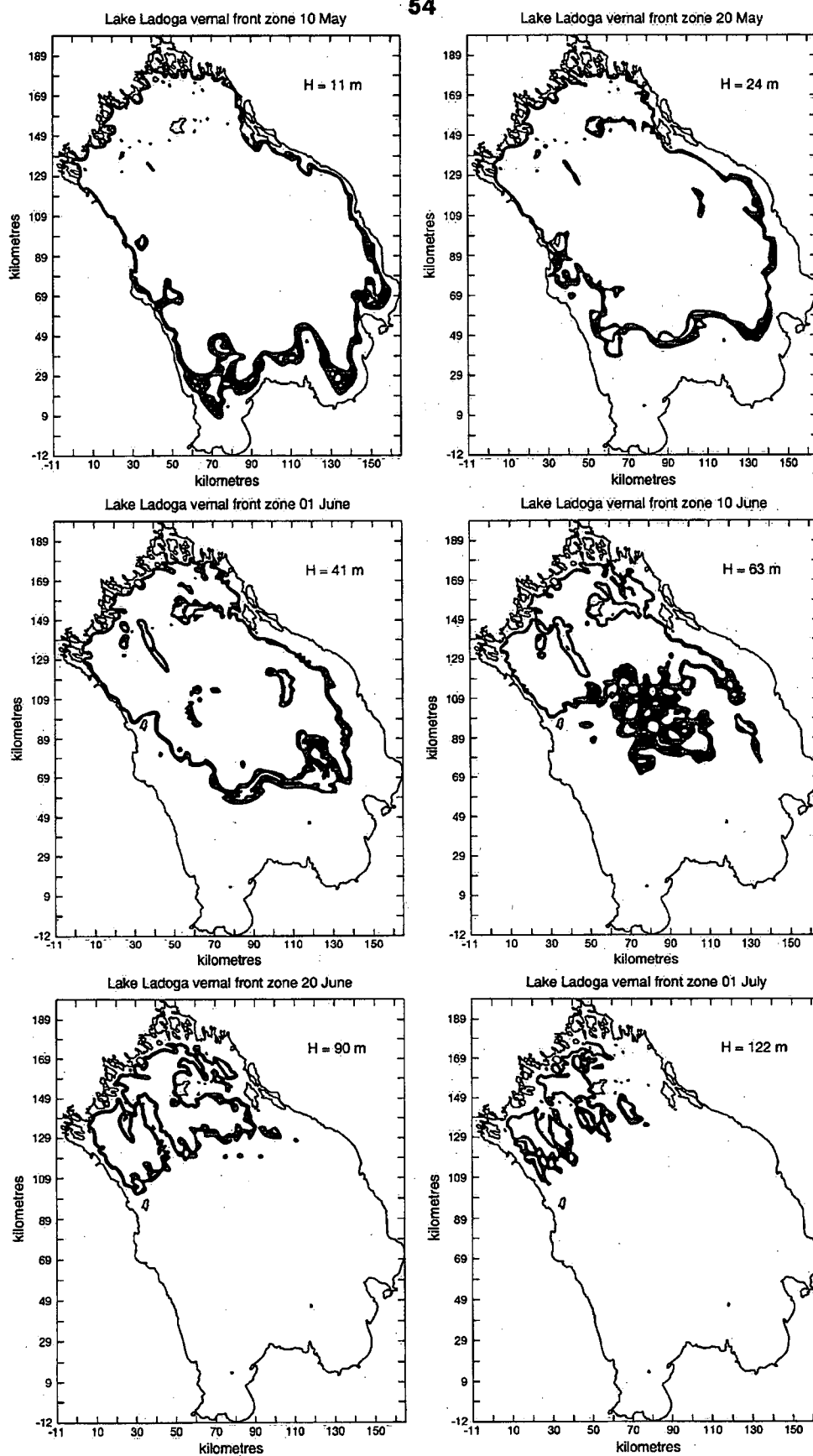


Figure 23 The position of the vernal thermal front for dates from May 10 to July 01 for several years, for Lake Ladoga. (H is the mean depth at the 4°C isotherm)

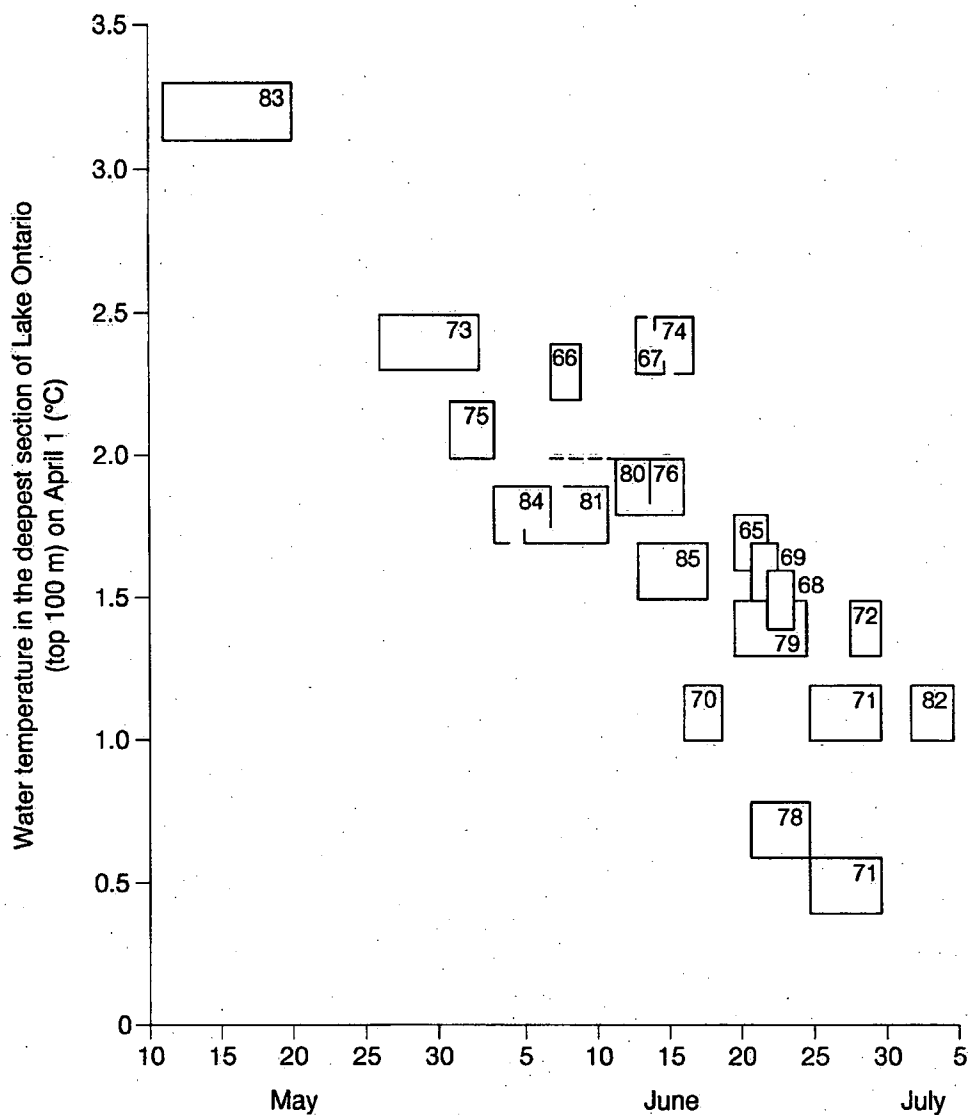


Figure 24 Date of full stratification or disappearance of the surface 4°C isotherm as a function of the April 1 water temperature in the deepest basin of Lake Ontario just east of 77°45'W. (from Rodgers, 1987)

3.4 Autumnal Thermal Front

The outline of the fall situation is given in section 3.1. Briefly, fall winds and strong surface cooling drive the residual thermocline deeper and the capacity to absorb this heat loss again becomes highly dependent on water depth. Shallower waters cool more quickly so that nearshore waters fall below 4°C while central or deeper waters are still above that temperature.

Higher winds, aided by unstable air masses over the lake, increase wind stress and consequent mechanical mixing. The fact that cooling increments are limited by ice formation factors that figure in the energy loss absorption process, also limit stratification in the shallower waters. The consequence is that fall thermal fronts associated with the 4°C surface temperature isotherms are barely noticeable if they form at all (see Figures 15 and 18).

While thermal fronts are not a main feature of this season, there are some circulation features which are density driven that can have important consequences for the movement of waters that enter from rivers or heated effluents. The most obvious are the patterns that develop around the effluent from electrical power plants (Tikhomirov, 1959; Murthy, 1985). In situations where ice cover forms solidly and quickly over sheltered deep (100 m) water, the thermal structure development is unique (Farmer and Carmack, 1981).

Where active effluents contain higher dissolved solids, another regime develops. Dissolved solids rather than temperature dominate the path of effluent into a lake. There are few observations of such situations, although they should be evident in the deep northern archipelago of Lake Ladoga, or the sheltered channel region of eastern Lake Ontario. To date, only the effects in restricted embayments have been studied where runoff from salted roads results in density

currents that stratify the embayment under winter conditions with associated apparent temperature inversions.

3.5 Coastal Current Regime

Coastal current regimes in the Great Lakes are complex and have particular relevance to water quality concerns. Climatologies of currents and thermal structure are a prerequisite for many practical problems. Problems encountered, requiring detailed examination of the physical limnology within the coastal zone, include waste disposal through sewage outfalls, shore erosion and sediment transport, installation of coastal structures, land reclamation, and recreation.

Since hydrodynamical models are insufficiently comprehensive to predict the complex array of coastal flow regimes encountered in the coastal zone, statistical descriptions of the measured flow properties are often used. Analyses of time-series data on currents and temperature exhibit extreme variability on spatial and temporal scales, and hence, "statistical" concepts traditionally used in the fields of meteorology and oceanography have been adopted to summarize the data. Based largely on the analysis of statistical measures of the flow regimes, the relative frequencies of occurrence and duration of various flow regimes can be identified, and a climatology of the flow regime can be produced for a particular location. Generalizations based on the climatology can be made for other similar locations. Understanding the structure of the currents has also been achieved through examination of episodic events in which generalizations can be made using segments of the data base with more or less similar characteristics. Such analyses are particularly relevant for analysis of water quality problems.

Near the coastal boundaries of large lakes, offshore meandering currents

undergo adjustment and move primarily along the boundaries as they approach close to the shore (Murthy and Blanton, 1975). A progressive vector diagram (Figure 25) indicates that at a distance of 16 km the current vector rotates every 17 hours at the local inertial period. At a distance of 11 km from shore the oscillatory motion is still present but the net flow is orientated parallel to the shore. At 6 km offshore, the rotary motion has essentially disappeared and the currents have assumed a well defined shore parallel flow. The adjustment zone typically extends from 5 to 10 km offshore and has been referred to as the "coastal boundary layer" (Csanady, 1972a,b). Coastal boundary layer characteristics have been analyzed at several transects in the Great Lakes (Csanady, 1972a,b; Boyce, 1977; Blanton, 1974, 1975).

Figure 26 shows an example of coastal boundary layer characteristics (Murthy and Dunbar, 1981; Murthy *et al*, 1984). The alongshore component dominates the flow field and peaks at a distance of 2 to 3 km from shore. This peak divides the flow field into two distinct zones, each of which exhibiting the traditional boundary layer characteristics. Close to the shore, an inner boundary layer flow develops with bottom friction gradually bringing the flow to a halt at the shoreline (frictional boundary layer - FBL). Beyond this an outer boundary layer develops as a consequence of the adjustment of inertial oscillations to the shore parallel flow (inertial boundary layer - IBL). FBL + IBL form the total coastal boundary layer.

3.6 Coastal Upwelling

An important manifestation of coastal circulation is coastal upwelling during which strong alongshore currents are observed. Under the thermally stratified conditions, upwelling brings cold nutrient-rich hypolimnion water into the

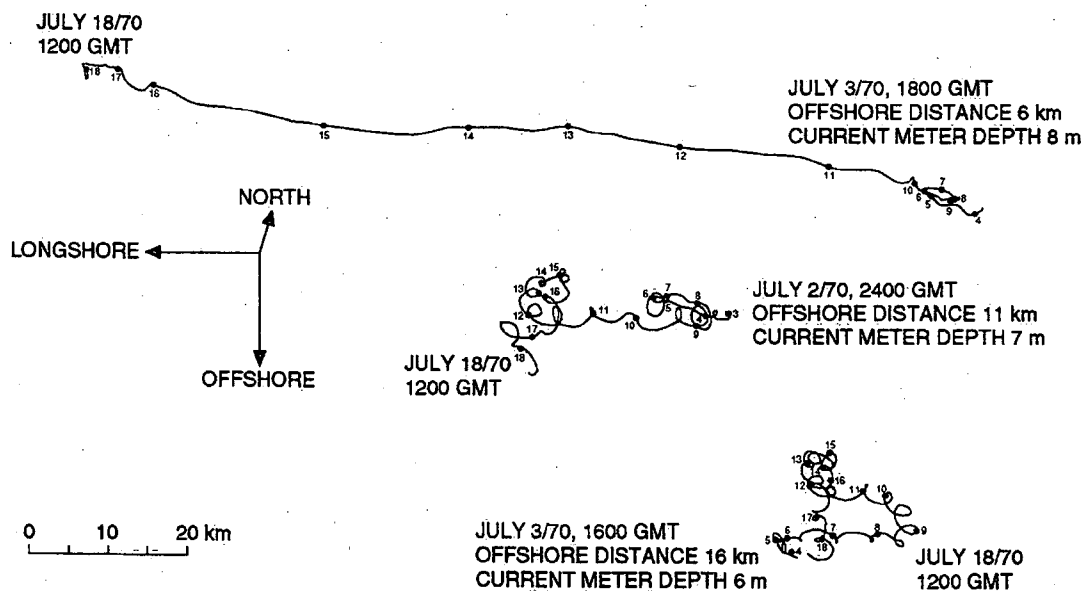


Figure 25

Frictional Boundary Layer (FBL)

dominated by bottom
and shore friction

Inertial Boundary Layer (IBL) Associated
with lakewide circulation

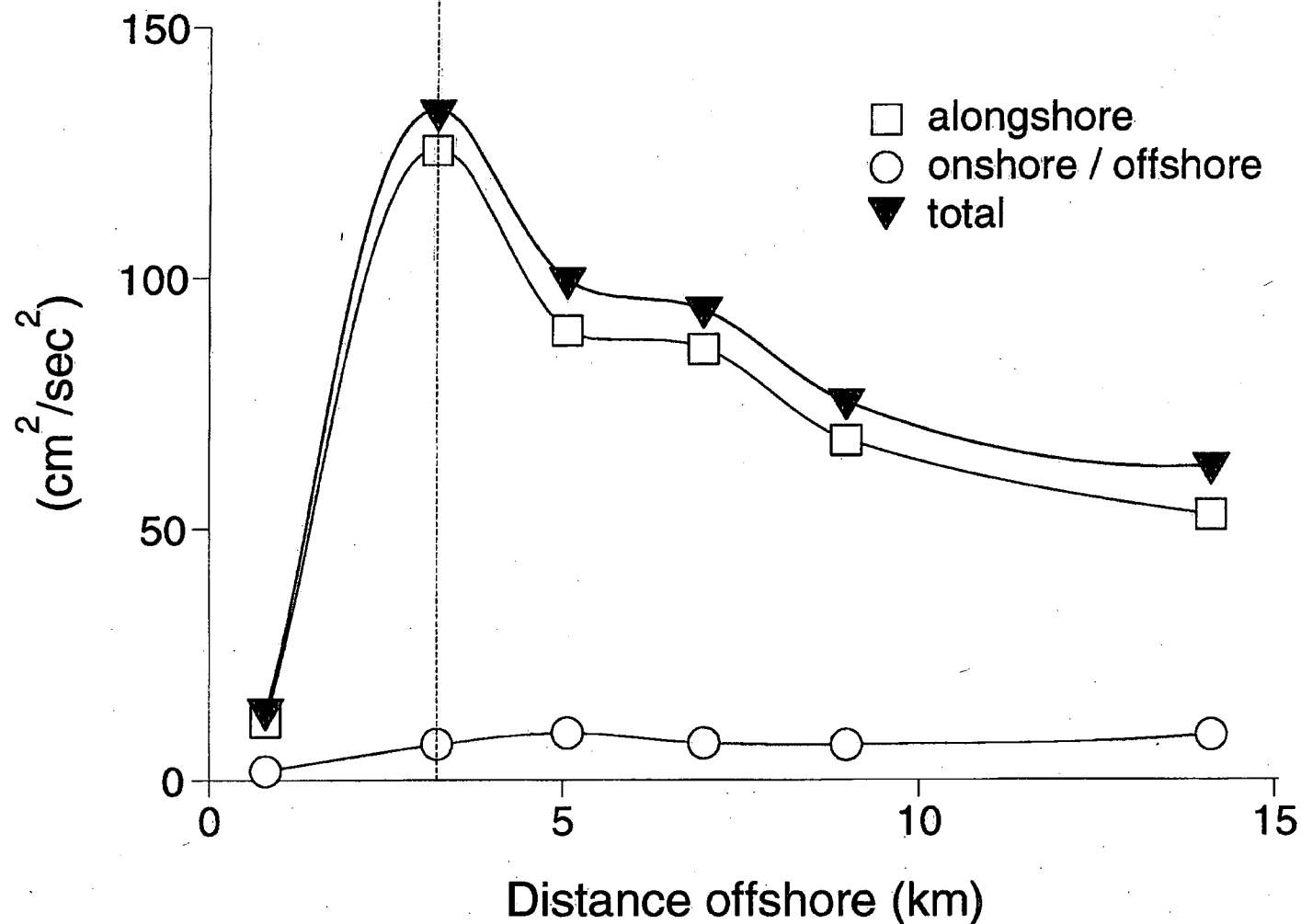


Figure 26

coastal zone, while downwelling results in the introduction of warm upper layer water to lower layers. 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. In the presence of stratification, thermocline displacements due to upwelling or downwelling decrease rapidly with offshore distance and affect only a strip of a few kilometres adjacent to the shore (Charney, 1955). Once established by the wind, a pattern of upwelling and downwelling may propagate around the lake. A thermocline wave of this type, confined to a narrow strip near the coast, is known as an internal Kelvin wave. The alongshore propagation of warm and cold water after major upwelling events was first observed in Lake Michigan (Mortimer, 1963).

An example of coastal upwelling along the north shore of Lake Ontario, showing the general thermal structure and coastal currents, is shown in Figure 27. The width of the coastal zone is about 10 km, and it is within this zone that the temperature can vary dramatically (as much as 8 to 10°C). Associated with such upwellings are strong eastward flowing coastal jets to about 10 km from shore (Csanady and Scott, 1974).

The dynamics of coastal upwelling dealing with the forcing of local winds and the alongshore counterclockwise propagation of internal Kelvin waves following major upwelling events are illustrated in Figure 28 (Simons and Schertzer, 1987). An initial downwelling and westward flow along the north shore (August 24 and 25) changes to upwelling and current reversal in response to the passage of a warm water wave (August 26 and 27). Along the south shore, the wind seems to have little effect, and a strong eastward current persists throughout the episode. The warm water wave has a thermocline excursion of approximately 19 m, with a propagation speed of approximately 20 km/d, based on the empirical model of Bennett and Lindstrom (1977). The thermocline excursions are accompanied by alongshore currents in a narrow coastal strip. Above the

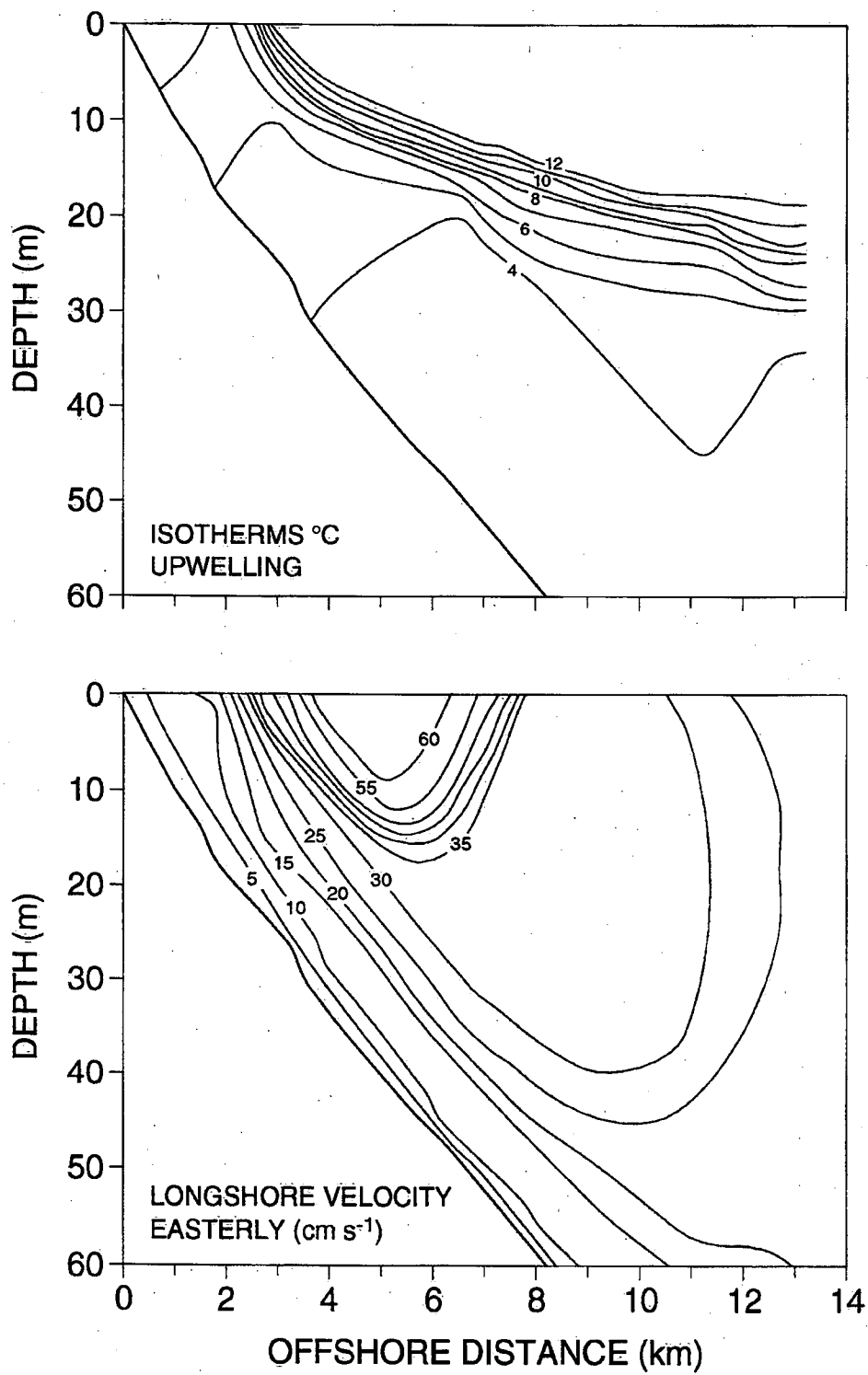
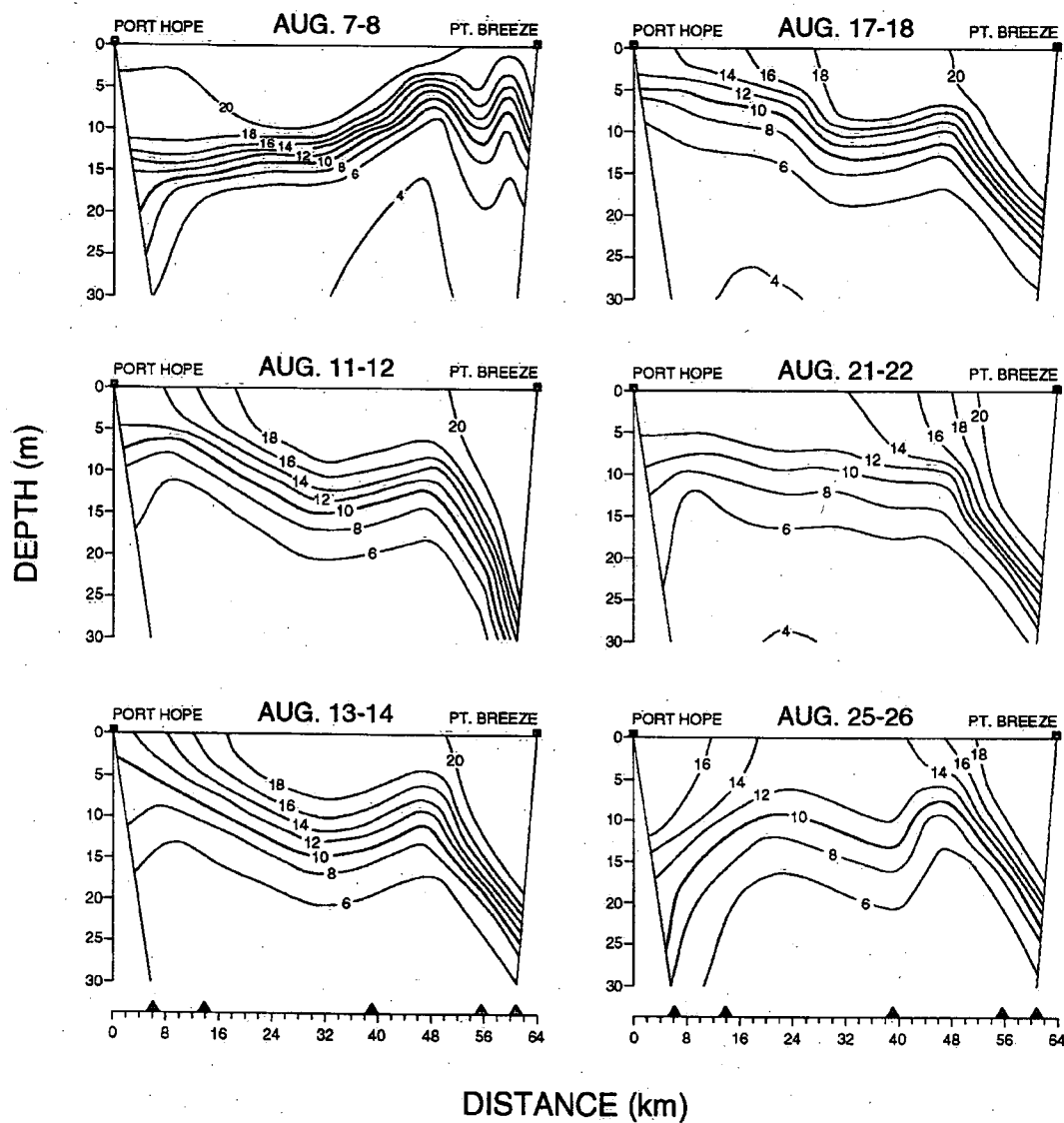
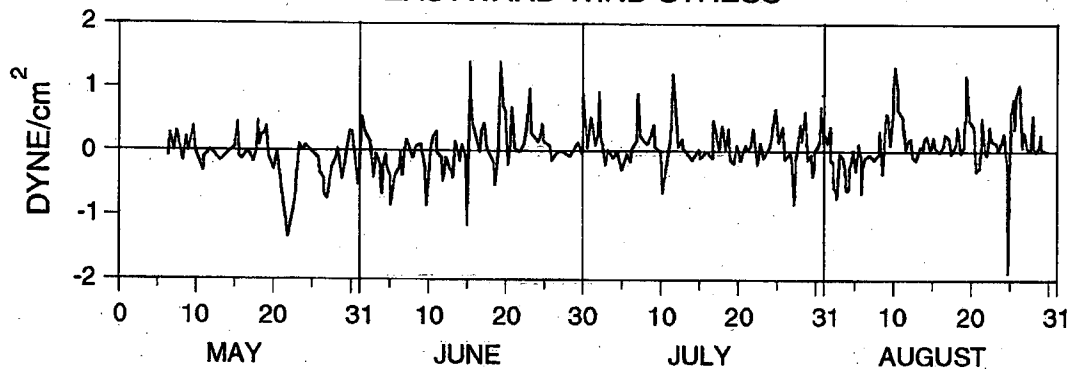


Figure 27

EASTWARD WIND STRESS



COASTAL UPWELLING

Figure 28

thermocline the currents run with the shore on their left in upwelling zones, and with the shore on their right in downwelling areas. As the warm water wave moves, so does the current pattern, such that eastward currents induced by the wind on the north shore will turn to the west as warm water approached. Under conditions of current reversals associated with upwelling and downwelling events, dye diffusion experiments show that the entire coastal water is renewed as a direct consequence of offshore mass exchange (Murthy, 1973).

4.0 SUMMARY

The broad characteristics of heating and thermal stratification are similar in Lakes Ladoga and Ontario. The major difference is the extensive formation of a solid ice cover in Lake Ladoga. Lake Ladoga is at a higher, colder latitude. This contrasts with Lake Ontario which usually has large unfrozen or moving ice areas throughout winter. This will have a major impact on differing mixing characteristics between the two lakes in winter.

Discharge from rivers and nearshore outfalls is subject to a circulation and diffusion regime determined largely by the volume of outflow and the local physical morphometry. And this latter can be quite restrictive as shallow water, embayments, nearshore ice cover conditions and island sheltering all constrain the mixing processes. This usually calls for a more detailed site-specific coastal climatology to be developed based on observational data.

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