

SPRING THERMAL FRONTS AND  
SALMONINE DISTRIBUTIONS IN LAKE ONTARIO

A Thesis

Presented to the Faculty of the  
Center for Applied Aquatic Science and Aquaculture  
Department of Biological Sciences  
of the State University of New York  
College at Brockport in Partial  
Fulfillment for the Degree  
of Master of Science

by

Dana C. Aultman

December 1991

THESIS DEFENSE

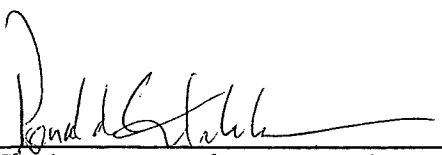
APPROVED

NOT APPROVED

✓

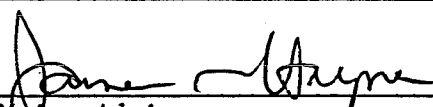
✓

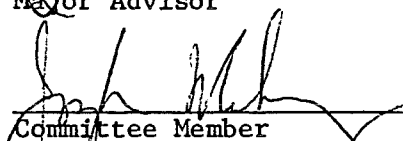
✓




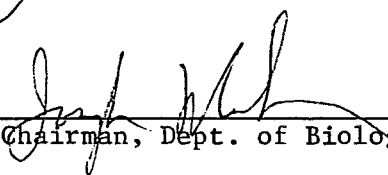
Chairman, Graduate Committee

MASTER'S DEGREE ADVISORY COMMITTEE

 12/13/91  
Major Advisor Date

 12/13/91  
Committee Member Date

 12/13/91  
Committee Member Date

  
Chairman, Dept. of Biological Sciences

THESIS DEFENSE

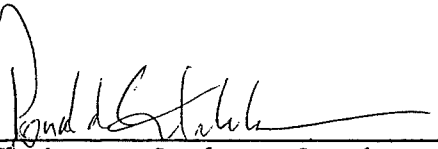
APPROVED

NOT APPROVED

✓

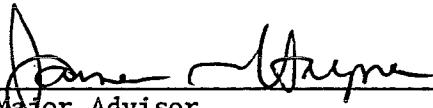
✓

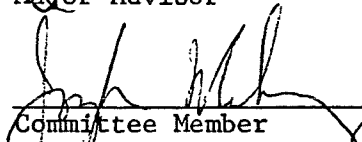
✓

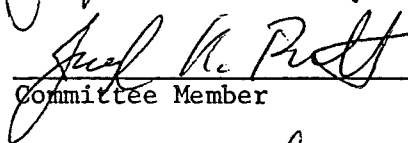


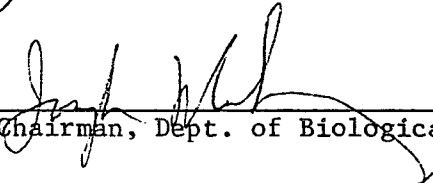
Chairman, Graduate Committee

MASTER'S DEGREE ADVISORY COMMITTEE

 12/13/91  
Major Advisor Date

 12/13/91  
Committee Member Date

 12/13/91  
Committee Member Date

  
Chairman, Dept. of Biological Sciences

## **Abstract**

The hypothesis that salmonine catches in Lake Ontario are greater at thermal fronts in spring and early summer was tested in 1990 by comparing catches in non-frontal water and three types of fronts (thermal bar, 4 °C; spring thermocline, 6-8 °C; thermal break,  $\geq 9$  °C). A thermal front in the spring on Lake Ontario is a rapid temperature cline across the surface of the lake (in this study defined as  $\geq 0.15$  °C/min at the standard 3.2 – 4.8 km/h trolling speed) parallel to shore that extends obliquely from the surface toward shore and the bottom. Surface temperature was recorded every 2 min during 45 hours of fishing. Only 20% of the time was spent fishing in thermal fronts where 35% of the 88 strikes occurred. Catch per unit effort (CPUE) for salmonines at thermal fronts was significantly greater than non-frontal CPUE on each of the 11 sampling dates ( $P < 0.001$ ). Catches were better in thermal breaks ( $P < 0.002$ ), spring thermocline ( $P < 0.01$ ) and thermal bar ( $P < 0.05$ ) than in non-frontal waters. The data support the hypothesis that there is a relationship between salmonine susceptibility to capture and thermal fronts. Relative to non-frontal water, coho salmon (Oncorhynchus kisutch) CPUE was greater in the spring thermocline ( $P < 0.01$ ); rainbow/steelhead trout CPUE was greater in thermal breaks ( $P < 0.05$ ), spring thermocline ( $P < 0.05$ ) and thermal bar ( $P < 0.002$ ). It appears that anglers can effectively catch specific salmonine species by fishing specific thermal structures. These results likely are applicable to other pelagic habitats utilized by salmonines.

## **Acknowledgments**

I would like to thank my major advisor, Dr. James M. Haynes, and my graduate committee, Drs. Joseph K. Buttner, Joseph Makarewicz and Edward E. Southwick for their support, ideas and patience throughout this investigation. Additionally, I would like to thank Drs. Stephen B. Brandt, Betty Lou Brett and Douglas S. Lee for reviewing this manuscript. This research would not have been possible without the volunteer help of charter professionals Bill and Mary Ashmore and sportfisher Paul Cowan. Their generosity, experience and patience were invaluable and much appreciated. I thank Dr. James N. McNamara for his expert help in the statistical analysis of the data. Finally, I would like to thank my wife, Maggie, for her unwavering support throughout the entire thesis project.

## **Table Of Contents**

Abstract .....	ii
Acknowledgments .....	iii
Table Of Contents .....	iv
List of Tables .....	v
List of Figures .....	v
Introduction .....	1
Materials and Methods .....	4
Results .....	7
Discussion .....	13
Literature Cited .....	17
Appendix 1. Derivation of 95% $\chi^2$ Confidence Intervals .....	20
Appendix 2. Summary data used to compute CPUE's. ....	22
Appendix 3. Daily Cruise Temperature Plots .....	23
Appendix 4. Raw data for strikes in Lake Ontario in Spring 1990 .....	36

### **List of Tables**

Table 1.	Comparison of depths where catches occurred between frontal and non-frontal waters and between species .....	11
Table 2.	Comparison of fish weights between frontal and non-frontal waters and fish weights among species.....	12

### **List of Figures**

Figure 1.	Idealized thermal bar, spring thermocline and thermal break structures of southcentral Lake Ontario .....	2
Figure 2.	Comparison of frontal and non-frontal catch per unit effort (based on strikes) for Lake Ontario salmonines for each cruise in spring 1990 .....	8
Figure 3.	Species-specific catch per unit effort of Lake Ontario salmonines for each frontal type in spring 1990.....	9
Figure 4.	Front-specific catch per unit effort for each species caught in Lake Ontario in spring 1990.....	10

## **Introduction**

In environments as diverse as the Great Lakes, Gulf Stream and Tasman Sea, thermal fronts act as ecotones or zoogeographic barriers that influence the distributions of aquatic organisms (Brandt and Wadley 1981) and resource partitioning (Brandt et al. 1980; Olson et al. 1988). Based on radiotelemetry data, Haynes et al. (1986) hypothesized that rainbow/steelhead trout, Oncorhynchus mykiss, in Lake Ontario moved offshore in the spring in association with thermal fronts. Subsequently, anglers reported anecdotally that catches were better at thermal fronts than in non-frontal waters. However, the relationship between salmonine catches and spring thermal structures has not been tested experimentally.

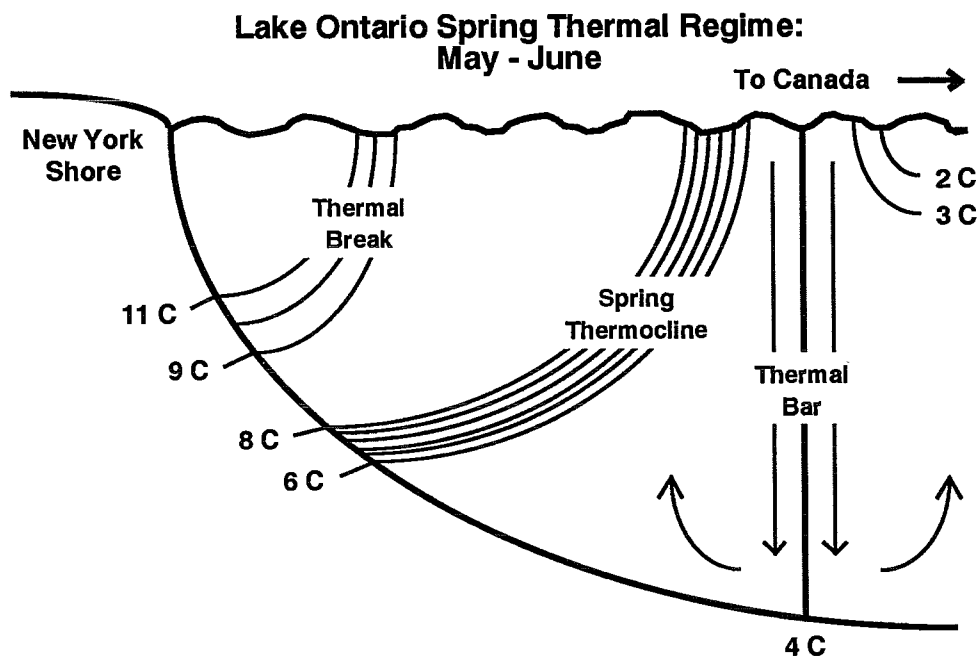
Lake Ontario is a large body of water vertically stratified by temperature during the summer months. This stratification has three distinct zones: a warm upper epilimnion, rapidly decreasing temperatures in the metalimnion and a cold lower hypolimnion (Cole 1983). These relatively stable zones of water are formed by highly dynamic and transitory thermal structures, called thermal fronts, originating in early spring. Thermal fronts are sharp horizontal or vertical temperature gradients at or near the surface of Lake Ontario (Rodgers 1965; Csanady 1974).

In a typical Lake Ontario winter, surface waters cool to less than 4 °C (Rodgers 1965; Csanady 1974). As surface temperatures near shore rise in the spring, water sinks at the 4 °C isotherm, producing a nearly vertical thermal front called the thermal bar (Rodgers 1965). This is the first thermal front to form and



the temperature change across this front can be as much as 5-7 °C per 100 m (Rodgers 1966).

On calm days other distinct physical characteristics besides rapid temperature change are associated with the thermal bar (Figure 1). Floating material, such as insects and plant debris, is visible on the surface as a thin line at the 4 °C isotherm (Rodgers 1966). The water on the offshore side of the bar is generally dark blue and glassy smooth at the surface. The nearshore side of the bar is usually turbid, greenish in color and rippled at the surface (Rodgers 1965, 1966, 1968).



**Figure 1.** Idealized thermal bar, spring thermocline and thermal break structures of southcentral Lake Ontario.

The second thermal front to form is the spring thermocline (Figure 1), characterized by closely spaced isotherms from 6-8 °C (Csanady 1974; Haynes et al. 1986). It is located between shore and the thermal bar, usually close to the thermal bar. Like the thermal bar, the spring thermocline is a surface emergent thermal front with subsurface features. The spring thermocline isotherms extend from the surface back toward shore and eventually intersect the bottom.

The last spring thermal fronts to form are thermal breaks (Figure 1). They are located between the spring thermocline and shore and are characterized by closely spaced isotherms at temperatures  $\geq 9$  °C (Haynes et al. 1986).

All three thermal fronts move offshore as the waters near shore warm. When north bound thermal fronts encounter their south bound Canadian counterparts, they submerge and form the summer metalimnion that persists until fall when the processes reverse.

In spring 1990, I tested the hypothesis that salmonine catches were greater in three types of thermal fronts (thermal bar, 4 °C; spring thermocline, 6-8 °C and thermal breaks,  $\geq 9$  °C) than in non-frontal waters. Additionally, I investigated the species composition and depths of capture of salmonines caught in thermal fronts and non-frontal waters.

## **Materials and Methods**

Eleven cruises were conducted during the day on the southern shore of Lake Ontario from late April to mid June 1990 by a professional charter boat ( $n = 8$ ) and a sportfishing boat ( $n = 3$ ). There were no restrictions on angling methods; pilots were encouraged to catch as many fish as possible. Angling techniques were typical for the spring season. Lures were mostly spoons and plugs. Trolling methods were downriggers, planer boards and dipsy-divers.

The pilots would begin a cruise using a variety of lures and trolling methods. When a strike occurred, they would note the combination and equip other rods in a similar manner. If the combination continued to be successful, more rods would be changed to maximize the catch.

Thermal fronts were detected by monitoring surface temperatures with hull-mounted sensors. The pilots trolled until thermal fronts were encountered, then repeatedly crossed the frontal and non-frontal waters perpendicular to the fronts (Appendix 3). Trolling speeds were relatively constant, typically 3.2 – 4.8 km/h (53 – 80 m/min), and were maintained by the pilots to optimize the action of lures being trolled. For this study, a thermal front was defined as a temperature gradient  $\geq 0.15$  °C/min. This criterion was empirically determined in a preliminary study in spring 1989. In both 1989 and 1990, temperature gradients in non-frontal waters seldom exceeded 0.015 °C/min so the temperature gradient selected,  $\geq 0.15$  °C/min, was an order of magnitude greater.

Every 2 or 3 minutes during each cruise, the time of day, surface temperature, water depth and number of rods being fished were recorded. When

a strike occurred, the time of day and depth of lure (if known) were logged. If the fish was landed, the species and weight were recorded.

For each 2 or 3 minute data interval, a rate of change of temperature ( $\Delta T$ ) across that interval was calculated. If  $\Delta T$  was  $\geq 0.15$  °C/min the interval was considered to be in a thermal front or frontal. If  $\Delta T$  was  $< 0.15$  °C/min the interval was considered non-frontal. Because lures were trolled at varying distances behind the boat, and thermal fronts angled obliquely toward shore with increasing depth, a strike was considered frontal if it occurred in a frontal interval or during the interval immediately preceding or following a frontal interval.

Catch per unit effort (CPUE) was calculated as the number of strikes or the number of fish landed  $\div$  mean number of rods fished  $\div$  number of minutes fished  $\times 1000$  (to get values greater than unity). Mean CPUE's were computed for frontal and non-frontal strikes for all 11 cruises and compared by the Mann-Whitney test (Zar 1984). The depths of strikes and the weights of fish caught in frontal and non-frontal waters were compared using the Kruskal-Wallis test (Zar 1984). All statistical tests were computed with SYSTAT 5.0™ software (Wilkinson 1989) on a Macintosh™ computer.

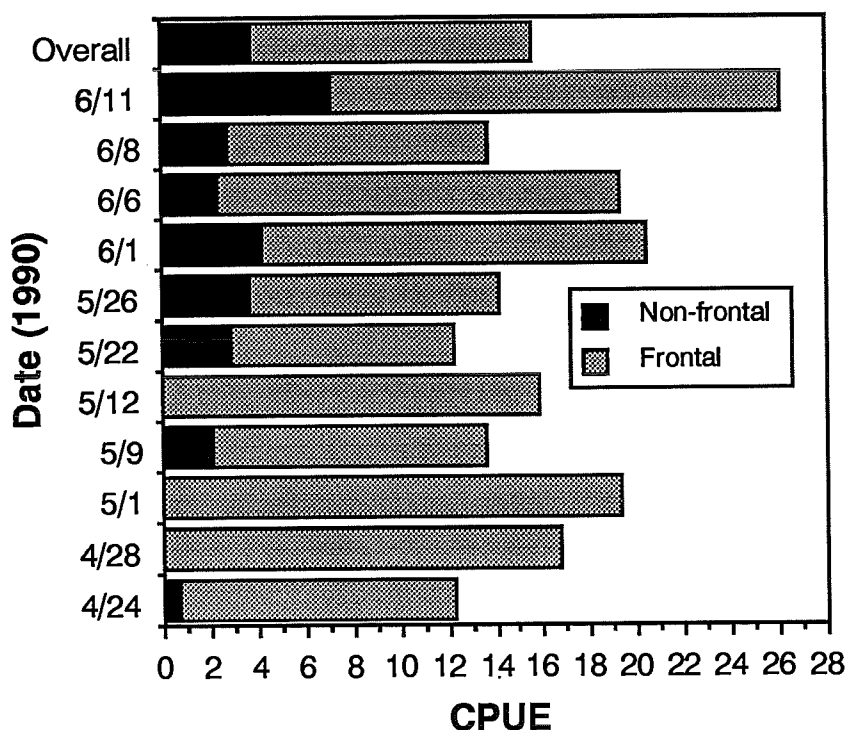
Catches at the thermal bar, spring thermocline and thermal breaks were compared by 95%  $\chi^2$  confidence intervals. For each frontal type, the number of minutes fished  $\times$  mean number of rods fished  $\div$  number of strikes (rod $\cdot$ min  $\div$  strike value) was considered a random variable with a gamma distribution (Lindgren 1962). This distribution is related to the  $\chi^2$  distribution (Hogg and Craig 1965). In a similar manner, catches by species were compared for each frontal type by considering fish that were landed and identified (strikes were excluded). Rod $\cdot$ min  $\div$  fish values for each species were calculated and analyzed

using 95%  $\chi^2$  confidence intervals. See Appendix 1 for the derivation of 95%  $\chi^2$  confidence intervals used in this study.

## **Results**

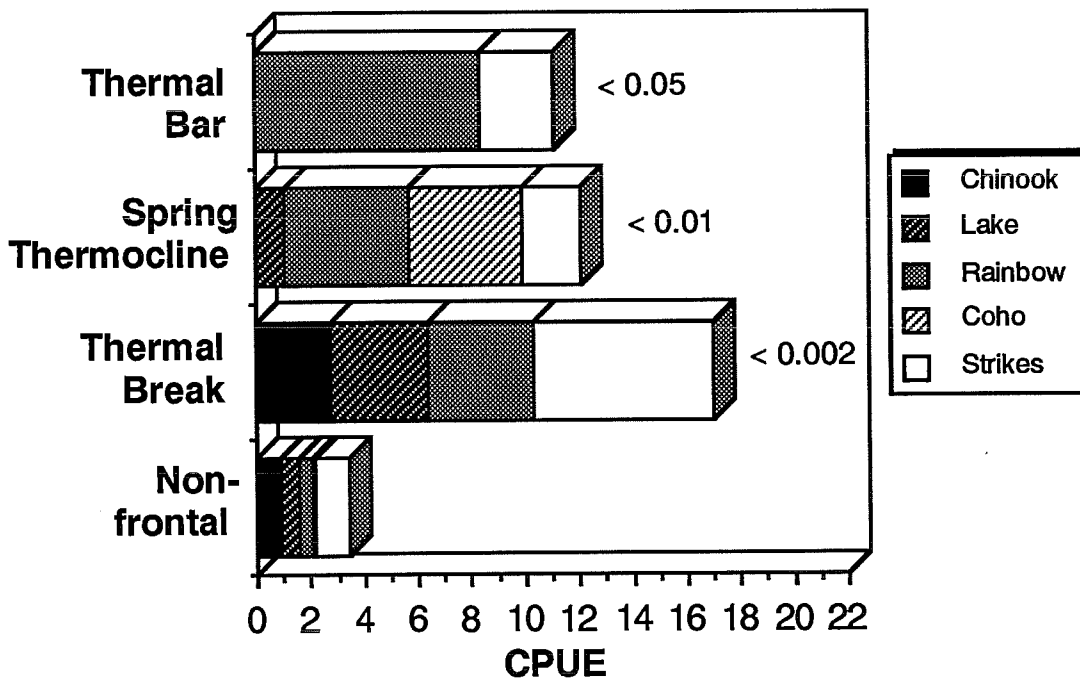
The sportfisher caught only 43% as many fish (based on CPUE), and never had a higher CPUE, than the charter pilot when fishing in thermal fronts ( $P = 0.01$ ). Consequently, frontal CPUE's were standardized for boats by dividing the sportfisher's CPUE in thermal fronts by a boat efficiency factor of 0.43. No significant difference was noted between the boats when fishing in non-frontal waters ( $P = 0.3$ ), so no efficiency correction was applied when calculating non-frontal CPUE. Appendix 2 lists the data used to compute CPUE with the efficiency correction. Appendix 3 lists the data without the efficiency correction. The comparison between frontal and non-frontal CPUE remained highly significant ( $P < 0.001$ ) when using the sportfisher's data uncorrected for efficiency. The efficiency correction was used to adjust the number of fish caught by the sportfisher in fronts for confidence interval calculations, providing more conservative comparisons.

Eleven cruises were conducted from April 24 to June 11, 1990 (Appendix 3). During 45 h of trolling, 20% of the effort was in thermal fronts and 80% was in non-frontal waters. In all, 88 strikes were recorded (Appendix 4) with 35% of those occurring in thermal fronts. The 59 fish landed consisted of 18 chinook salmon (*Oncorhynchus tshawytscha*), 17 rainbow/steelhead trout (*O. mykiss*), 7 coho salmon (*O. kisutch*), 16 lake trout (*Salvelinus namaycush*) and 1 brown trout (*Salmo trutta*). Twenty two of the fish were caught in thermal fronts. For strikes, frontal CPUE was significantly higher than non-frontal CPUE for each of the 11 cruises ( $P < 0.001$ , Figure 2). Overall, frontal CPUE was more than three times greater than non-frontal CPUE.



**Figure 2.** Comparison of frontal and non-frontal catch per unit effort (based on strikes) for Lake Ontario salmonines for each cruise in spring 1990. Sportfisher cruises, corrected for efficiency, occurred on 28 April, 12 May and 26 May 1990.

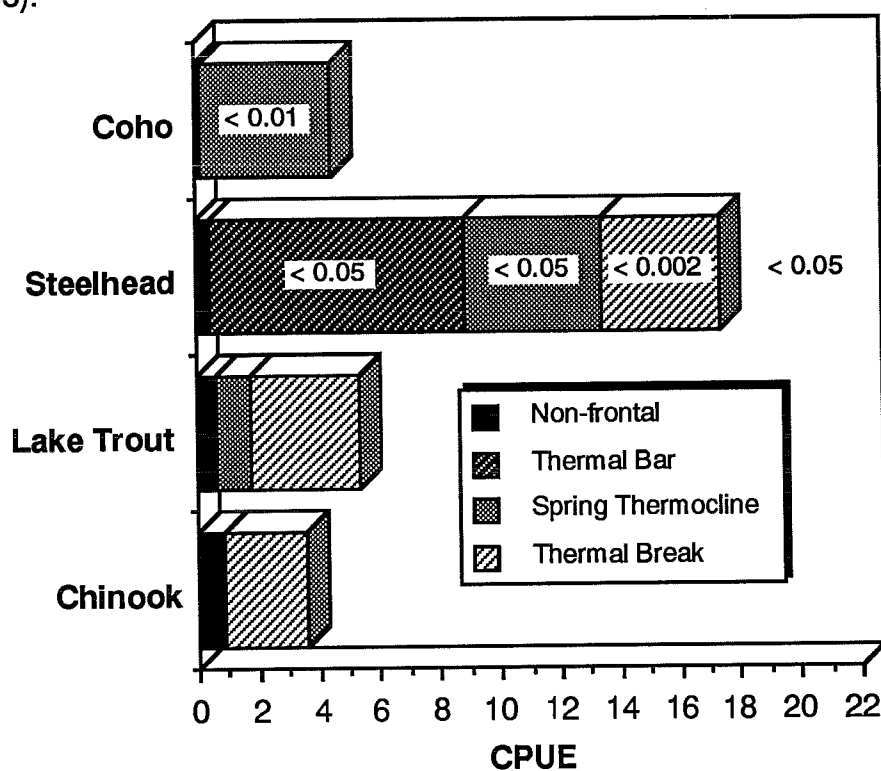
When all species were combined within each frontal type, strikes in the thermal bar ( $P < 0.05$ ), spring thermocline ( $P < 0.01$ ) and thermal break ( $P < 0.002$ ) were significantly greater than strikes in non-frontal waters (Figure 3). Within each frontal type, there was no difference in species catches ( $P > 0.05$ ). Only rainbow/steelhead trout were caught in the thermal bar.



**Figure 3.** Species-specific catch per unit effort of Lake Ontario salmonines for each frontal type in spring 1990. P values outside the stacked bars indicate significant differences between frontal CPUE's and non-frontal CPUE.



Comparisons of front-specific CPUE's for each species suggest that species distribution is related to front type (Figure 4). For coho salmon, CPUE was greater in the spring thermocline ( $P < 0.01$ ) than for non-frontal CPUE. For rainbow/steelhead trout, CPUE was greater in the thermal bar ( $P < 0.05$ ), spring thermocline ( $P < 0.05$ ) and thermal breaks ( $P < 0.002$ ) when compared to non-frontal CPUE. When all three frontal types were combined within each species and then compared across species, rainbow/steelhead trout CPUE was significantly greater than CPUE for chinook salmon, lake trout and coho salmon ( $P < 0.05$ ).



**Figure 4.** Front-specific catch per unit effort for each species caught in Lake Ontario in spring 1990. P values inside the stacked bars indicate the significances of frontal vs. non-frontal catch per unit effort within a species. P values outside the stacked bars indicate a significantly different catch per unit effort among species.

Fish caught in frontal waters were closer to the surface than fish caught in non-frontal waters ( $P = 0.014$ , Table 1). There was a significant difference in the depths where species were caught ( $P < 0.001$ ). Chinook salmon were caught in deeper water than lake trout ( $P = 0.01$ ), rainbow/steelhead trout ( $P < 0.001$ ) and coho salmon ( $P < 0.001$ ). Lake trout were caught in deeper water than rainbow/steelhead trout ( $P = 0.039$ ) and coho salmon ( $P = 0.058$ ).

Frontal Type	n	Mean Depth (m)	Std. Dev. (m)
frontal	18	2.3	5.5
non-frontal	32	7.4	8.8

Taxa	n	Mean Depth (m)	Std. Dev. (m)
chinook salmon	14	16.5	6.3
lake trout	14	7.6	8.2
rainbow/steelhead	16	1.9	4.8
coho salmon	6	0.2	0.4

**Table 1.** Comparison of depths where catches occurred between frontal and non-frontal waters ( $P = 0.014$ ) and between species ( $P < 0.001$ ).

There was no difference in fish weights between frontal and non-frontal waters ( $P = 0.242$ , Table 2). There were differences in weights among species ( $P = 0.018$ ). Lake trout ( $P = 0.001$ ) and rainbow/steelhead trout ( $P = 0.045$ ) were heavier than coho salmon, but chinook salmon were not ( $P = 0.769$ ). Most of the chinook salmon caught were small (median = 0.45 kg), but a few weighing nearly 10 kg accounted for the high variance and the lack of difference in weight between chinook and coho salmon.

Frontal Type	n	Mean Weight (kg)	Std. Dev. (kg)
frontal	19	2.53	2.09
non-frontal	35	2.08	1.99

Taxa	n	Mean Weight (kg)	Std. Dev. (kg)
lake trout	16	2.59	1.05
chinook salmon	15	2.57	3.35
rainbow/steelhead	16	2.14	1.33
coho salmon	7	0.94	0.28

**Table 2.** Comparison of fish weights between frontal and non-frontal waters ( $P = 0.242$ ) and fish weights among species ( $P = 0.018$ ).

## **Discussion**

Ecotones typically have higher abundance and diversity of organisms than adjacent habitats (Brandt 1980; Smith 1986). In small lakes and streams, edge effects are pronounced; logs, weeds, rocks and banks influence the distribution of fishes. Because of high wave energy and exceedences of thermal preferenda near shore, and great depth off shore, near shore ecotones and the bottom cannot be utilized by Great Lakes salmonines. In large aquatic systems, pelagic thermal ecotones do provide edge effects for fishes (Brandt and Wadley 1981). In Lake Ontario, do thermal fronts influence distribution of salmonines as measured by fishing success?

My data support the hypothesis that fishing success is greater at thermal fronts than in non-frontal waters. However, the relationships between species and thermal structures differed somewhat from previous reports. Haynes et al. (1986) reported that rainbow/steelhead trout tended to move offshore with the 10 °C isotherm. In my study rainbow/steelhead trout were abundant near all frontal types. Voiland and Kuehn (1990) reported anecdotally that rainbow/steelhead trout and lake trout typically were found in the thermal bar and that rainbow/steelhead trout, coho salmon and chinook salmon typically were found in the spring thermocline. In my study only rainbow/steelhead trout were caught in the thermal bar; rainbow/steelhead trout, coho salmon and lake trout were caught in the spring thermocline, but not chinook salmon. In general, all species except chinook salmon were caught near the surface; chinook salmon were caught in deeper water in thermal breaks. Voiland and Kuehn (1990) cautioned that the precise relationships between species and the different fronts may change from

year to year, although the strong general association between salmonines and thermal fronts is consistent across years.

It is likely that fishing success for salmonines is greater at thermal fronts because their abundance is greater. However, other explanations may account for their apparently greater abundance at thermal fronts. Perhaps salmonines feed more actively at fronts or greater prey abundance at fronts encourages more feeding. In Lake Michigan, Brandt (1980) reported that alewife (Alosa pseudoharengus) abundance was related to the position of the summer metalimnion. In my study and from anecdotal reports from anglers using standard chart recorders, there was no evidence of abundant fish prey in frontal or non-frontal waters. However, Brandt (1986) reported that terrestrial insects in the stomachs of salmonines caught by sportfishers were most abundant in the spring, particularly in the diet of rainbow/steelhead trout. Terrestrial insects are abundant at the surface of thermal fronts in Lake Ontario in the spring, and in my study fish were caught near the surface. Therefore, it is likely that salmonines, particularly rainbow/steelhead trout, are attracted to thermal fronts to feed on insects.

Olson et al. (1988) observed that brown trout and lake trout distributions were correlated with prey fish distributions in the summer metalimnion. They suggested that salmonines consume the prey most abundant in their preferred thermal habitat, rather than selecting thermal habitats based on prey availability. In the spring, salmonines may be attracted to thermal fronts by the rapidly changing range of temperatures within their thermal preferenda (6-15 °C). While my study does not prove that salmonine abundance is greater at thermal fronts,

greater fishing success combined with availability of insect prey and optimal temperatures suggest that abundance is greater.

Several researchers have reported a relationship between pelagic marine species distributions and ecotones. Albacore (Thunnus alalunga) movements were correlated with thermal transition zones and boundaries, and albacore were often found near the surface and close to their temperature preferenda (Owen 1968; Laurs et al. 1977; Laurs and Lynn 1977; Fiedler and Bernard 1987). Skipjack (Katsuwonus pelamis) appear to follow productive waters associated with temperature and salinity gradients (Seckel 1972; Fiedler and Bernard 1987). Sockeye salmon (Oncorhynchus nerka) movements in British Columbia coastal waters were correlated with temperature and salinity gradients (Quinn and terHart 1987). My data are consistent with distribution and abundance studies for marine fishes and thermal fronts.

My study could be improved in several ways if repeated. A larger sample could be obtained by employing more boats for fishing. However, it is difficult to find charter captains willing to give up paying customers to conduct experimental fishing. The short spring season on Lake Ontario is economically important to charter captains active in this highly competitive business. Repeating the experiment also would test the hypothesis that species and frontal relationships are similar from year to year. The scope of a future study should quantitatively address the abundance of salmonines in frontal and non-frontal waters as well as the distribution and abundance of prey species. Concurrent bioacoustic sampling of salmonines and their prey would allow researchers to directly address the abundance issue.

Great Lakes fisheries managers may find that these data present them with a dilemma. The results of my study will help spring sportfishers improve their angling success with certain species and may enhance the fishing industry. Fisheries managers may find the results useful for optimizing their sampling efforts for individual species. On the other hand, the information could accelerate the exploitation of certain species without regard to the objectives of fisheries managers. Targeted salmonine fisheries in thermal fronts, particularly with regard to efforts to restore natural self-sustaining populations of lake trout in the Great Lakes (Schneider et al. 1990), may warrant closer scrutiny by fisheries managers.

### **Literature Cited**

- Brandt, S. B. 1980. Spatial segregation of adult and young-of-the-year alewives across a thermocline in Lake Michigan. Transactions of the American Fisheries Society 109:469-478.
- Brandt, S. B. 1986. Food of trout and salmon in Lake Ontario. Journal of Great Lakes Research 12:200-205.
- Brandt, S. B., and V. A. Wadley. 1981. Thermal fronts as ecotones and zoogeographic barriers in marine and freshwater systems. Proceedings of the Ecological Society of Australia 11:13-26.
- Brandt, S. B., J. J. Magnuson, and L. B. Crowder. 1980. Thermal habitat partitioning by fishes in Lake Michigan. Canadian Journal of Fisheries and Aquatic Sciences 37:1557-1564.
- Cole, G. A. 1983. Textbook of Limnology (3<sup>rd</sup> ed.). Waveland Press, Inc. Prospect Heights, IL.
- Csanady, G. T. 1974. Spring thermocline behavior in Lake Ontario during IFYGL. Journal Physical Oceanography 4:425-445.
- Fiedler, P. C., and H. J. Bernard. 1987. Tuna aggregation and feeding near fronts observed in satellite imagery. Continental Shelf Research 7:871-881.
- Haynes, J. M., D. C. Nettles, K. M. Parnell, M. P. Voiland, R. A. Olson, and J. D. Winter. 1986. Movement of rainbow and steelhead trout (Salmo gairdneri) in Lake Ontario and a hypothesis for the influence of the spring thermocline. Journal of Great Lakes Research 12:304-313.



- Hogg, R. V., and A. T. Craig. 1965. Introduction to Mathematical Statistics (2nd ed.). The Macmillan Company, New York.
- Laurs, R. M., and R. J. Lynn. 1977. Seasonal migration of North Pacific albacore, Thunnus alalunga, into North American coastal waters: Distribution, relative abundance, and association with transition zone waters. Fishery Bulletin 75:795-822.
- Laurs, R. M., H. S. H. Yuen, and J. H. Johnson. 1977. Small-scale movements of albacore, Thunnus alalunga, in relation to ocean features as indicated by ultrasonic tracking and oceanographic sampling. Fishery Bulletin 75:347-355.
- Lindgren, B. W. 1962. Statistical Theory. The Macmillan Company, New York.
- Olson, R. A., J. D. Winter, D. C. Nettles, and J. M. Haynes. 1988. Resource partitioning in summer by salmonids in south-central Lake Ontario. Transactions of the American Fisheries Society 117:552-559.
- Owen, R. W. Jr. 1968. Oceanographic conditions in the northeast Pacific Ocean and their relation to the albacore fishery. Fishery Bulletin 66:503-526.
- Quinn, T. P., and B. A. terHart. 1987. Movements of adult sockeye salmon (Oncorhynchus nerka) in British Columbia coastal waters in relation to temperature and salinity stratification: Ultrasonic telemetry results. Canadian Special Publication of Fisheries and Aquatic Sciences 96:61-77.
- Rodgers, G. K. 1965. The thermal bar in the Laurentian Great Lakes. Proceedings of the 8<sup>th</sup> Conference of Great Lakes Research Division Publication 13:358-363.

- Rodgers, G. K. 1966. The thermal bar in Lake Ontario, spring 1965 and winter 1965-66. Proceedings of the 9<sup>th</sup> Conference of Great Lakes Research Division Publication 15:369-374.
- Rodgers, G. K. 1968. Heat advection within Lake Ontario in spring and surface water transparency associated with the thermal bar. Proceedings of the 11<sup>th</sup> Conference of Great Lakes Research Division pp. 480-486.
- Schneider, C. P., and 8 coauthors. 1990. Lake trout rehabilitation in Lake Ontario, 1989. Pages 359-377 in Great Lakes Fishery Commission, Lake Ontario Committee, Annual Meeting Reports. Ann Arbor, MI.
- Seckel, G. R. 1972. Hawaiian-caught skipjack tuna and their physical environment. Fishery Bulletin 72:763-787.
- Smith, R. L. 1986. Elements of Ecology, 2nd edition. Harper & Row, New York.
- Voiland, M., and D. Kuehn. 1990. Thermal fronts: Magnets for Great Lakes salmon and trout. Coastal Sportfisheries Fact Sheet. New York State Sea Grant - Cornell Cooperative Extension, Ithaca, NY.
- Wilkinson, L. 1989. SYSTAT: The system for statistics. SYSTAT, Inc. Evanston, IL.
- Zar, J.H. 1984. Biostatistical Analysis (2<sup>nd</sup> ed.). Prentice-Hall, Inc. Englewood Cliffs, NJ.

Appendix 1. Derivation of 95%  $\chi^2$  Confidence Intervals based on the gamma distribution of rod-minutes per strike or fish.

If  $\mu$  = average number of rod-minutes required to catch 1 fish, a 95% confidence interval would be:

$$\left( \frac{2 \times TF}{\chi^2(2 \times N, 0.975)}, \frac{2 \times TF}{\chi^2(2 \times (N+1), 0.025)} \right)$$

where TF = total number of rod-minutes used to catch fish (Lindgren 1962).

The random variable TF has a gamma distribution and parameters:

$$\alpha = N$$

$$\beta = \mu \text{ (Lindgren 1962)}$$

$\therefore$  the probability is 95% that:

$$\text{gamma}(N, \mu, 0.975) < TF < \text{gamma}(N+1, \mu, 0.025) \quad (\text{equation 1})$$

The gamma distribution is related to the  $\chi^2$  distribution by:

$$\text{gamma}(\alpha, \beta, P) = \left( \frac{\beta}{2} \right) \times \chi^2(2 \times \alpha, P) \text{ (Hogg and Craig 1965)}$$

Substituting this into equation 1:

$$\left( \frac{\beta}{2} \right) \times \chi^2(2 \times \alpha, 0.975) < TF < \left( \frac{\beta}{2} \right) \times \chi^2(2 \times \alpha, 0.025)$$

substituting  $\beta = \mu$  and  $\alpha = N$  and  $N + 1$ :

$$\left( \frac{\mu}{2} \right) \times \chi^2(2 \times N, 0.975) < TF < \left( \frac{\mu}{2} \right) \times \chi^2(2 \times N + 1, 0.025)$$

Multiplying by  $\frac{1}{\mu \times TF}$  yields:

$$\frac{\chi^2(2 \times N, 0.975)}{2 \times TF} < \frac{1}{\mu} < \frac{\chi^2(2 \times N + 1, 0.025)}{2 \times TF}$$

Solving for  $\mu$ , we get:

$$\frac{2 \times TF}{\chi^2(2 \times N + 1, 0.025)} < \mu < \frac{2 \times TF}{\chi^2(2 \times N, 0.975)}$$

Example Calculation:

$N = 10$  = number of fish caught

$TN = 935$  = number of rod-minutes to catch  $N$  fish

From "Critical values of the  $\chi^2$  distribution table" (Zar 1984):

$$\chi^2(2 \times N, P) = \chi^2(2 \times 10, 0.975) = \chi^2(20, 0.975) = 9.591$$

$$\chi^2(22, 0.025) = 36.781$$

$$\frac{2 \times 935}{36.781} < \mu < \frac{2 \times 935}{9.591} \text{ rod-minutes}$$

$$51 < \mu < 195 \text{ rod-minutes}$$

Therefore,  $p\{51 < \mu < 195\} = 0.95$

Source: Dr. James N. McNamara, Department of Mathematics, State University of New York, College at Brockport.

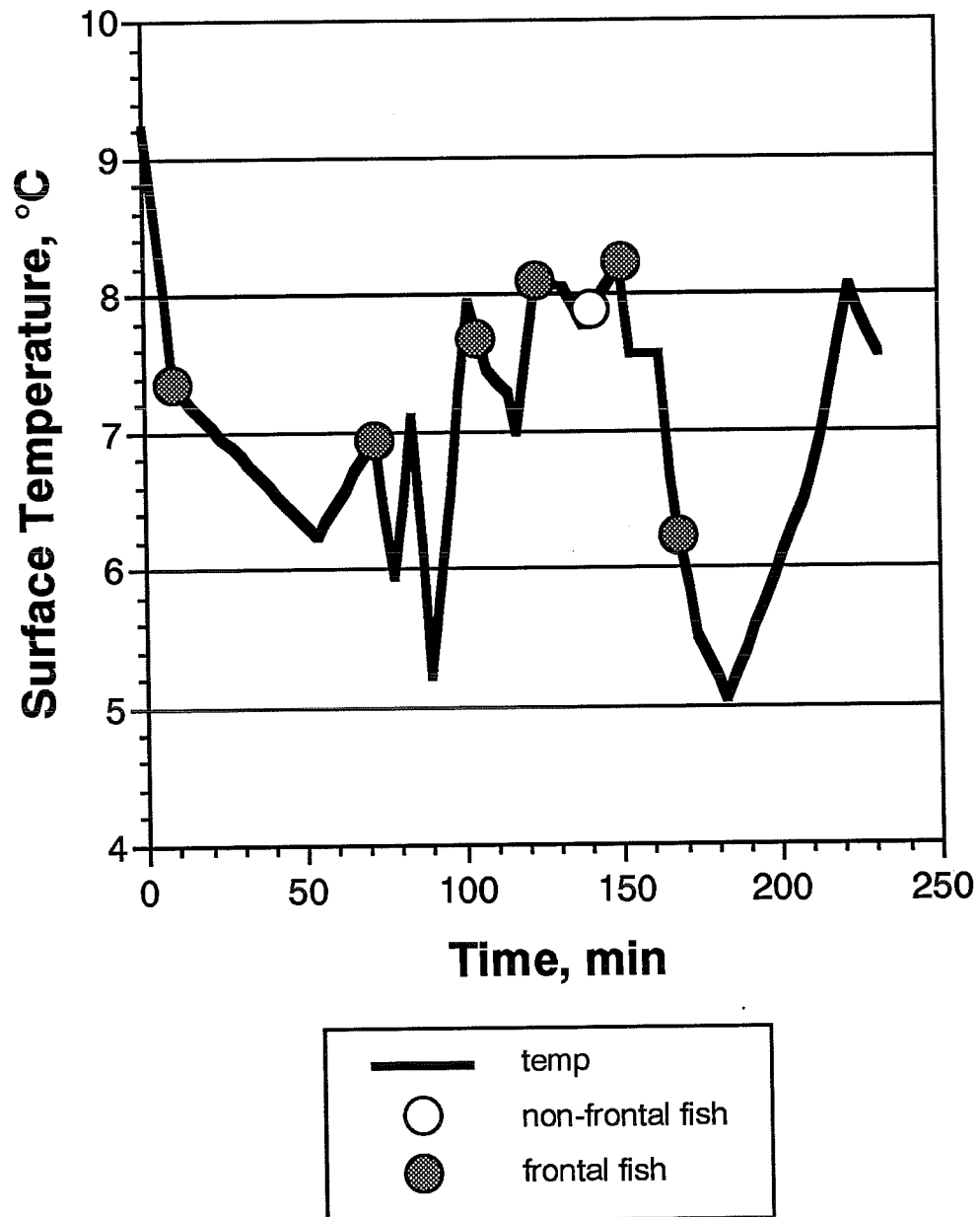
Appendix 2. Summary data used to compute CPUE's. For frontal and non-frontal waters,  $CPUE = \#Str \div \#Rods \div \#Min \times 1000$ . Efficiency differences between boats for frontal CPUE's were corrected by dividing the mean frontal CPUE for the sportfisher boat (6.21) by the mean frontal CPUE for the charter boat (14.35) to get an efficiency ratio (0.43). The number of frontal strikes by the sportfisher boat was adjusted by dividing by the efficiency ratio. #Str = number of strikes, F = frontal, NF = non-frontal, % T = percent time fished.

Cruise Date	#Str (F)	#Rods (F)	#Min (F)	#Str (NF)	#Rods (NF)	#Min (NF)	Total Min	% T (F)	% T (NF)	CPUE (F)	CPUE (NF)	CPUE Ratio
24 April	6	10.1	51	1	8.9	180	231	0.22	0.78	11.6	0.6	18.6
28 April <sup>a</sup>	9.3	3.8	147	0	3.5	135	282	0.52	0.48	16.7	0	
1 May	3	4.7	33	0	6.5	75	108	0.31	0.69	19.3	0	
9 May	1	5.4	16	2	9.8	98	114	0.14	0.86	11.6	2.1	5.5
12 May <sup>a</sup>	4.6	3.0	98	0	2.9	156	254	0.39	0.61	15.8	0	
22 May	1	6.7	16	6	8.8	236	252	0.06	0.94	9.4	2.9	3.2
26 May <sup>a</sup>	2.3	3.7	60	3	3.7	222	282	0.21	0.79	10.5	3.7	2.9
1 June	4	9.5	26	26	11.6	534	560	0.05	0.95	16.3	4.2	3.9
6 June	3	8.0	22	3	7.9	162	184	0.12	0.88	17.0	2.3	7.3
8 June	4	7.4	50	1	7.1	50	100	0.50	0.50	10.9	2.8	3.9
11 June	2	8.1	13	15	7.0	299	312	0.04	0.96	18.9	7.2	2.6

<sup>a</sup> = sportfisher boat data

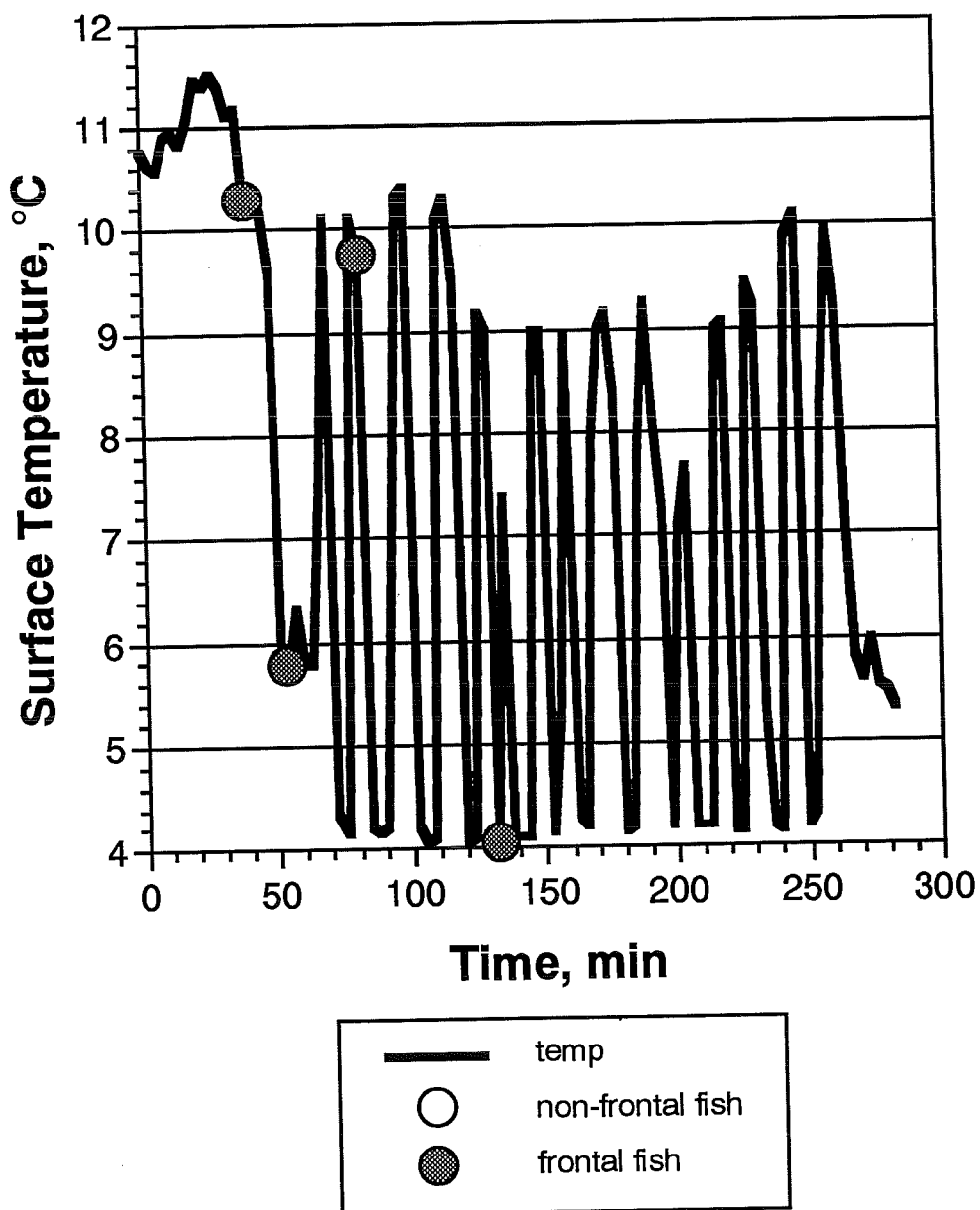
## Appendix 3. Daily Cruise Temperature Plots

4/24/90 Cruise



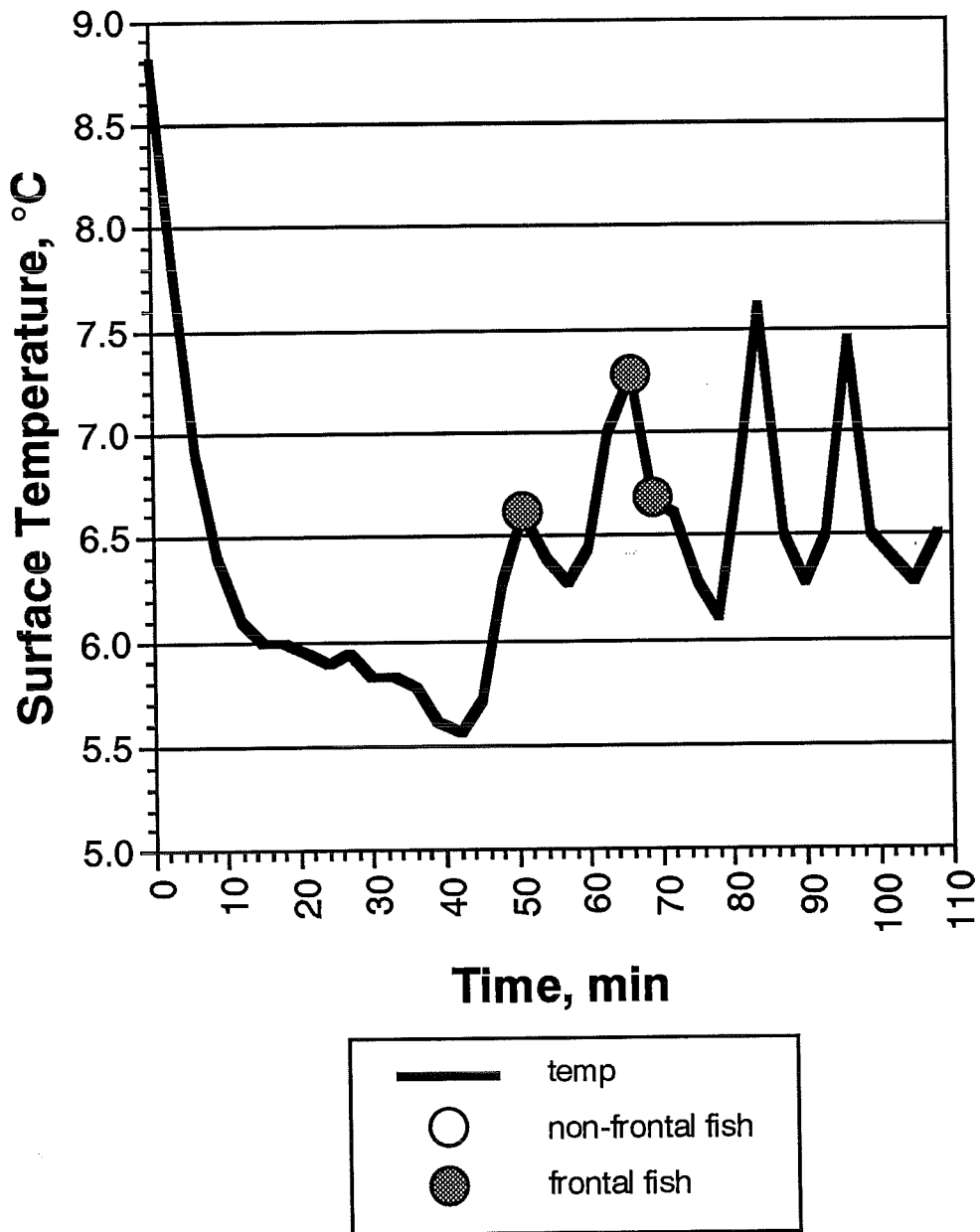
## Appendix 3. Daily Cruise Temperature Plot (continued)

4/28/90 Cruise



## Appendix 3. Daily Cruise Temperature Plot (continued)

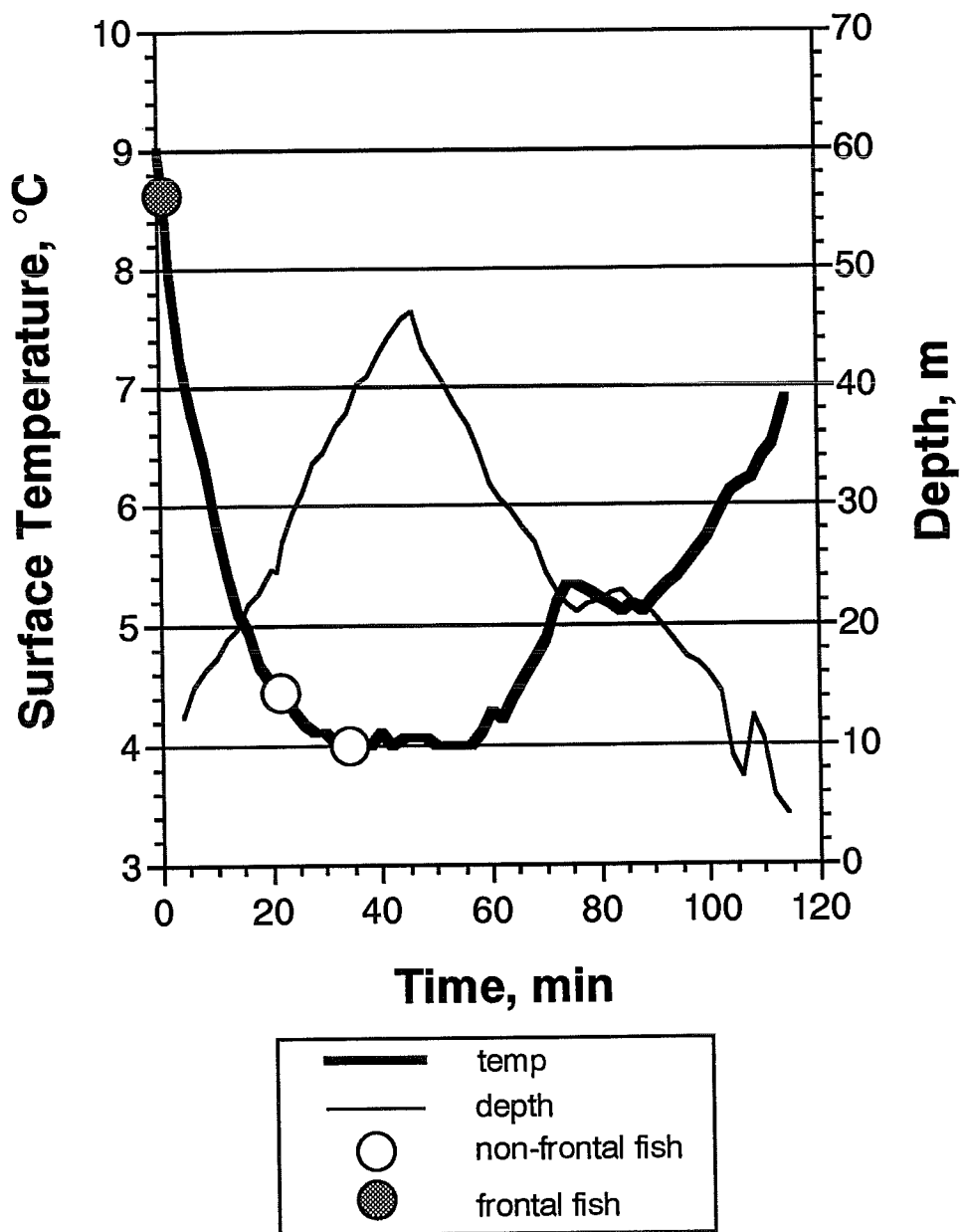
5/1/90 Cruise





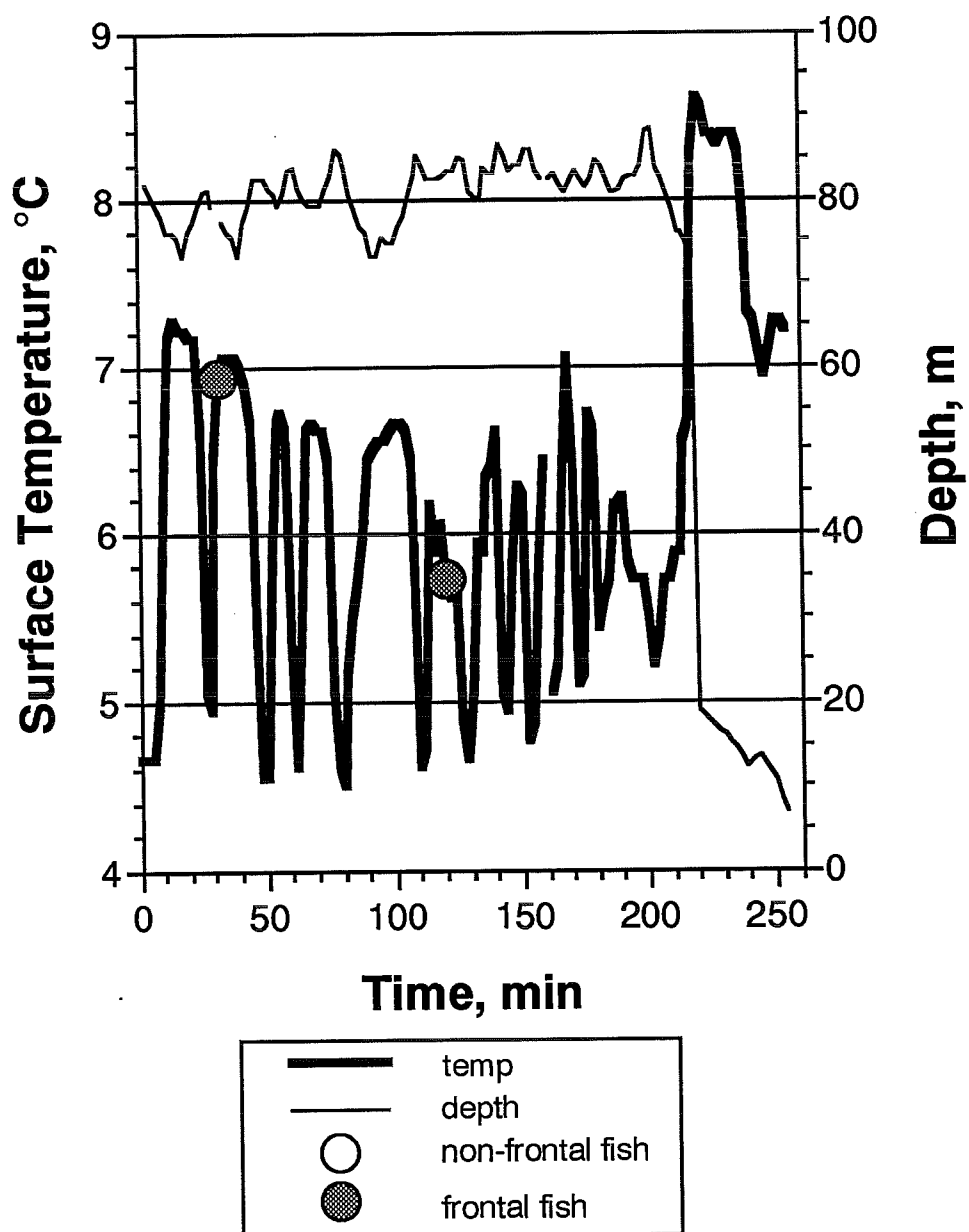
## Appendix 3. Daily Cruise Temperature and Depth Plot (continued)

5/9/90 Cruise



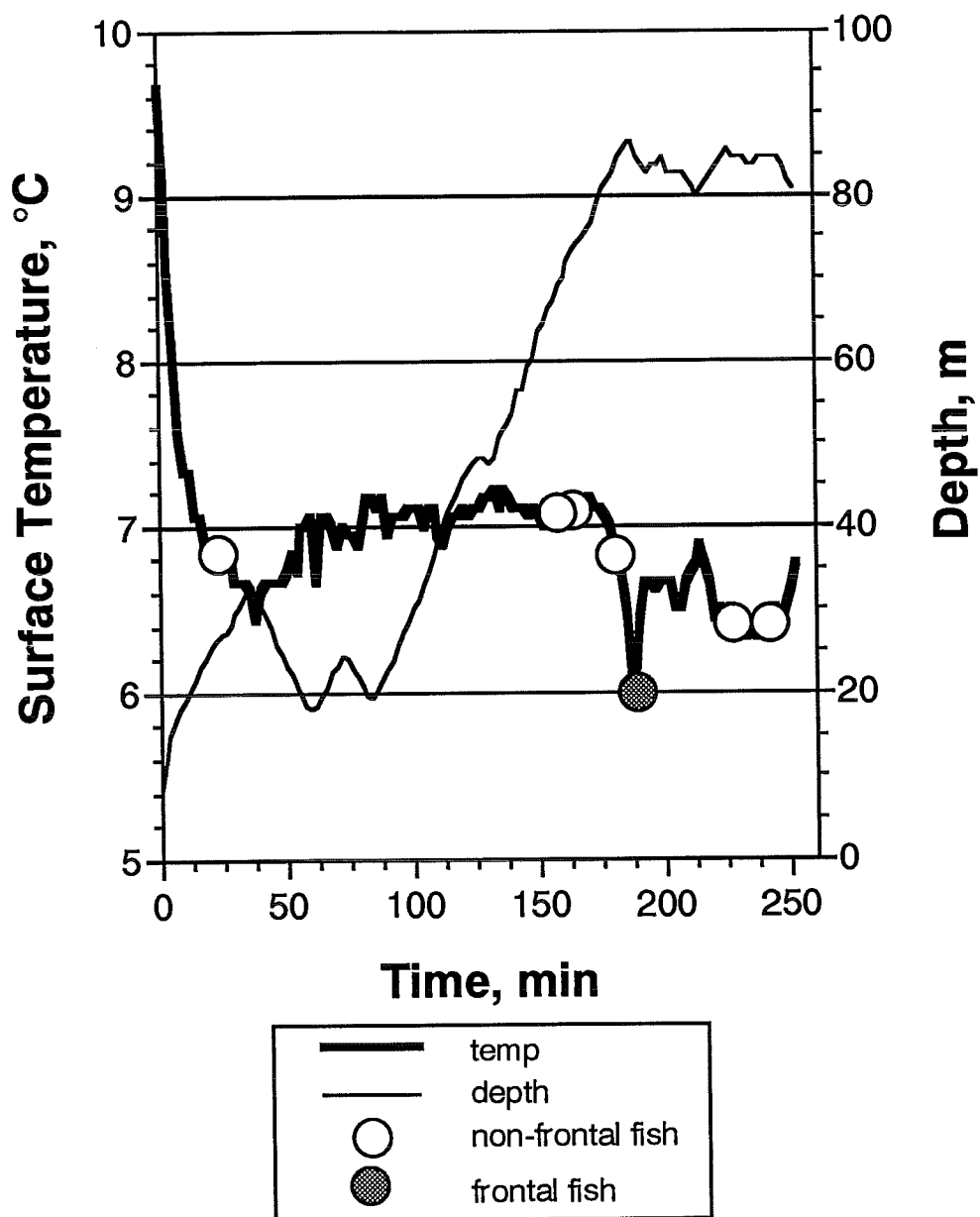
## Appendix 3. Daily Cruise Temperature and Depth Plot (continued)

5/12/90 Cruise



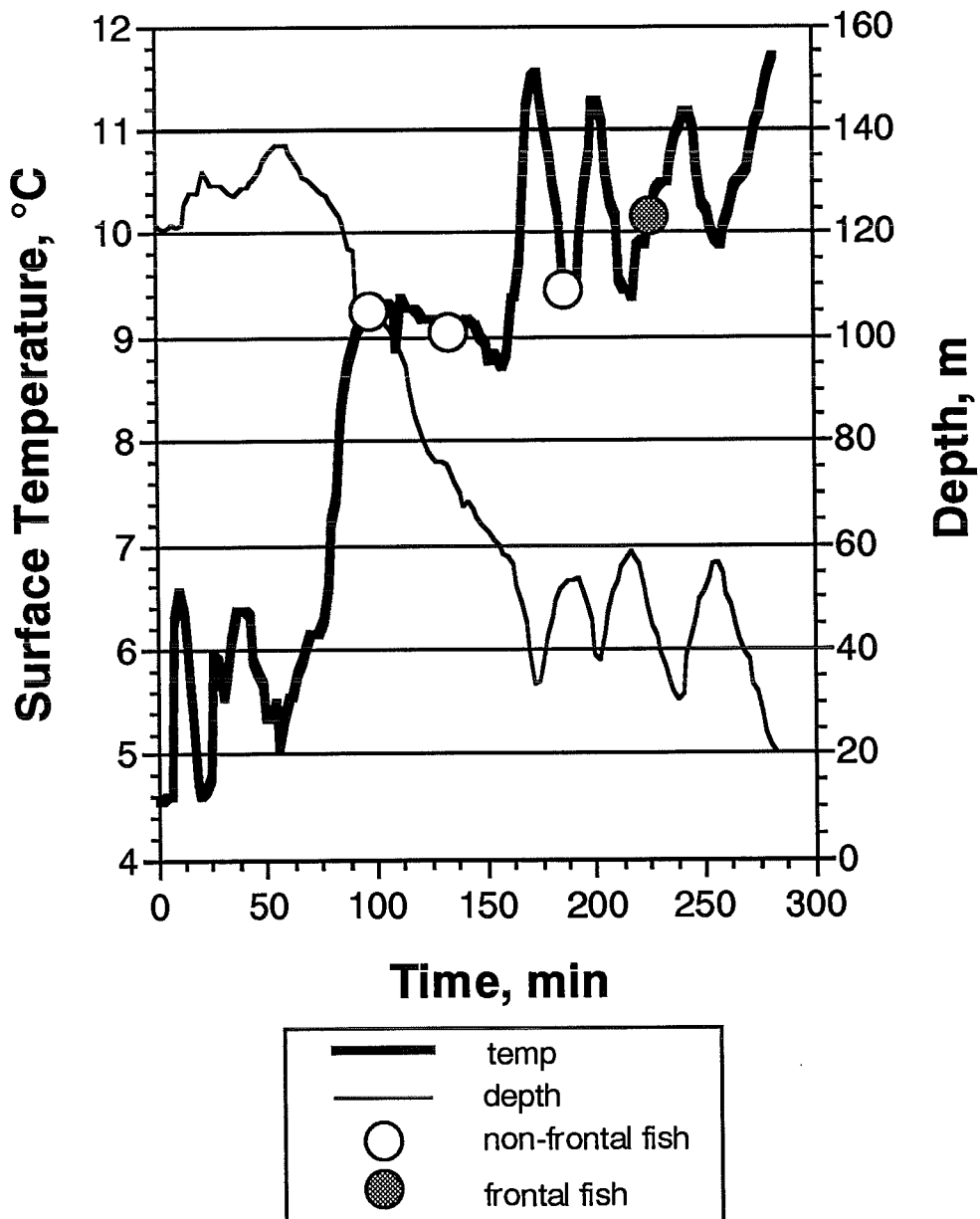
## Appendix 3. Daily Cruise Temperature and Depth Plot (continued)

5/22/90 Cruise



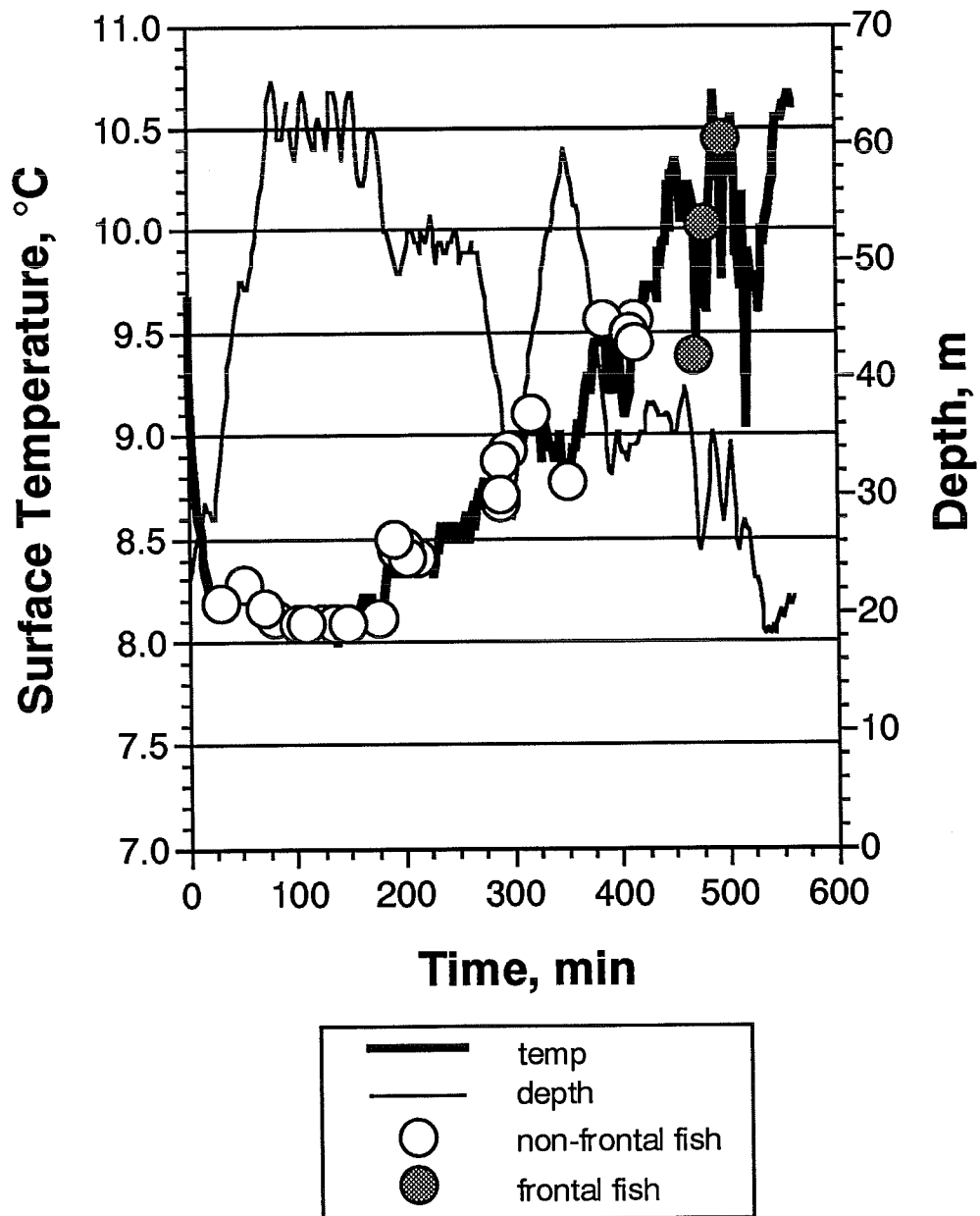
## Appendix 3. Daily Cruise Temperature and Depth Plot (continued)

5/26/90 Cruise



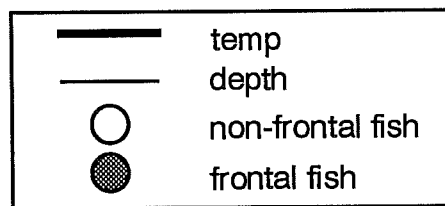
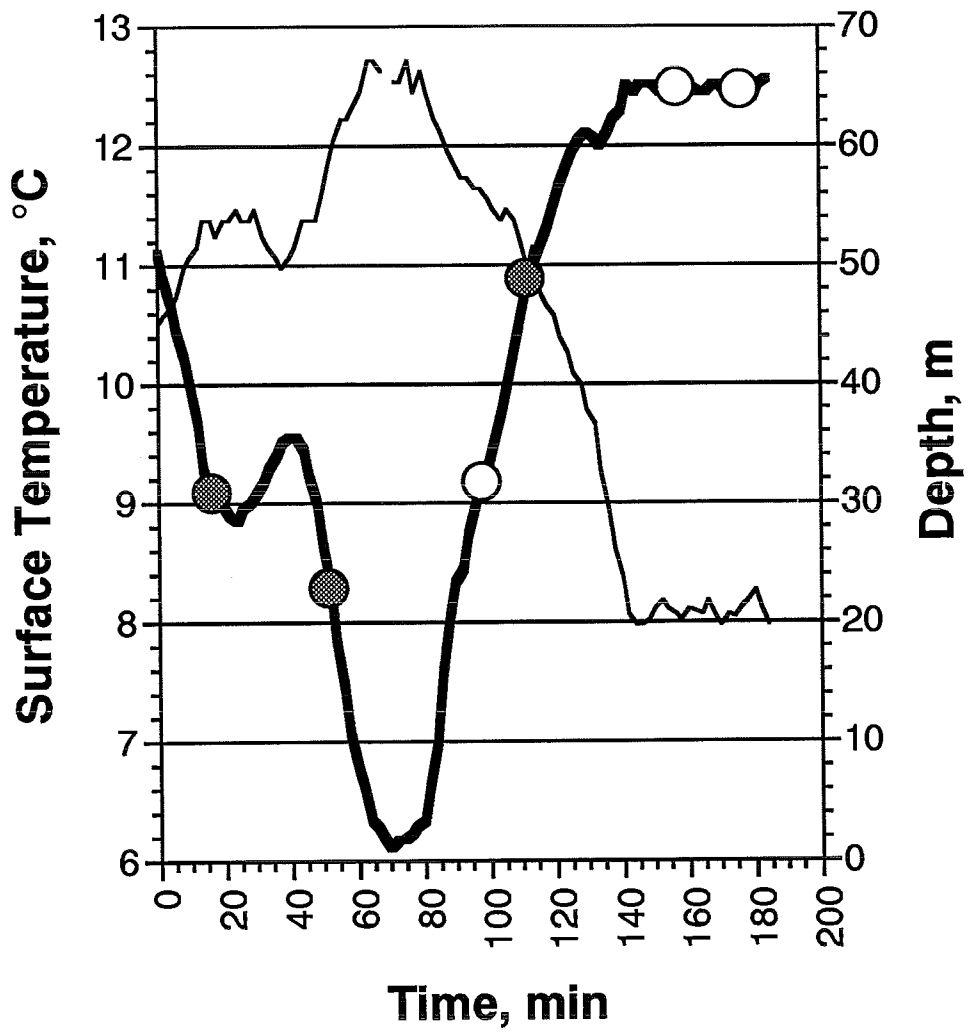
## Appendix 3. Daily Cruise Temperature and Depth Plot (continued)

6/1/90 Cruise



### Appendix 3. Daily Cruise Temperature and Depth Plot (continued)

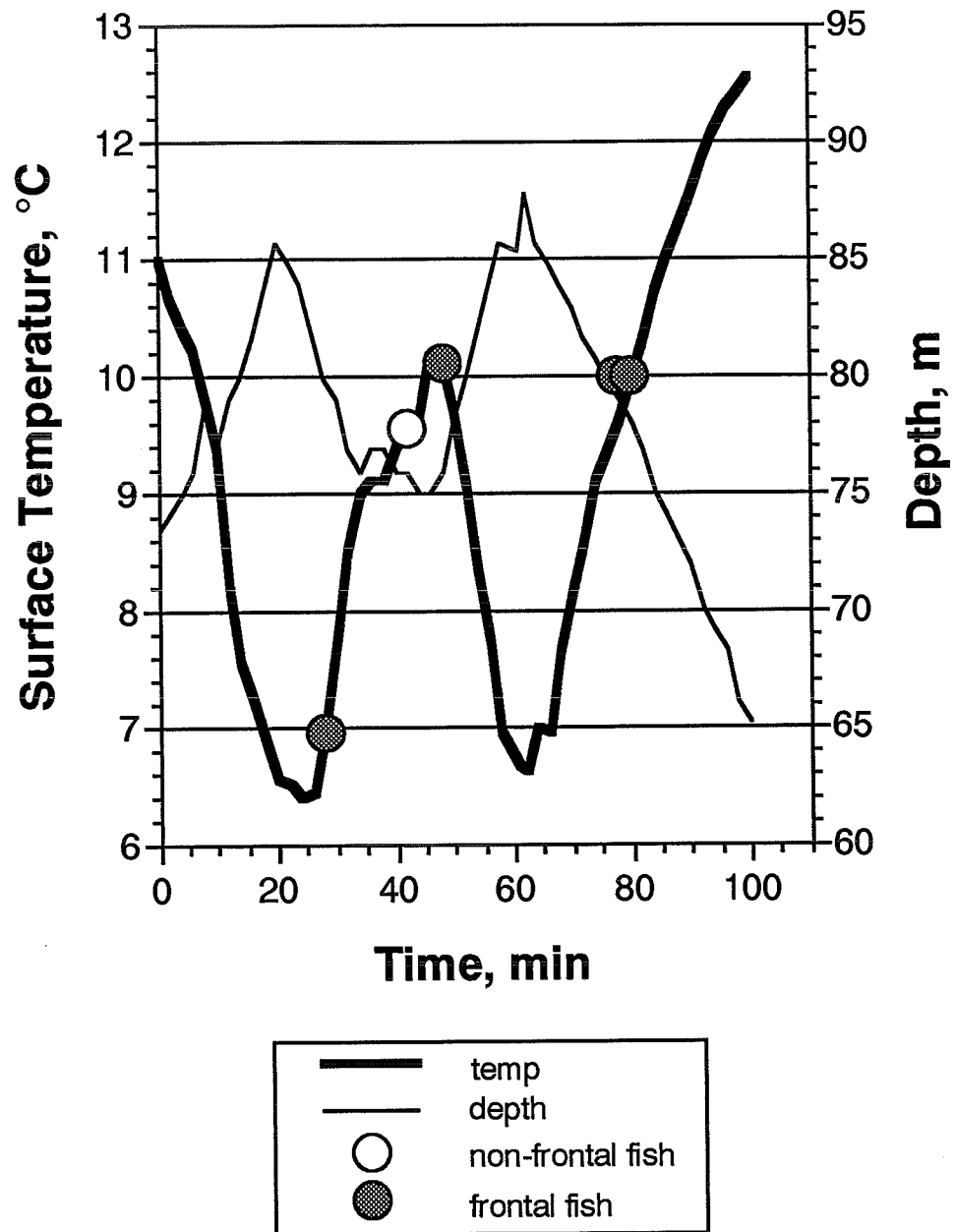
6/6/90 Cruise



### Appendix 3. Daily Cruise Temperature and Depth Plot (continued)

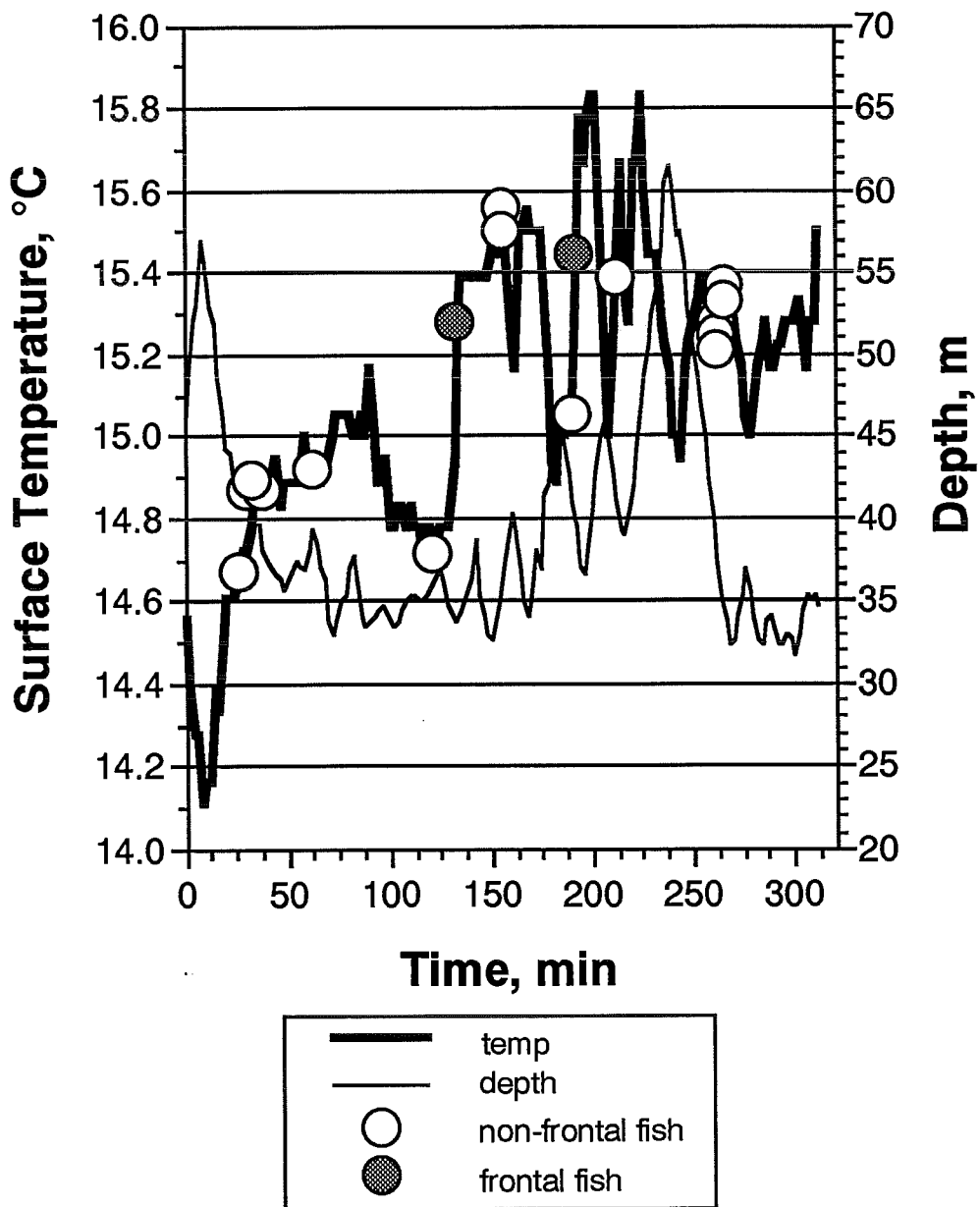
6/8/90 Cruise





## Appendix 3. Daily Cruise Temperature and Depth Plot (continued)

6/11/90 Cruise



Appendix 4. Raw data for strikes in Lake Ontario in Spring 1990 (date caught, mean number of rods fished, type of thermal front and, if known, species, weight and depth of capture). Depth values of zero indicate lures trolled from planer boards near the surface.

Fish	Date	# Rods	Structure	Species	Wt, kg	Depth, m
1	4/24/90	7	spring thermocline	coho salmon	1.1	0.9
2	4/24/90	11	spring thermocline	lake trout	0.9	0
3	4/24/90	11	spring thermocline	coho salmon	0.9	0
4	4/24/90	10	spring thermocline	steelhead	4.5	0.9
5	4/24/90	8	non-frontal	coho salmon	0.9	0
6	4/24/90	8	spring thermocline	coho salmon	0.9	0
7	4/24/90	9	spring thermocline	steelhead	2.7	0
8	4/28/90	4	thermal break	steelhead	4.3	0
9	4/28/90	4	spring thermocline	steelhead	0.9	0
10	4/28/90	4	thermal bar	steelhead	0.9	0
11	4/28/90	4	thermal bar	steelhead	3.2	0
12	5/1/90	9	spring thermocline	coho salmon	1.4	0
13	5/1/90	6	spring thermocline			
14	5/1/90	5	thermal break	brown trout	4.8	0
15	5/9/90	1	thermal break			
16	5/9/90	10	non-frontal			
17	5/9/90	10	non-frontal	lake trout	1.4	13.7
18	5/12/90	4	thermal bar			
19	5/12/90	3	thermal bar	steelhead	3.6	0
20	5/22/90	10	non-frontal	chinook salmon	10.0	10.7
21	5/22/90	10	non-frontal	lake trout	1.8	0
22	5/22/90	10	non-frontal	steelhead	2.7	0
23	5/22/90	10	non-frontal	coho salmon	0.5	0
24	5/22/90	9	spring thermocline			
25	5/22/90	9	non-frontal	chinook salmon	0.5	9.1
26	5/22/90	9	non-frontal	steelhead	1.4	10.7
27	5/26/90	4	non-frontal	lake trout	2.5	0
28	5/26/90	4	non-frontal	lake trout	3.2	0
29	5/26/90	4	thermal break			
30	5/26/90	4	non-frontal	steelhead	0.9	0
31	6/1/90	13	non-frontal			9.1
32	6/1/90	13	non-frontal			0
33	6/1/90	13	non-frontal	steelhead	0.7	1.5
34	6/1/90	10	non-frontal	lake trout	3.2	1.5
35	6/1/90	10	non-frontal			9.5

Fish	Date	# Rods	Structure	Species	Wt, kg	Depth, m
36	6/1/90	9	non-frontal	chinook salmon	3.2	
37	6/1/90	12	non-frontal	lake trout	3.4	10.7
38	6/1/90	13	non-frontal			1.5
39	6/1/90	13	non-frontal			9.5
40	6/1/90	13	non-frontal			0
41	6/1/90	13	non-frontal	chinook salmon	0.9	25.0
42	6/1/90	12	non-frontal			1.5
43	6/1/90	12	non-frontal	chinook salmon	0.5	29.0
44	6/1/90	11	non-frontal	coho salmon	0.9	
45	6/1/90	11	non-frontal			1.5
46	6/1/90	13	non-frontal			25.9
47	6/1/90	13	non-frontal			0
48	6/1/90	12	non-frontal			
49	6/1/90	13	non-frontal	steelhead	3.2	
50	6/1/90	13	non-frontal	steelhead	0.9	16.8
51	6/1/90	9	non-frontal	lake trout	1.8	19.8
52	6/1/90	13	non-frontal	lake trout	4.3	
53	6/1/90	13	non-frontal			0
54	6/1/90	13	non-frontal			15.2
55	6/1/90	12	non-frontal			15.2
56	6/1/90	11	non-frontal	steelhead	2.0	0
57	6/1/90	13	thermal break	lake trout	1.4	16.8
58	6/1/90	12	thermal break	chinook salmon	9.1	16.8
59	6/1/90	8	thermal break			0
60	6/1/90	11	thermal break			0
61	6/6/90	7	thermal break	chinook salmon	0.5	6.4
62	6/6/90	9	thermal break	lake trout	3.2	9.1
63	6/6/90	9	non-frontal	lake trout	3.6	
64	6/6/90	9	thermal break			
65	6/6/90	9	non-frontal	chinook salmon	0.5	12.2
66	6/6/90	9	non-frontal	steelhead	0.9	0
67	6/8/90	7	thermal break	steelhead	1.34	0
68	6/8/90	9	non-frontal	lake trout	1.8	0
69	6/8/90	9	thermal break	steelhead		0
70	6/8/90	9	thermal break	lake trout	3.2	0
71	6/8/90	9	thermal break	chinook salmon		16.8
72	6/11/90	6	non-frontal			18.3
73	6/11/90	8	non-frontal	lake trout	1.8	16.8
74	6/11/90	7	non-frontal	chinook salmon	6.8	18.3
75	6/11/90	6	non-frontal	chinook salmon	3.6	12.2
76	6/11/90	4	non-frontal			

Fish	Date	# Rods	Structure	Species	Wt, kg	Depth, m
77	6/11/90	8	non-frontal	chinook salmon	0.5	18.3
78	6/11/90	7	thermal break	lake trout	4.1	18.3
79	6/11/90	8	non-frontal	chinook salmon		
80	6/11/90	7	non-frontal	chinook salmon		13.7
81	6/11/90	9	non-frontal			
82	6/11/90	9	thermal break			18.3
83	6/11/90	9	non-frontal	chinook salmon	0.5	21.3
84	6/11/90	9	non-frontal	chinook salmon	0.5	
85	6/11/90	8	non-frontal			
86	6/11/90	7	non-frontal	chinook salmon	1.4	
87	6/11/90	6	non-frontal			
88	6/11/90	5	non-frontal	chinook salmon	0.5	21.3