EFFECTS OF SUMMER TEMPERATURES ON THE GROWTH AND CONDITION OF JUVENILE ATLANTIC TOMCOD, *MICROGADUS TOMCOD*

A Final Report of the Tibor T. Polgar Fellowship Program

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ABSTRACT

Atlantic tomcod, *Microgadus tomcod*, is a small anadromous gadid whose southernmost spawning population inhabits the Hudson River and smaller adjacent estuaries. Prior studies suggest that growth of juvenile Hudson River tomcod slows during summer as a result of warm temperature, however, this has not been experimentally evaluated. The objectives of this study were to (1) estimate the effects of temperature on growth and condition of juvenile tomcod in the laboratory, and (2) evaluate seasonal changes in length, weight, and condition of tomcod in the Hudson River. We exposed populations of laboratory-reared juvenile tomcod to three water temperature regimes that mimicked cool, moderate, and warm summers. Tomcod growth rates were suppressed and their condition deteriorated when temperatures exceeded 20°C, but were unaffected by temperatures below 20°C. Two summer surveys of the lower Hudson River between the Battery and West Point (rkm 0 to 80) using a 4.9-m otter trawl were also conducted. Tomcod were collected in all regions sampled and were more abundant and smaller in size in June than in July. Abundance was highest at the upriver stations where temperatures exceeded those that retard growth as determined in the laboratory. Although our experimental estimates of juvenile tomcod growth rates are similar to earlier field-based estimates, they are free of the confounding factors typical of field collections and are the first to unambiguously link warm summer temperatures to reduced growth rate in juvenile tomcod.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

INTRODUCTION

Atlantic tomcod, *Microgadus tomcod*, is a small anadromous gadid distributed principally along the Atlantic coast of North America from southern Labrador to the Hudson River that occurs incidentally as far south as Virginia (Scott and Crossman 1973). Tomcod inhabiting the Hudson River estuary represent the southernmost spawning population of the species (Dew and Hecht 1976). The Hudson River population is largely self-contained and is an important member of the Hudson River biota. It is a dominant component of the ichthyofauna, a resident species whose status is indicative of the system's health, and a critical prey resource for a variety of predators including juvenile bluefish, *Pomatomus saltatrix*, and striped bass, *Morone saxatilis* (Klauda et al. 1988, McLaren et al. 1988, Juanes et al. 1993). Furthermore, Hudson River tomcod has been relatively well studied in nature because it has been the subject of numerous monitoring programs (Dew and Hecht 1994, Dew 1995).

Tomcod spawn in the Hudson River from mid December through January in low salinity (<10 ppt), upstream habitats (Klauda et al. 1988). Eggs are demersal and hatch 4 to 6 weeks after fertilization. Young larvae are transported downstream by the current during the spring. From mid May to October, juvenile tomcod are widely dispersed throughout the river with the area of highest abundance shifting from higher salinity (>10 ppt), downstream habitats to lower salinity (<10 ppt), upstream habitats during the summer (Klauda et al. 1988, CHGEC 2000). In fall, juveniles mature into adults and aggregate to spawn during their first winter. Few adults survive to spawn again in their second winter.

Earlier studies have proposed that summer water temperatures in the Hudson are too warm to sustain high tomcod growth rates (McLaren et al. 1988). Length-at-date data for juvenile tomcod collected in the Hudson River appear to show that tomcod increase in size rapidly in the spring and fall, but display little if any growth during July and August. This reduction in growth rate may mean that optimal temperatures for growth are exceeded during the summer (Grabe 1978, McLaren et al. 1988). McLaren et al. (1988) report that growth rates of juveniles, inferred by changes in length-frequency distributions, were highest from mid May through June, after which they were suppressed by warm water temperatures in July and August. The upper lethal limit of tomcod, based on laboratory trials, is reported to be ~ 26.5°C (Ecological Analysts 1978).

The pattern of decelerated tomcod growth during periods of warm water temperature has yet to be experimentally evaluated. Current estimates of growth have been based on size-at-date information from field collections. Those size-at-date data, however, may reflect several processes in addition to temperature-dependent growth, including sampling artifacts, size-specific habitat shifts, size-dependent predation, and gear selectivity. As a result, it may be premature to conclude that the seasonal changes in tomcod sizes referred to above reflect solely the effects of temperature on growth rate. In addition, seasonal changes in sizes-at-date provide, at best, an indirect measure of the functional relationship between temperature and growth rate. This study was designed to provide a more direct assessment of the effects of temperature, specifically summer temperatures, on growth rate and condition of juvenile tomcod.

Objectives

The objectives of this study were to (1) estimate the effects of temperature on growth and condition of juvenile tomcod in the laboratory, and (2) evaluate seasonal changes in length, weight, and condition of tomcod in the Hudson River. Because this study used both laboratory and field data to estimate growth and condition, we also sought to compare estimates between these two sources and with estimates from previously reported tomcod length data.

METHODS

Temperature-dependent growth experiment

A laboratory experimental approach was used to quantify the effect of temperature on growth rate and condition of tomcod. Three different temperature regimes, each replicated twice, were chosen to mimic the summer temperatures experienced by tomcod throughout the species' range. The temperature regimes were simplified by forcing each to be a triangular distribution wherein all regimes began and ended at 15°C but differed in their peak temperatures. These three regimes were intended to reflect a warm (peak at 25.6°C), moderate (21.6°C), and cool (17.6°C) summer. The continuously changing temperatures observed in nature were simplified in this experiment by increasing or decreasing temperatures every two or three weeks with interim temperatures held constant (Fig. 1). Water temperatures were monitored daily and adjusted when necessary (+/- 0.5°) by modifying the mixture of heated and ambient seawater, which filled the 1.2-m diameter fiberglass tanks. All tanks were maintained under flow-through conditions using seawater (20-24 ppt salinity) that was pumped into the laboratory from nearby Sandy Hook Bay.

Six experimental populations of laboratory-reared juvenile tomcod (n=150 tomcod per population) were established from a mixed group of offspring from crosses of three male and three female tomcod. These adult tomcod were collected using traps in the Hudson River at approximately river kilometer (rkm) 80, in Garrison, New York during January, 2000. All fish used in the experiment were drawn from a pool of tomcod that were of the same age (105 d post-hatch), comparable size (31.5 ± 2.27 mm total length, TL), and had been maintained under identical conditions prior to the experiment.

Growth of tomcod in the laboratory was estimated for each population from weekly samples of 20 fish from each of the six tanks. Measurements of TL were made to the nearest 0.1 mm using a dial caliper and wet weights (WW) were determined to the nearest 0.01 g. Ten of the 20 fish sampled were returned to the tank and 10 were frozen so that dry weights, otoliths, and lipid contents could be obtained at a later date. The robustness or leanness of fish was calculated as wet weight per unit length as an indicator of fish condition.

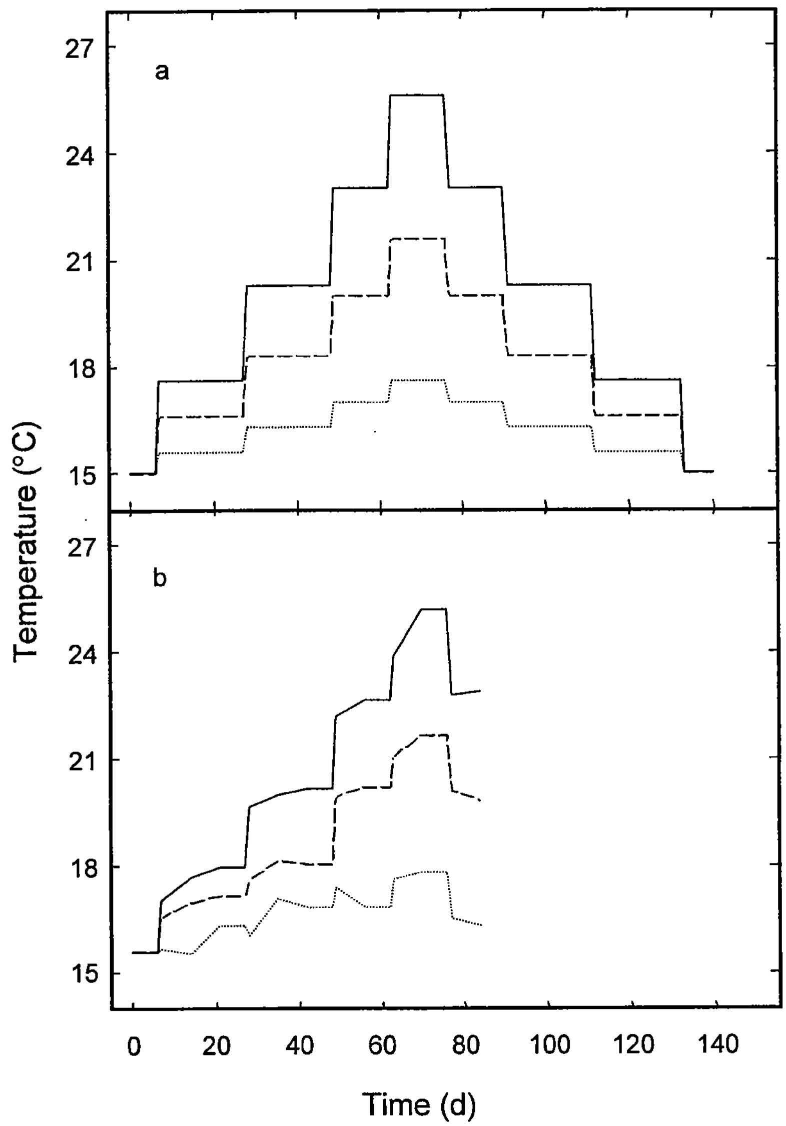

Figure 1. Targeted (a) and actual (b) temperatures for the three temperature regimes used in the tomcod growth experiment. The solid, long-dashed, and short-dashed lines represent the warm, moderate, and cool regimes, respectively.

Field collections of juvenile tomcod

We conducted monthly summer surveys of the lower Hudson River between the Battery and West Point (rkm 0 to 80) in order to (1) evaluate seasonal changes in length, weight, and condition of juvenile tomcod, (2) determine whether the spatial distribution of juvenile tomcod changed during the summer, and (3) correlate seasonal changes in fish size and distribution with water temperatures. Two sampling cruises in the Hudson River were conducted aboard the *NMFS R/V Gloria Michelle* during the summer of 2000. We sampled at six (June) or nine (July) stations with each station separated by approximately 10 km. The stations were chosen so as to cover the full salinity gradient (0-28 ppt) of the lower Hudson River (Fig. 2). One channel tow and two shoal tows on opposite sides of the channel were made at each station using a 4.9-m otter trawl. This sampling scheme enabled us to gather information about tomcod and water quality parameters from different depths at the same km on the Hudson River (depth 4-26.5 m).

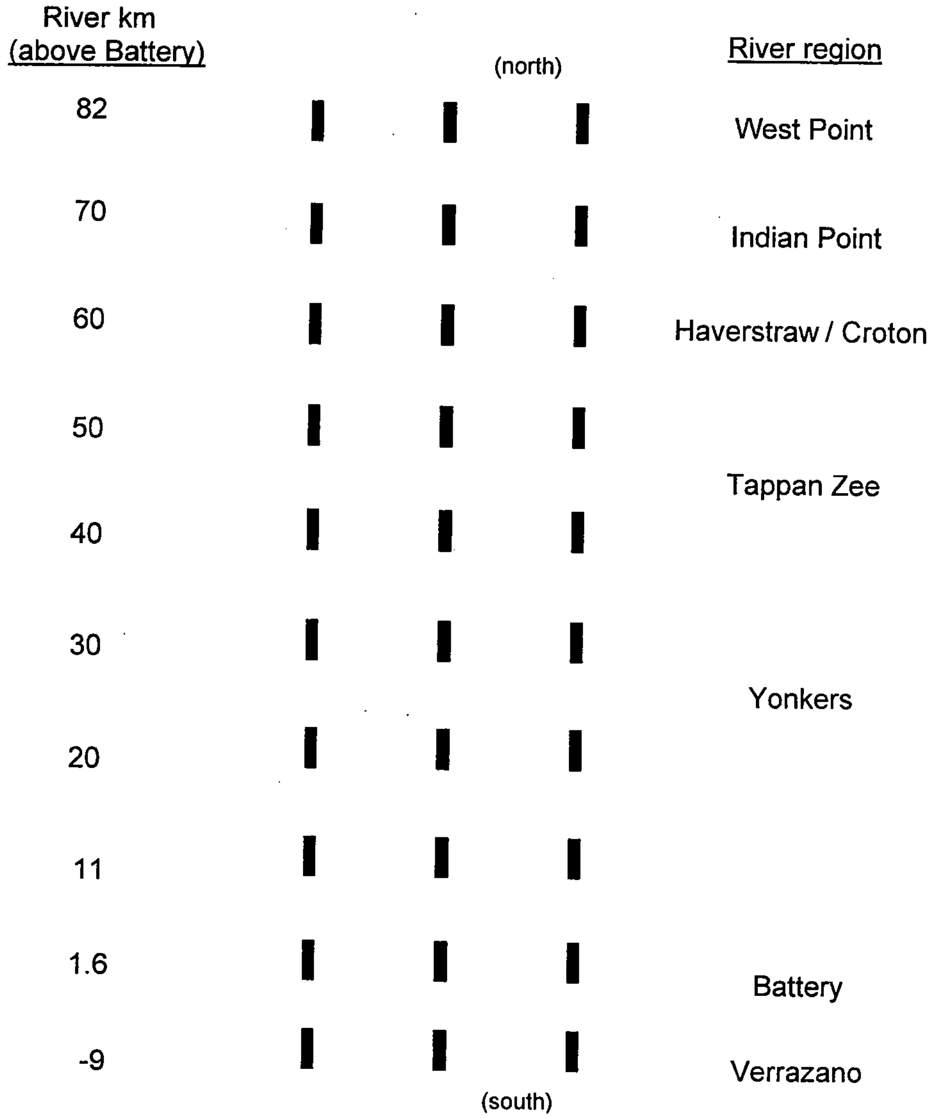

Figure 2. Hudson River otter-trawl sampling design for juvenile tomcod. Each bar represents a 5-min tow with a 4.9-m otter trawl.

Nets were towed against the current at a targeted 0.8 – 1 m/sec for a 5-min duration. Tow distances were determined using an on-board Global Positioning System (GPS) and ranged from 216 to 1,264 m (358 ± 132). All juvenile tomcod collected in each tow were counted, weighed (combined weight), and frozen for later analysis (TL, WW) at the laboratory. Tomcod abundance was standardized and converted to density by calculating the number of individuals collected per 100 m of river bottom, based upon the known distance the net was towed and the number of tomcod collected. After each tow, measurements of dissolved oxygen, temperature, salinity, conductivity, and turbidity of the water were made with a Hydrolab® at 2-m depth intervals ranging from the surface to the bottom.

RESULTS

Temperature-dependent growth experiment

The pattern of growth of juvenile tomcod differed among the three temperature regimes tested. The effects of temperature regime did not manifest themselves during the first seven weeks of the experiment despite as much as a 4°C difference between the warm and cool regimes (Figs. 1, 3). The average sizes of tomcod began to diverge at approximately Day 50, when temperature in the warm regime reached approximately 21°C (Figs. 1, 3a,b). At this time, growth rate of tomcod decelerated in the warm and moderate regimes while growth rate of tomcod experiencing the cool temperature remained constant at approximately 0.63 mm/d. The magnitude of this deceleration in tomcod growth rate was greater for fish experiencing the warm regime. Our index of condition followed the same pattern as length and weight with the cool regime producing individuals with the highest condition and the warm regime producing individuals with the lowest condition (Fig. 3c).

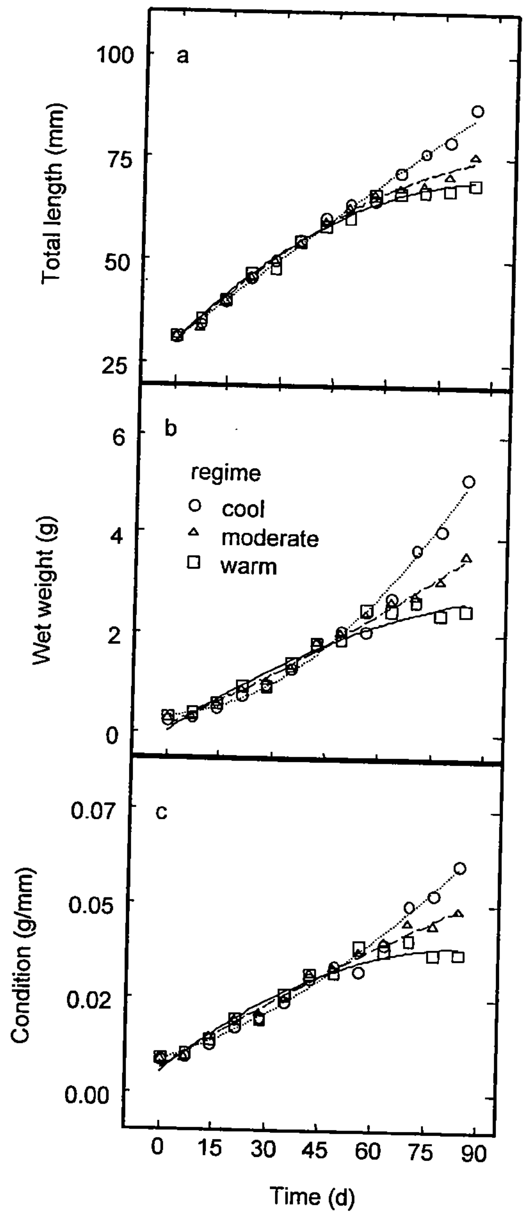

Figure 3. Total length (a), wet weight (b), and condition (c) of juvenile tomcod that were exposed to three different temperature regimes.

Field surveys – physical data

A significant gradient existed in both salinity and temperature along the portion of the Hudson River that we sampled (Fig. 4) with higher temperatures and lower salinities upriver. In addition, we found significant differences in salinity and temperature between sampling dates. June bottom water temperatures were approximately 2°C cooler than bottom water temperatures recorded on the July cruise. In both cruises, water temperatures were higher upriver with an approximately 2°C difference in temperature between the extreme upriver and downriver stations in June, and a 4°C difference in July (Fig. 4a). The July cruise covered a larger portion of the river, which may partially explain the greater range of temperature recorded during that month. Salinity was lower in the upriver station and increased with decreasing river kilometer with a range of 0 to 27 ppt (Fig. 4b). Salinity was higher in July than in June with a difference in average salinity of 5.6 ppt between the two months.

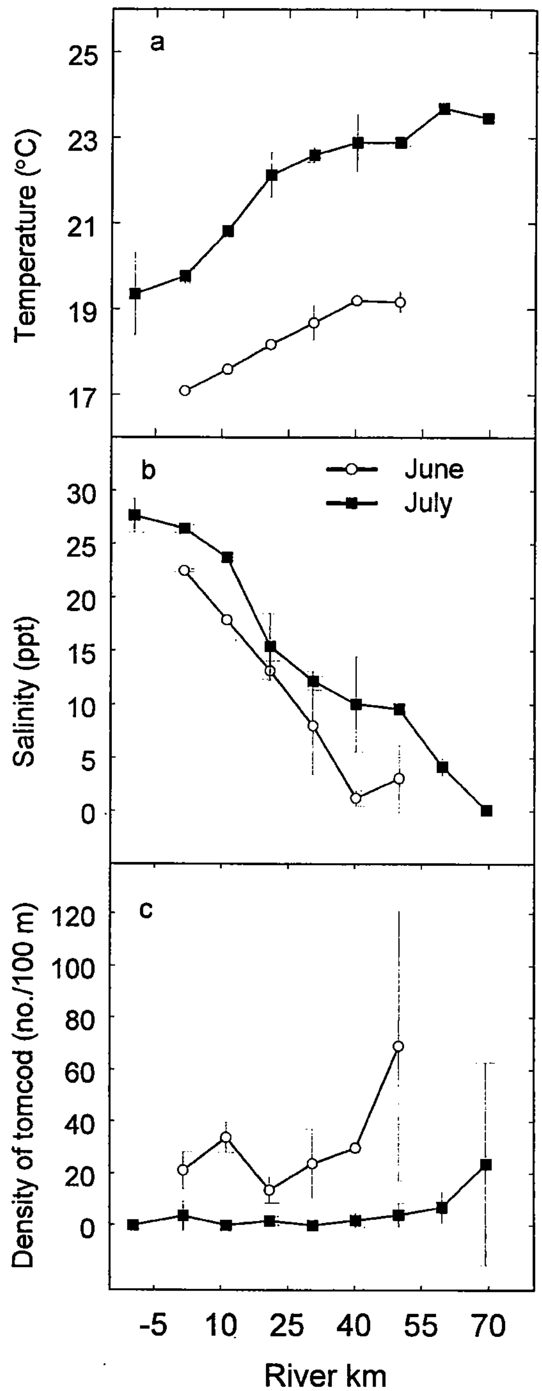

Figure 4. Temperature (a), salinity (b), and tomcod density (c) plotted against Rkm for the June and July Hudson River surveys.

Field surveys – tomcod size, abundance, and distribution

Tomcod abundance was higher in June than in July. The largest numbers of fish were located at the most upriver stations for both cruises (Fig. 4c). Tomcod collected in the July sampling cruise were larger than those collected in the June cruise (Fig. 5). The average TL increased from 80 mm in June to 95 mm in July. Growth rate, based on differences between average size-at-date information collected during this study, was estimated to be 0.42 mm/d (Fig. 5a). Average tomcod wet weight increased from 4.5 g in June to 8.0 g in July resulting in an estimated growth rate of 0.097 g/d (Fig. 5b).

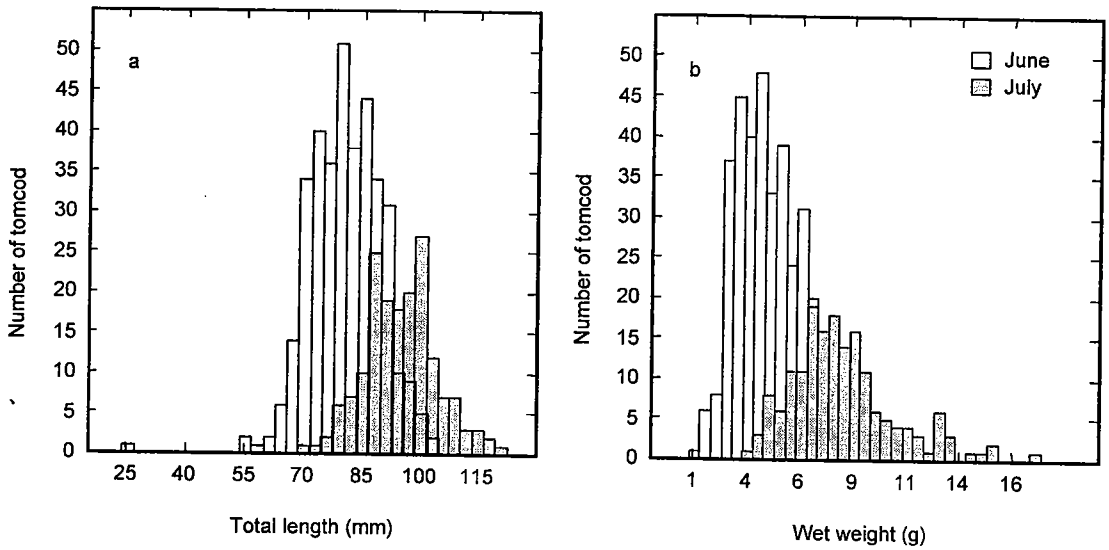

Figure 5. Length (a) and wet weight (b) frequency distribution of juvenile tomcod collected by otter trawl in June (open bars) and July (closed bars) in the lower Hudson River.

DISCUSSION

Temperature-dependent growth experiments

The temperature-dependent growth experiments conducted in this study clearly demonstrate that temperature has a significant effect on growth of juvenile Hudson River tomcod. Specifically, tomcod growth rates were suppressed by temperatures >20°C and were unaffected by temperatures between 15 and 20°C. This pattern of reduced growth rate at high temperatures was repeated in both length and weight measures of fish size. Our measure of condition, which is based on the ratio of length to weight, also declined at warm temperatures. These results are consistent with prior laboratory experiments that tested the effects of a broader range of temperatures (2-20°C) than those tested here on growth rate of larval and young juvenile tomcod (Chambers and Witting, in preparation). That work found a dome-shaped response of tomcod growth rate to temperature. Such a dome-shaped response of growth rate to temperature has been identified for several fish species (Ursin 1979, Ricker 1979, Jones 1976) and the specific form of the response curve is likely to play an important role in determining the geographic range of a species.

The results of our laboratory experiment show that growth slowed to nearly zero when temperatures reached approximately 24°C, which is consistent with earlier work on acute responses to temperature that determined an upper lethal temperature of ~ 26.5°C (Ecological Analysts 1978). The results of this work and other published studies suggest that juvenile Hudson River tomcod experience temperatures that are at or slightly above this lethal temperature during the summer. The laboratory-derived estimates of temperature effects on tomcod growth rate also support earlier conclusions based upon field collections that mid summer Hudson River temperatures result in a reduction in the growth rate of tomcod (Grabe 1978, McLaren et al. 1988).

Field collections of juvenile tomcod

Although juvenile tomcod were collected throughout the lower Hudson River (rkm −10 to 80), our results and the results of others suggest that higher densities of tomcod occur in the upriver portions of the river during the summer (i.e., rkm 60-80). Klauda et al. (1988) found that juvenile tomcod were most abundant in the lower portion of the Hudson River in April and May, but moved upriver during the early summer and were most abundant between Indian Point (rkm 62) and West Point (rkm 80) during July and August (Klauda et al. 1988 did not sample below rkm 20). They also suggested that the timing and magnitude of this upstream movement of juvenile tomcod varied substantially from year to year and they speculated that the specific timing of upstream migration may be related to movements of the salt front during the summer. Field sampling conducted by the utilities consortium from 1974-1996 also suggests that the highest abundance of juvenile tomcod occurs in the Yonkers region, particularly in the spring and early summer (CHGEC 2000). As in Klauda et al. (1988), this longer-term study suggests that tomcod move upriver in the mid to late summer and that the degree to which juvenile tomcod move upriver during the early summer varies from year to year.

Water temperatures recorded during our July cruise, particularly at stations above rkm 25, were similar to those that retarded growth in the laboratory portion of this study (i.e., >20°C). The Hudson River temperatures observed in this study are similar to those reported for the same portion of the river in prior investigations (e.g., Grabe 1978, McLaren et al. 1988). In addition, the change in temperature with increasing Rkm that we observed is similar to the 2-3°C increase in temperature between the Battery (rkm 0) and West Point (rkm 80) found in earlier surveys of the Hudson River (CHGEC 2000). In our study and the long-term Hudson River survey data, the mid summer temperatures recorded in the lower portions of the river were just below the reported lethal temperature for tomcod (Ecological Analysts 1978), while the upriver temperatures were near or just above the lethal temperatures. Our results combined with prior field sampling emphasize the need to address the question, 'Why do the highest densities of juvenile tomcod typically occur in regions of the river that are clearly sub-optimal for growth?' The answer to this question is likely to be complex and is beyond the scope of the present study.

Tomcod growth rates – this study vs. published values

We calculated seasonal growth rates of juvenile tomcod from data in several field studies to compare with our growth rate estimates (Table 1). The laboratory and field estimates of juvenile tomcod growth rates generated by this study are similar to those derived from prior studies with some exceptions. In our laboratory experiments, tomcod

Table 1. Summary of growth rate estimates of juvenile Hudson River tomcod.

Source	Year	Rkm	Spring (<6/30)	Summer (7/1-9/15)	Fall (>9/15)
McLaren et al. 1988	1974-'79	21-225	0.81	0.14	0.68
Grabe 1978	1974	60-66	0.46	- 0.03	1.19
CHGEC 2000 (River survey)	1996	2-260	0.81	0.18	0.61
CHGEC 2000 (Shoals survey)	1995	2-260	-	0.09	0.48
CHGEC 2000 (Shoals survey)	1996	2-260	-	0.17	0.46
This study (field)	2000	0-82	-	0.42	-
This study (laboratory)	2000	-	0.63[1]	0.22[2]	-

[1]temperatures < 20° C
[2]temperatures > 20° C

grew at a rate of approximately 0.63 mm/d when exposed to temperatures typical of spring and fall (<20°C) and at a rate of approximately 0.22 mm/d when exposed to temperatures typical of summer (>20°C). Three estimates for growth rate of juvenile Hudson River tomcod during the spring were calculated from the literature (Table 1). These values ranged from 0.46 to 0.81 mm/d thus bracketing the estimates of spring growth rate from our laboratory experiments. Similarly, five estimates for growth rate of juvenile Hudson River during the fall were calculated from prior studies. These estimates ranged from 0.46-1.19 mm/d, also bracketing the values obtained from our laboratory experiment for growth rate at temperatures typical of the fall (i.e., <20°C). Our laboratory estimate of tomcod growth rate under summer temperatures (0.22 mm/d) was higher than the five values calculated from prior studies (-0.03-0.18 mm/d), but lower than the estimate of summer growth from our field survey (0.42 mm/d). This discrepancy between our laboratory and field estimates verses results derived from prior studies may be partly due to the specific period over which the growth estimates were made. Our field estimate of tomcod growth during the summer was generated from June and July data. In our June survey, the temperature in the river was largely below the point at which the laboratory populations showed slower growth (i.e., ~20°C). It is likely that the river temperature remained sufficiently cool to sustain growth for a portion of the time spanned by our two sampling cruises. Although our laboratory estimates of growth were also higher than previous field values, these estimates are not entirely comparable because the experimental populations were not affected by factors including size-specific mortality, gear biases, and movements that often confound estimates based on field data. Thus, our laboratory estimates of growth may more closely reflect the underlying temperature-dependent growth than do earlier field estimates.

Conclusion

The Hudson River, which is home to the southernmost spawning population of Atlantic tomcod, reaches water temperatures in the summer that retard the growth of juvenile tomcod. The laboratory experiments conducted in this study are the first to experimentally validate the hypothesis generated by earlier work that tomcod experience a reduction in growth rate during the summer due to high temperatures. This reduction in growth rate appears to begin when temperatures reach 20°C. Growth rates fall to zero as temperatures approach 26°C, the approximate upper lethal limit for tomcod. Our field collections demonstrate that juvenile tomcod occupy upstream habitats whose water temperatures are in excess of those that produce maximal growth rates. The basis of this paradox requires further investigation.

The combination of reduced growth and lower condition of juveniles at summer temperatures may also result in lower recruitment of tomcod in warmer years. The possible reasons for a reduction in recruitment include: 1) the direct negative effects of excessively warm temperatures on survival, 2) decreased resilience to periods of food shortages at warm temperatures, and 3) lower mobility at warmer temperatures leads to a