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Spring Thermal Fronts and Salmonine Sport Catches in Lake Ontario

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Abstract.—The hypothesis that salmonine catches in Lake Ontario are higher at thermal fronts in spring and early summer was tested in 1990 by comparing catches in nonfrontal water and three types of fronts: thermal bar (4°C); spring thermocline (6–8°C); and thermal break ($\geq 9^\circ\text{C}$). A thermal front in the spring in Lake Ontario is a pronounced temperature cline across the surface of the lake (in this study defined as 0.15°C/min or greater at standard boat speeds) parallel to shore that extends obliquely from the surface toward shore and the bottom. Surface temperature was recorded every 2 min during 45 h of trolling for fish at a standard 3.2–4.8 km/h. Only 20% of the time was spent fishing in thermal fronts, where 35% of the 88 strikes occurred and 37% of the 59 fish were caught. Catch per unit effort (CPUE) for salmonines at thermal fronts was greater than nonfrontal CPUE ($P < 0.001$ for all strikes; $P < 0.05$ for fish caught). Catches were better in thermal breaks ($P < 0.002$) and the spring thermocline ($P < 0.05$) than in nonfrontal waters. Relative to nonfrontal water, CPUE for coho salmon *Oncorhynchus kisutch* was greater in the spring thermocline ($P < 0.01$). Salmonines were caught deeper in nonfrontal waters than in frontal waters ($P = 0.014$). Chinook salmon *O. tshawytscha* and lake trout *Salvelinus namaycush* were caught deeper than were coho salmon and steelhead *O. mykiss* ($P < 0.05$). Anglers can effectively enhance their catch of salmonines by fishing the spring thermocline and thermal breaks. These results likely are applicable to other pelagic habitats utilized by salmonines.

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). Concentrations of organisms at ecotones may be related to habitat diversity, food availability, or physical conditions (Smith 1986). Based on radiotelemetry data, Haynes et al. (1986) hypothesized that offshore movements of steelhead *Oncorhynchus mykiss* in Lake Ontario in the spring occurred in association with thermal fronts. Subsequently, anglers reported anecdotally that catches were better at thermal fronts than in nonfrontal waters (Voiland and Kuehn 1990). However, the relationship between salmonine catches and spring thermal fronts 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, a metalimnion with rapidly decreasing temperatures, and a cold lower hypolimnion (Cole 1983). These relatively stable

zones of water are formed by highly dynamic and transitory thermal fronts that originate around the perimeter of the lake 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 winter, Lake Ontario 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 where colder offshore waters mix with warmer nearshore waters. This process produces a nearly vertical thermal front called the thermal bar (Figure 1; Rodgers 1965). The thermal bar is the first thermal front to form, and the surface temperature change across this front can be as much as 5–7°C per 100 m (Rodgers 1966). The second thermal front to form, the spring thermocline (Figure 1), is 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 that extends from the surface obliquely back toward shore and eventually intersects the bottom.

As the thermal bar and spring thermocline move offshore during May and June, thermal breaks form (Figure 1). These fronts are located between the spring thermocline and shore and are character-

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Lake Ontario Spring Thermal Regime: May - June

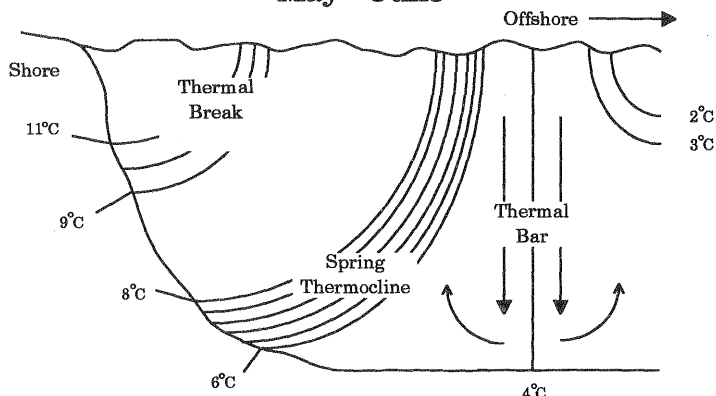


FIGURE 1.—Idealized thermal bar, spring thermocline, and thermal break structures of south-central Lake Ontario.

ized by closely spaced isotherms at temperatures of 9°C or greater (Haynes et al. 1986). All three thermal fronts continue to move offshore as the waters near shore warm. In Lake Ontario, when northbound thermal fronts from the southern shore encounter their southbound counterparts, they submerge and form the summer metalimnion that persists until fall when the processes reverse.

In spring 1990, we tested the hypothesis that salmonine sport catches were greater in these three thermal fronts (thermal bar, 4°C; spring thermocline, 6–8°C; and thermal breaks, 9°C or greater) than in nonfrontal waters. Additionally, we investigated the species composition and depths of capture of salmonines caught in thermal fronts and nonfrontal waters.

Methods

Cruises were conducted during the day on Lake Ontario from late April to mid-June 1990 by either a professional charter captain ($N = 8$) or a recreational angler ($N = 3$). Cruises left any time between sunrise and several hours before sunset from three ports, separated by 80 km, on the southern shore. There were no restrictions on angling methods; pilots were encouraged to catch as many fish as possible. The senior author, onboard for each cruise, supervised all angling and recorded all data. Angling techniques were typical for the spring season. Lures were mostly spoons and plugs. Trolling methods were downriggers, planer boards, and dippy-divers. As a cruise began, a variety of lures and trolling methods were used. When a strike occurred, pilots noted the combination and equipped other rods (4–14 per boat) in a similar manner. If the combination stopped being suc-

cessful, lure combinations were diversified again to establish new successful combinations.

For this study, a thermal front was conservatively defined as a temperature gradient of 0.15°C/min or greater at typical trolling speeds. This criterion was empirically determined in a preliminary study in spring 1989. In 1989 and 1990, temperature gradients in nonfrontal waters seldom exceeded 0.05°C/min, and gradients in frontal waters exceeded 0.1°C/min. Thermal fronts were detected by monitoring surface temperatures with hull-mounted sensors. The pilots trolled until thermal fronts were encountered, then repeatedly crossed frontal and nonfrontal waters perpendicular to the fronts (Figure 2). Trolling speeds were relatively consistent, 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.

Every 2 or 3 min during each cruise, the time of day, surface temperature, water depth, and number of rods being fished were recorded. When a fish was felt or seen at the end of a line, a strike was 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 also were recorded.

For each 2- or 3-min data interval, a rate of change in temperature (ΔT) across that interval was calculated. If ΔT was 0.15°C/min or greater, the interval was considered to be in a thermal front. If ΔT was less than 0.15°C/min, the interval was considered nonfrontal. 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

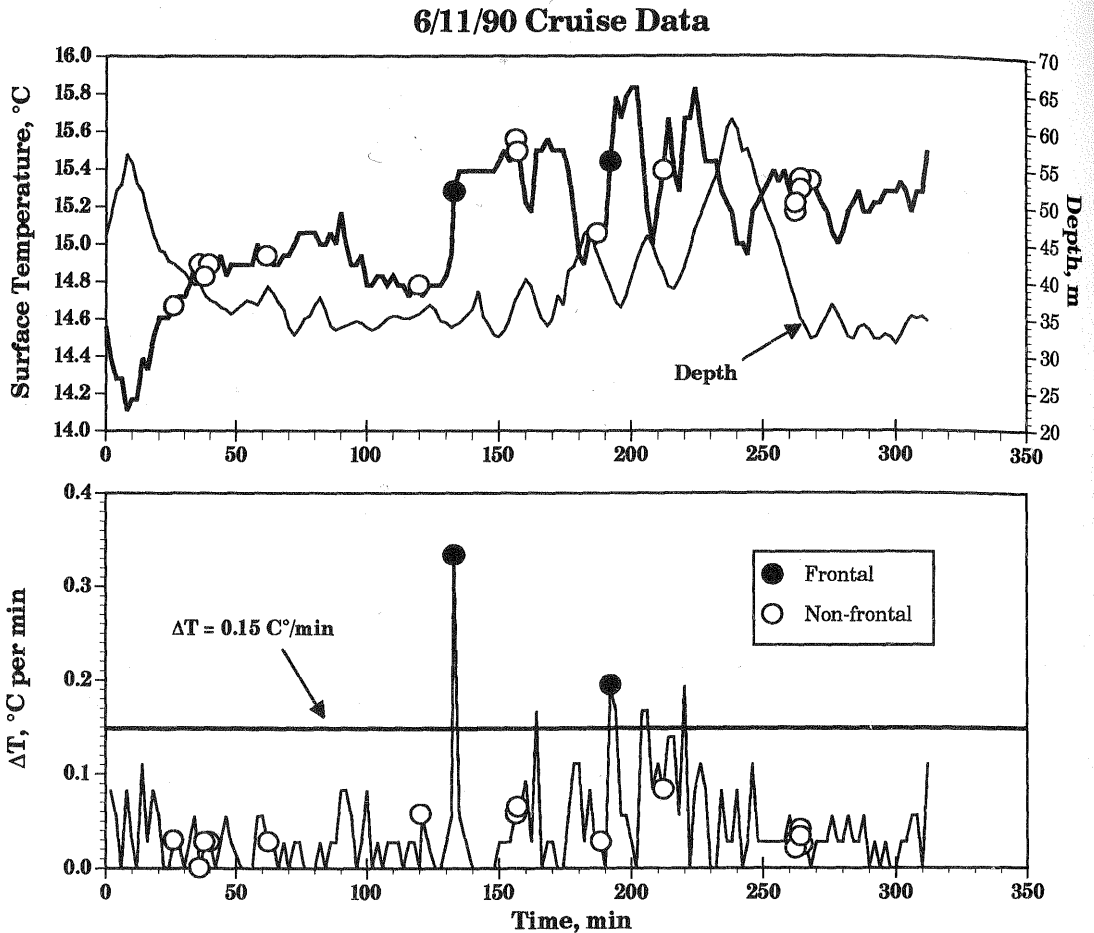


FIGURE 2.—Example surface temperature and ΔT (change in temperature) plots showing fish strikes (circles) in relation to thermal fronts during the June 11, 1990, cruise on Lake Ontario. A strike was considered frontal if it occurred during a 2-min interval in which ΔT was $0.15^{\circ}\text{C}/\text{min}$ or greater or during an interval immediately before or after this gradient was observed. For this cruise, 4% of the angling effort occurred in fronts, and frontal CPUE was 18.9 compared with a nonfrontal CPUE of 7.1.

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 divided by the mean number of rods fished and the number of minutes of fishing; this quotient was multiplied by 1,000 to get values greater than unity. For each cruise, CPUEs were computed for frontal and nonfrontal catches (including and excluding strikes for which fish were not landed) and compared by the Wilcoxon paired-sample test (Zar 1984).

Catches at the thermal bar, spring thermocline, and thermal breaks, and in nonfrontal areas were compared by χ^2 confidence intervals (Appendix). For each frontal type, the number of minutes fished

times the mean number of rods fished divided by the number of strikes (rod·min/number of strikes) was considered a random variable with a gamma distribution (Lindgren 1962), which is related to the χ^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 (i.e., strikes without landings were excluded). Values (rod·min/number of fish) for each species also were analyzed with χ^2 confidence intervals.

Planer boards trolled lures at depths less than 1 m; strikes on these lures were recorded as depth zero. The depths of strikes from dippy-divers were not recorded due to high variability. When strikes occurred on downriggers, the length of extended

cable was recorded as a maximal estimate of depth. The depths of strikes and the weights of fish caught in frontal and nonfrontal waters were compared with Kruskal-Wallis tests (Zar 1984).

Results

Eleven cruises were conducted from April 24 to June 11, 1990. During 45 h of trolling, 20% of the effort was in thermal fronts and 80% was in nonfrontal waters (Table 1). In all, 88 strikes were recorded and 35% of those occurred in thermal fronts. The 59 fish landed consisted of 18 chinook salmon *Oncorhynchus tshawytscha*, 17 steelhead *O. mykiss*, 7 coho salmon *O. kisutch*, 16 lake trout *Salvelinus namaycush*, and 1 brown trout *Salmo trutta*. Twenty-two of these fish (37%) were caught in thermal fronts. For strikes, frontal CPUE was higher than nonfrontal CPUE for each of the 11 cruises ($P < 0.001$; Figure 3). For fish landed, frontal CPUE was higher than nonfrontal CPUE for 8 of 11 cruises ($P = 0.047$). The difference in P -values resulted from three cruises on which fish that struck in frontal waters were not landed and the total number of fish that struck was less than four. Overall, frontal CPUE was 2.4 times greater than nonfrontal CPUE for strikes and 2.7 times greater than nonfrontal CPUE for fish landed.

When all species were combined within each frontal type, strikes in the thermal breaks ($P < 0.002$) and in the spring thermocline ($P < 0.05$) were greater than strikes in nonfrontal waters (Figure 4). Within each frontal type, there was no difference in species catches ($P > 0.05$). Only steelhead were caught in the thermal bar. When all

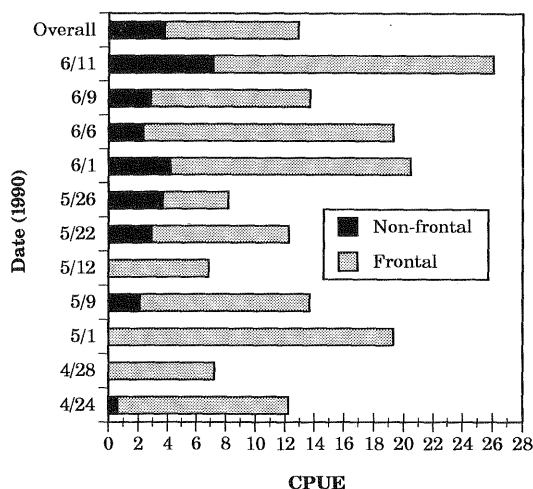


FIGURE 3.—Comparison of frontal and nonfrontal CPUE (based on strikes) for Lake Ontario salmonines for each cruise in spring 1990. Overall bar length represents the sum of frontal and nonfrontal CPUE for each cruise.

frontal types were combined within each species (Figure 5), only coho salmon catches were greater in frontal than in nonfrontal waters ($P < 0.01$). Although the data suggest that steelhead were caught more often in thermal fronts than other species, differences were not significant ($P > 0.1$; Figure 5).

Fish caught in frontal waters were closer to the surface than fish caught in nonfrontal waters ($P = 0.014$; Figure 6). Among species, fish were caught at different depths ($P < 0.001$; Figure 6). Chinook

TABLE 1.—Summary of data used to compute CPUEs for frontal and nonfrontal waters ($CPUE = 1,000 \times \text{number of strikes} \div \text{mean number of rods fished} \div \text{number of minutes of fishing}$). Data were collected on cruises conducted on Lake Ontario in 1990.

Cruise date	Frontal			Nonfrontal			Total min-utes	Percent total time		CPUE		Frontal: non-frontal
	Number of strikes	Number of rods	Min-utes	Number of strikes	Number of rods	Min-utes		Frontal	Non-frontal	Frontal	Non-frontal	
Apr 24	6	10.1	51	1	8.9	180	231	22	78	11.6	0.6	18.6
Apr 28 ^a	4	3.8	147	0	3.5	135	282	52	48	7.2	0	
May 1	3	4.7	33	0	6.5	75	108	31	69	19.3	0	
May 9	1	5.4	16	2	9.8	98	114	14	86	11.6	2.1	5.5
May 12 ^a	2	3.0	98	0	2.9	156	254	39	61	6.8	0	
May 22	1	6.7	16	6	8.8	236	252	6	94	9.4	2.9	3.2
May 26 ^a	1	3.7	60	3	3.7	222	282	21	79	4.5	3.7	1.2
Jun 1	4	9.5	26	26	11.6	534	560	5	95	16.3	4.2	3.9
Jun 6	3	8.0	22	3	7.9	162	184	12	88	17.0	2.3	7.3
Jun 8	4	7.4	50	1	7.1	50	100	50	50	10.9	2.8	3.9
Jun 11	2	8.1	13	15	7.0	299	312	4	96	18.9	7.1	2.6
Totals	31	6.4	532	57	7.1	2,147	2,679	20	80	9.1	3.8	2.4

^a Cruise conducted by a recreational angler.

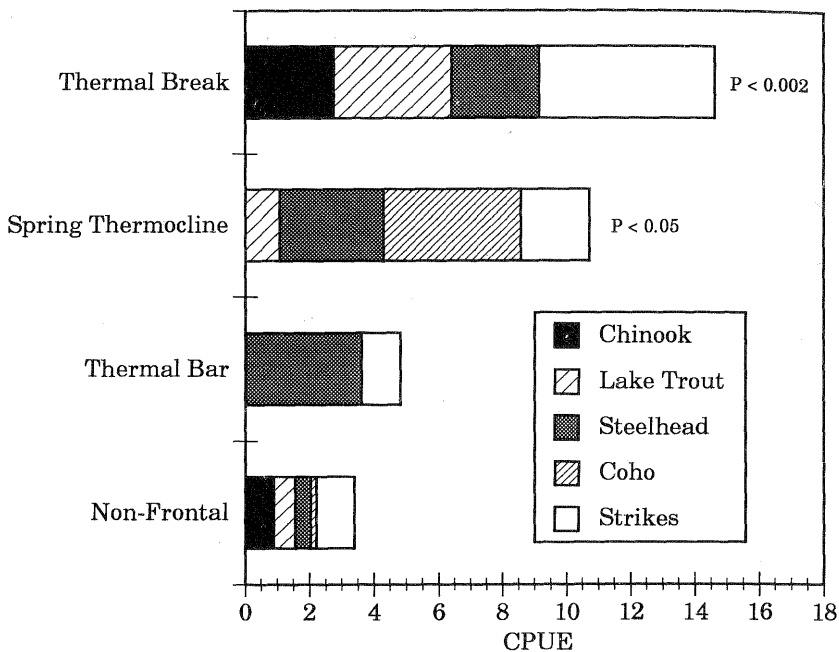


FIGURE 4.—Species-specific CPUE of Lake Ontario salmonines for each frontal type in spring 1990. *P*-values indicate significant differences between overall frontal CPUEs and overall nonfrontal CPUE for fish landed. Strikes refer to fish that were not landed. Overall bar length represents the total CPUE in each frontal type.

salmon were caught in deeper water than were lake trout ($P = 0.01$), steelhead ($P < 0.001$), and coho salmon ($P < 0.001$). Lake trout were caught in deeper water than were steelhead ($P = 0.039$) and coho salmon ($P = 0.058$). There was no difference in fish weights between frontal and nonfrontal waters ($P = 0.242$).

Discussion

Ecotones typically have higher abundance and diversity of organisms than do 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. The nearshore ecotone and the bottom cannot always be utilized by Great Lakes salmonines because of frequently high wave energy in spring and fall, temperatures exceeding thermal preference near shore in summer, and great depth off shore. In large aquatic systems, however, pelagic thermal ecotones do provide edge effects for fishes (Brandt and Wadley 1981). In Lake Ontario, do thermal fronts concentrate salmonines as measured by angling success?

Our data support the hypothesis that angling success is greater at thermal fronts than in non-frontal waters. Haynes et al. (1986) reported that

steelhead tended to move offshore with the 10°C isotherm. In our study steelhead were caught near all frontal types. Voiland and Kuehn (1990) reported anecdotally that steelhead and lake trout typically were caught by anglers in the thermal bar and that steelhead, coho salmon, and chinook salmon typically were caught in the spring thermocline. In our study only steelhead were caught in the thermal bar; steelhead, 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 studies.

It is likely that fishing success for salmonines is greater at thermal fronts because salmonines are more abundant there. However, other explanations may account for increased angling success at thermal fronts. Perhaps salmonines feed more actively at fronts or greater prey abundance at fronts encourages more feeding, although we are aware of no studies that support these hypotheses. Brandt

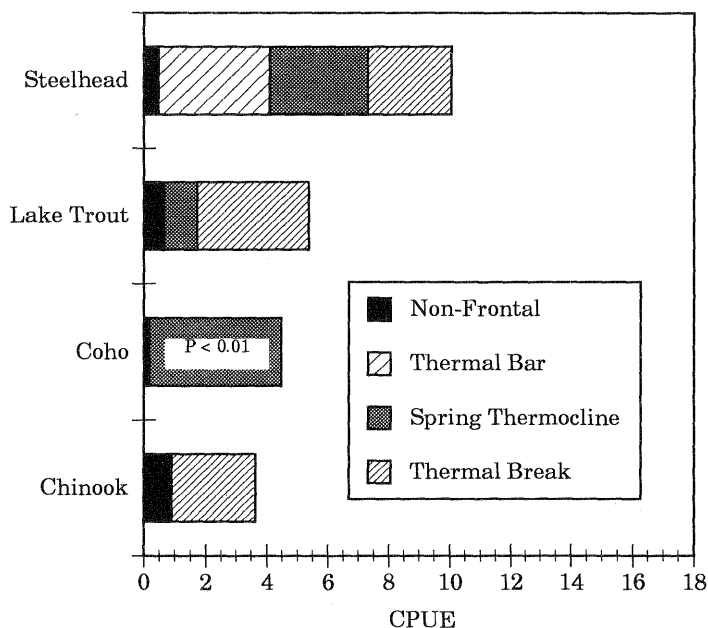


FIGURE 5.—Front-specific CPUE for each species caught in Lake Ontario in spring 1990. The P -value for coho salmon indicates that catch was significantly greater in the spring thermocline than in nonfrontal waters. Overall bar length represents the total CPUE for each species.

(1986) reported that terrestrial insects were most abundant in the stomachs of salmonines caught by anglers in the spring, particularly in the stomachs of steelhead. He did not distinguish between fish caught in frontal and nonfrontal waters. We observed terrestrial insects at the surface of thermal fronts in Lake Ontario in the spring, and in our study many fish were caught near the surface (Figure 6). Therefore, salmonines, particularly steelhead, may be attracted to spring thermal fronts to feed on insects. Fish were caught deeper in nonfrontal waters (Figure 6), where they did not have access to insects.

Brown trout and lake trout distributions in Lake Ontario have been correlated with prey fish distributions in the summer metalimnion (Olson et al. 1988). Olson et al. (1988) suggested that salmonines consume the most abundant prey 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 range of temperatures within their thermal preferenda (6–15°C). In Lake Michigan, Brandt (1980) reported that alewife *Alosa pseudoharengus* abundance was related to the position of the summer metalimnion. Typically, alewives provide about 90% of the diet of salmonines in Lake Ontario (Brandt 1986). However, based on

the use of standard chart recorders in our study and on anecdotal reports from anglers, there was no evidence of abundant fish prey in frontal or nonfrontal waters. Although our study does not prove that salmonine abundance is greater at thermal fronts, greater fishing success at fronts plus availability of insect prey and optimal temperatures suggest that abundance probably is greater there.

Several researchers have reported a relationship between the distribution of pelagic marine species and ecotones. Movements of albacore *Thunnus alalunga* 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 and Lynn 1977; Laurs et al. 1977; Fiedler and Bernard 1987). Skipjack tuna *Katsuwonus pelamis* appeared to follow productive waters associated with temperature and salinity gradients (Seckel 1972; Fiedler and Bernard 1987). Movements of sockeye salmon *O. nerka* in British Columbia coastal waters were correlated with temperature and salinity gradients (Quinn and terHart 1987). Our data are consistent with distribution and abundance studies for these marine fishes and their associations with thermal fronts.

We chose professionally supervised angling as

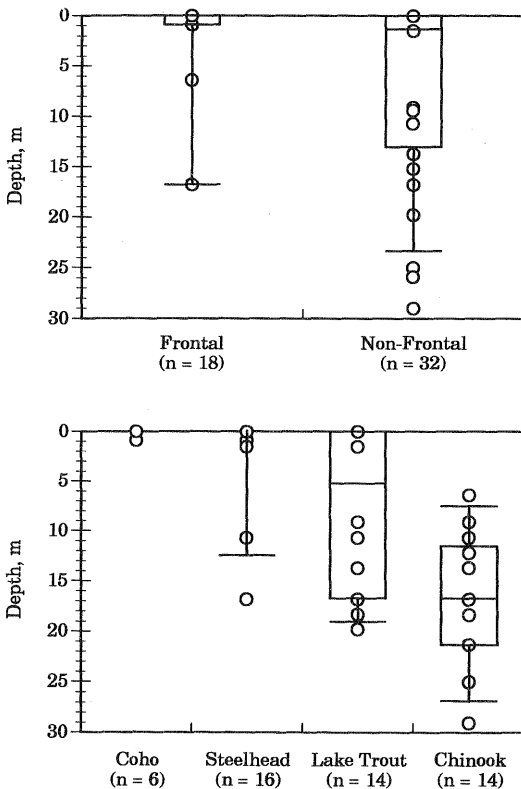


FIGURE 6.—Depths where catches occurred grouped by frontal and nonfrontal waters and by species. Circles mark depths of individual fish or groups of fish caught at the same depth. Box ends mark the 25th and 75th percentiles. The horizontal line inside the box marks the median. The horizontal lines outside the box, where shown, mark the 10th and 90th percentiles. Coho salmon and steelhead were caught so close to the surface that not all percentiles can be shown.

our sampling method because conventional methods could not provide the data needed to test our hypotheses. Given the highly transitory nature of spring thermal fronts on an hourly time scale (Rodgers 1966), and the known avoidance of nets by some salmonine species (Olson et al. 1988; Haynes, personal observation), gill nets cannot be used to collect these kinds of data. Bioacoustics cannot discriminate among salmonine species or between salmonines and other equivalently sized fish in Lake Ontario.

To the extent possible, both frontal and non-frontal waters were sampled with the same angling methods and tackle on each sampling date. Given the consistency of sampling methods in frontal and nonfrontal waters, greater salmonine catches in fronts likely is related to increased abundance or

greater feeding activity. A future study should quantitatively address the abundance of salmonine-sized fishes in frontal and nonfrontal waters as well as the distribution and abundance of prey-sized species. Concurrent bioacoustic sampling of predators and prey would allow researchers to directly address the abundance issue.

Our results are the first to demonstrate experimentally a strong association of salmonines with spring thermal fronts in the Great Lakes. Fisheries managers dealing with large pelagic systems may find these results useful for understanding local salmonine ecology and for optimizing sampling efforts. However, these data also may present a dilemma for Great Lakes fisheries managers. Knowledge of salmonine associations with spring thermal fronts will help anglers to improve their catches, but the information could also help accelerate the exploitation of certain species without regard to the objectives of the managers. For example, excessive harvesting of lake trout, which are strongly associated with thermal fronts in spring and summer (Olson et al. 1988), may hinder efforts to restore natural self-sustaining populations of this species (Schneider et al. 1990) in the Great Lakes.

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Appendix: Derivation of Confidence Intervals³

Herein we describe the derivation of 95% confidence intervals for χ^2 based on the gamma distribution of rod-minutes per strike or fish.

If μ is the average number of rod-minutes required to catch 1 fish, a 95% confidence interval would be

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

where TF is the total number of rod-minutes used to catch fish, N is the number of fish caught, and the subscripts on χ^2 denote (df, probability criterion) (Lindgren 1962). The random variable TF has a gamma distribution and parameters $\alpha = N$ and $\beta = \mu$. Therefore the probability is 95% that

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

The gamma distribution is related to the χ^2 distribution (Hogg and Craig 1965) by

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

³ Source: James N. McNamara, Department of Mathematics, State University of New York College at Brockport.

Substituting this equality into equation (A.1), we get

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

Substituting μ for β and N and $N + 1$ for α , we get

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

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

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

and solving for μ , we get

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

Example calculation

$N = 10 =$ number of fish caught.

$\text{TF} = 935 =$ number of rod-minutes to catch N fish.

Referring to "critical values of the χ^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, $P(51 < \mu < 195) = 0.95$.