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ARCTIC FISH HABITAT USE INVESTIGATIONS: NEARSHORE STUDIES IN THE ALASKAN BEAUFORT SEA, SUMMER 1990

by

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NOTICES

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ABSTRACT

During summer 1990, NOAA conducted research to evaluate temporal and spatial patterns of fish habitat utilization in the coastal Beaufort Sea. Two distinct approaches were followed to address various issues that have been identified with respect to OCS development in the Arctic. One approach involved systematic fish sampling across geographically large areas and offshore habitats where many fish occur. The second method involved intensive study of the movement behaviors of several individuals equipped with ultrasonic tags. Large numbers of small fish were captured in the offshore sampling. Their distribution and relative abundance was then related to various oceanographic properties. Fish telemetry involved fewer and much larger anadromous fish. Individual movement responses were evaluated with respect to telemetered temperature data and other habitat attributes measured during the course of tracking.

More than 17,000 fish representing 12 families were collected in 77 townet sets. Arctic cod, capelin, and Arctic cisco were the numeric dominants of the catch. Relative abundance varied by time and location of sampling and all species appeared to be patchily distributed. Strong east winds and low river discharges resulted in the prevalence of marine conditions throughout the offshore study area. The abundance of numerous small pelagic fish in the offshore catches suggests their potential availability as an abundant food resource for anadromous species using outer portions of the coastal water band and adjacent marine environments.

Young-of-the-year (YOY) Arctic ciscoes were captured between August 2 and September 5 at stations ranging from 0.5 km to more than 12 km from the coast. The lack of environmental contrast between marine and brackish habitat conditions precluded definitive analysis regarding habitat preferences (i.e., mean CPUE brackish = 7.45 fish, mean CPUE marine = 7.23); however, the presence of juvenile Arctic ciscoes outside their suspected modal temperature range suggests the possibility of acclimation. The highest densities were reported in catches where temperatures ranged from 4 to 6°C and salinities from 27 to 29 ppt. Instantaneous increases in mean body weight per day (G) was estimated at 4.95% during early August and 2.54% during the later part of the sampling period. The occurrence of juvenile Arctic ciscoes in catches off West Dock in mid-August is indicative of the movement of small fish in coastal currents being deflected offshore by the causeway structure during east winds. Young fish were abundant in the marine conditions detected in Stump Island Lagoon at this time, suggesting that strong currents at the western end of the causeway, and not thermoregulatory behaviors, may be responsible for their presence in the lagoon. Passive and directed migration rates of 15 and 18 km/d, respectively, are presented for YOY fish.

YOY Arctic cod were abundant throughout the eastern and central portions of Camden Bay in early September. Area and volume swept methods were used to calculate population and biomass estimates for the young cod sampled on September 2 and 3. A total of 83.6 million cod (95% CI = 52.7 to 114.5 million fish) were estimated in the upper 2 m of the bay. The estimated population weight was 1.6 million kg (95% CI = 1.275 to 1.98 million kg). The wet-weight biomass of YOY cod was estimated to be 0.8-0.9 g/m^2.

During the period July 30–August 11 we conducted an ultrasonic telemetry study of char and Arctic cisco in Camden Bay. Movement patterns and rates, as well as temperature occupancy and preferences, were monitored. Six large char and one cisco were tracked over a total of 120 km. Most fish sought the shoreline, but the directedness of their movements was quite variable. The chars' average gross ground speed was 55.8 cm/s (range 48.2–74.2 cm/s), or 1.04 L/s (range 0.96–1.37 L/s). Net speeds of char ranged from 9.5 to 63.2 cm/s. No significant differences in alongshore and offshore speeds were evident. The mean temperature occupied by the char was 3.6°C (range –0.5 to 6.5°C, n = 493). The frequency distribution of temperature was multimodal. The char used the entire range of observed temperatures in the study area. Temperature preference observations indicated that the fish selected the warmer halves of the available ranges in the water column. However, no consistent avoidance of cold water was evident in the horizontal dimension so the former observations may be more reflective of depth selection. The tagged Arctic cisco displayed very directed movement toward the vicinity of its capture site. Its gross ground speed was 48.9 cm/s, or 1.14 L/s, while its net ground speed was 44.1 cm/s. The mean temperature occupied by the cisco was 2.8°C (range 1.5–3.5°C, n = 51). The temperature frequency histogram was unimodal. The results are discussed in the context of similar observations on chars and other salmonids.

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PART I. BACKGROUND

Key Species

The exploration and development of Arctic oil reserves has prompted numerous fishery investigations in the Alaskan sector of the Beaufort Sea. The study of anadromous[1] fish populations has received special attention because of their importance in rural economies and coastal ecosystems, and the possibility that industrial developments associated with petroleum activities could affect these populations. Additionally, the management of several species is of international concern. In these instances, the anadromous life cycle includes long-distance migrations, extended rearing at sites far removed from natal origins, and overwintering in transboundary rivers.

Arctic cisco (*Coregonus autumnalis*), Arctic char (*Salvelinus alpinus*), least cisco (*C. sardinella*), and broad whitefish (*C. nasus*) have been the focus of most coastal fish studies in the Alaskan Beaufort Sea. These anadromous fish tend to be the largest and most conspicuous members of the nearshore fish community in the arctic. Actually, several of the less-studied marine species are numerically much more abundant. Anadromous fish stocks are characterized by low recruitment rates and other density-dependent mechanisms that allow their populations to survive arctic conditions (Craig 1989a). Availability and quality of overwintering habitat are viewed by many as the greatest determinant of population size.

Brackish Water Habitats

A common feature of arctic anadromy is the annual migration of fish from freshwater overwintering areas to summer feeding habitats. Summer habitats are located within the narrow band of relatively warm, low salinity water that develops during summer along the Beaufort Sea coast. The brackish water band is an ephemeral and dynamic habitat that, typically, is continuous early in the summer and discontinuous later. Discontinuity coincides with declines in runof and the mixing of coastal and oceanic water masses. The width of the brackish water band differs with location and has been estimated to extend from 1 to 10 km from the coast (Craig 1989a). Wind stress, horizontal pressure gradients, and tides are the driving forces of the coastal circulation (Colonell and Niedoroda 1990a,b). Such geophysical forcing occurs across a wide range of temporal and spatial scales and its expression may be periodic (tides) or less regular (upwelling). For instance, the hydrographic properties at any given time in summer at Prudhoe Bay result not only from prevailing meteorological and river discharge conditions, but also from conditions several hours to several weeks prior (Hale et al. 1989). A similar generalization is pertinent to any location along the coast.

Maughan (1990) likened the brackish water band to a "constantly changing mosaic of salinity and temperature patches driven by wind and water inflow and bathymetric conditions." Superimposed on the physical environment he envisioned heterogeneous distributions of predators and their prey. This variability in hydrographic regimes is evident at mesoscales (10's - 100 km) from satellite observations of the nearshore environment during

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[1]Anadromous is synonymous with amphidromous in this paper (see McDowall 1987).

the summer. A qualitative analysis of thermal images taken during 13 days in 1988 revealed a general trend for warmest waters to be located nearest the coast and coldest waters to be found nearest the ice pack (Thorsteinson et al. 1990). The heterogeneity of the coastal band was confirmed by the "patchwork" distribution of temperature regimes noted in the thermal images.

Offshore Habitats

We have argued previously that the existing arctic fish database is largely one-dimensional in space, reflecting the inshore concentration of existing research efforts (Thorsteinson et al. 1990). This inshore emphasis has led to generalizations about use of coastal waters by fish in poorly sampled areas. For instance, Colonell and Gallaway (1990) state that research has demonstrated the anadromous species are generally restricted in distribution, from the coastline out to a depth of 2 m, where cold (0°C), marine bottom water occasionally upwells near or to the surface. Such a restricted range is probably more true for some species than others. In fact, considering the annual variability in ocean conditions, it may reflect depth-imposed gear limitations as much as availability of suitable fish habitat. As a consequence, the onshore–offshore features of movements and migrations, habitat use, and general ecology of several species are unknown.

Few studies have addressed fish use of habitats in outer portions of the coastal brackish band or in the marine habitats beyond. Craig (1984) concluded that the wide variations in temperature and salinity distributions across the coastal habitats defied their easy description by any physical attribute such as depth or distance from shore. Instead, he reasoned that the categorization of habitats by water mass characteristics was probably the most meaningful approach within the context of existing information.

In 1988, NOAA conducted offshore purse seining to augment the meager offshore data and to provide an "offshore dimension" to an ongoing Arctic char stock identification project (Everett and Wilmot 1990). Fish sampling was conducted in three hydrographically defined habitat types (Thorsteinson et al. 1990). It was hypothesized that Arctic char occupy the entirety of the coastal brackish water habitat, but do not habitually venture into the colder, more saline waters. An inferential analysis was performed to describe frequency of occurrence patterns indicative of habitat associations in coastal, transitional, or marine habitats. Anadromous species were associated with the coastal habitat while marine species were distributed throughout the habitats sampled. The structural occurrence of coastal waters overlaying other water masses was thought to provide the physical pathway enabling offshore dispersals by anadromous fish. It was suggested from qualitative observations of food habits that the offshore movements were a distributional response to density of prey.

Arctic char and Arctic cisco were the only anadromous species captured in the offshore seining. The greatest number of Arctic char was captured approximately 5 km off Bullen Point in eastern Stefansson Sound. These char were generally small (FL 240 mm) and may have been moving with Sagavanirktok River water that had been transported to the east under west wind conditions. Gallaway (1990) indicates that there is considerable evidence that small fish, at least, travel in the direction of drift and that fish displaying such movement behavior have a bioenergetic advantage. Dempson and Kristofferson (1987) characterized the ocean movements of Arctic char as a feeding migration influenced by the spatial and temporal distribution of a major prey, the capelin (*Mallotus villosus*).

Rose and Leggett (1989) hypothesized that the geographic distribution of Atlantic cod (*Gadus morhua*) in the northeastern Gulf of St. Lawrence is determined by geophysically forced oceanographic conditions. Within these limits, cod distribution is further delimited by interacting physical (e.g., water temperature) and biotic (prey) conditions. They argued that: (1) cod distribution is largely controlled by water temperature; (2) most species frequent a much narrower "modal" temperature range; and (3) highly mobile migratory species reduce their exposures to environmental extremes by moving in synchrony with preferred conditions. Correlation analysis (univariate methods) between cod catch and sea temperature, and cod catch and prey (capelin) density variables did not adequately explain the observed patterns of cod distribution or catch. Regression analysis, on the other hand, indicated that under mesoscale conditions of high prey density and favorable temperatures cod distributions closely matched those of capelin throughout their distributional range (–0.5 to 8.5°C). When prey density was low, the distribution of cod was unaffected; they remained within their modal range (0–5°C). In the latter instance, the infrequent occurrence of cod at temperatures outside their modal range was thought to reflect a distributional response to prey density. In conclusion the authors note that the interaction of sea temperature and prey density to regulate cod distribution may apply to all cod populations.

Thermal Requirements

In the study above, "modal" and "preferred" temperature ranges were distinguished by reference to observations of free-ranging and experimentally held fish, respectively. Houghton et al. (1990) conducted a habitat use analysis based on a 4-year arctic fish database containing some 180,000 fyke-net catch records from Prudhoe Bay. This analysis provides preliminary information about the temperature-dependent range limits of the four most common species of anadromous fish in the Beaufort Sea. The analysis was limited to early (mid-June) and midsummer (mid-August) periods. As presented below, modal range reflects temperatures associated with peak utilization as indicated by daily CPUE.

Species	*Geographic Range (°C)*	*Modal Range (°C)*
Arctic cisco	0–>12	6–12
Arctic char	0–12	4–10
Least cisco	0–12	8–>12
Broad whitefish	2–>12	8–>12

The thermal ranges described above undoubtedly underestimate the true distributional limits of the fish during the open-water season. Craig (1984) reported additional information on the temperature ranges of the anadromous fish from a synthesis of many research projects; however, his ranges are in good agreement with those presented above. The Houghton et al. (1990) analysis was truncated in mid-August to reflect coastal usage patterns during summer periods of greatest fish dispersal. The result is that at least 1 month of open-water season is excluded from the analysis. Water temperatures below 0°C are not uncommon in the coastal zone during summer months and are especially evident just prior to freeze-up. After August 15, the nearshore tends to experience steadily decreasing temperatures and increasing salinities. Anadromous fish are able to withstand such conditions for at least brief periods (Colonell and Gallaway 1990). As an example, Johnson (1980) reports Arctic char in Creswell Bay, Canada, withstanding subzero temperatures (–1.4 to 1.44°C) at depths to 15 m.

Selected oceanographic data from Camden Bay in "warm" and "cold" years illustrate the annual variability in temperature conditions of anadromous fish habitats. Hale (1991) indicates that water temperatures during the 1989 season were above average. A maximum temperature of 11.4°C was reported on August 8 at a Fish and Wildlife Service sampling station (CB06) located 2.6 km (9-m water depth) off Carter Creek in Camden Bay. Closer inshore at station CB02 (located approximately 0.7 km off Carter Creek, 3-m water depth), a maximum temperature of 14.2°C was observed. At shallow-water stations located in Simpson Cove and in the lagoons east of Barter Island, water temperatures in excess of 14°C were observed. Similar temperatures from these stations on August 8, 1988, were 2.2°C at CB06 and 2.2°C at CB02 (Hale 1990).

Temperature preference data are lacking for most of the arctic anadromous fishes. Fechhelm and Gallaway (1984) reported temperature preferenda of small Arctic cisco (83–136 mm) acclimated to several temperature and salinity regimes representative of the brackish water zone. Their experiments showed a preference by Arctic cisco for temperatures generally greater than 10°C over the range of salinities studied (5–30 ppt). In fact, the test fish selected the warmest available temperatures (14–15°C). Such conditions approach the upper limits of the thermal spectrum that might be encountered in the coastal Beaufort Sea (Fechhelm et al. 1982). These authors noted that the apparent preference for warmer water explains the Arctic cisco's utilization of a relatively narrow coastal corridor (20–50 m wide) during summer. The physiological benefits conferred by such habitat use, especially on growth and migration, have been discussed elsewhere (Fechhelm et al. 1982; Craig 1984, 1989a; Gallaway 1990; Thorsteinson et al. 1990; English, in press).

Similar experimental results for other anadromous species are not available. The large body of field data that has been obtained from the Prudhoe Bay area over the past 15 years indicates varying tolerances of the major anadromous species (cf., Ross 1988). Besides Arctic cisco, only Arctic char are expected to disperse farther than 1 km offshore (Craig 1984; Fruge et al. 1989). Circumstantial evidence suggests Arctic char may prefer slightly cooler temperature conditions than the Arctic cisco. Berg and Berg (1989) studied the at-sea growth of anadromous Arctic char in northern Norway. Optimal growth in char was observed during June when temperatures ranged from 5 to 10°C. The authors suggested that ocean temperatures in excess of 14°C limit the southern distribution of the species. Elsewhere, in arctic lakes, optimum growth in Arctic char has been observed at temperatures between 12 and 16°C (Johnson 1980).

Environmental Influences

Water temperature may be the greatest physical determinant of fish distribution (e.g. Rose and Leggett 1989). In the Arctic, the brackish water nearest the coast is typically characterized as hydrographically most favorable for anadromous fish (e.g., Craig 1984).

Houghton et al. (1990) and others (see Fechhelm et al., in press) report a general trend for greater use of warm (4–12°C), low- to moderate-salinity (0–20 ppt) water. Other interacting factors such as currents, food habits, prey availability, and size and condition of the fish, influence dispersal patterns (cf. Dempson and Kristofferson 1987). Colonell and Gallaway (1990) subjectively list (in order of importance) the most important ingredients of anadromous fish habitat quality: (1) abundance of prey, (2) temperature, (3) salinity, and (4) "predictability" or stability of the other three factors. Temperatures at or below 5°C seem to represent a lower limit for habitat use by arctic anadromous fish (i.e., reduced growth rates and return migrations begin below this temperature) (Colonell and Gallaway 1990).

Temperature–salinity challenge experiments conducted on small Arctic ciscoes support the generalized trend of reliance on brackish water habitats by anadromous fish (Fechhelm et al., in press). The size range of Arctic cisco in these bioassays was 120 to 170 mm (FL). Young-of-the-year (YOY) fish were not studied. Prior to experimental testing the ciscoes were held at ambient conditions approximating those of their capture location for a minimum of 3 d. The experimental protocol required acclimation rates of 2°C and 5 ppt changes/d to one of three temperature (12, 7, and 3°C) and salinity (0, 15, and 32 ppt) regimes. The ciscoes were held at acclimation conditions for at least 14 d before starting 96-h bioassays involving instantaneous exposures to various temperature and salinity combinations.

Acclimation appeared to enhance the tolerances of experimental fish to elevated salinity (Fechhelm et al., in press). Osmoregulatory failure and lethal effects were, however, observed at salinities of 25 ppt or greater. The observed deleterious effects of prolonged exposures to cold water on osmoregulation in Arctic cisco may be similar for other anadromous species. This result would indicate avoidance, or very limited use, of marine areas in the wild. Other experimental evidence supports this conclusion. The few bioenergetic studies from which data are available indicate minor effects on growth rate at salinities of 0–15 ppt and significant reductions in growth and increased mortality at higher salinities (e.g., English in press).

Colonell and Gallaway (1990) suggest that salinity has little effect on the distributional response of anadromous fish until some threshold level is reached. Salinity tolerance evidently varies by species and with size of fish. Among the anadromous species, small fish tend to be less tolerant than larger fish. Conversely, immature Atlantic cod are able to endure temperatures well below those tolerated by older fish (Rose and Leggett 1989). Many factors such as size, age, and sexual condition of the fish influence its tolerance and ability to acclimate to changing salinity. These relationships remain undescribed for most arctic fish.

In situ growth experiments conducted in 1988 (English, in press) reinforce the concept of anadromous fish preference for brackish water habitats. Arctic cisco and broad whitefish were held for 6 wk in mesh enclosures at Endicott and Niakuk study areas. Water depths at these sites averaged about 1.5 m. Mean weekly temperature and salinity conditions were similar at each site, ranging from about 7°C and 11 ppt (early season) to 2°C and 25 ppt (late season). Test fish ranged in length from 120 to 180 mm (FL) and in weight from 15 to 45 g. Differences in growth and survival were noted between enclosure sites and species. Highest growth rates were observed during late July to mid-August. In 1988 these corresponded to periods of highest ambient temperatures (about 7°C) and low to intermediate salinities (>15 ppt). Broad whitefish held at the Niakuk site suffered higher mortalities and lower growth rates than fish rearing near Endicott. While temperature and salinity conditions were partially responsible, the Niakuk site was more exposed, resulting in increased mortalities to fish during inclement weather. Broad whitefish fared poorly at each location, suggesting poor habitat conditions for this species at these sites in 1988. The growth rate observed in Arctic cisco was 6 times higher than that of broad whitefish. This was thought to reflect the greater flexibility in habitat use by the Arctic cisco.

Arctic Cisco Migration

The lack of discovery of spawning or spawned-out Arctic cisco in the Colville River and delta led Gallaway et al. (1983) to hypothesize that Arctic cisco in the Alaskan Beaufort Sea are of Mackenzie River origin. Prevailing east-to-west longshore currents provide the dispersal mechanism for age 0 fish from the Mackenzie estuary to reach Alaskan overwintering sites. Gallaway et al. (1983) proposed that the Arctic cisco migration involves a passive transport of fish in wind-driven currents. A passive migration is supported in part by comparisons of summer wind conditions with (1) commercial catch statistics from the Colville Delta (Fechhelm and Fissel 1988); and (2) relative abundance estimates of YOY fish in Prudhoe Bay (Fechhelm and Griffiths 1990). Average northeasterly wind conditions (5 m/s), and current speeds approximating 3 to 4 percent of the winds (15 cm/s), imply a 35 d (13 km/d) migration period for YOY fish travelling between Mackenzie and Colville river habitats (Gallaway et al 1983). The average rate of westward movement by Arctic cisco of 13.6 km/d observed by Moulton (1989) is consistent with this estimate.

Neill et al. (1983) developed a biased random walk model to evaluate the movement patterns of Arctic cisco around the West Dock causeway. Under various scenarios, high changes in modeled catch rates could not be explained by swimming rate alone. It was suggested that either the fish were being entrained in strong currents in the causeway area or that catchability rates (and not fish density) were being affected (delayed or obstructed) by hydrographic changes. The "pulsing" observed in the model's results was attributed to distributional responses by the fish to shifting winds and currents and altered nearshore conditions.

One constraint of the model was that it was unable to address adequately the width-of-path effect of the Arctic cisco migration (Neill et al. 1983). No information (physical or biological) was available regarding this aspect of migration and it was therefore assumed that the fish either (1) do not venture farther offshore than 0.5 km north or northwest of West Dock (which extended 3.9 km from the coast at this time); or (2) venture offshore but only into waters possessing conditions equivalent to those found closer inshore. The first attempt to obtain information on the offshore distribution and abundance of age 0 Arctic cisco in Prudhoe Bay and to study their migration in the causeway areas was undertaken by Houghton and Whitmus (1988). Unfortunately, their sampling objectives were confounded because few recruits moved into the study area in 1988 (Schimdt et al., in press). Variable and westerly wind conditions in 1988 may have been responsible agents for the lack of YOY Arctic cisco.

Only three Arctic cisco were captured in NOAA's seining in 1988: one off Bullen Pt. (FL = 375 mm); one in Camden Bay (84 mm); and one near Thetis Island (146 mm). The juvenile fish sampled in Camden Bay on August 21, 1988 (station C04081, 5.5-m depth), was captured approximately 0.75 km off the coast. This catch provides preliminary evidence that a wider migration corridor is being utilized than has been suggested elsewhere.

More recently, modeling (random walk with advection) of the movement of young Arctic cisco in Prudhoe Bay was performed by Bryan (1990) as part of the Endicott Development Fish Monitoring Program. The study focused on the migration of the fish past the Endicott Causeway from August 20 to September 1. Initial fish density distributions were selected on the basis of actual fyke-net data and the temperature preference data of Fechhelm and Gallaway (1984). Oceanographic data inputs (current vectors, etc.) from other sources were indicated by the author but were not clearly specified. Fine-scale (1 km) movement patterns were apparently biased such that fish were generally moving toward more optimal water quality conditions. The algorithms used were successful predictors of the relative magnitudes and general trends in observed catches. A major conclusion was that currents, and not thermoregulatory behavior, had the greatest effect on YOY Arctic cisco distribution. The effects of temperature and salinity different from those modeled require further investigation.

The above is not meant to downplay the role of currents in anadromous fish migrations and movements. Previously, we argued that the development of realistic predictive models would require a more detailed history of fish movements along known environmental gradients than is presently available (Thorsteinson et al. 1990). Catch data from passive gears with long set periods are not amenable to correlation with physical phenomena of brief temporal and spatial scales, such as the passage of fronts, eddies, and wind-driven events, which are prevalent in North Slope coastal waters. Such short-lived phenomena are important because they influence the local distributions, movements, and other daily activities of fish and their prey. Colonell and Gallaway (1990) argue that because fish distributions are not static, sampling with active gear will not necessarily provide data that would define preference. It will, however, with adequate sampling intensity delimit the "modal" range described above and provide more precise data on fish abundance.

The Issues

Solid-fill gravel causeways have proven to be a cost-effective technology for onshore transport of (1) seawater via pipelines for waterflooding, and (2) produced crude oil to the Trans-Alaska Pipeline (Standard Alaska Production Company 1989). However, environmental issues have been identified concerning causeway construction and subsequent effects on coastal oceanography. For instance, Hale et al. (1989) describe the major effects of West Dock on local circulation. They include offshore deflection of alongshore flow (including river plumes) and the blockage of alongshore movement and mixing of water mass properties. As a result, other marine processes are influenced as well, including coastal hydrographic conditions, upwelling, and vertical mixing. These authors conclude that under either easterly or westerly winds, West Dock can deflect alongshore surface currents and plumes northward around the tip at least 4 km offshore.

Other authors indicate that the marine environment has been little affected by the construction of causeways. Colonell and Gallaway (1990) also provide an assessment of marine environmental impacts of West Dock causeway. Colonell and Niedoroda (1990a) maintain (from a physical oceanographic perspective) that Stump Island Lagoon is a minor appendage of Simpson Lagoon that "never has played a major role in establishing the hydrographic conditions there, even in the eastern part of Gwydyr Bay." This conclusion is based on the cross-sectional area of the barrier island channels in eastern Simpson Lagoon.

The relative time and spatial dimensions of the marine areas affected by causeway obstruction are dependent on the prevailing oceanographic and meteorological conditions at any given time. The extents of coastal areas affected by changes in water quality are therefore difficult to determine. Colonell and Gallaway (1990) assert that the geographic extent of salinity increase attributed to the Waterflood extension of West Dock is of the order of 800 ha but that this area is not easily determined. Ross (1988) estimated that water quality and circulation patterns along as much as 60 km of coastline have been altered by the West Dock and Endicott causeways.

Prediction of biological effects on anadromous fish populations of the North Slope associated with oil and gas development in or near Prudhoe Bay has proven to be an arduous and controversial process. It has been hypothesized that in the marine environment causeways and waterflood projects may interfere with fish migrations, habitat quality, and overall fish use of coastal waters. Since estimates of population size are unreliable for most species, parameters such as growth and condition have been evaluated for several years in the Prudhoe Bay area. The sensitivity of the condition analysis is questionable as it tends only to include fish in good condition. With increasing industrialization of the North Slope, the resolution of these and other fishery issues (e.g., oil spills, availability of fresh water, and gravel excavation) will be required on regional as well as local scales.

Information is lacking concerning the environmental tolerances and responses of most anadromous fish species to hydrographic conditions they may confront in the coastal Beaufort Sea. This, in part, has limited our ability to accurately assess the probable effects of certain development activities. The coastal brackish band serves as an avenue for the alongshore movement of anadromous fish between feeding, spawning, and wintering locations. Because anadromous fish must acquire so much of their annual energy supply during the brief open-water season (Craig 1989a), the availability and quality of feeding habitats are of primary concern. Access to these habitats is critical during summer months. Blockage, or delays, of fish migration may result from physical barriers imposed by the causeways. The potential effects of causeways on YOY Arctic cisco migration have been of concern (MBC 1990). There are two issues: (1) blockage or delay of migration in the causeway areas, and (2) the transport and fate of young fish entrained in coastal currents that have been deflected offshore.

PART II. ACTIVE SAMPLING

INTRODUCTION

The goal of NOAA's Arctic Fish Habitat Use Investigations is to ensure the protection of fishery populations and their habitats from potential adverse effects of OCS development in the Alaskan Beaufort Sea. The research has focused on the identification and characterization of important marine habitats and temporal–spatial features of their use by arctic fishes. Anadromous species are of special management concern. Their populations tend to be small in size, possessing low recruitment rates and other traits common to K-strategists (Craig 1989a). Such populations (i.e., characterized by great longevity coupled with low adult mortality and recruitment) differ from truly stable populations where recruitment and mortality rates are nearly equal. Several species are valued subsistence resources and others are targeted in small commercial fisheries located in the lower Colville River. In addition, the management of several species is of international concern because of the transboundary nature of migration routes and overwintering areas.

In an ecological sense, the aim of our research is to gain an understanding of the dispersal mechanisms and processes responsible for observed patterns of fish distribution and abundance across the Beaufort Sea shelf. This has required oceanographic sampling in habitats occupying outer portions of the brackish water band and beyond. This is significant because it provides an offshore component to the existing arctic fish database. Fishery information is essentially lacking from marine environments of the Beaufort Sea (Craig 1984). The offshore sampling provides an opportunity to incorporate different sampling methods into the research design than have been practical closer inshore. We chose an active sampling gear approach because resultant indices of abundance provide quantitative estimates of standing stock densities that can be directly related to ambient environmental conditions (e.g., temperature, salinity, winds and currents, and food availability).

Exploratory oil drilling in Camden Bay, to the northeast of Barter Island, and northwest of Harrison Bay, are indicators of impending industrial expansion in the Beaufort Sea. With few exceptions, fishery resource information from these areas is sparse or nonexistent. The possible opening of the Arctic National Wildlife Refuge (ANWR) to oil and gas exploration has prompted coastal fishery surveys in the eastern Beaufort Sea (e.g., Fruge et al. 1989). Unlike the open lagoon systems characteristic of Stefansson Sound, exposed nearshore waters and limited exchange lagoons predominate in the east. Such geomorphological differences are important because the structural gradients defined by freshwater inflows, wind-mixing, upwelling, and other physical processes ultimately define the useable boundaries of available habitat for marine and anadromous fish. They may also establish important mechanisms which may enhance or impede migrations, dispersals, or other uses of the coastal zone by fish.

Four species of anadromous fish have been of primary concern in fishery investigations in the Alaskan Beaufort Sea. These are the Arctic cisco, Arctic char, least cisco, and broad whitefish. The research has consisted of various assessments of the potential impacts to fish populations associated with oil and gas development in or near Prudhoe Bay. In particular, the effects of solid-fill causeways on coastal oceanography and anadromous fish habitats have been a special environmental concern. It has been hypothesized that causeways and water-flood projects may interfere with fish migrations, habitat quality, and overall fish use of coastal waters. The range of possible impacts varies by species and appears to be largely a function of their tolerance to coastal temperature and salinity conditions. With increasing industrialization of the North Slope the resolution of these, and other issues, will be required on regional as well as local scales.

OBJECTIVES

A primary focus of the 1990 sampling was the coastal migration of juvenile Arctic cisco (*Coregonus autumnalis*) in Alaskan waters. Gallaway et al. (1983) had proposed a wind-aided, passive transport of Mackenzie River cisco to the Colville River delta. Evidence is mounting to support the "fish from Canada" hypothesis (Fechhelm and Fissel 1988; Fechhelm and Griffiths 1990) and it has been suggested that the migration is primarily a shoreline-directed nearshore phenomenon. There is, however, little reliable offshore catch data available to support the latter contention and it is not yet possible to delineate the migratory corridor itself.

Although our sampling targeted on juvenile Arctic ciscoes, various other species were collected in the offshore fishing. A secondary objective was, therefore, to describe the general features of habitat use by these fish and, if possible, to evaluate growth and condition parameters for the dominant species involved.

The specific objectives of the 1990 fieldwork were (1) to determine the spatial–temporal distributions, relative abundances, and habitat associations of dominant fish species in the nearshore Beaufort Sea; and (2) to delineate the migratory corridor of juvenile Arctic cisco at several locations in the Alaskan Beaufort Sea.

STUDY AREA

The study area included the coastal waters lying between Prudhoe Bay and Barter Island (Fig. 1).

Most operational activities were based at Camden Bay. Camden Bay is a relatively deep embayment in the western portion of the ANWR. It is located between Barter Island, in the east, and the Canning River delta, to the west. The natural setting of Camden Bay (see Fruge et al. 1989) provides easy access to coastal and marine fish habitats, while at the same time providing close proximity to safe anchorages at Simpson Cove and Barter Island.

Camden Bay is typical of many of the exposed nearshore habitats characteristic of the eastern Beaufort Sea. With respect to oil and gas development, some exploratory drilling in the western bay has already occurred. Further development can be expected. If oil leasing occurs in the ANWR, Camden Bay is a likely site for port expansion and other shore-based support. With respect to our study objectives, the deep nature of the bay, particularly on the

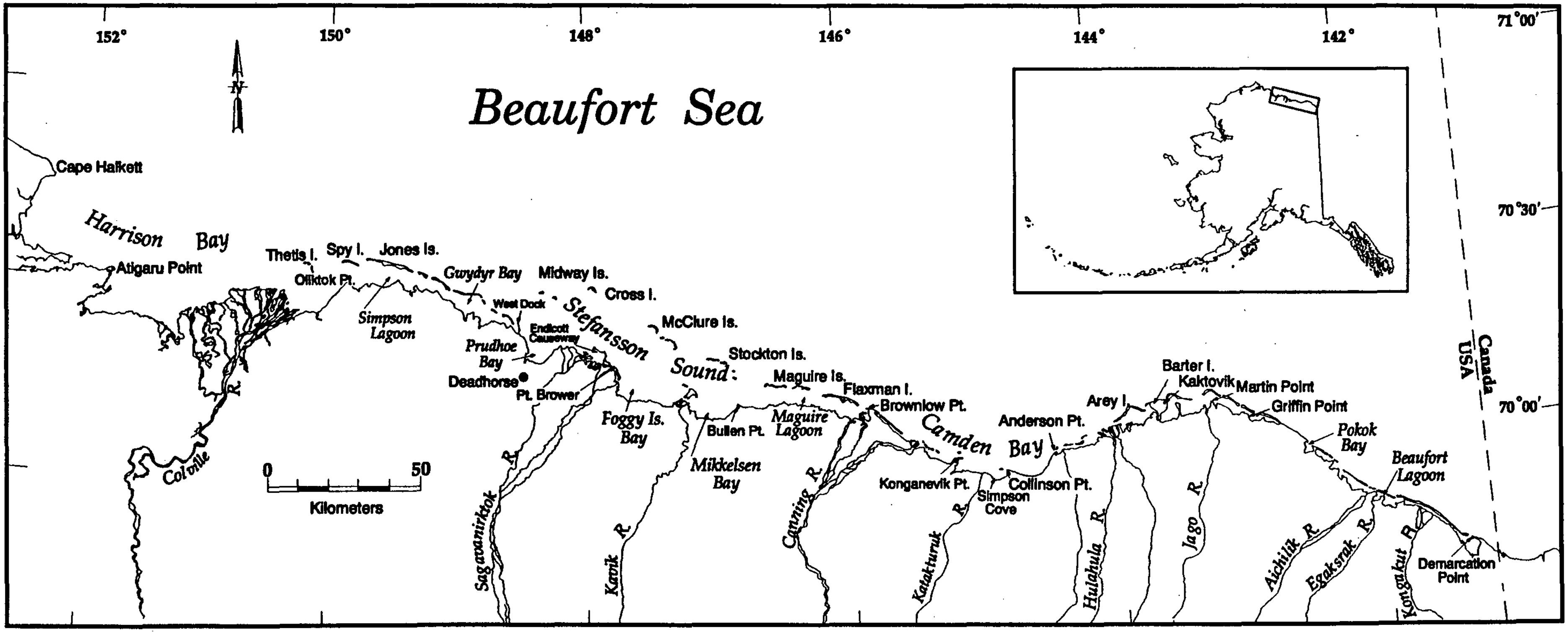


Figure 1.—Study area, Beaufort Sea coast, Alaska.

eastern shore, allows towed gears to be deployed quite close inshore. This is an important operational feature of the migration and dispersal components of the research.

The research vessel was regularly provisioned and serviced at West Dock in Prudhoe Bay. Since these activities required regular travel between Camden and Prudhoe bays, several additional sampling stations were established in the causeway areas (Fig. 2). These stations coincided with the sampling locations of Houghton and Whitmus (1988). Mid- to late August sampling periods were given highest priority as they would encompass periods of peak YOY Arctic cisco migration through Prudhoe Bay.

METHODS

Fish Sampling

All oceanographic research was conducted from NOAA vessel *1273*, an 11-m aluminum craft with a draft of 1.3 m. This boat is currently configured as a drum seiner. It has a maximum speed of 8 knots, a range of 730 km, and an endurance of 7–10 d, and can accommodate four persons. Other attributes of *1273* for working in the shallow Beaufort Sea have been described by Thorsteinson et al. (1990).

Five transects were selected for fish sampling in 1990 (Fig. 3). From west to east, they were located (1) west of West Dock, (2) on the east side of the Endicott Causeway, (3) off Brownlow Point, (4) off Collinson Point, and (5) off Arey Lagoon to the west of Barter Island. The transect placements reflect entry and exit locations of migratory fish passing through Camden and Prudhoe bays. The Collinson Point transect increased the spatial resolution of sampling in Camden Bay (mid-point transect) and added a necessary onshore–offshore dimension to our monitoring of the Arctic cisco migration through the center of the bay.

Our study plan also included fish sampling near Carter Creek in Camden Bay. It was anticipated that this sampling would coincide with FWS coastal sampling in the area. Our expectation was that synoptic fishing efforts would facilitate the description of a realistic relationship between catches associated with active and passive gear types.

A single station (MS01) was positioned near Flaxman Island and the Mary Sachs Entrance to eastern Stefansson Sound. This station was strategically located to examine its role as a potential "choke" point for migrant cisco en route to Prudhoe Bay.

In most instances the locations of stations on each transect were stratified by their relative distance from the mainland coast. Inner transect stations, or "base stations," were generally defined by the shallowest working limitations of the primary sampling gear. Two exceptions included the location of base stations on Arey Island and Brownlow Point transects. Along these transects, the bases were located 3.5 km from the coast. In Camden Bay, once the base station had been defined, other transect stations were located approximately 1.5, 4.5, 7.0, and 9.0 km from the base (and 11.0 km on the Collinson Pt. transect).

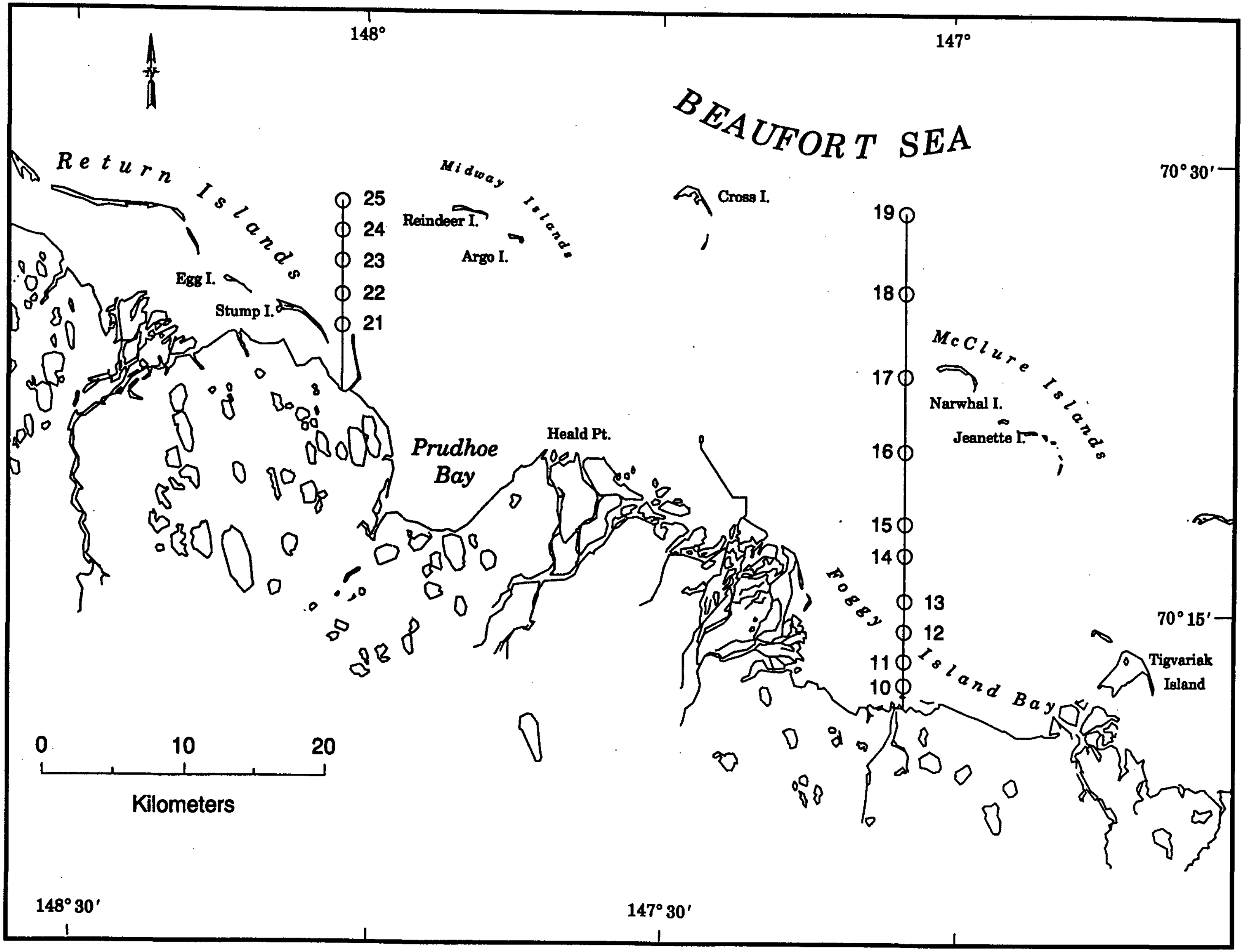


Figure 2.—Townet sample station locations in the vicinity of Prudhoe Bay.

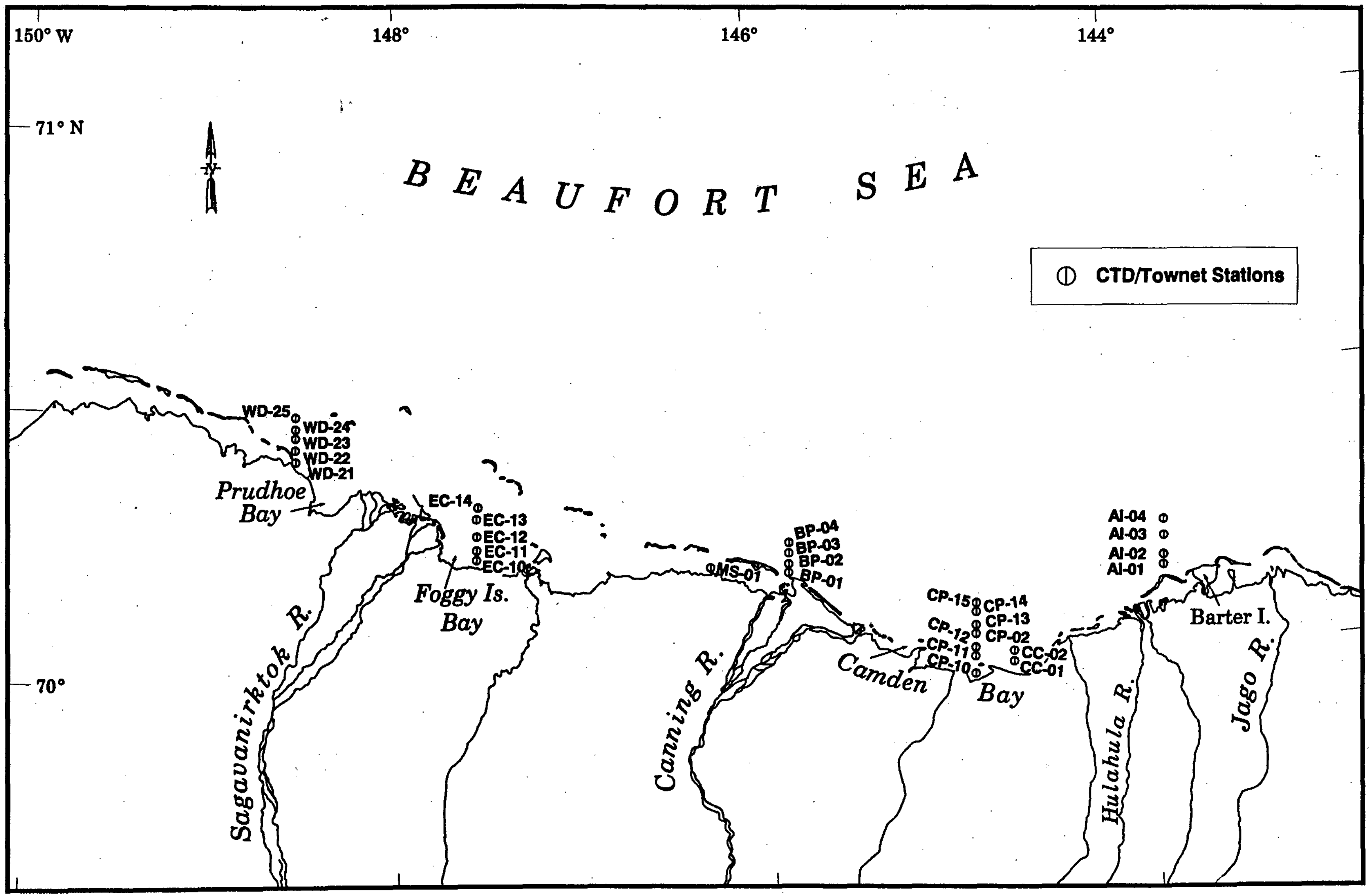


Figure 3.—CTD/Townet stations.

A description of the Prudhoe Bay transects and stations has been provided by Houghton and Whitmus (1988) and is briefly described here. The Endicott transect stations were located at 0, 1, 3, 5, 7, 10, 15, 20, 25, and 30 km from a base lying 1.3 km from the shoreline in Foggy Island Bay. At West Dock the base station was 0.6 km from the east end of Stump Island and the causeway. This translates to a distance of approximately 3 km from the coast. Stations were sampled at about 0, 2, 4, and 6 km from this base. An additional station (WD25), located about 11 km offshore, was added to the transect.

The stations in Simpson Cove (CP10) and Mary Sachs Entrance (MS01) were located almost 2 km from the mainland coast. In each instance, this position roughly demarked midway points in the respective lagoons. The Carter Creek stations were originally selected as a function of depth (i.e., 5 and 20 m, respectively).

Fish sampling was accomplished with an 11.0-m-long townet. The mouth of the net was 6.8 × 1.8 m tapering to a 0.3 × 0.3 m cod end bag. Net panels were of variable mesh size as follows: front panel, 50.8 mm; 2nd panel, 38.1 mm; 3rd panel, 19.1 mm; and bag, 7.9 mm. At each station replicate sampling consisted of two 10-minute hauls to the east. The net was towed at an approximate speed of 0.5 m/s.

A Magnavox MX 5400 GPS Satellite Navigation System was utilized in the field to locate the townet sampling stations. The accuracy of the GPS is better than ± 100 m. However, because the GPS system was not fully operational in 1990, satellite coverage was intermittent during the field season. During periods when fewer than 3 satellites were available for GPS fixes, a Furuno Model FR805D 48 nm radar was used to determine position information. The accuracy of radar fixes is assumed to be 0.5 km.

Physical Data

Thermohaline structure was recorded at each transect station prior to the conduct of replicate townet sampling with a portable conductivity–temperature–depth instrument (Applied Microsystems STD–12) having an internal recording capability. The instrument's depth, temperature, and salinity sensors are accurate within 0.10 m, 0.03°C, and 0.2 ppt, respectively. The CTD stores data in an internal memory and records eight samples of temperature, conductivity, and pressure per second. During oceanographic casts, the CTD's sensors were held just below the sea surface and allowed to equilibrate, then the instrument was slowly lowered ($\bar{x}$ = 6.89 cm/s, SD = 3.95, n = 39) to the sea floor. Upon completion of the cast, CTD data were downloaded to a Zenith laptop portable computer, reviewed for accuracy, and stored on minidiskettes for processing.

Summer 1990 wind data from the eastern Beaufort Sea were obtained from the Fish and Wildlife Service. These data were acquired from weather stations maintained at Simpson Cove and Beaufort Lagoon. Wind speed, direction, temperature, and barometric pressure were recorded every 0.5 h. The Simpson Cove record was truncated due to sensor malfunctioning and data were available only for the period July 20–31, 1990. The Beaufort Lagoon record was longer, extending from July 21 to September 10, 1990.

Other physical measurements were taken in concert with oceanographic casts. Water depths were determined with a Ray Jefferson Color Telescan 2000 sounder. Wind speed (from the vessel's anemometer) and direction (estimated) were recorded during townet operations.

Fish Sample Processing

Townet catches were sorted to species, counted, and individually measured. All catches were enumerated in the field. A volumetric approach (known quantities/unit volume) was utilized to estimate total numbers in several instances of very large catches. Fork length (nearest mm) and wet weight measurements (0.1 g) were taken immediately following fish capture. An OHAUS (2610 g) Dial-O-Gram was used to measure fish weights as sea conditions allowed. All station, measurement, and environmental data were recorded on field forms for later data entry.

Some fish were kept for additional processing and taxonomic verification. Specimens were either (1) frozen on dry ice in seawater, or (2) preserved in a solution of 10% formalin in seawater, with preservation technique dependent on the work to be conducted ashore. A total of 290 frozen samples (121 Arctic cisco; 69 capelin; and 100 Arctic cod, *Boreogadus saida*) are currently being maintained at –40°C in Anchorage. Forty-two (42) specimens collected for taxonomic purposes have been identified (6 species), transferred to an alcohol solution, and archived in the Alaska Office.

Analysis of Fisheries Data

The relative abundance of the catch at each station was described in units of fishing effort and fish density. Catch per unit of effort (CPUE) was expressed as total number of fish/10-minute set, and, in special cases, as kilograms of fish/kilometer. Fish densities were estimated by computing the volume (m^3) of water fished per 10-minute set (distance towed [m] × area of townet mouth [m^2]) and standardizing the catch to numbers/1,000 m^3.

Length frequency analyses were performed to determine size and approximate age composition of the species sampled. Fork length frequencies were plotted for the major species captured by total numbers captured or subsets of this as appropriate to the analysis being performed.

The catch (C) was summarized using standard descriptive and graphical techniques available on Statgraphics Version 4.0 software. The coefficient of variation (CV) was calculated (as in Zar 1984) to describe the relative variability of the station catches and to serve as an indicator of spatial patchiness in selected species' distributions. The classification of CV values used by Grossman et al. (1990) was adapted to indicate patchiness by station, between transects, and with relative distance from shore as:

$CV \leq 25\%$	Even distribution;
$25\% < CV \leq 50\%$	Relatively even distribution;
$50\% < CV \leq 75\%$	Moderately patchy; and
$CV > 75\%$	Highly patchy.

After initial testing for normalcy, the catch data were transformed [ln(x + 1)] for conduct of parametric tests. Green (1979) indicates that species abundance data are nearly normally distributed and recommends the logarithmic transformation. The significance level for all statistical tests was 0.05 ($\alpha = 0.05$). Relative abundance (mean CPUE and density estimates) was associated with environmental parameters (e.g., mean temperature and salinity conditions of the upper 2 m) using multivariate frequency plots and univariate correlation analyses for the major species studied. The frequency presentations would demonstrate modal temperature and salinity preferences of the fish species captured offshore.

Arctic Cisco

Time and area.—Logistical constraints and environmental factors precluded routine use of *a priori* random sampling design for statistical testing. Thus, statistical partitioning of the data into time, area, and size class categories was performed after the data had been collected. Emphasis was placed on relative abundance and distributional attributes of the juvenile catch. Relationships examined by one- or two-way ANOVA included variations in (1) mean fish size stratified by relative distance from the coast; (2) mean stratum fish size with respect to time; (3) mean stratum CPUE in relation to sampling time; and (4) mean station CPUE and transect CPUE with respect to time, distance, and habitat (defined by hydrographic properties averaged over the upper 2 meters). Means and their 95% confidence intervals (CI) were calculated using standard descriptive techniques. A non-hierarchical clustering procedure (Hair et al. 1987) was used to investigate salinity and temperature influences on juvenile distribution and abundance [ln (density + 1)]. Analysis of variance and the Tukey multiple comparison tests were employed to further examine habitat relationships within the cluster groups.

Size and growth.—Changes in mean fork length were examined over time to evaluate seasonal growth rate in young-of-the-year fish (<100 mm). Relative rates of increase in mean length (%) and instantaneous rates of weight increase (G) were calculated after Ricker (1975). In order to compute G it was necessary to know the b coefficient (slope) from the weight–length relationship for Arctic ciscoes. The coefficient described for Arctic ciscoes in 1990 by the FWS Fishery Assistance Office in Fairbanks was used in this analysis where:

b = 3.22 for July 10 through July 24; and
b = 3.19 for August 28 through September 12.

Because growth in the young fish is exponential ($W = aL^b$) the instantaneous increase in weight is described by the expression:

$$G = 100\,[b\,(\ln l_2 - \ln l_1)/t]$$

where G is the instantaneous rate in weight increase (%) during the time period t, in this case on a per day basis. For these calculations l_1 and l_2 represent mean fish length at the beginning and end, respectively, of time period t.

Migration.—The migration rate of young-of-the-year fish was examined as a function of winds and nearshore currents using vector analysis techniques. Both passive and directed wind-aided migrations were hypothesized. A passive migration was premised on the assumption that the direction of fish movement is always with the current, whereas in the directed migration the swimming direction is always to the west. The sustained, or voluntary, swimming speed of the fish was assumed to be 1 body length per second.

It was further assumed that the Beaufort Lagoon wind record was representative of winds along the eastern Beaufort Sea in 1990. This record was relied on exclusively to estimate nearshore currents (see Physical Oceanography in Results section) because of its length—extending from July 21 to September 10. By comparison, the Camden Bay record was too short (July 20–31) to be effectively incorporated into the migrational study. Mean daily nearshore current components (u_c and v_c) were calculated as 4% of the mean daily wind speed ($-0.04 \times$ u and v where negative sign corrects wind direction in the oceanographic sense, i.e. an east wind has a positive u component but the current it produces is in the negative u direction).

The mean daily speeds (in km/d) and directions of passive and directed migration were computed as follows:

Passive: It is assumed that the fish moves with the wind-driven current. Therefore, a fish's

u component (u_f) is S sin (Ac);
v component (v_f) is S cos (Ac);
Total u component (Up) is $u_c + u_f$;
Total v component (Vp) is $v_c + v_f$;
Daily migration rate (Mp) is SQRT ($Up^2 + Vp^2$); and
Mean daily direction of migration is ARCTAN (Up/Vp);

where S is the fish's mean daily swimming speed and Ac is the mean daily current direction.

Directed: It is assumed that the fish always moves alongshore to the west. Therefore, a fish's

u component (u_f) is S;
v component (v_f) is 0;
Total u component (Ud) is $u_c - u_f$;
Total v component (Vd) is v_c;
Daily migration rate (Md) is SQRT ($Ud^2 + Vd^2$); and
Mean daily direction of migration is ARCTAN (Ud/Vd).

Onshore–offshore comparisons.—An exploratory analysis was undertaken to examine catch comparisons between active and passive gear types, the latter being more common to the arctic coast. In order to determine whether the inshore (fyke-net) catches differed greatly from those offshore (townet), a simple linear regression analysis was performed relating CPUE and instantaneous density distributions (expanded to hourly catch rates) reported in the townet catches. Fyke-net catches (catch per day) were acquired from FWS (Fairbanks) and LGL Research Associates (Anchorage) for selected dates on which townetting had been conducted. Fyke-net catches were adjusted to an hourly basis assuming the 24-h catches reflected a constant migration rate.

A bivariate response surface analysis (Menke 1973; Grant 1986) was used to further investigate dynamic relationships between relative abundance and thermal conditions at selected onshore and offshore fishing sites. Fish density was used as an index of relative abundance. Temperature was selected as the independent variable that elicits the catch response because of its suspected great influence on distribution and abundance. Depth-averaged temperatures for the upper 2 m were used as a proxy for environmental temperature at the time of capture.

The response surface plot represents the three-dimensional surface for the function describing the relationship between density and water temperature. A matrix of Z values (normal deviate) describes the response of the density–temperature relationship. Parameters of the normal distribution were estimated using standard descriptive techniques (i.e., means and their standard deviations). The quantitative response to the bivariate normal function was obtained by converting the calculated Z to a random variate from the specified distribution of interest using the formula:

$$X = u + \sigma Z$$

where X is the normal random deviate from the specified normal distribution of interest, u is estimated by the mean, and σ is estimated by the standard deviation of the mean.

Arctic Cod

Population and biomass.—Area swept methods (Bakkala and Smith 1978) were used to describe Arctic cod population abundance and biomass parameters in Camden Bay. With respect to relative abundance portrayals, these methods were slightly modified to reflect "volume swept" approximations. There are several reasons for this. First, in our sampling, we are more confident about the effectiveness of the gear in the vertical, rather than the horizontal, dimension. Second, the expression of fish density as a standardized unit volume is viewed as the most quantitative index of CPUE. Finally, unlike many demersal fish surveys where most of the fish being sampled occur on a horizontal plane along the bottom, Arctic cod apparently occur throughout the water column, and volume swept methods more adequately address this vertical distribution.

Ninety-five percent (95%) confidence intervals were computed for population standing stock and wet-weight biomass as described by Bakkala and Smith (1978). Sample sizes were based on the computation of effective degrees of freedom as estimated by the Cochran (1963) approximation.

Analysis of Physical Data

CTD data were quality controlled and processed by conventional methods. Sensor readings were converted to engineering units and sorted by pressure into 0.1-m bins. Data in each bin were then averaged to derive the temperature and conductivity for that pressure. Empty bins were filled by a value derived from interpolating between closest non-empty bins. Salinity and density were calculated and stored along with temperature as a function of depth. Data recorded during the lowering of the instrument were primarily used for analyses in order to minimize turbulence-induced effects on the sensors due to the passage of the instrument through the water. Plots of temperature, salinity, and density (sigma-t) versus depth and plots of temperature vs. salinity were examined to detect erroneous data and to categorize stations in terms of thermohaline structure and properties. Due to the frequency of suspected erroneous readings at the sea surface, 1-meter data are used in the following discussions to represent conditions at the sea surface (see Thorsteinson et al. 1990). Selected profiles were used to construct contoured vertical temperature and salinity sections to show the temporal and spatial distribution of these parameters.

Data from the meteorological stations at Camden Bay and Beaufort Lagoon were in electronic format and had been converted to engineering units; however, the data had not received any preliminary processing. Each station sampled wind speed every 5 minutes and, every 0.5 hour, recorded values for average wind speed (mph), maximum wind speed, temperature (°C), and barometric pressure (in-Hg). Of these we were interested in resolving the wind vector into its alongshore and cross-shore components. This was accomplished by rotating the coordinate system such that the alongshore axis (u component) lay parallel to the coastline while the cross-shore axis (v component) lay perpendicular to the coast. An observer standing at the origin of the rotated coordinate system, looking offshore with his shoulders parallel to the coastline, would have the positive u axis on his right and the positive v axis directly in front of him.

Initial processing of the wind data consisted of several steps. First, the wind speeds were converted from mph to m/s. Next, wind angles were computed for the rotated coordinate system according to the following:

$A_i = B_i - C_i - D_i$ where:

A_i = Wind angle in the rotated coordinate system.
B_i = Wind angle as recorded by the instrument.
C_i = Angular difference between the instrument's north and magnetic north (MN). This value is positive if MN is rotated clockwise from the instrument's north and negative if counterclockwise. In Camden Bay, the instrument's north was 27° E of MN while in Beaufort Lagoon it was 22° E.
D_i = Angular difference between MN and north of the rotated coordinate system. The sign convention is the same as above.

At the location of the meteorological station in Camden Bay, the coastline is oriented approximately parallel to true east–west; thus, the rotated coordinate system coincides with true directions and D_i is just the magnetic variation measured in Camden Bay (32° E). The Camden Bay correction angle is therefore:

$$A_i = B_i - (-27°) - (-32°) = B_i + 59°.$$

At Beaufort Lagoon, the coastline is oriented approximately 133°–313° true or 98°–278° magnetic. The rotated coordinate system is 8° clockwise from MN and the correction angle for Beaufort Lagoon is:

$$A_i = B_i - (-22°) - (8°) = B_i + 14°.$$

The alongshore (u) and cross-shore (v) components were then computed as:

$$u = S \sin (A_i), \text{ and}$$
$$v = S \cos (A_i),$$

where S is the wind speed in m/s and A_i is the wind angle computed above. Mean daily values for u and v were used to compute the mean daily wind speed and direction using descriptive and circular statistics methods described by Zar (1984).

In the shallow, nearshore regions of the Beaufort Sea, currents generally run in the direction of the wind at 3 to 5 percent of the wind speed. Therefore, in this report, current speeds are estimated at 4 percent of the wind speed and are converted to units of cm/s.

RESULTS

Distribution of Effort

Fish sampling was conducted at 28 stations on 13 days beginning on August 2 and ending on September 5, 1990 (Fig. 4). On-station activities involved completion of a CTD cast prior to the conduct of replicate townet sampling. Only one townet sample was completed at WD22 on September 5; replicate sampling was achieved at all other stations. While fishing, the net was towed at an average speed of 0.5 m/s over a mean distance of 317.67 m. An average volume of 3,873.61 m^3 was strained during each tow.

Seventy-seven townet sets were successfully completed in 1990. The temporal sequence of the 1990 fishing season is depicted in Figure 5. Each point in the figure reflects a townet set, thus the cumulative effort is shown. Fish tracking experiments and poor weather conditions resulted in numerous disruptions to the sampling schedule and these are apparent in the graph. The Collinson Pt. and West Dock transects received the heaviest sampling effort in 1990. The fishing effort was distributed, in decreasing order, as follows: Collinson Pt., 23 sets; West Dock, 18 sets; Endicott and Arey Island, 10 sets each; and Brownlow Pt., 8 sets. Four sets (each) were completed off Carter Creek and at Mary Sachs Entrance to eastern Stefansson Sound. While all of the stations were sampled at least once during the summer, the coverage was inadequate both in time and space for rigorous analysis of fish migration through the study area. Depth and distance characteristics of the sampling are shown in Figures 6–9. The townet was fished in depths ranging from 2.0 to 25.8 m and from 0.32 to 15.25 km from the mainland coast. In this instance, the 15.25 km reflects the distance from the southern shore of Simpson Cove to station CP15. If Collinson Pt. is assumed to be the mainland, the distance is about 12 km to station CP15.

Physical Oceanography

Hydrographic data (CTD) were collected at 39 stations in association with the townet sampling. A solitary CTD cast was completed at the Endicott base station (EC10) on September 4; wind and sea conditions prohibited further sampling on this date. Vertical temperature and salinity plots for the CTD casts are provided in Appendix A. Sea surface and bottom water temperatures ranged between 1.03 and 6.05°C ($\bar{x}$ = 3.6, SD = 1.2) and 0.11 and 6.05°C ($\bar{x}$ = 2.8, SD = 1.3), respectively, during the sampling period. The mean water temperature of the upper 2 m was 3.6°C (SD = 1.2) for all stations combined. Surface salinities ranged from 23.5 to 32.5 ppt ($\bar{x}$ = 29.8, SD = 2.5) and bottom salinities between 23.5 and 32.3 ppt ($\bar{x}$ = 31.1, SD = 1.5). The average salinity of the upper 2 m was 30.2 ppt (SD = 2.0).

The salinity ranges described above are indicative of a primarily marine environment. Plots of the 1-meter and bottom temperature and salinity values obtained during the fish

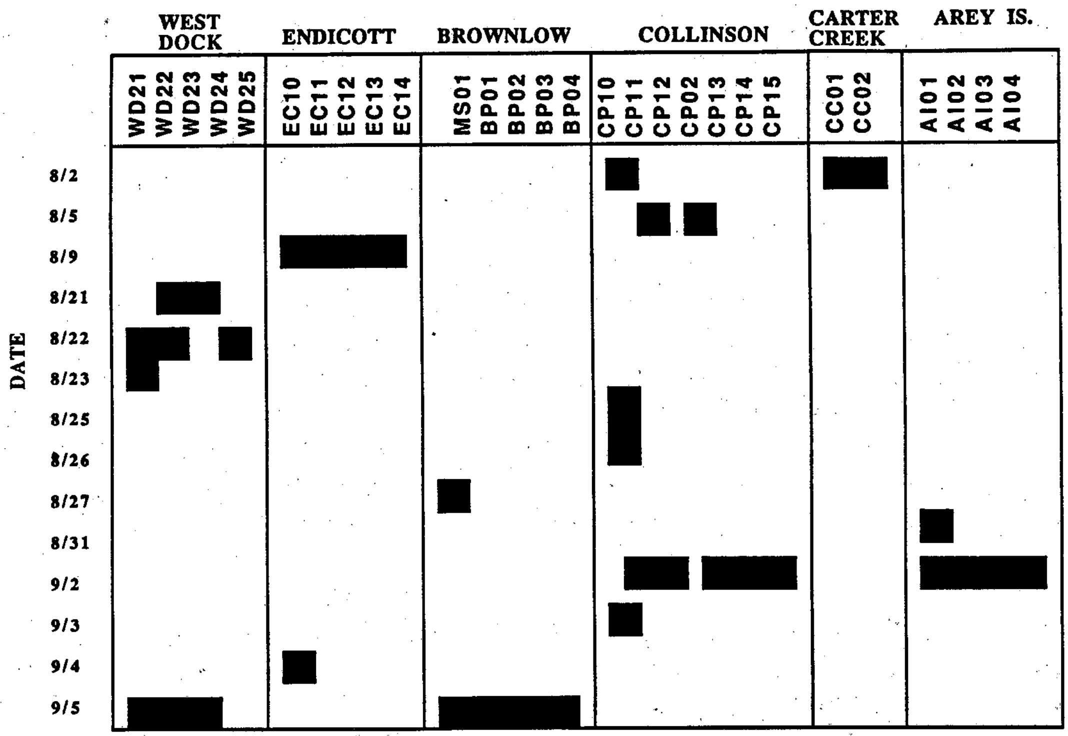


Figure 4.—Distribution of townet sampling effort by date and location.

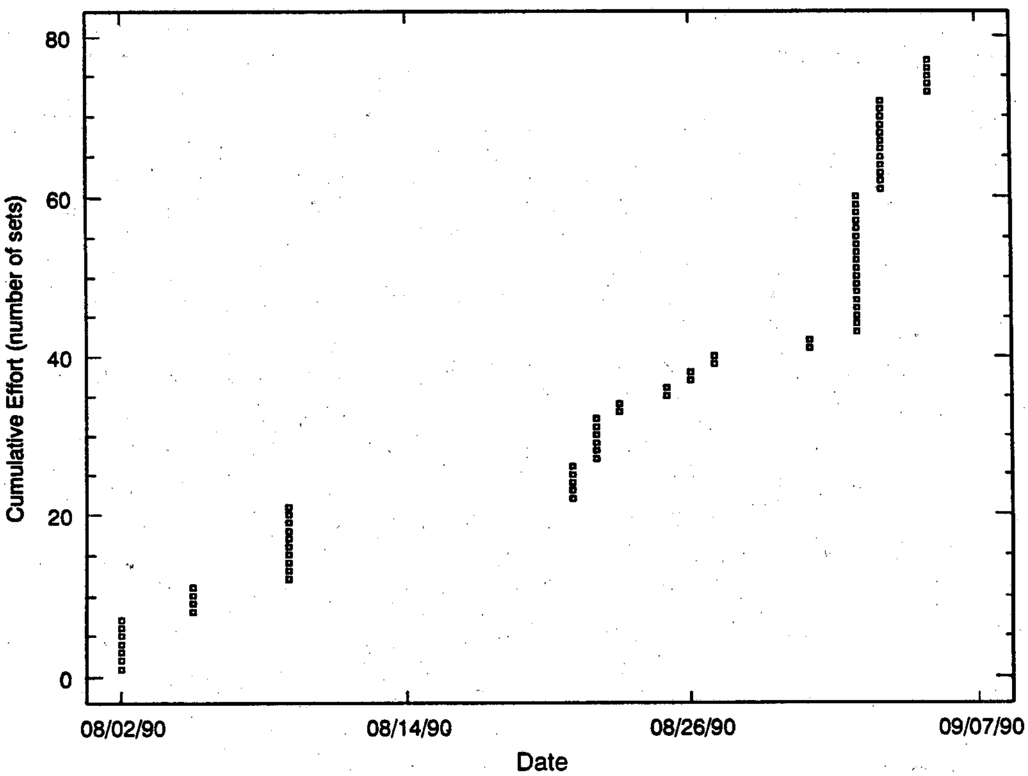


Figure 5.—Distribution of fishing effort by date and location.

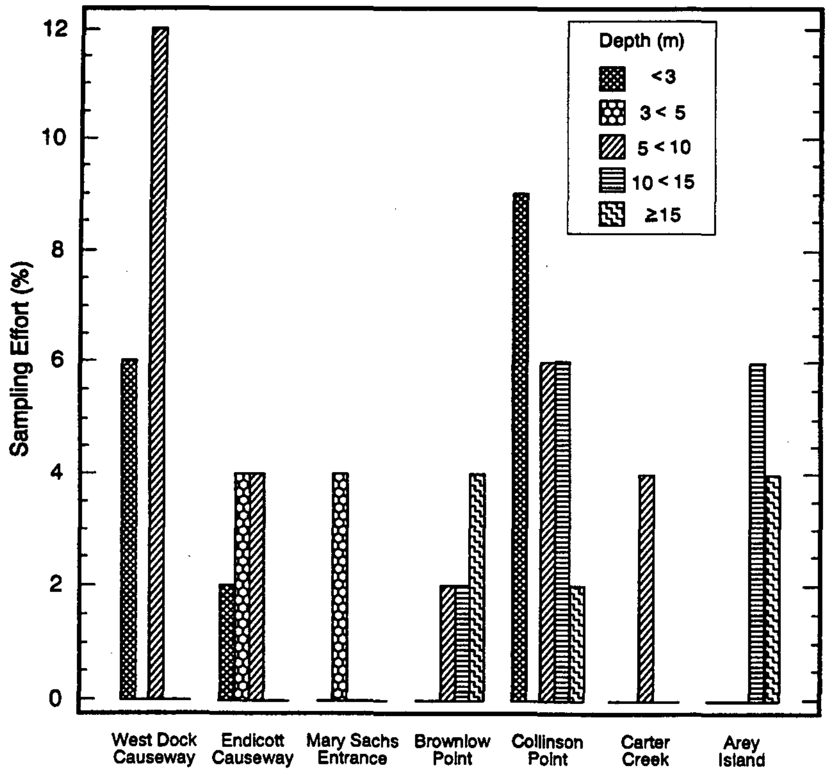


Figure 6.—Percent fishing effort by depths sampled on the coastal transects.

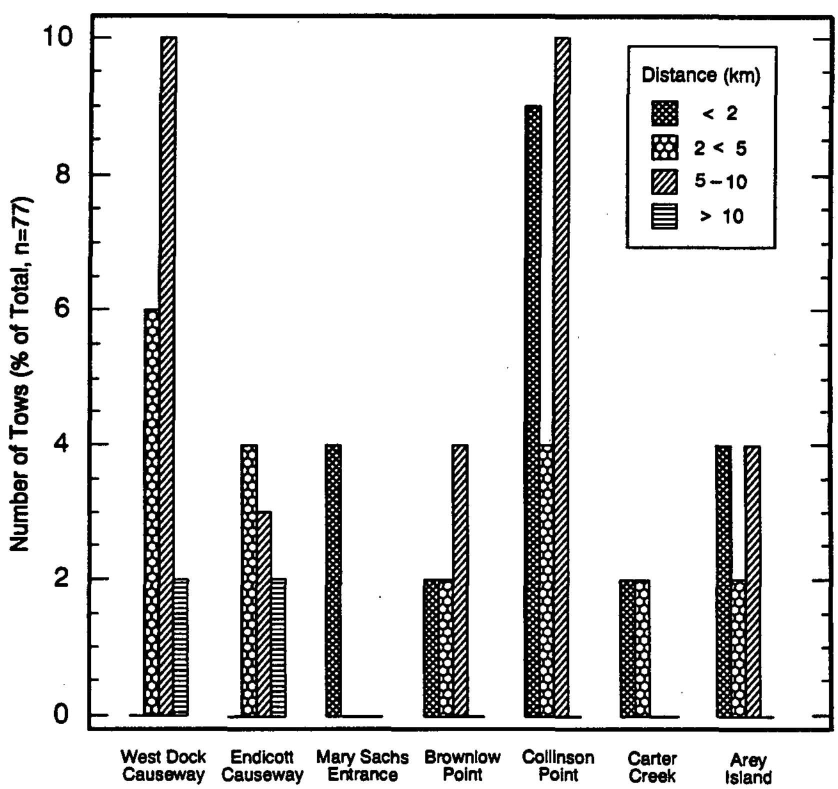


Figure 7.—Percent distribution of sampling effort by distance from the coast.

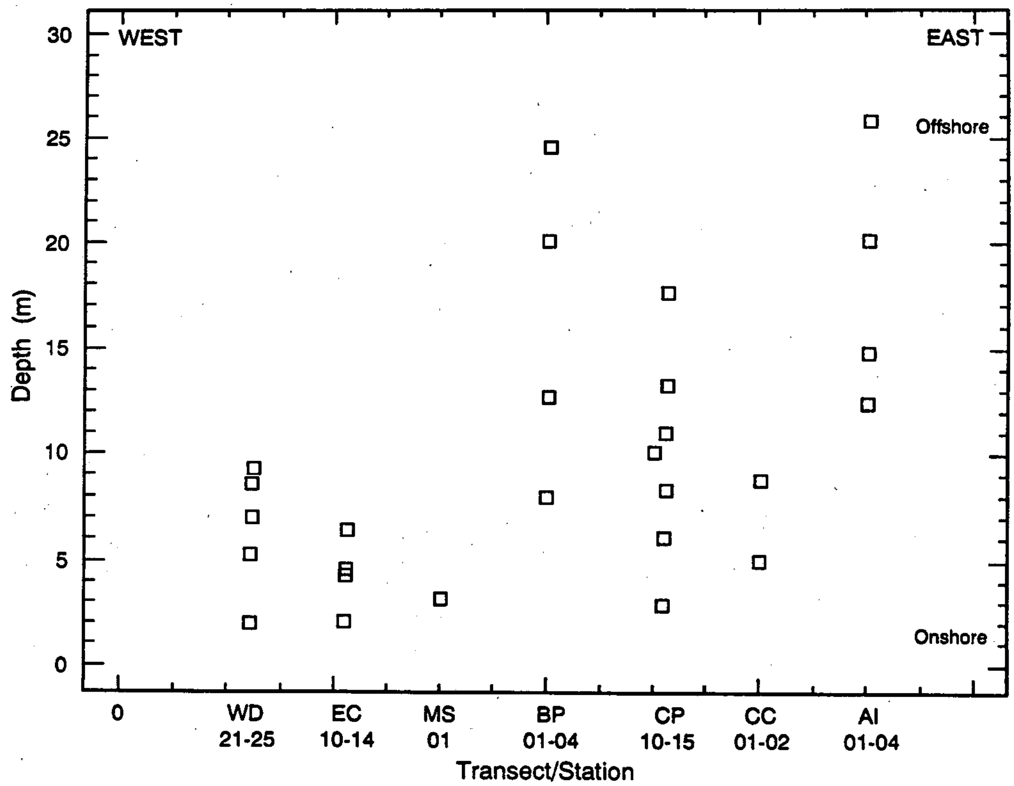


Figure 8.—Townet station depths along coastal transects in the Beaufort Sea.

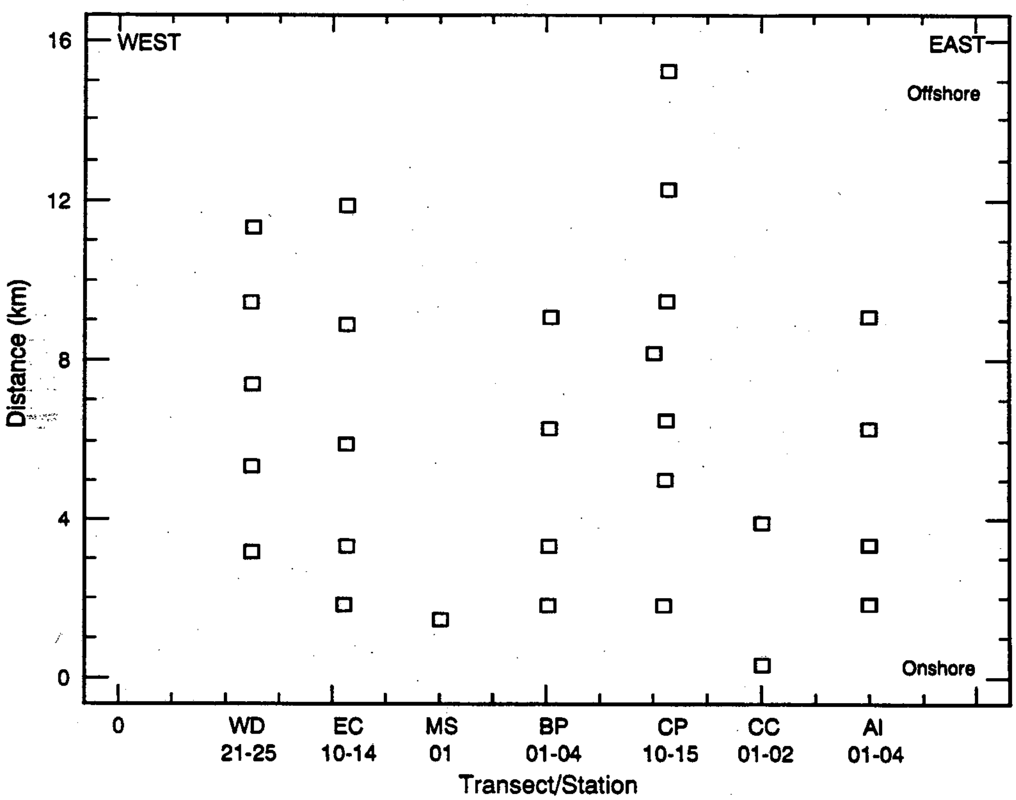


Figure 9.—Location of nearshore sampling locations with distance from the coast.

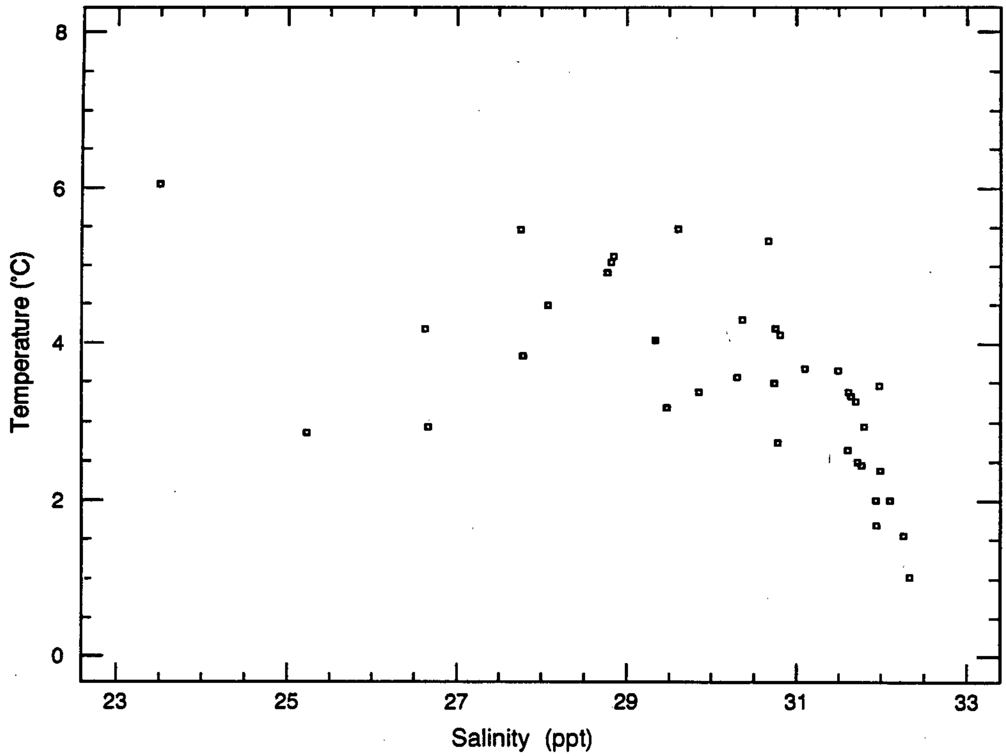


Figure 10.—One-meter temperatures versus one-meter salinities.

sampling confirm this condition (Fig. 10). The apparent warming of the marine waters was probably due to insolation. The temperatures and salinities of surface waters are also indicative of a relatively homogeneous environment for fish. Observed temperature and salinity differences between surface and 2-m depth intervals were small. Temperature differences ranged from –0.34 to 1.22°C ($\bar{x}$ = 0.11°C). Salinity differences were more pronounced ($\bar{x}$ = –0.43 ppt; range 6.20 to –6.21 ppt). However, large salinity gradients were observed at very few stations; the majority of data indicate a well-mixed upper layer.

Prior to August, brackish influences may have been greater in the nearshore areas sampled. If coastal water was present early on, our data suggests that it had been washed out quickly by the prevailing east wind conditions. Easterly wind conditions were dominant in Camden Bay during the latter part of July (Fig. 11). Meteorological data collected at Beaufort Lagoon reflect a dominance of northerly and southwesterly winds in this sector of the eastern Beaufort Sea; conditions that would promote the transport or presence of marine waters in nearshore areas (Fig. 12). (It should be remembered that the time series shown in Figure 12 are in the rotated coordinate system).

Daily mean time series of wind speed and direction of the wind records were computed for Camden Bay and Beaufort Lagoon (Figs. 11 and 12). Mean vector winds from the east prevailed for 8 of the 12 d for which wind data were collected in Camden Bay. The easterly winds had daily average speeds of 3.31 to 8.22 m/s. Mean daily winds for July 20–31 were from a northwesterly direction with daily mean speeds of 0.56 m/s and 5.08 m/s, respectively. The remaining 2 d had mean winds from the north with mean speeds of 2.0 m/s (July 22) and

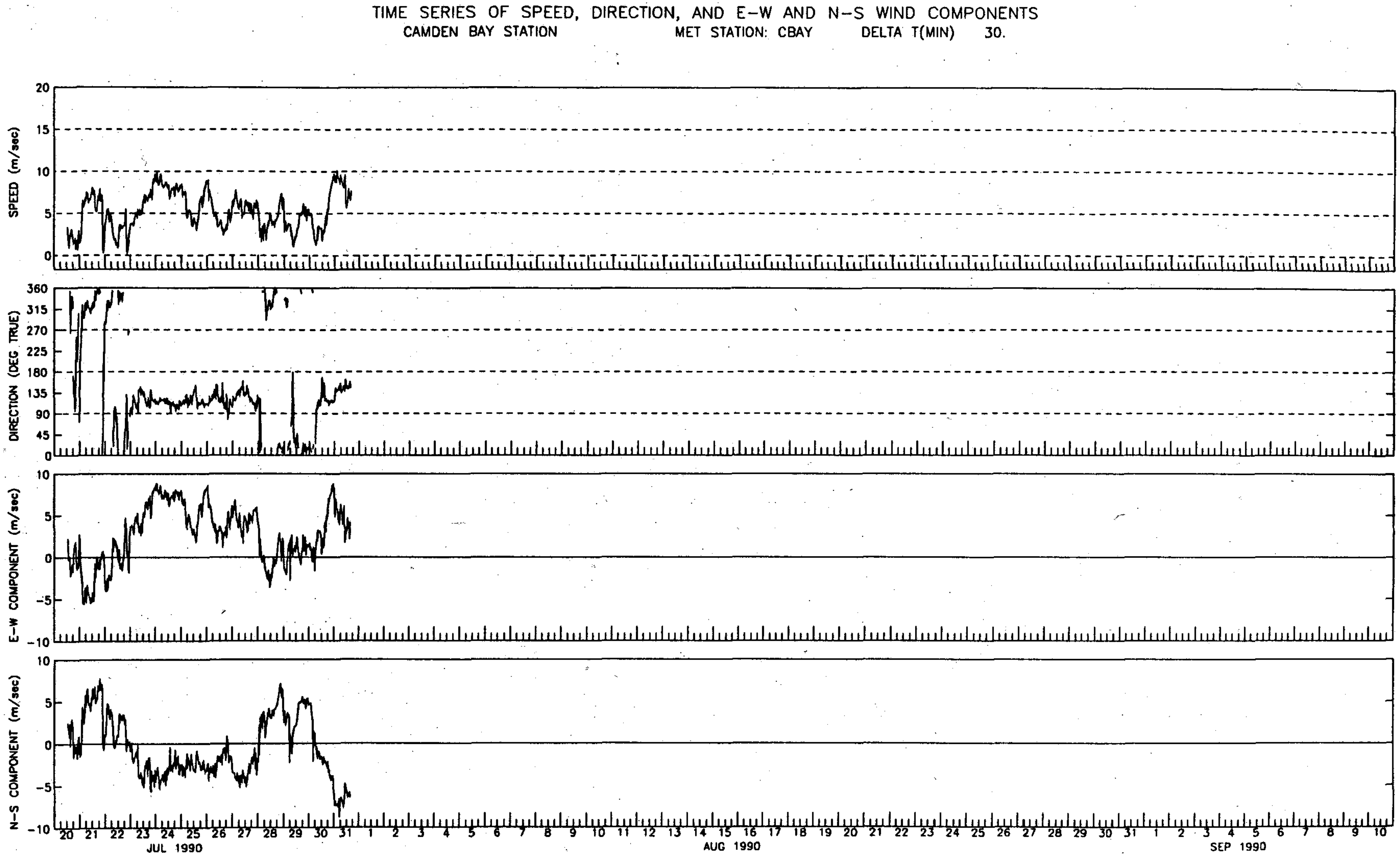


Figure 11.—Time series of speed, direction, and E–W and N–S wind components in Camden Bay.

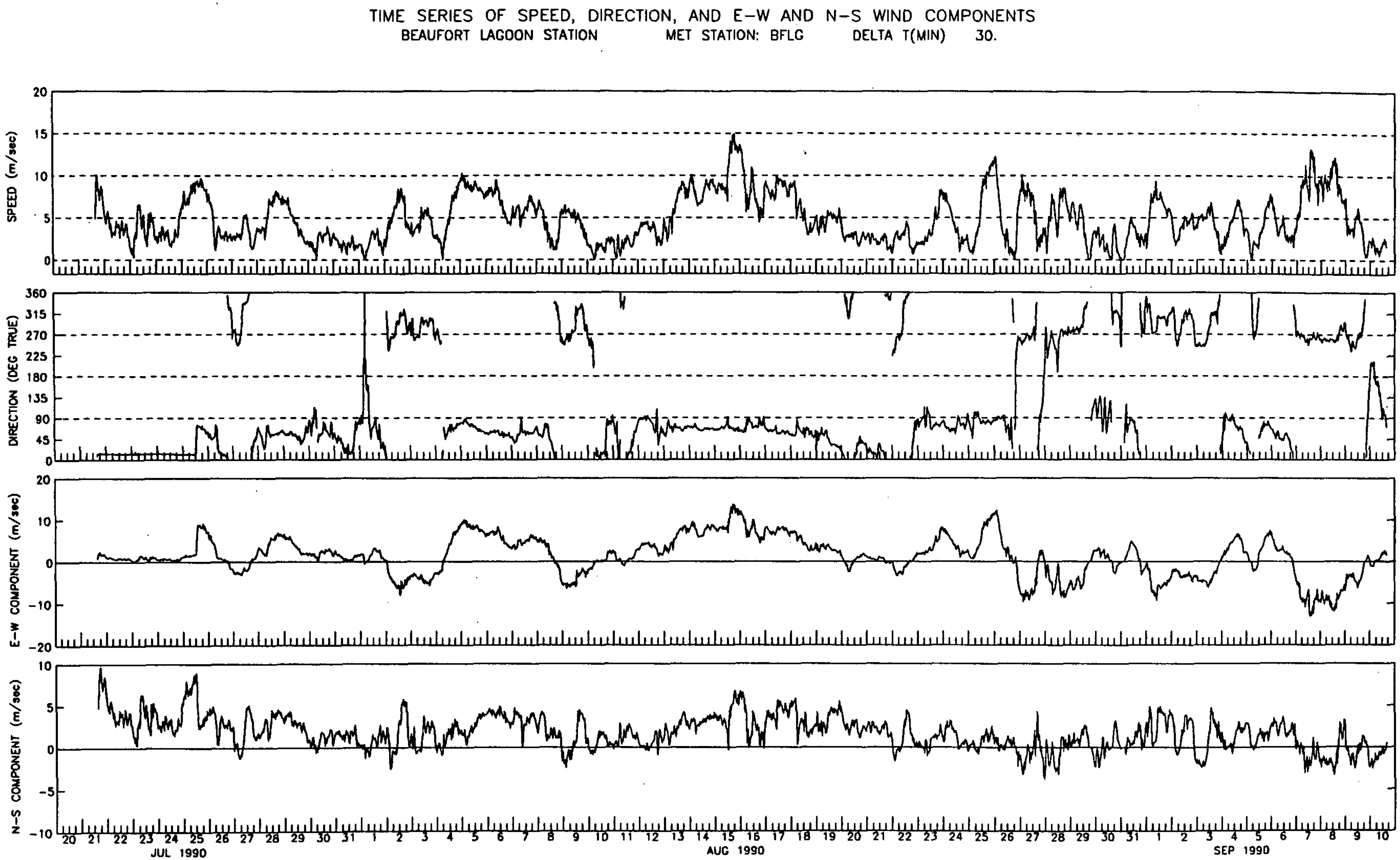


Figure 12.—Time series of speed, direction, and E–W and N–S wind components in Beaufort Lagoon.

3.53 m/s (July 29). The hydrographic profiles for CTD stations occupied in Camden Bay during late July (Appendix A) indicate nearshore salinities exceeding 27 ppt.

The wind record from Beaufort Lagoon shows that during July and August the strongest winds were from the northeast: the mean daily wind speed was 5.51 m/s from the northeast on July 28; 8.62 m/s on August 5; 10.52 m/s on August 15; and 5.97 m/s on August 25. Hydrographic data from CP11 (equals CP01 in Appendix A) shows nearly isohaline conditions of around 30 ppt just offshore of Collinson Point.

A sustained period of northwesterly winds occurred between July 21 and 26. The winds were strong (7.22–7.84 m/s) to moderate (3.03–3.90 m/s) and probably sufficient to depress marine conditions offshore (i.e., piling of coastal water against the coast). The strongest westerlies occurred in early September (8.85–9.10 m/s) after fishing had been terminated. By this time little coastal water remained in the nearshore and marine conditions were observed at all but the shallowest of stations sampled. For instance, on September 3 it appears that Katakturuk River water had been transported into the eastern portion of Simpson Cove (CP10).

During periods of lower wind speeds the data become much noisier with respect to direction of wind. This switching of winds is apparent in the mean daily wind speed and direction records for Camden Bay and Beaufort Lagoon. The variability is much more noticeable in the plots of the raw data depicting alongshore components of the wind and nearshore currents at 0.5-h intervals. The u components have not been corrected in the oceanographic sense and therefore the high frequency of positive values is indicative of the predominance of east winds. Such conditions would promote the transport of juvenile Arctic cisco under the Mackenzie River hypothesis.

A summary of the shipboard observations of wind speed and direction at the time of sampling (n = 77) indicated that easterly winds were reported 52% of the time; westerly winds 21%; northerly 14%; and no winds the remaining proportion of the time. These observations provide additional circumstantial evidence of prevailing east to northeasterly wind conditions that dominated the 1990 open-water season.

In several instances, the hydrographic data were collected over short enough time spans that they could be construed as synoptic. This allowed the construction of vertical temperature and salinity sections for selected times and areas during the 1990 field season. Brief descriptions of each follow:

Endicott Causeway.—Hydrographic data were collected on August 9 for this section (Fig. 13). The distribution of temperatures indicates the lack of a strong thermal gradient as temperatures varied by only 2°C over the 12-km transect. Colder marine water was observed at approximately 8 km from the coast. Transitional waters (< 30 ppt with temperatures of 4 to 6°C) were found inshore of 8 km. The base station, EC10, was isothermal and isohaline. Nearshore waters were nearly isothermal to a distance of 6 km offshore. At this distance there was slight stratification with indications of marine waters 8 km offshore. The salinity section shows similar trends with transitional waters lying

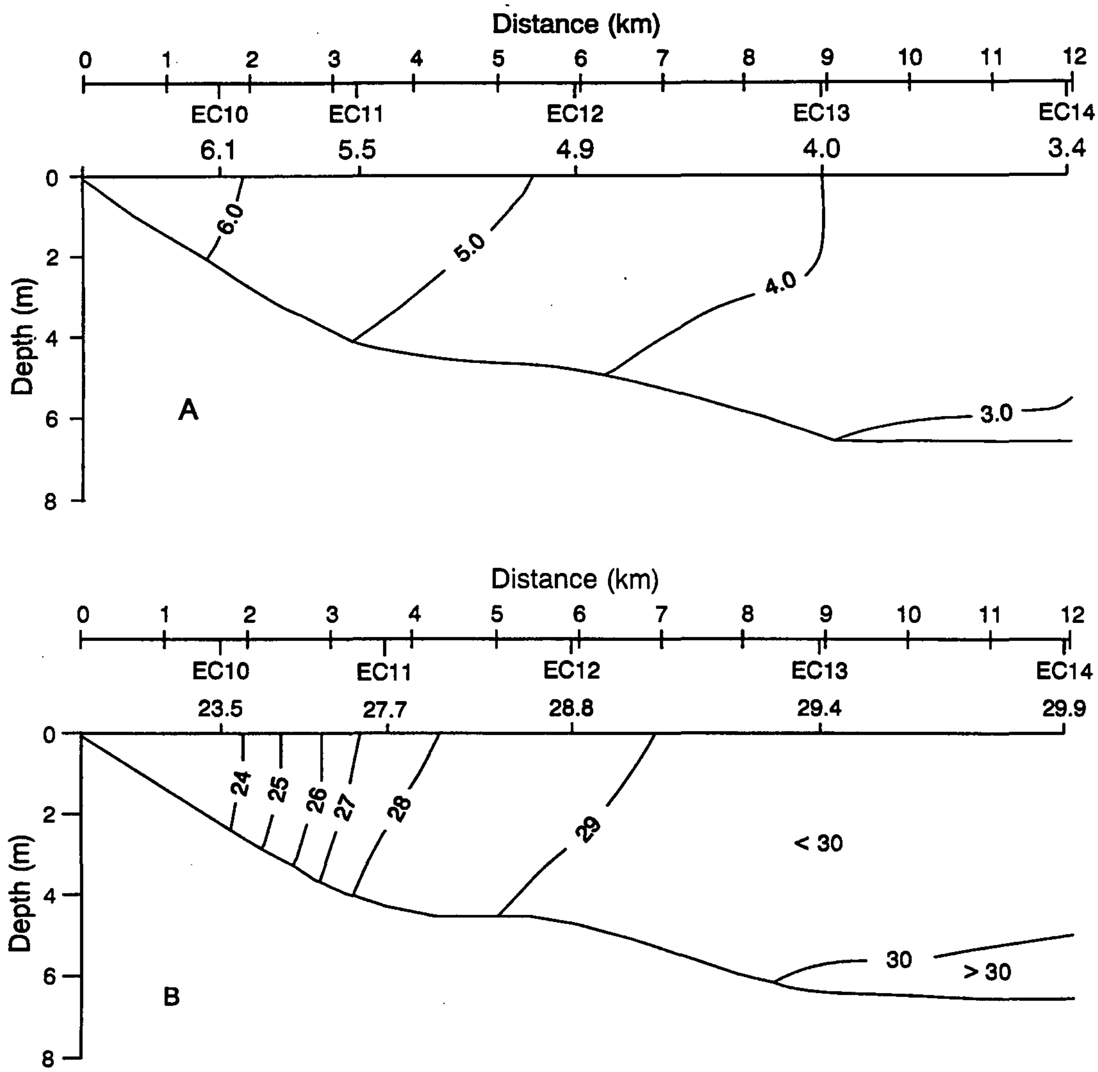
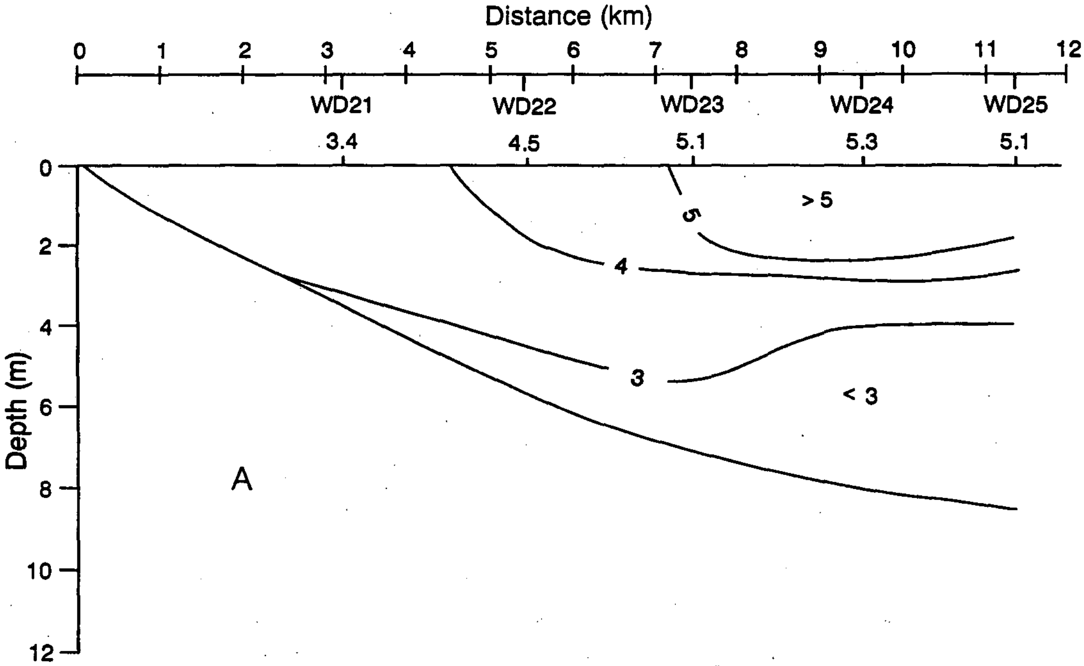


Figure 13.—Vertical sections of temperature (A) and salinity (B) from the Endicott transect, August 8, 1990.

within 8 km of the coast and salinities greater than 30 ppt beyond. The mean daily winds at Beaufort Lagoon were from the west at a speed of 4.34 m/s.

West Dock Causeway.—This section was reconstructed from hydrographic measurements taken over a 22-h time period on August 21 and 22 (Fig. 14). The section indicates the encroachment or upwelling of marine waters along the bottom to within about 2 km of the coast with salinities in excess of 31 ppt. It is interesting that the waters inshore of station WD21 appear to have salinities in excess of 31 ppt. Warmer transitional waters (5°C and greater and 25 ppt) have been displaced to at least 5 km offshore. The presence of brackish waters extends beyond WD25 and below the depth of fish sampling; however, salinities are high offshore representing transitional waters. The indication is that this represents the offshore deflection of the Sagavanirktok River plume. The hydrographic properties suggest east wind conditions.



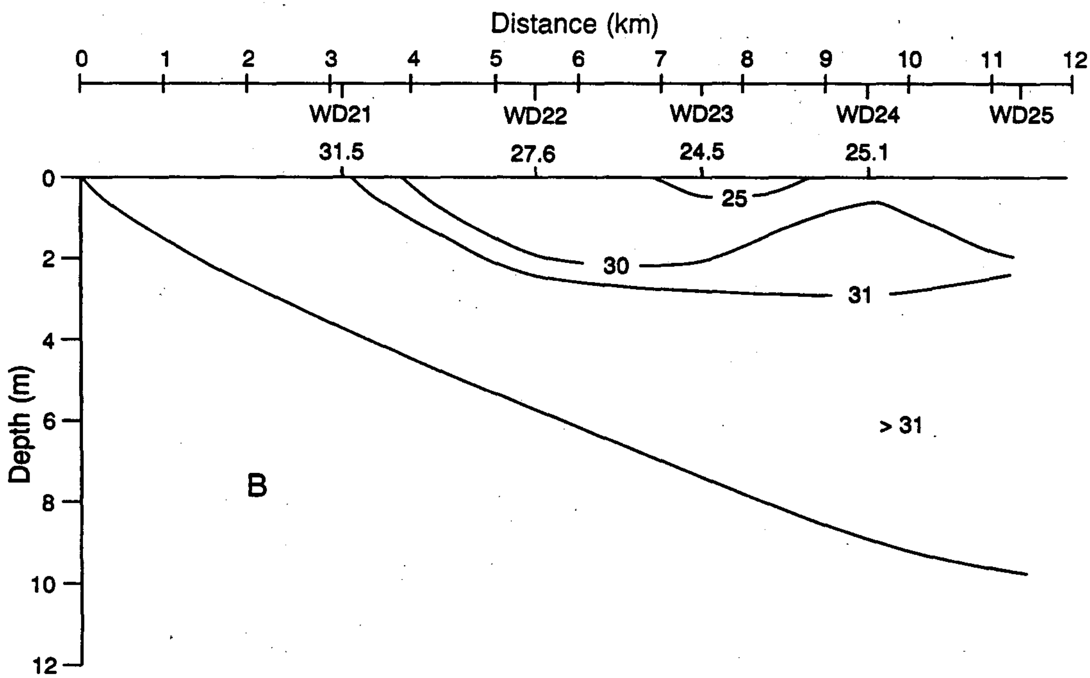


Figure 14.—Vertical sections of temperature (A) and salinity (B) from the West Dock transect, August 21-22, 1990.

Arey Island.—The transect was sampled on September 2 (Fig. 15). The temperature and salinity sections indicate the presence of purely marine waters with temperatures slightly greater than 2.5°C less than 1 km from the coast. Salinities greater than 30 ppt were found nearest the shore, and greater than 32 ppt beyond 4 km of the coast. Mean daily winds from the northwest at 3.51 m/s were reported at Beaufort Lagoon on this date.

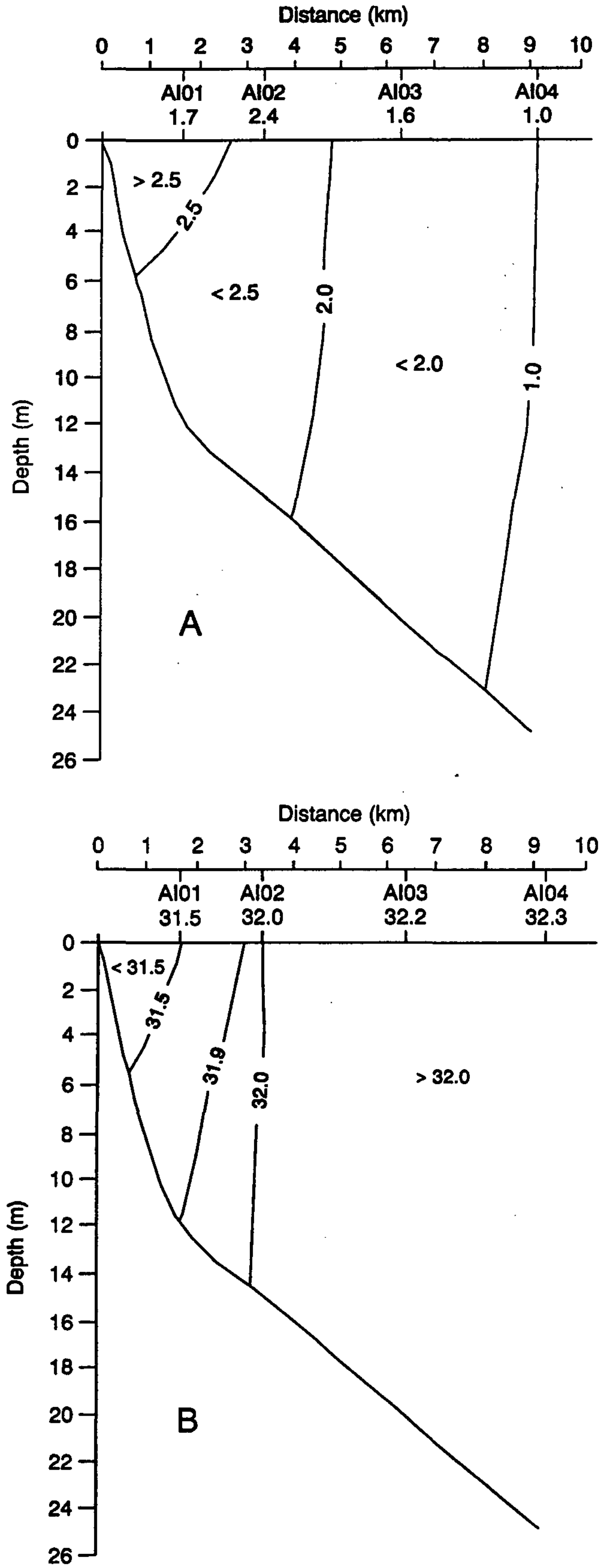


Figure 15.—Vertical sections of temperature (A) and salinity (B) from the Arey Island transect, September 2, 1990.

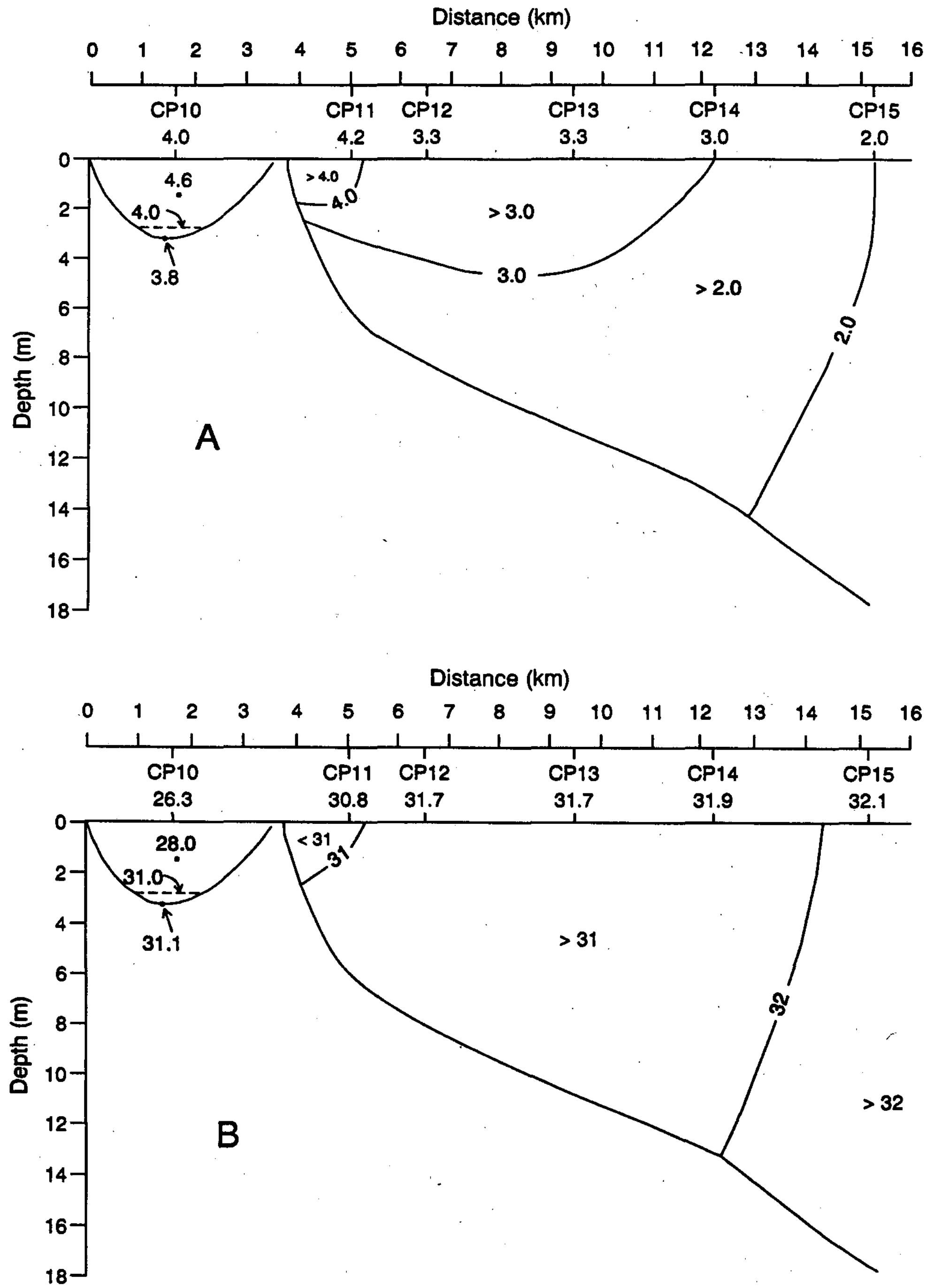


Figure 16.—Vertical sections of temperature (A) and salinity (B) from the Collinson Point transect on September 2 (CP11–15) and September 3 (CP10), 1990.

Collinson Point.—The transect was sampled late in the evening of September 2 and early morning of September 3 (Fig. 16). Marine conditions were found at all exposed sites. Transitional waters with surface temperatures of 4°C and salinities of 26 ppt were observed within Simpson Cove (CP10). A strong salinity gradient was evident at this station with 31 ppt, < 4°C water, near the bottom of the water column. Offshore waters were primarily marine with temperatures greater than 4°C extending just beyond 1 km of Collinson Pt. and decreasing to less than 3°C about 8.5 km offshore. Sea temperatures < 3°C were found at all depths exceeding 5 m. Salinities were > 30 ppt at all stations seaward of Collinson Pt. Winds were from the northwest during the sampling period with mean daily speeds of 3.51 and 3.65 m/s, respectively. However, due to the lateness of the season, and extent of marine conditions, the effects of west winds on all but the nearshore were negligible.

Brownlow Point.—Hydrographic data were obtained on September 3 (Fig. 17). The sections look very similar to what was reported off Arey Island. Marine conditions were found at all stations, and, under the northwesterly winds reported for this date, Canning River influences are not expected or evident in the data.

General Catch Summary

A total of 17,087 fish were captured by the 1990 townetting effort. Eleven species from eight families were represented in the catch (Table 1). Fish were captured at almost all of the sampling stations. Only nine water hauls (zero catches) occurred, and of these, several resulted from sets discontinued due to weather or mechanical difficulties. The mean number of fish caught per set was 222 (SD = 487.6, range 0–3,451). This corresponds to a mean fish density of 67 fish/1,000 m^3 (SD = 153.5, range 0–898.5). The species composition of the catch and corresponding mean CPUE and density indices for all but the rarely encountered species are shown in Table 2.

The largest catches were generally reported within 10 km of the coast in depths shallower than 15 m. This may reflect the distribution of the sampling effort as much as relative abundance of the fish species in nearshore habitats. Perhaps more revealing is the presentation of total catch (all species combined) according to the mean environmental conditions of the upper (2 m) water column. The majority of the catch was sampled in marine waters with temperatures of 3 to 5°C and salinities less than 31 ppt. Density distributions followed a similar pattern (Figs. 18 and 19).

The offshore sampling began midway through the open-water season. By this time, brackish water influences on nearshore areas, particularly exposed coastal environments such as Camden Bay, were not evident. Under such habitat conditions, marine species would be expected to dominate the catch. Not surprisingly, Arctic cod, capelin, and juvenile kelp snailfish (*Liparis tunicatus*) composed the bulk (almost 96%) of the fish collected offshore. The catches of juvenile Arctic cisco in marine habitats were more unexpected. Their occurrence in offshore waters is examined in more detail in the next section.

The catch results have been summarized in several tables appended to this report. Appendix B provides a summary of CPUE (catch per set) for the major species by station and date. Appendix C provides a similar summary for density information. Appendix D provides a summary of the replicate sampling by station, date and location of sampling. Standard descriptive statistics including CVs by species and total catch for each station are also provided in Appendix D. Appendix E lists the geographical coordinates of the offshore stations.

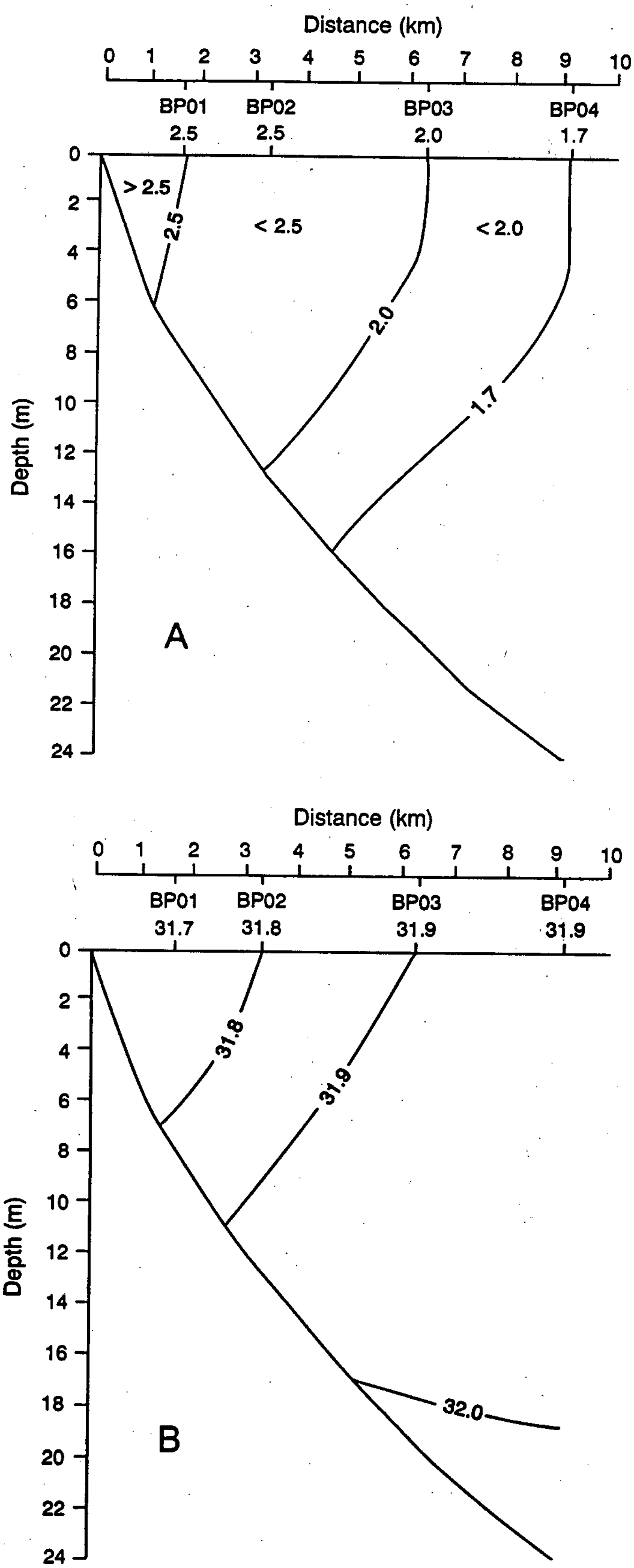


Figure 17.—Vertical sections of temperature (A) and salinity (B) from the Brownlow Point transect, September 3, 1990.

Table 1.–Scientific and common names of fish collected by townetting in 1990, coastal Beaufort Sea, Alaska.

Family	Species	Common name
Salmonidae	*Coregonus autumnalis*	Arctic cisco
	Salvelinus alpinus	Arctic char
Gasterosteidae	*Pungitius pungitius*	Ninespine stickleback
Osmeridae	*Mallotus villosus*	Capelin
Gadidae	*Boreogadus saida*	Arctic cod
Stichaeidae	*Lumpenus medius*	Stout eelblenny
	Lumpenus fabricii	Slender eelblenny
Liparidae	*Liparis tunicatus*	Kelp snailfish
Cottidae	*Gymnocanthus tricuspis*	Arctic staghorn sculpin
	Myoxocephalus quadricornis	Fourhorn sculpin
Pleuronectidae	*Liopsetta glacialis*	Arctic flounder

Table 2.–Species composition and relative abundance of the 1990 townet catch.

Species	Number caught	Percent composition	Mean CPUE	Mean density
Arctic cod	14,945	87.46	194.09	57.94
Capelin	906	5.32	4.77	4.15
Arctic cisco	560	3.27	7.29	1.83
Snailfish	521	3.05	6.77	2.48
Stickleback	97	0.57	1.26	0.33
Sculpins	36	0.21	0.47	0.12
Eelblennies	12	0.07	—	—
Arctic flounder	5	0.03	—	—
Unidentified species	4	0.02	—	—
Arctic char	1	0.01	—	—

Catch size varied widely at the 19 stations where juvenile Arctic ciscoes were sampled; CV values ranged from 0% to 142% with a mean of 67.4%. The relative abundance of juveniles was typically low and characterized by a high degree of patchiness throughout the season. This was especially true of early August (sampling through August 9) when a mean CV of 124.5% (n = 5 stations) was indicated by the catch. A moderately patchy distribution was observed throughout the remainder of the season (mean CV = 55.9%, n = 14). Similarly contagious distributions were indicated on finer temporal and spatial scales. For instance, a mean CV of 66.2% (n = 6) was calculated from West Dock catches on August 21 and 23. However, if the outer transect stations WD24 and WD25 are treated as outliers, the catch

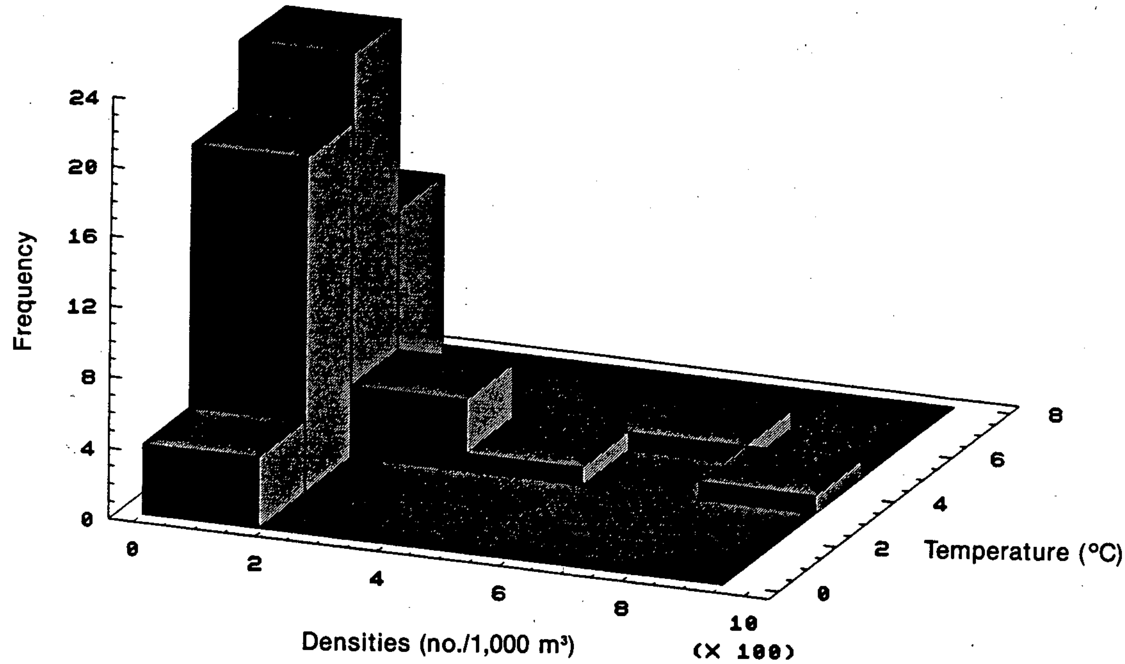


Figure 18.—Total fish densities versus mean temperatures of the upper 2 meters.

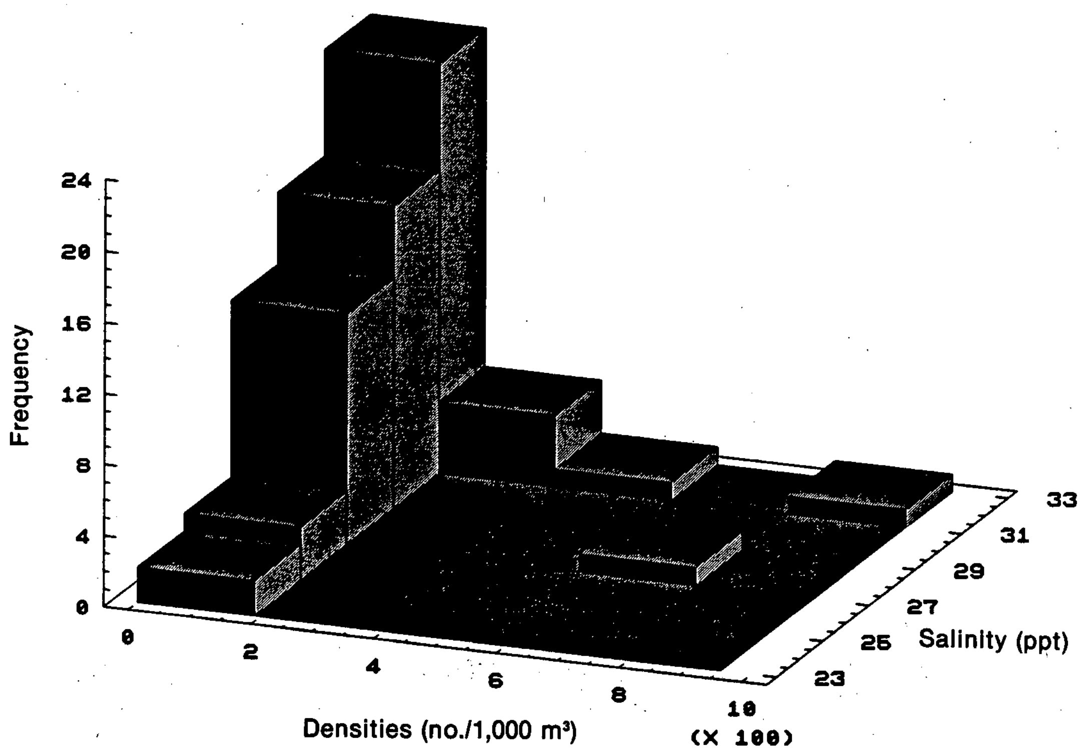


Figure 19.—Total fish densities versus mean salinities of the upper 2 meters.

rates were much less variable (mean CV = 29%, n = 4) and the limited data suggest the migration was centered within 9 km of the coast.

Although Arctic cod were the most abundant species captured in 1990, their relative abundance was quite variable with respect to location and time of sampling (mean CV = 70.3%, range 0–142%, n = 28 stations). The townet appeared to select for small individuals (FL < 100 mm). Gear avoidance and size-related differences in the vertical distribution of the Arctic cod may be responsible for much of the observed variability. Although several instances of highly uniform fish distribution were reported (e.g. station CP01 on August 2) the overall trend was for fluctuating abundance and spatial patchiness throughout most of the summer. However, a trend of increasing abundance of YOY cod was observed late in the season. Prior to August 28, the mean CV for Arctic cod sampled at 11 stations was 89.5%. During the remainder of the season cod were sampled at 17 stations and the mean was 57.9%.

Arctic cod were especially abundant in Camden Bay during early September. On September 2 and 3 the species was present at 14 of 15 stations sampled. Station CV's ranged from 2 to 142% with an overall mean of 48.4%. In most instances, their abundance was observed to decrease with increasing distance from the coast. Other distributional patterns were evident. Arctic cod were abundant in catches taken off Arey Island and Collinson Point. Conversely, they were nearly absent in sampling conducted off the Canning River delta (Brownlow Pt. transect). With the exception of sampling at station CP10, marine conditions were encountered throughout the bay. The mean transect CV's were (from east to west) 52.6%, 26%, and 102%, for Arey Island, Collinson Pt., and Brownlow Pt., respectively.

Capelin and snailfish were also numeric dominants of the catch. Both species were captured at inshore and offshore stations, although there appeared to be a greater tendency for capelin to be distributed closer to the coast. The mean CV's were 108.8% for capelin (range 16–142%, n = 11 stations) and 86.9% for snailfish (range 5–142%, n = 17). These values are indicative of the highly contagious distributions observed for each species in 1990.

Species Characterizations

Juvenile Arctic cisco and Arctic cod were dominant components of the catch. Both fishes have been identified as "key" species of the southeastern Beaufort Sea and thus much of the focus of this report has been placed on them. Other dominant species included capelin, ninespine stickleback, and juvenile snailfish. Separate accounts are provided for each of these species. The remaining species in the catch were viewed as incidental and are treated together; these species were either apparently unable to avoid the gear or were collected at shallow stations where the net accidentally touched bottom.

Arctic Cisco

A total of 560 Arctic cisco were captured in 32 of the 77 sets completed in 1990. The earliest date of capture was reported on August 2 near Carter Creek (CC01) in Camden Bay and the latest on September 5 in Stump Island Lagoon (WD21) in Prudhoe Bay.

Juvenile ciscoes were sampled at stations on four of the five transects, in eastern Stefansson Sound (MS01), and near Carter Creek in Camden Bay. No fish were captured off Brownlow Pt. in early September; the inner station on this transect is located approximately 3 km offshore and small numbers of juveniles were likely to have been present inshore of station BP01. Juvenile ciscoes were captured at all stations on the West Dock transect on August 21 and 22. Mean CPUE and density by transect, and other areas fished, are shown in Table 3.

Young Arctic ciscoes were captured at stations located from 0.32 km to more than 12 km off the mainland coast. The catch ranged from 0 to 154 fish per set ($\bar{x} = 7.29$) with corresponding densities of 0–32.3 ciscoes/1,000 m^3 ($\bar{x} = 1.83$). Most fish were collected within 9 km of the coast and relative abundance was generally highest within the first 5 km offshore. A trend of decreasing catch size with relative distance offshore was observed. The juveniles were sampled in water depths of 2 to 10 m and were most abundant at stations of less than 6.5 m.

Table 3.—Arctic cisco catch summary by transect or other coastal area sampled by townet in 1990.

Sampling area	CPUE (number of fish/set)			Density (number of fish/1,000 m^3)		
	Mean	SD	Range	Mean	SD	Range
West Dock Causeway	23.0	38.4	0–154	5.9	8.6	0–32.6
Endicott Causeway	1.1	1.9	0–6	0.3	0.5	0–1.5
Mary Sachs Entrance	20.8	26.4	0–55	4.0	5.1	0–10.6
Brownlow Point	0.0	—	—	0.0	—	—
Collinson Point	1.8	3.3	0–12	0.5	0.9	0–3.9
Carter Creek	0.8	1.5	0–3	0.1	0.3	0–0.6
Arey Island	0.9	2.2	0–7	0.5	1.4	0–4.5

The distribution of catch by transect fished is shown in Figure 20. More than 90% of the total catch was reported from the causeway areas. Juvenile ciscoes were especially abundant at West Dock during the second half of August and this may suggest the timing of peak migration through Prudhoe Bay.

Size and Growth

Length frequency distributions indicate that the majority of Arctic ciscoes sampled were young-of-the-year fish (Fig. 21). The mean length was 77.2 mm (SD = 9.45, range 51–123 mm). Only one cisco was longer than 100 mm. This fish was captured near the Endicott Causeway (EC12) on August 9 and measured 123 mm long. This size is indicative of an age 1 fish. A summary of length measurements by station and date is provided in Table 4.

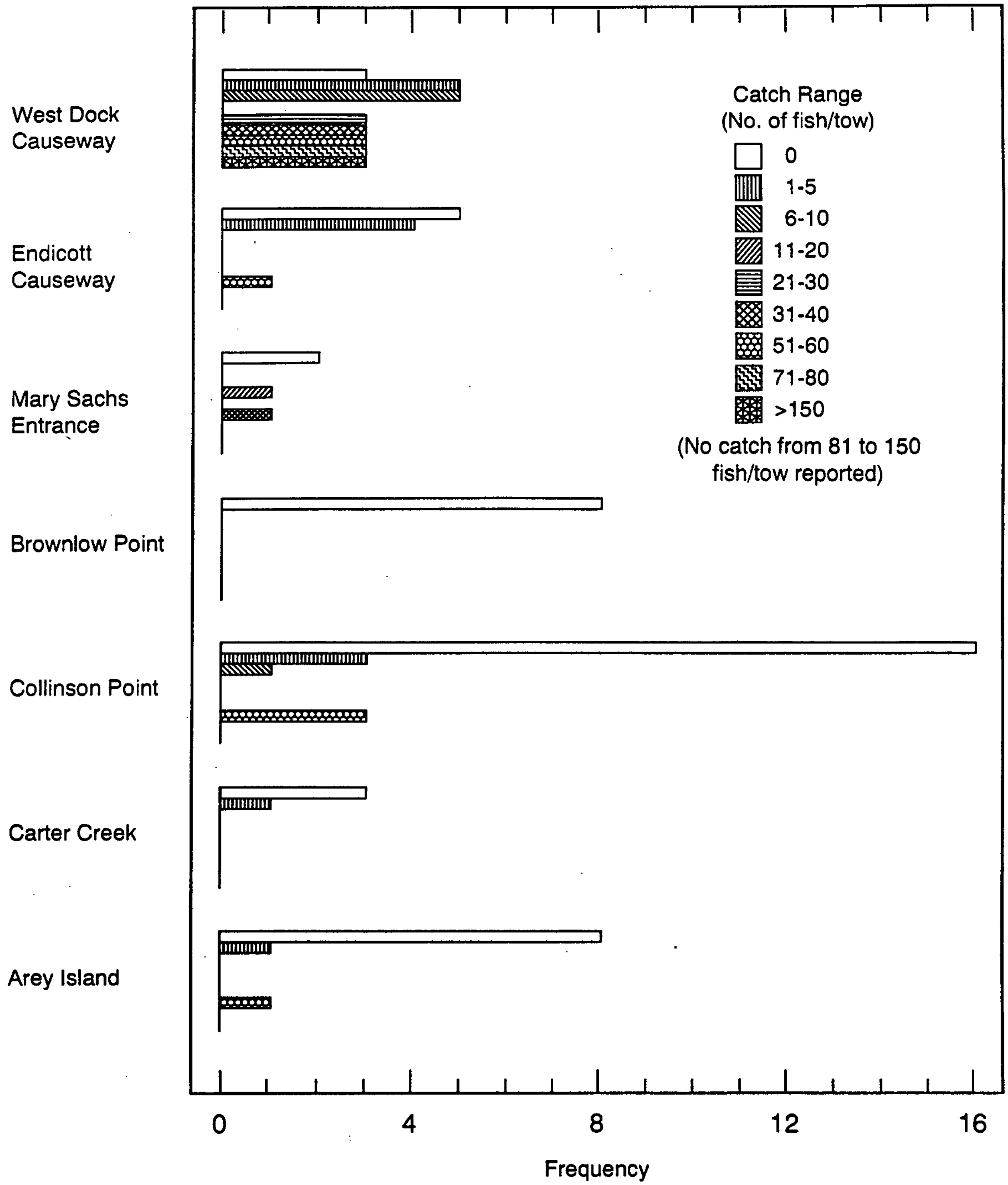


Figure 20.—Arctic cisco CPUE (catch/10-min tow) by sampling transect in 1990.

The average size of migrating fish was examined during three time periods approximating early, middle, and late portions of the field season. The early season included the townetting conducted prior to August 10 in Camden Bay and near the Endicott Causeway. Enough time had elapsed between the two sampling efforts (4–8 d) for juveniles to have moved from Camden Bay, into Stefansson Sound, and the causeway area. Thus, it

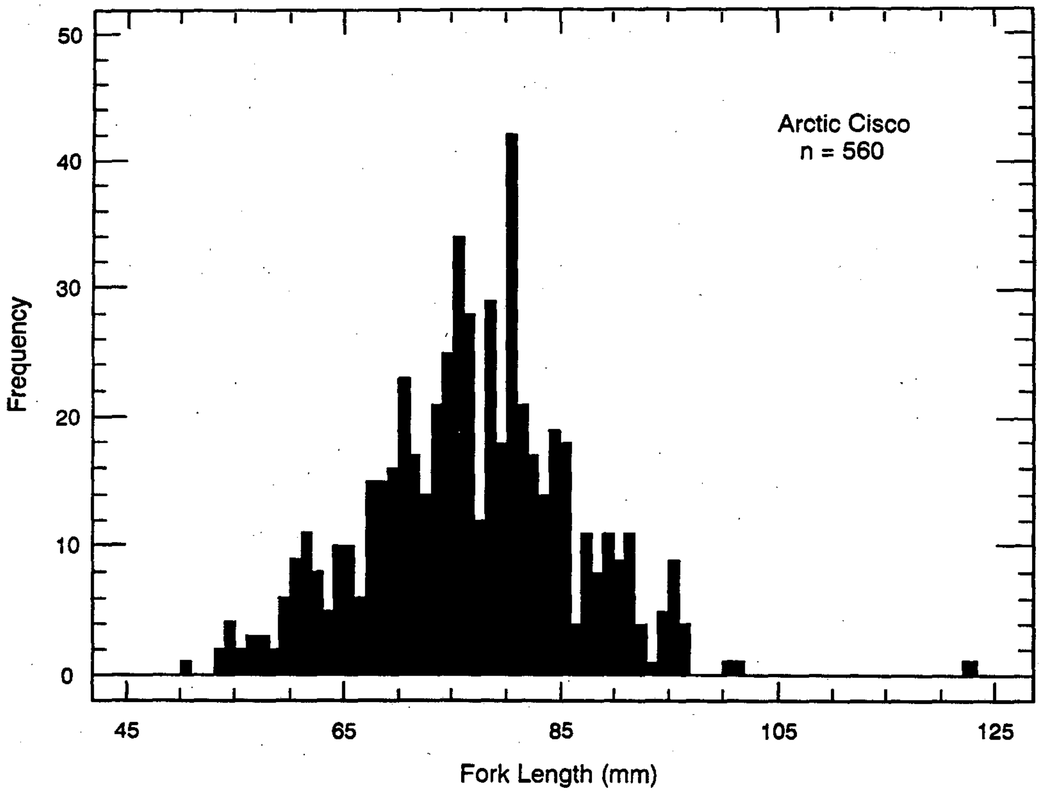


Figure 21.—Arctic cisco length frequencies, all stations.

is likely that the same cohort was sampled throughout the early season. The middle season included all the sampling that was conducted at West Dock between August 21 and 23. All fishing activities after this were pooled into a late season category. During the late period fishing was conducted between Camden and Prudhoe bays.

A comparison of the mean length of juveniles with time revealed a significant difference in average size with respect to time ($F_{2,558} = 4.835, P = .0083$). The observed trend was for decreasing size with advancing summer (Fig. 22). The mean length of the juveniles during each time period was 82.1 mm, 77.7 mm, and 75.6 mm, respectively. Although the data are limited by the small sample size, it appears that larger-sized individuals lead the migration across the coast. Because the age 1 cisco captured off Endicott Causeway on August 9 could have been migrating with younger fish it was included in the analysis.

The size of juvenile Arctic ciscoes was also examined (one-way ANOVA) with respect to relative distance (in kilometers) of capture from the coast. Fish catches were pooled and partitioned into 11 distance categories based on the geographic location of the stations. A null hypothesis of equal population means was tested and rejected ($F_{10,550} = 8.135, P < .0005$). This was not unexpected since we were (1) studying a migrating population, (2) the sampling was not synoptic, and (3) environmental conditions, especially winds, varied throughout the sampling period.

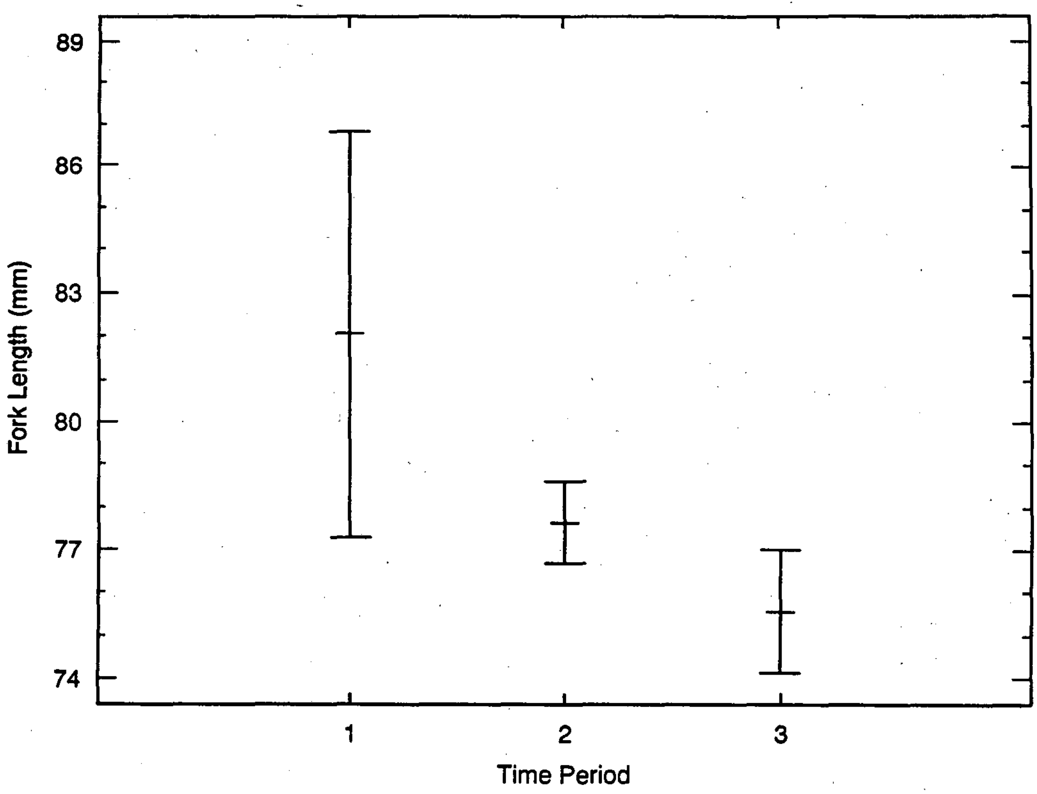
Table 4.—Length measurements of juvenile Arctic ciscoes collected by townet in 1990.

Date	Station	Number of fish	Fork length (mm) Mean	SD	Range
8/02	CC01	3	72.7	5.5	69–79
8/05	CP11	1	68.0	—	—
8/09	EC12	2	107.0	22.6	91–123
8/09	EC11	2	86.0	7.1	81–91
8/09	EC10	7	79.9	3.0	74–83
8/21	WD24	57	84.7	5.6	72–96
8/21	WD23	53	76.7	5.2	62–88
8/22	WD21	226	76.3	5.2	54–102
8/22	WD22	34	77.9	6.5	63–93
8/22	WD25	4	76.5	4.5	73–83
8/23	WD21	9	70.0	7.2	55–81
8/25	CP10	11	73.3	14.5	51–97
8/26	CP10	11	69.5	11.8	54–90
8/27	MS01	83	76.0	9.1	55–97
8/31	AI01	6	76.3	5.6	67–83
9/02	AI01	2	85.5	0.7	85–86
9/03	CP10	18	71.2	10.9	56–96
9/05	WD22	2	83.0	8.5	77–89
9/05	WD21	29	77.8	9.3	65–96

"Nearly synoptic" sampling was, however, conducted at West Dock on August 21 and 22. The length frequency data for Arctic ciscoes captured on these dates are shown in Figure 23. The average length of the 372 fish sampled was 77.83 mm. A comparison of mean lengths indicated a significant difference in the average size of the fish at stations located along the transect ($F_{4,367} = 2.40$, $P < .0005$). The ciscoes tended to be smallest at inner and outer stations of the transect. The hydrographic properties observed at these stations were more marine than temperature and salinity conditions along the middle portion of the transect. The larger fish may have been able to avoid the marine conditions.

If the mean sizes noted above are true estimates of the population, seasonal growth can be evaluated. For the early season it was assumed that the ciscoes sampled in Camden Bay on August 2 represented the same cohort of migrating fish that was sampled 8 d later on the Endicott transect. A comparison of mean fork length size from the two dates suggests (1) a 1.64% relative increase in mean length per day, and (2) a 4.95% instantaneous rate of increase in mean body weight per day (G).

Since the distance between Collinson Pt. and West Dock is approximately 140 km, it would take a fish migrating at an assumed rate of 13 km/d about 10 d to travel this distance.



Level	Count	Average	Standard Error (internal)	Standard Error (pooled s)	95% Confidence Intervals for Mean	
1	15	82.066667	3.4149066	2.4239293	77.304457	86.828877
2	381	77.648294	.4571338	.4809535	76.703381	78.593207
3	164	75.597561	.7829127	.7330670	74.157330	77.037792
Total	560	77.166071	.3967085	.3967085	76.386672	77.945471

Figure 22.—Mean size of juvenile Arctic ciscoes for early, middle, and late periods in 1990.

This interval roughly corresponds to the time separating eastern and western sampling in the late season. Fish sampled in Simpson Cove (CC10) on August 25 had a mean length of 71.4 mm (n = 22). Ciscoes sampled at West Dock 11 d later averaged 78.1 mm (n = 31). Under the assumptions outlined above, this suggests late season growth rates of (1) 0.85% relative increase in mean length per day, and (2) 2.54% instantaneous increase in mean body weight per day (G).

Time and Area

In order to assess temporal and areal aspects of the catch the study area was divided into eastern and western strata or "catch districts." The division, while arbitrary, was based on geomorphological characteristics of the Beaufort Sea coastline. The western portion of the

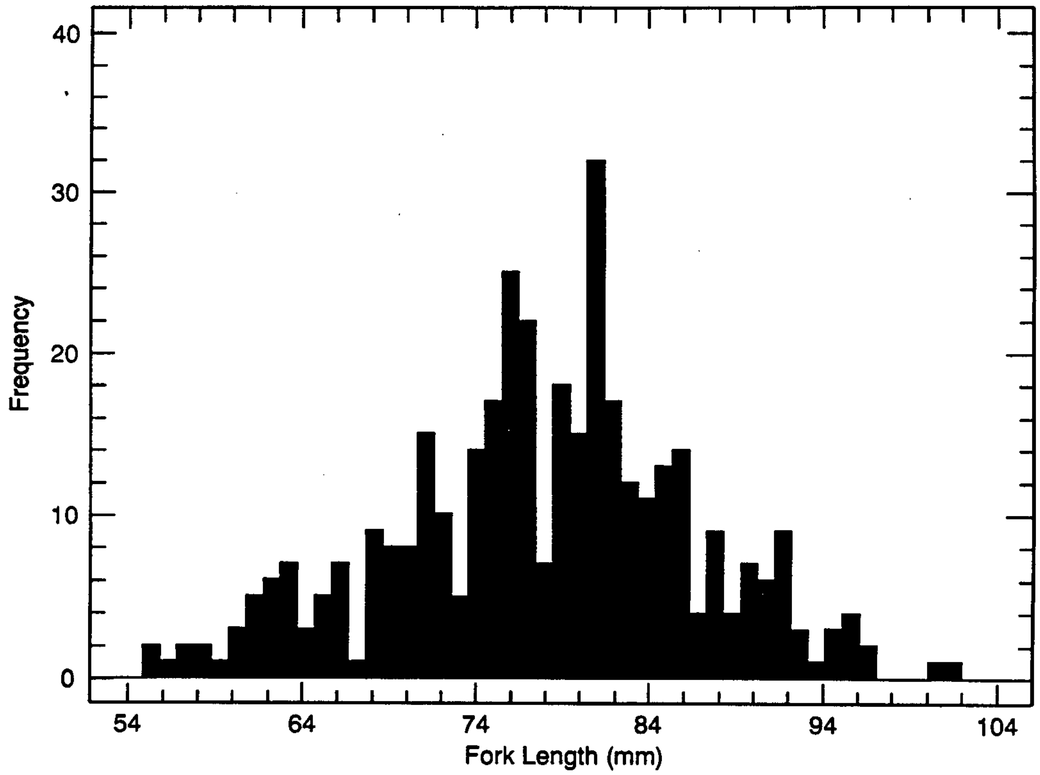


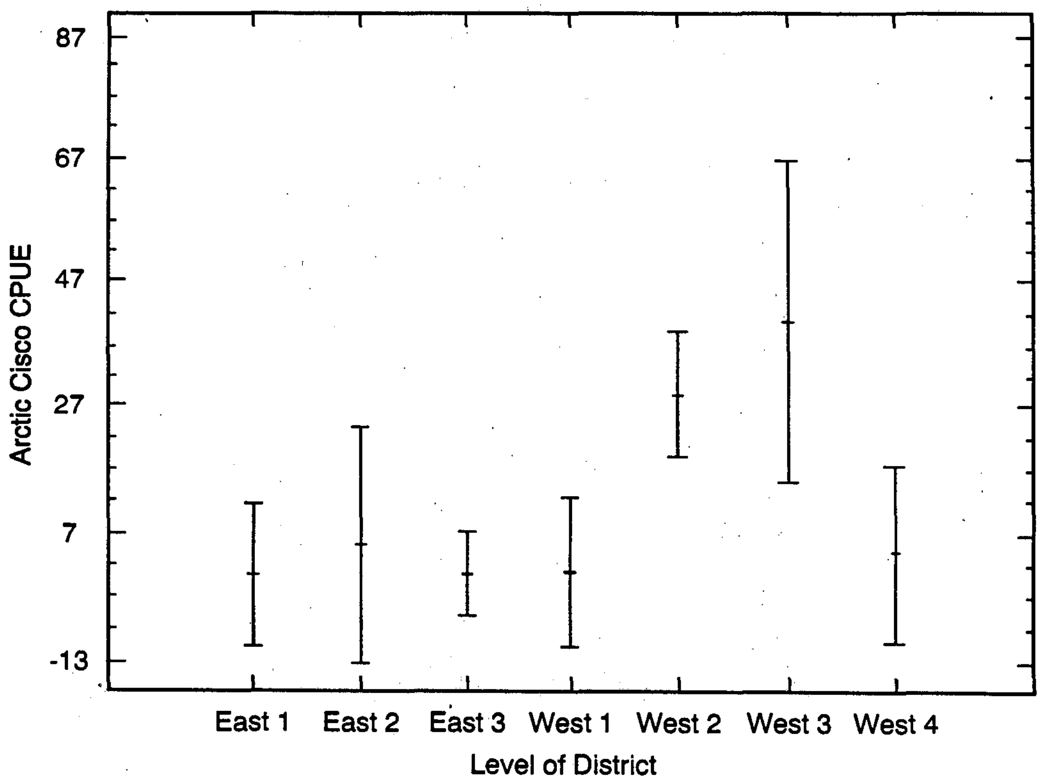
Figure 23.—Length frequencies of YOY Arctic ciscoes sampled at West Dock, August 21–22, 1990.

study area includes the open lagoon systems of eastern Stefansson Sound and Prudhoe Bay. The eastern district encompasses Camden Bay. By contrast, the western area is under greater estuarine influence during the open-water period.

The townet sampling was generally conducted in three nearshore areas (Prudhoe Bay, eastern Stefansson Sound, and Camden Bay) during four "time periods" in August and September. For analytical purposes the catch data were thus assembled in the following manner:

	Eastern catch district		*Western catch district*	
Time period	*Fishing area*	*Sampling dates*	*Fishing area*	*Sampling dates*
1	Carter Creek Collinson Pt.	8/02–8/05	Endicott	8/09
2	Simpson Cove	8/25–8/26	West Dock	8/21–8/23
3	Camden Bay	8/31–9/03	Mary Sachs Mary Sachs	8/27 9/03
4			West Dock	9/05

During 1990, the sampling was concentrated in fishing areas in the east during the early and late August periods and to the west during the mid-August and early September periods.



Level	Count	Average	Standard Error (internal)	Standard Error (pooled s)	95% Confidence Intervals for Mean	
East 1	11	.363636	.278722	5.560831	-10.729598	11.456871
East 2	4	5.500000	1.040833	9.221595	-12.896049	23.896049
East 3	30	.900000	.489781	3.367251	-5.817287	7.617287
West 1	10	1.100000	.585947	5.832249	-10.534683	12.734683
West 2	13	29.461538	12.115690	5.115221	19.257247	39.665830
West 3	2	41.500000	13.500000	13.041305	15.484058	67.515942
West 4	7	4.428571	2.608203	6.970871	-9.477534	18.334677
Total	77	7.285714	2.101797	2.101797	3.092866	11.478563

Figure 24.—Ninety-five percent confidence intervals for Arctic cisco CPUE by catch districts.

Mean CPUE and associated 95% CI are shown for each district in Figure 24 and by time in Table 5. It should be noted that Period 4 in these instances includes the replicate sampling that was conducted at station MS01 on September 3. The inclusion reflects the sorting of catch data into early August, mid-August, late August, and early September categories.

Regional comparisons of longitudinal abundance patterns were investigated (two-sample t tests; i.e., Ho: Diff = 0; Ha: NE) between districts during similar time periods. This would help to characterize the strength and duration of the juvenile migration observed in the offshore catches. No significant differences were observed between the eastern and

Table 5.—Mean CPUE and density of YOY Arctic cisco during four sampling periods in August and September 1990.

Period*	Number of stations sampled	CPUE (number of fish/set) Mean	CPUE 95% CI	Density (number of fish/1,000 m³) Mean	Density 95% CI
1	21	0.71	–7.43 to 8.86	0.17	–1.65 to 2.00
2	13	29.46	19.11 to 39.81	7.32	5.00 to 9.64
3	6	17.50	2.26 to 32.74	3.55	0.13 to 6.96
4	37	1.57	–4.57 to 7.71	0.56	–0.87 to 1.93
Overall	77	7.29	3.03 to 11.54	1.83	0.87 to 2.78

*Period 1 = August 2–9; Period 2 = August 21–23; Period 3 = August 25–27; and Period 4 = August 31–September 5.

western districts during periods 1 ($t_{.05(2),19}$ = 2.093; P = 0.1969) or 2 ($t_{.05(2),17}$ = 2.110; P = 0.4985). In the first instance, the comparison was between mean CPUE's from the central portion of central Camden Bay ($\bar{x}$ = 0.36, SD = 0.92) and the east side of the Endicott Causeway ($\bar{x}$ = 1.1, SD = 3.43). The second comparison was between mean CPUE's in Simpson Cove ($\bar{x}$ = 5.5, SD = 2.08) and along the West Dock transect ($\bar{x}$ = 29.46, SD = 43.68). The results suggest a relatively steady pulse of fish through the study area between August 10 and 25.

A significant change in mean abundance was detected between Camden Bay (including Simpson Cove) and Mary Sachs Entrance (MS01) during late August ($t_{.05(2),32}$ = 2.037; P = .0030). No Arctic ciscoes were captured on the Brownlow Pt. transect or at station MS01 on September 3, thus the possibility of emigrational effects (i.e., sampling the same fish twice) was negated. The relatively large catch of juveniles at Mary Sachs Entrance on August 27 (83 fish in combined replicates) suggests the presence of a large pulse of migrating fish.

The large pulse of fish sampled in eastern Stefansson Sound on August 27 apparently had migrated through Prudhoe Bay by September 3. A comparison of the mean catch reported during period 4 and that of station MS01 from August 27 is indicative of a significant decline in fish abundance ($t_{.05(2),9}$ = 2.262; P = .0225). While it remains possible that the juveniles were migrating closer inshore than our fishing, the small catches and apparent low abundance of juveniles suggests that we were sampling the tail end of the migration. However, juveniles were still present in coastal waters west of Barter Island in early September and thus the migration period extended beyond September 5.

Other temporal and spatial features of the migration were evaluated. Catch was shown to vary by time ($F_{3,70}$ = 3.31, P < .0005) and location (Ho: equal means, $F_{3,73}$ = 2.74, P = .0869). Such results would be expected for a migratory species. In the latter instance, the catch data were partitioned into 0–2, 2–5, 5–10, and >10 km categories (depending on station location); the corresponding pooled mean CPUE's were 6.4 fish/set (SE = 4.64, n = 21); 17.1 (SE = 5.31, n = 16); 4.7 (SE = 3.8, n = 32); and 0.5 (SE = 7.5, n = 8); respectively. The interaction between treatment effects (time and location) was nonsignificant (two-way ANOVA, $F_{3,70} = 2.74$, $P = .1213$) and this may reflect the lack of environmental contrast in habitat (i.e., marine or nearly marine conditions) observed in 1990.

Migration

Interruptions in the fishing schedule resulted in a sporadic time series for the offshore catch. The discontinuities render any attempts at assessing changes in fish abundance or size mode distributions with time difficult on all but very coarse scales (weekly or biweekly intervals). Over the study period longitudinal changes in juvenile density patterns were observed. For example, a one-way ANOVA of fish density versus time (periods as above except that MS01 sampling on September 3 was included in Period 4) demonstrates gross temporal changes in relative abundance ($F_{3,73} = 2.74$, $P < .0005$) and these may be attributable to fish migration (Table 5). These trends may parallel similar observations about the timing of migration from fyke-net catches along the coast in 1990.

The migration rate was examined using vector analysis techniques and both passive and directed fish migrations were considered. During 1990, the average-sized fish measured 77.2 mm (FL). This length was converted to a total length measurement of 84.2 mm and, under the assumption of a voluntary rate of movement of 1 body length/s, expanded to an average daily fish swimming speed of 7.3 km/d.

The time series for the mean daily rates and directions of passive and directed fish migrations are shown in Figures 25 and 26, respectively. If the juvenile migration was one of passive transport in wind-driven currents the average rate of fish movement (an average-size individual) would be 15.3 km/d (range 2.8–38.2 km/d). The mean direction of the migration off Beaufort Lagoon was 219° in the rotated coordinate system (i.e., the mean speed in the u direction was –9.6 km/d and –11.9 km/d in the v direction). This is indicative of a mean westerly migration with an onshore component. A mean speed of 18.1 km/d (range 3.9–39.3 km/d) was computed for fish undergoing a directed migration. The mean direction of such a migration would have been to the southwest (241° rotated, i.e., the mean speed in the u direction was –15.8 km/d and –8.8 km/d in the v direction). By comparison, a directed migration would not only have been faster, it would also have possessed a less significant onshore component than was predicted for the passive migration.

Habitat

The townet effectively sampled the upper 2 m of the water column during each haul. Unless otherwise stated, "average conditions" shall refer to the mean temperature and salinity of this surficial layer.

The greatest numbers and densities of juvenile Arctic cisco were sampled in nearshore waters with temperatures ranging from 4 to 6°C and salinities from 27 to 29 ppt (Figs. 27 and 28). The average conditions were 4.1°C and 29.0 ppt, respectively. An exceptionally large catch of 154 ciscoes (32.26 fish/1,000 m^3) was captured at WD21 on August 22. The mean temperature and salinity at the time of capture were 4.4°C and >28.5 ppt, respectively.

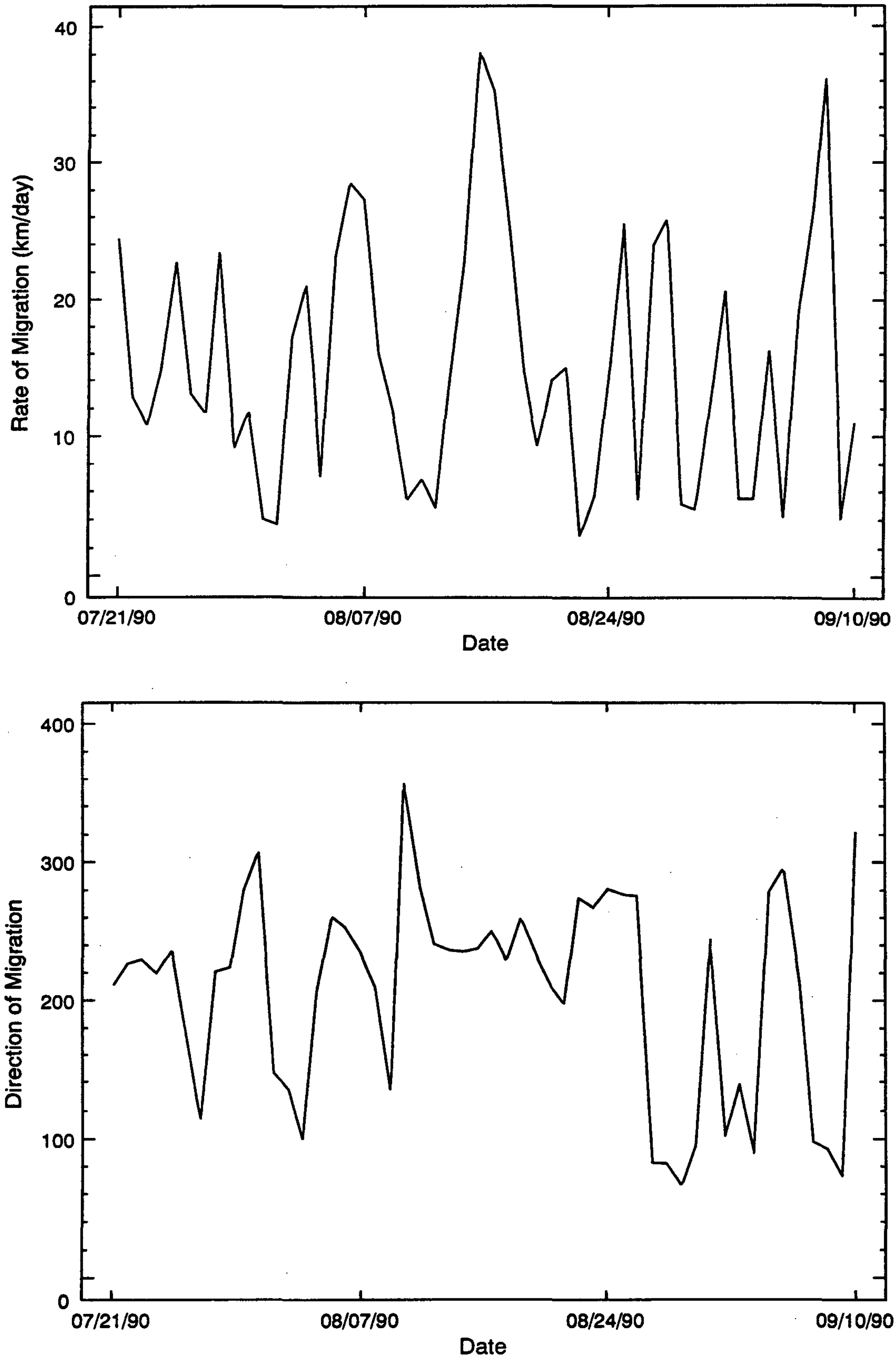


Figure 25.—Mean daily rates and mean daily directions of a passive migration.

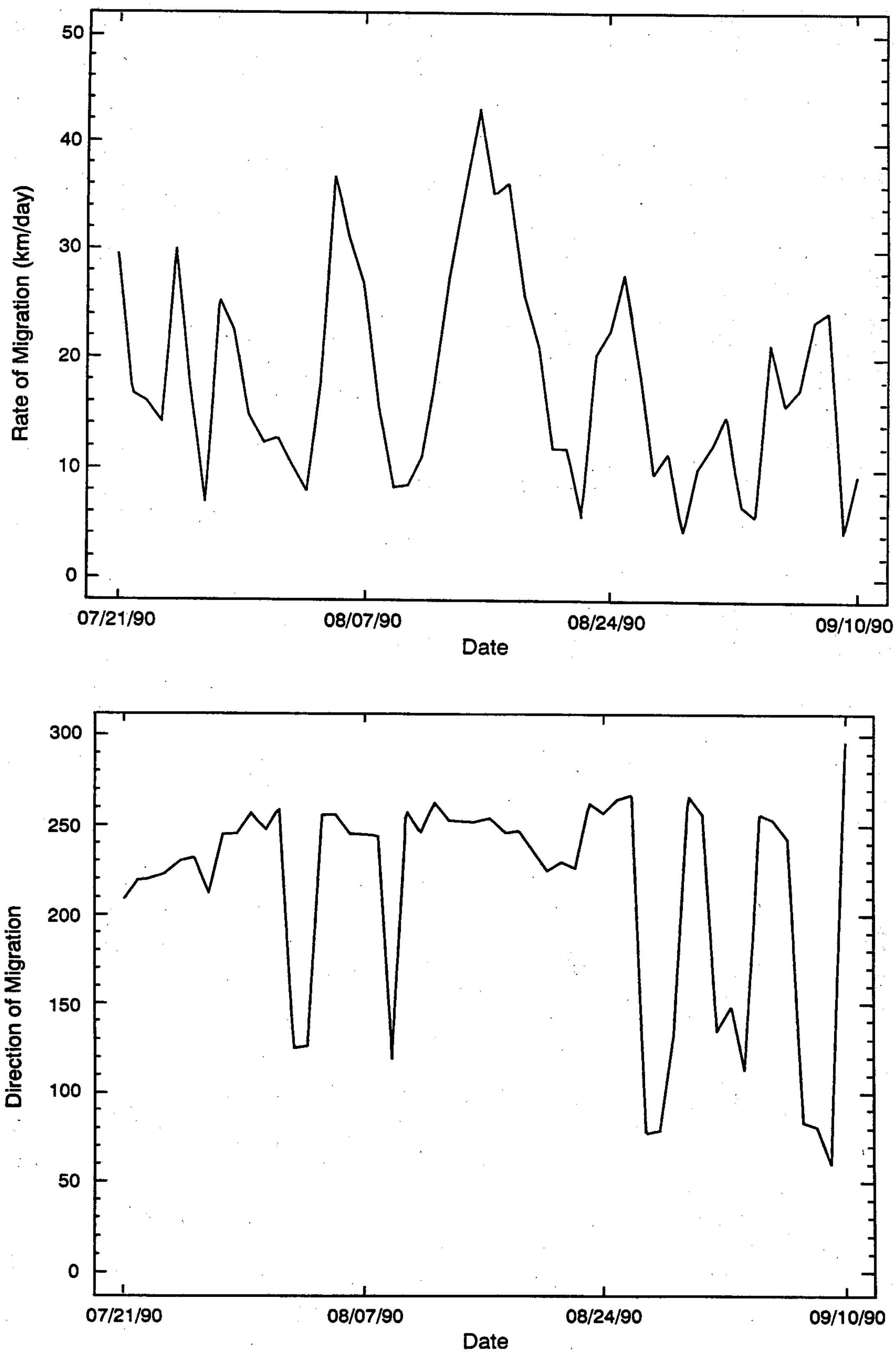


Figure 26.—Mean daily rates and mean daily directions of a directed migration.

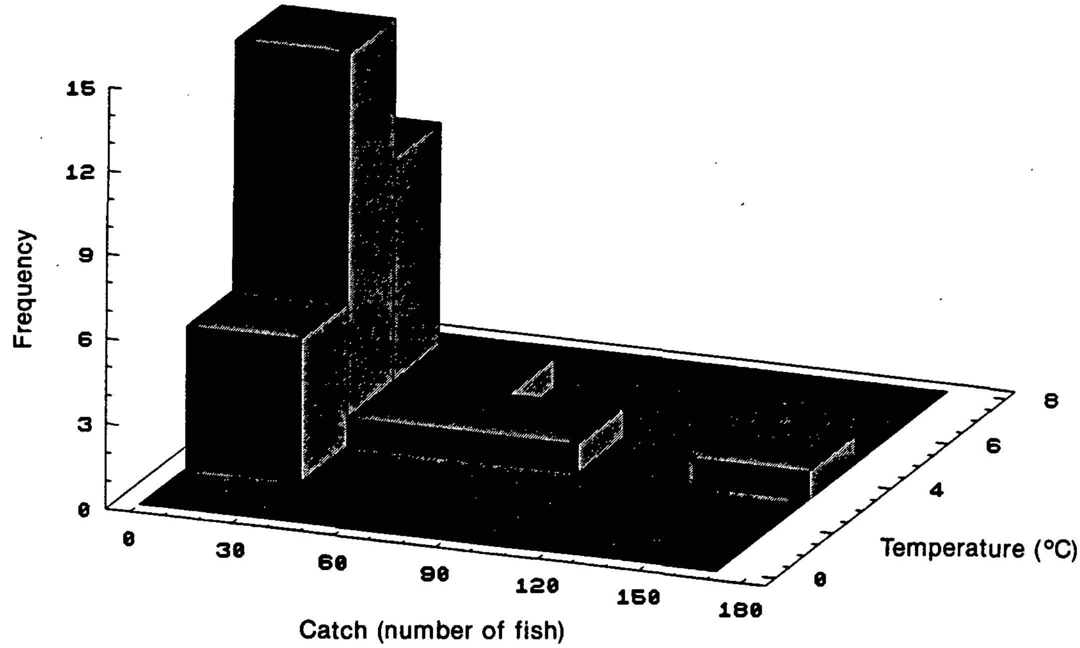


Figure 27.—YOY Arctic cisco catch versus mean temperatures of the upper 2 meters.

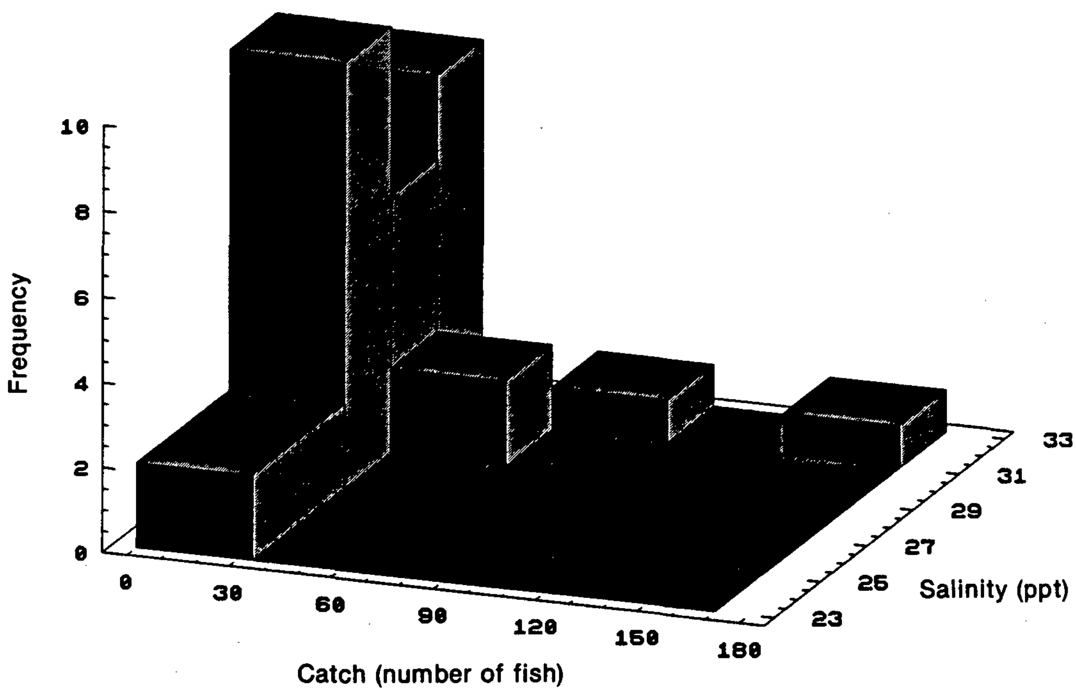


Figure 28.—YOY Arctic cisco catch versus mean salinities of the upper 2 meters.

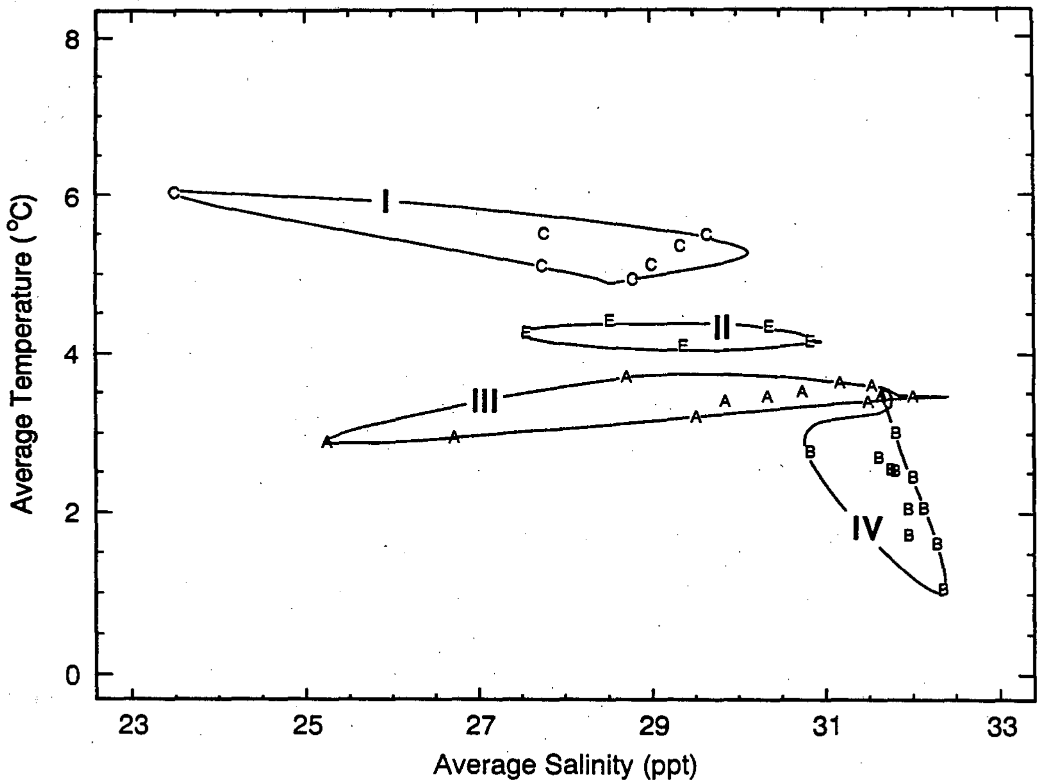


Figure 29.—Cluster plot of YOY Arctic cisco CPUE with mean temperature and salinity conditions of the upper 2 meters.

The station data were assembled into brackish and marine habitats according to the hydrographic properties measured with each catch. The mean salinity conditions at 11 stations along the coast were brackish (< 28 ppt). The mean catch of juvenile Arctic ciscoes in brackish habitats was 7.45 fish/set versus 7.23 fish/set in marine (> 28 ppt) habitats. The mean densities within brackish and marine habitats were 1.77 and 1.84 fish/1,000 m^3, respectively. Juvenile Arctic cisco abundance (CPUE) did not vary by habitat ($F_{1,69} = 3.98$, $P = 0.47$) but significant differences occurred between transects ($F_{6,69} = 2.23$, $.01 > P > .005$). Brackish water conditions were observed most frequently in the protected waters of Simpson Cove or in the nearshore areas of Prudhoe Bay most influenced by the Sagavanirktok River (e.g., EC10).

The Arctic cisco CPUE data cluster into four groupings defined by mean temperature and salinity habitat variables (Fig. 29). There are clear thermal differences separating the clusters with the exception of ten catches shared between Clusters III and IV. In this instance, the ability to discriminate between catches associated with marine salinities is not 100%. The distribution of townet sampling effort within each cluster was 14 sets in Cluster I, 14 in II, 17 in III, and 22 in IV. A general summary including average catch and environmental conditions for each cluster is provided in Table 6.

Cluster I represents a "High Temperature, Low Salinity" grouping from which 22% (123 fish) of the Arctic cisco catch was reported. These fish were captured in the most

Table 6.—Summary of cluster analysis including stations, sampling dates, and mean indices of relative abundance and environmental conditions for each cluster.

	Cluster group[a]			
	I	II	III	IV
Number of samples	14	14	17	22
Average				
CPUE (number of fish/set)	8.8	9.9	15.7	0.1
SE	4.5	4.2	9.6	0.1
Density (number of fish/1,000 m^3)	2.6	2.5	3.7	0.02
SE	1.5	0.9	2.0	0.02
Temperature (°C)	5.4	4.2	3.4	2.6
Salinity (ppt)	28.1	29.6	30.9	31.8
Distance from coast (km)	5.9	4.6	4.4	6.0
range	2.0–11.5	1.5–9.0	0.3–12.0	2.0–11.5
Depth (m)	5.7	5.0	5.7	12.8
range	2.0–9.0	3.0–6.5	2.0–12.5	2.0–26.0
Station information				
Stations	WD23–25 EC10–11 CP10	WD22 EC12–13 MS01 CP10–11	WD21 EC14 MS01 CP10 CP12–13 CP02 WD22–23	WD21 BP01–04 CP10 CP12–15 CC01 AI01–04
Sampling dates[b] (in order of stations above)	821–822 809 802	822 809 827 903, 902	[822, 823, 905] 809 903 902 902, 805 825, 826 802 831 905	823 903 [825, 826] 902 802 902

[a] Ten samples shared between Clusters III and IV.

[b] Bracketed dates indicate sampling occurred at station on more than one date.

brackish water conditions we observed in 1990. The stations included in this cluster tend to be located nearest to the coast (i.e., at the Endicott transect or in Simpson Lagoon) or otherwise influenced by freshwater inflows. With respect to the latter, stations WD23–25 on the West Dock transect appear to have been located within the plume of Sagavanirktok River water that had been deflected offshore and to the north of the causeway on August 21–22. The sampling contained in Cluster I occurred during early and mid-portions of the August–September sampling period.

Cluster II can be characterized by its "Intermediate Temperature and Salinity" conditions indicating a greater degree of mixing with marine waters than was observed in Cluster I. Twenty-four percent of the total catch, or 138 fish, was reported from this cluster. Most catches were reported from inshore stations along the transects in late August. The exception was station EC13 which was sampled on August 9. The conditions at EC13 were transitional between coastal waters inshore and marine waters offshore.

Cluster III stations were sampled during the latter part of the migration period in late August and early September. Roughly 47% of the total catch (267 fish) was reported from stations included in this group. The water conditions of Cluster III indicated a greater amount of mixing with marine waters than Clusters I and II. With respect to the other clusters it could be designated the "Transitional" grouping. However, habitat conditions were really marine; perhaps the degree of modification of coastal water masses was slightly less than that of Cluster 4. The stations included in Cluster III were located at inner and middle segments of the survey transects. The largest CPUE's reported from Stump Island Lagoon (WD21), at Simpson Cove (CP10), and in eastern Stefansson Sound (MS01) are included in this association. The Cluster III habitat conditions existed coastally throughout the field season, although these may have been more common in late August. The largest catches may coincide with the period of peak migration. The high relative abundance of juveniles in marine or "near-marine" water that was observed at WD21 on August 23 indicates possible fish movement in the onshore currents which exist at the northern tip of West Dock under east wind conditions.

Cluster IV represents a "Low Temperature, High Salinity," or marine, association of stations. Two fish, composing less than 1% of the total catch, were captured in this habitat. Most of the stations occurring farthest offshore were grouped in this cluster. The sampling at WD21 (August 23), at CP10 in Simpson Cove (August 25 and 26), and at two stations off Collinson Pt. (CP12 and 13) is shared with Cluster III. All of the stations sampled on September 2 and most of those on September 3 occurred in marine habitats of Camden Bay. The majority of stations included in this cluster were sampled after August 22 although marine conditions existed in coastal waters throughout the sampling period.

The ten stations shared between Clusters III and IV represented about 6%, or 31, of the ciscoes captured in 1990. The average CPUE and density reported from these stations were 3.1 (SE = 0.95) and 0.75 (SE = 0.22), respectively. These data indicate that significant numbers of fish were present in marine conditions.

Results of a single factor analysis of variance rejected the multisample hypothesis of equal means (CPUE) between cluster groups ($F_{4,72}$ = 2.50, 0.01 < P > 0.005). A Tukey multiple comparison test (critical $q_{.05,72,5} = 3.977$) evaluated differences in the cluster means. The null hypothesis of equal means was rejected for Clusters II vs. IV (q = 5.806), I vs. IV (q = 5.03), and III vs. IV (q = 5.287). This suggests the possibility of only two homogeneous groups (brackish and marine habitats) had the sampling effort been greater.

We conducted a series of pairwise correlation analyses seeking associations between Arctic cisco CPUE and various environmental variables that were measured or derived. These variables included salinity, temperature, depth, distance, u and v components of winds and currents, as well as biological associations with other species in the catch. No strong relationships (r generally ranged from –0.2 to 0.2) were found.

A bivariate response surface analysis was conducted to further investigate relationships between fish density and offshore thermal conditions. A matrix of Z values (normal distribution) describes the three-dimensional surface for the function describing the density–temperature relationship (Fig. 30). Parameters of the normal distribution were estimated by the variable means and their standard deviations. These were 1.83 fish/1,000 m^3 and 4.88 fish/1,000 m^3 for the density variable, and 3.47°C and 1.19°C for the temperature variable, respectively. Minimum and maximum values were 0 and 32.26 fish/1,000 m^3 and 1.02 and 6.05°C. The correlation between the two variables was $r = 0.177$ ($P = .1235$). For example, if we are interested in a random estimate of density at 3°C, we calculate $X = 1.83 + (4.88)(Z_{.021})$. The $Z_{.021} = 0.4916$, thus $X = 4.23$ fish/1,000 m^3.

Arctic Cod

Arctic cod were present at most sampling locations in 1990. The average catch was 194 fish/set (SD = 466.9). This corresponds to a mean density of 57.9 fish/1,000 m^3 (SD = 137.3). Of general interest were numerous observations of cannibalism of smaller cod by larger cod while being held for field processing. Such observations have not been confirmed by stomach contents analysis but suggest a potential density dependent mechanism that may affect recruitment as has been described for other gadoids. It also suggests the apparent segregation of YOY cod that was observed in a single set near Collinson Pt. (CP02) on August 5. A catch of 397 fish was reported with fork lengths ranging from 25 to 37 mm. Smaller catches of similar-sized fish (20–25 mm) were noted in sampling at the inshore stations of the Endicott transect on August 9.

Length Frequencies

Arctic cod ranged in length from 20 to 167 mm (Fig. 31). The average size was 50.4 mm (SD = 19.4). The length frequencies are clearly bimodal, with peaks between 35–45 mm and 80–120 mm. Age determinations were made from an existing age–length relationship for Arctic cod sampled in Prudhoe Bay (Craig et al. 1982). Cod measuring less than 60 mm were YOY fish. Those measuring 60–120 mm were probably age 1. Older fish, ages 2 and 3, are indicated by the remaining catch.

A trend of decreasing size of fish with advancing season was noted in the catch. The mean length of cod captured prior to August 15 was 68.1 mm (n = 260). Between August 15 and 31 the mean size fell to 51.6 mm (n = 445). In early September the mean length dropped even lower, to 45.8 mm (n = 1,115).

An examination of the size of fish captured versus sampling distance from the coast indicated fish averaging 44.7 mm within 2 km of the coast (n = 582), 64.9 mm between 2 and 5 km (n = 311), 50.3 mm between 5 and 10 km (n = 822), and 39.7 mm at distances greater than 10 km (n = 105). All of the cod larger than 120 mm were captured within 2 km of the coast. Their comparatively low abundance, even at catch locations where the net was

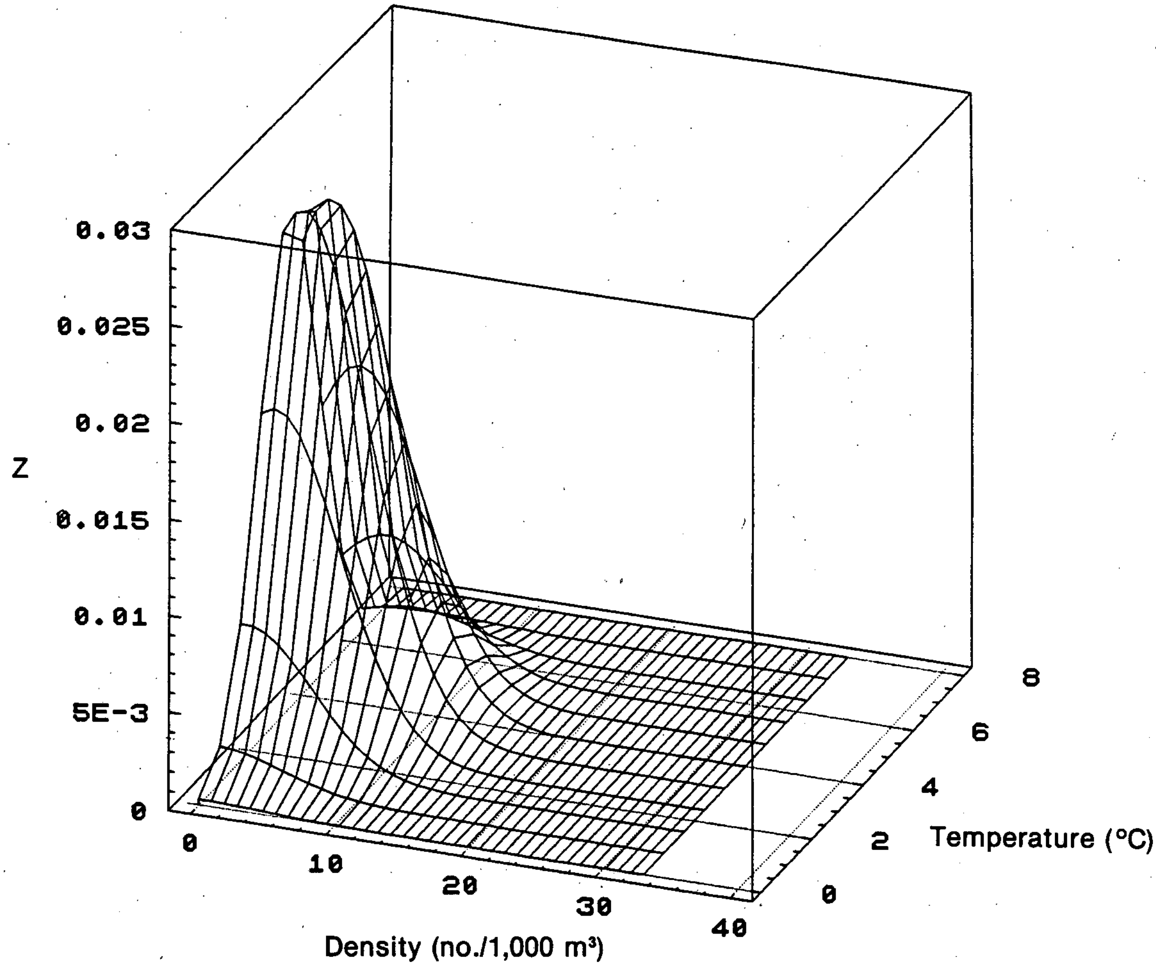


Figure 30.—Bivariate normal surface plot of temperature (upper 2 m) and Arctic cisco density.

sampling virtually the entire water column, suggests gear avoidance. More likely, the larger fish were occurring at greater depths or inshore of our sampling effort.

Habitat

The bulk of the Arctic cod catch was reported in waters having temperatures of 2–6°C and salinities of greater than 26 ppt (Figs. 32 and 33). The data indicate a definite preference for marine conditions by all sizes sampled.

Standing Stock Estimates

Sampling in Camden Bay was of sufficient intensity and areal coverage on September 2–3, 1990 (over 31-h interval), to permit population size and weight estimations to be made for young Arctic cod. The catch was almost exclusively composed of YOY cod (Fig. 34). The mean size was 45 mm. According to Fruge et al. (1988), the average weight of a cod this size would be 11.6 g.

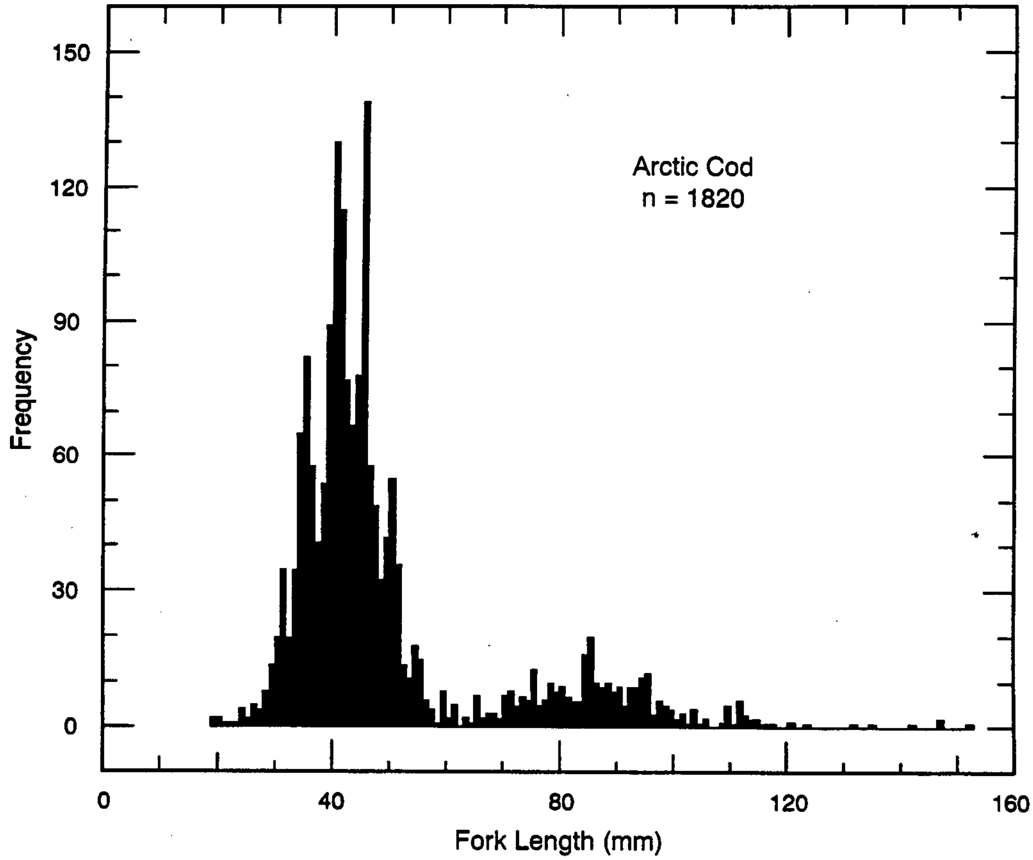


Figure 31.—Arctic cod length frequencies, all stations.

Although the offshore sampling was designed for other purposes, it was possible, given the transect and station locations, to partition the bay *a posteriori* into nearly equal subdivisions for estimation procedures. Two different gridding schemes were used to derive independent estimates of population size and biomass parameters. Assumptions regarding uniformity of fish distribution within Camden Bay were based on the widespread availability of marine habitat conditions and diminished variability in numbers observed in the replicated sampling conducted on these dates.

Cell block method

Survey area.—The cell block method involved the division of Camden Bay into four major subareas: Brownlow Point, Camden Bay, Arey Island, and Simpson Cove (Fig. 35). The single station (CP10) in Simpson Cove was assumed to represent the entire lagoonal system. Within the remaining three subareas, the northern and southern boundaries of the cells were delineated by the longitudinal lines connecting equidistantly located stations from the coast. The location of the transects was such that they bisected each subarea. Considering that the transects are located 41 km apart, areal dimensions for subareas and cell blocks were easily computed. Unless otherwise noted, the cell blocks have alphanumeric designations determined by transect name (BP, CP, and AI) and cell number (e.g., G1, G2) increasing from north to south.

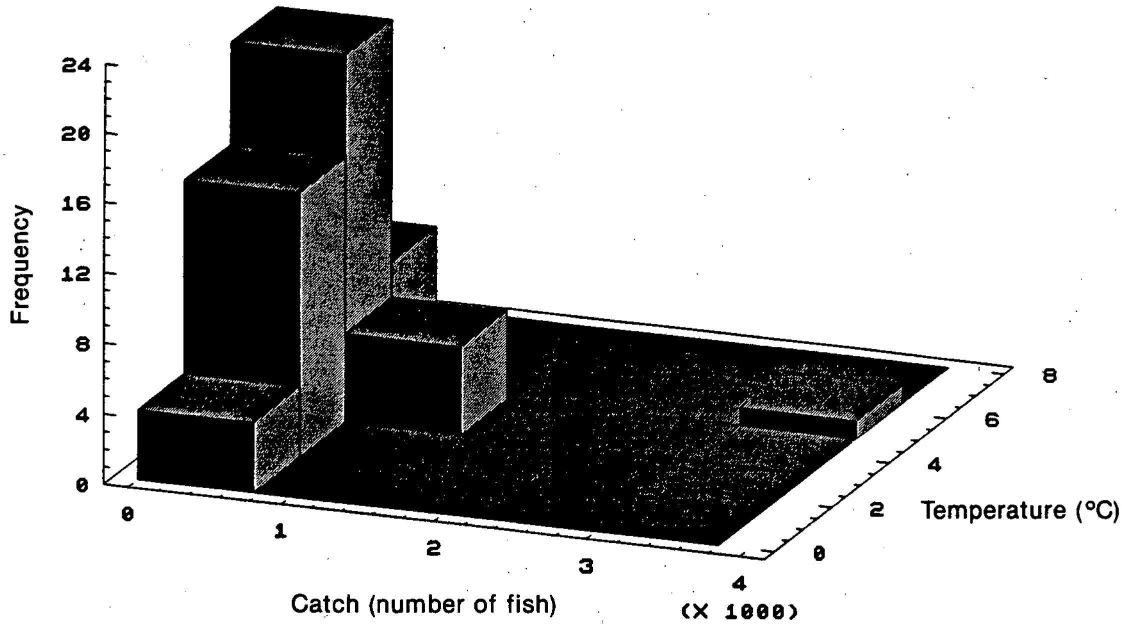


Figure 32.—Arctic cod catch versus mean temperatures of the upper 2 meters.

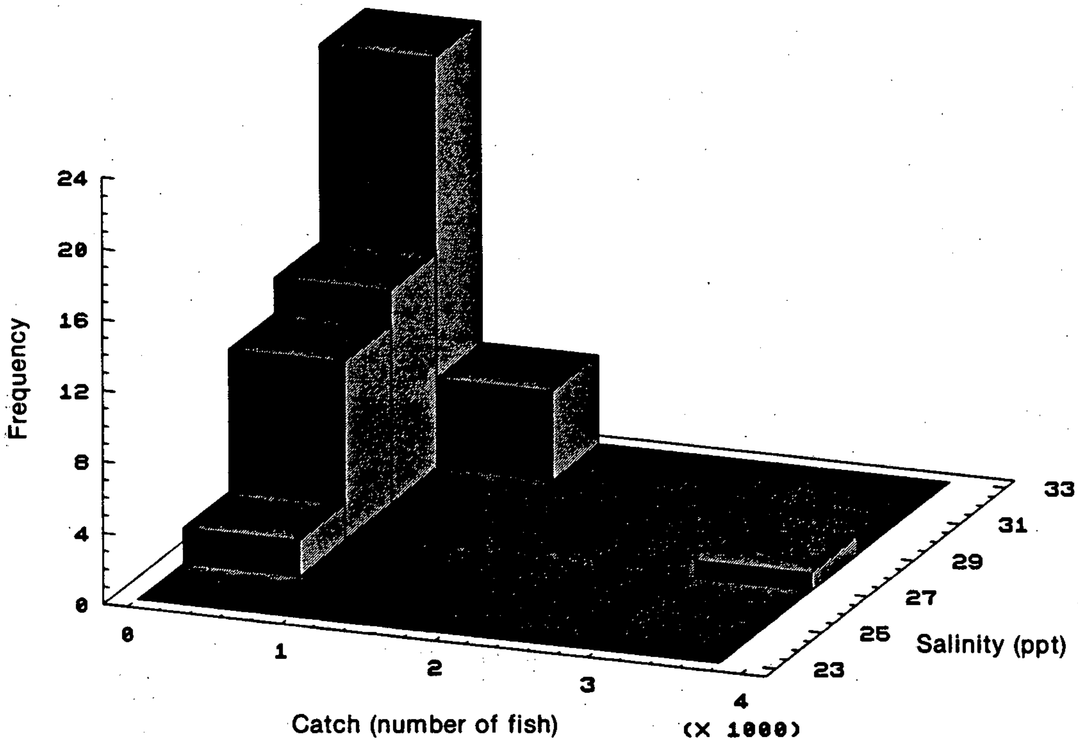


Figure 33.—Arctic cod catch versus mean salinities of the upper 2 meters.

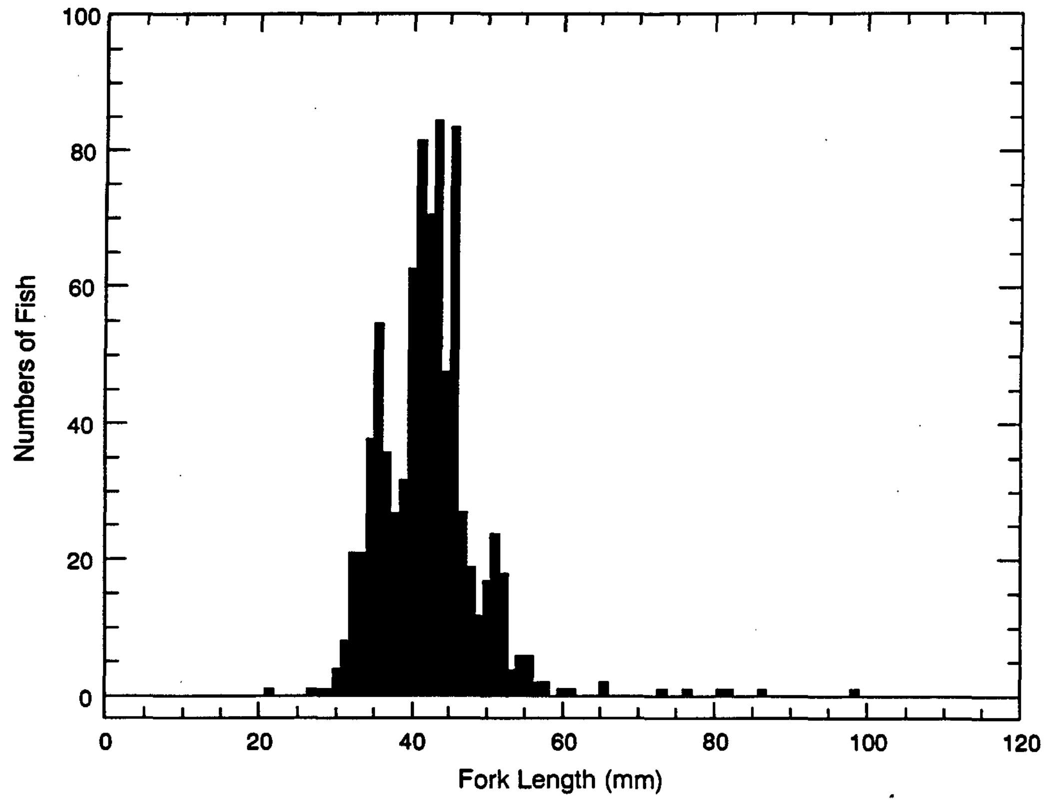


Figure 34.—Length frequency distribution of Arctic cod in Camden Bay, September 2–3, 1990.

The areal dimensions of the subareas were estimated as: Brownlow Pt., 215 km^2; Camden Bay, 580 km^2; Arey Island, 215 km^2; and Simpson Cove, 60 km^2. With respect to the northernmost cells in Camden Bay, several important assumptions were made for ease of area computation. First it was assumed that the eastern and western boundaries of the northern cell of the Camden subarea were of equal length. Second, that the northern cells in Brownlow Pt. and Arey Island subareas were assumed to be right triangles with hypotenuses equal to 21 km. A right triangular cell (85 km^2) was also taken to encompass the bight of Camden Bay proper (CAM in Figure 35). The total area of the entire Camden Bay study area was conservatively estimated to be 1,070 km^2.

Sampling stations were generally located 1.9, 3.4, 6.3, and 9.1 km offshore. A single station (CP10) in Simpson Cove was located about 1.85 km from the mainland shore, roughly halfway (north–south direction) across the cove. An additional station was located 11.75 km offshore of Collinson Pt. Because stations CP12, CP13, and CP14 were located approximately 4, 10, and 12 km offshore, respectively, their positions did not conform to specifications outlined for boundary determinations. Indices of fish abundance for stations located 3, 6, and 9 km off Collinson Pt. were therefore developed from (1) appropriate mean station data, or (2) regression analysis [ln (mean station density + 1) vs. sampling distance (km)].

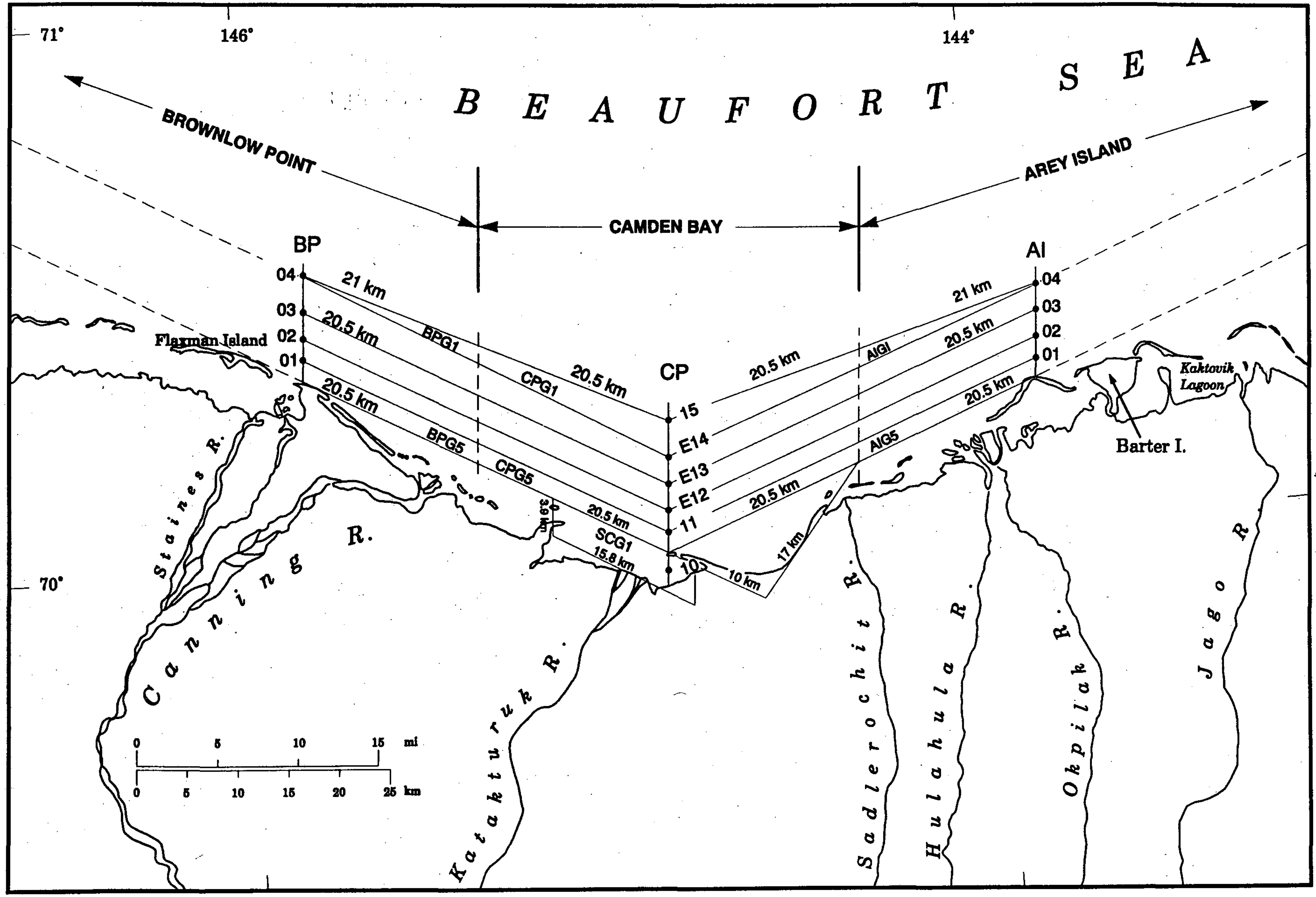


Figure 35.—Cell blocks in Camden Bay.

In the first case, the mean Arctic cod catches at stations CP12 and CP13 were not significantly different from each other ($t_{.05(2)2} = 4.03$, $P > 0.50$). Therefore, assuming a uniform cod distribution, a mean density of 230 fish/1,000 m^3 was accepted for the 3.4 km station. In the second case, where regression analysis was employed, the relative abundance of cod located 6 and 9 km from the coast was estimated by:

$$\ln(\text{density}) = 4.15103 - (0.310024)(\text{km offshore})$$

$$SE(a) = 0.909965$$
$$SE(b) = 0.147277$$
$$SE(est) = 1.74906$$
$$r^2 = 26.97\%$$
$$n = 13$$

The estimated cod densities for these stations were 9.0 and 3.8 fish/1,000 m^3, respectively. Stations where cod densities were estimated on the Collinson Pt. transect are shown as E12, E13, and E14 in Figure 35.

Mean density data were also used to estimate the relative abundance of cod in several other cells where little or no sampling occurred. Fish densities in the CAM cell were estimated as the mean of the innermost stations of the Collinson Pt. (CP10) and Arey Island (AI01) transects and the single station in Simpson Cove. The use of a weighted average in this instance reflects the similarity in habitat conditions at CP10 and AI01. The density estimate for CAM was 107.6 fish/1,000 m^3. Mean density estimates from AI04 and BP04 were assumed to be representative of cells AIG1 and BPG1, respectively.

Because the transect lines bisected the coastal subareas, replicate samples occurred near the northern center of each cell. The townet catches at each station were assumed to be representative of cod densities throughout the upper 1.8 m of the entire cell. This depth reflects the vertical sampling dimension of the townet employed and was therefore used to compute the volume estimates for subareas and cells (i.e., area × 0.0018 km). The total volume of the study area was thus estimated to be 2.12×10^9 m^3.

Coastal waters near the Canning, Sadlerochit, and Hulahula rivers would appear to be excluded from the analysis. The inclusion of shallow and land areas in Simpson Cove and the bight of Camden Bay should compensate for such differences. Realistically, given the propensity of the species for marine conditions, these areas probably do not provide suitable habitat for Arctic cod. Other information used to develop population and biomass estimates is shown in Table 7.

Population numbers.—Population estimates were computed by (1) multiplying the average Arctic cod densities per cell by the cell's estimated volume, and (2) summing the population estimates for each subarea (Table 8). A total of 83.6×10^6 YOY Arctic cod were estimated in the study area. By subarea, Arctic cod numbers were estimated as: Simpson Cove, 2.7×10^6 fish; Camden Bay, 76.8×10^6 fish; Arey Island, 6.6×10^6 fish; and Brownlow Pt., 0.203×10^6 fish. Within Simpson Cove, east of a line running due south of Collinson Pt. the numbers were estimated to be 0.7×10^6 Arctic cod.

Table 7.—Grid cell information for YOY Arctic cod in Camden Bay study area, September 2–3, 1990.

Subarea	Grid cell	Station	Number of samples	Station distance offshore (km)	Mean density (fish/1,000 m³)	Volume (×10⁹ m³)
Simpson Cove	SCG1	CP10	2	1.9	22.5	.12
Camden Bay	CPG5	CP11	2	1.9	166.9	.16
	CPG4	E12	4	3.4	230.0	.12
	CPG3	E13	13*	6.3	9.0	.24
	CPG2	E14	13*	9.1	3.8	.23
	CPG1	CP15	2	11.75	2.4	.22
	CAM	—	6	6.0	107.6	.15
Arey Island	AIG5	AI01	2	1.9	48.4	.08
	AIG4	AI02	2	3.4	13.1	.06
	AIG3	AI03	2	6.3	13.6	.12
	AIG2	AI04	2	9.1	1.9	.12
	AIG1	AI04	2	—	1.9	.06
Brownlow Point	BPG5	BP01	2	1.9	2.2	.08
	BPG4	BP02	2	3.4	0.0	.06
	BPG3	BP03	2	6.3	0.0	.12
	BPG2	BP04	2	9.1	0.2	.12
	BPG1	BP05	2	—	0.2	.06

*Includes samples used in the regression analysis. The predicted values were assumed to have one degree of freedom associated with them.

The mean $CPUE_{overall}$ in Camden Bay for September 2–3 was estimated to be 39.4 cod/1,000 m³ (83.6×10^6 cod/2.12×10^9 m³). The variance of this estimate was calculated as the weighted sum of the individual variances for each cell:

$$\mathrm{VAR}\ \overline{CPUE}_{overall} = \Sigma\,[(V_i/V_T) * \mathrm{VAR}\ \overline{CPUE}_{ik}] \text{ where,}$$

$CPUE_{ik}$ = mean density of species k (Arctic cod) in ith cell,
V_i = volume of the ith cell, and
V_T = total volume of all subareas combined.

The variance estimates for each cell are shown in Table 9. The estimates for stations E13 and E14 were developed from the entire catch set (all stations combined). The total variance of 209.62 is indicative of the low variability in cod catches observed in the replicate sampling.

Confidence intervals for the population estimates ($\hat{P}_{ik}$) were computed as:

$$\hat{P}_{ik} \pm t_{.05,(2),v} * \mathrm{SQRT}(\mathrm{VAR}\ \overline{CPUE}_{overall}) \text{ where}$$

v = the effective degrees of freedom. The total population estimate was 83.6×10^6 with 15 effective degrees of freedom, and 95% confidence limits of 52.7×10^6 and 114.5×10^6.

Table 8.—Estimated population of YOY Arctic cod in Camden Bay during September 2–3, 1990, using the cell block method.

Subarea	Grid cell	Estimated numbers ($\times 10^6$)
Simpson Cove	SCG1	2.7
Camden Bay	CPG1	0.5
	CPG2	0.9
	CPG3	2.2
	CPG4	27.6
	CPG5	26.7
	CAM	16.2
Arey Island	AIG1	0.1
	AIG2	0.2
	AIG3	1.6
	AIG4	0.8
	AIG5	3.9
Brownlow Point	BPG1	0.1
	BPG2	0.02
	BPG3	0.0
	BPG4	0.0
	BPG5	0.2

Subareal contributions to the total were: Simpson Cove, 2.7 million cod; Camden Bay, 74.1 million cod; Arey Island, 6.6 million cod; and Brownlow Pt., 203,000 cod.

Population weight.—Standard "area swept" procedures were used to compute the estimated standing stock weight (kg) of YOY Arctic cod within each subarea and throughout the study area. The population weight within a subarea was estimated by the expansion:

$$\hat{B}_{ik} = (A_i/\bar{p}_i) * \overline{CPUE}_{ik} \quad \text{where}$$

$\hat{B}_{ik}$ = weight (kg) of species k (Arctic cod in this instance) in subarea i, and
A_i = area (km^2) of subarea i, and
$\bar{p}_i$ = the effective horizontal path of the net (0.0068 km), and
$\overline{CPUE}_{ik}$ = CPUE (kg/km) of species k in subarea i.

To express CPUE in units of kg/km several conversions were necessary. First, standardized fish densities for each station were converted to "numbers of fish caught per volume fished per tow." The average volume fished was 3,488.3 m^3 (SD = 682.1, range 2,274.2–4,513.4 m^3). Next, the numbers of fish per set were divided by the actual distance (km) fished per tow ($\bar{x}$ = 285.1 m, SD = 55.7, range 186.4–368.7 m) to compute "numbers per km." Finally, CPUE's (kg/km) were estimated for each station by multiplying the numbers of fish/km by 0.0116 kg. Variance estimates were derived as above except that area [i.e., $(A_i/A_T)^2$] rather than volume was used to weight the cell block estimates.

Table 9.—Variance estimates of $\overline{CPUE}_{ik}$ in Simpson Cove, Camden Bay, Arey Island, and Brownlow Point subareas. Subareal estimates determined as the weighted sums of individual cell block variances.

Cell	Subarea: Simpson Cove	Camden Bay	Arey Island	Brownlow Point
SCG1	0.05			
Total	0.05			
CPG5		3.34		
CPG4		8.62		
CPG3		85.71		
CPG2		85.71		
CPG1		0.001		
CAM		25.31		
Total		200.08		
AIG5			0.75	
AIG4			0.06	
AIG3			0.05	
AIG2			0.01	
AIG1			0.00	
Total			0.87	
BPG5				0.01
BPG4				0.00
BPG3				0.00
BPG2				0.0003
BPG1				0.00
Total				0.0103
Grand total: 209.62 (SE = 14.48)				

Mean CPUE's (kg/km) and their respective variances were computed for each subarea. The estimate of variance for the entire study area was computed as the sum of the variances reported for each subarea.

Subarea	$\overline{CPUE}_{ik}$ (kg/km)	VAR $\overline{CPUE}_{ik}$
Simpson Cove	3.2	0.0008893
Camden Bay	17.8	3.75477
Arey Island	2.5	0.0139369
Brownlow Pt.	0.08	0.0011432
All Camden Bay	7.3	3.7707394

Population weight and variance [VAR $\hat{B}_{ik} = (A_i/\bar{p})^2 *$ VAR $\overline{CPUE}_{ik}$] estimates were computed.

Estimates for the entire bay were obtained by summing the subareal components.

Subarea	$\hat{B}_{ik}$ ($\times 10^4$ kg)	VAR $\hat{B}_{ik}$ ($\times 10^6$)
Simpson Cove	2.8235294	0.0695242
Camden Bay	151.823	2.7316275×10^5
Arey Island	7.904412	0.1393237×10^2
Brownlow Pt.	0.25294	1.14282
All Camden Bay	162.80387	2.7331419×10^5

Confidence intervals for the population weight estimates were computed as:

$$\hat{B}_{ik} \pm t_{.05,(2),v} \text{ (SQRT VAR } \hat{B}_{ik}) \text{ where}$$

v = effective degrees of freedom (v = 15). The total estimated biomass ($\hat{B}_{ik}$) was 1,628,038 kg, with 95% confidence limits of 1,275,736 kg and 1,980,339 kg. Subareal contributions to the total estimated cod biomass included: Simpson Cove, 28,235 kg; Camden Bay, 1,518,230 kg; Arey Island, 79,044 kg; and Brownlow Pt., 2,529 kg.

Biomass and density.—The estimates of population size and weight allow computation of (1) fish density on a per meter basis, and (2) wet weight biomass (g/m^2) for YOY Arctic cod. In the first instance, the estimated numbers of fish per square kilometer were reduced to numbers per square meter for each subarea: Simpson Cove, 0.05/m^2; Camden Bay, 0.13/m^2; Arey Island, 0.04/m^2; and Brownlow Pt., 0.0001/m^2. An overall density of 0.08 cod/m^2 was estimated in Camden Bay on September 2–3, 1990.

Two independent measures of biomass can be derived from the $\hat{P}_{ik}$ and $\hat{B}_{ik}$ parameters. One method involves a simple conversion of $\hat{B}_{ik}$ estimates to a per meter unit basis. The second approach involves (1) reduction of $\hat{P}_{ik}$ to estimated numbers/km^2; (2) multiplication of numbers/km^2 by 11.6 g to express biomass in g/km^2; and (3) conversion of g/km^2 to g/m^2. A comparison of the two estimates is presented below.

Subarea	$\hat{B}_{ik}$ (g/m^2)	$\hat{P}_{ik}$ (g/m^2)
Simpson Cove	0.5	0.5
Camden Bay	2.6	1.5
Arey Island	0.4	0.5
Brownlow Pt.	0.01	0.01
All Camden Bay	0.8	0.9

Zone method

Seven zones were described using the same station locations as identified for the cell block method (Fig. 36). Northern and southern boundaries of all zones, except for Zone 2, are equal to those of the grid cell method. The inshore limits of Zone 2 include a line paralleling the southern boundary of Zone 3 and extending between coordinates that would lie on the southernmost extensions of Collinson Pt. and Arey Island transects for which such conditions are met. Zone 1 is equal in area to cell SCG1 (Simpson Cove) above.

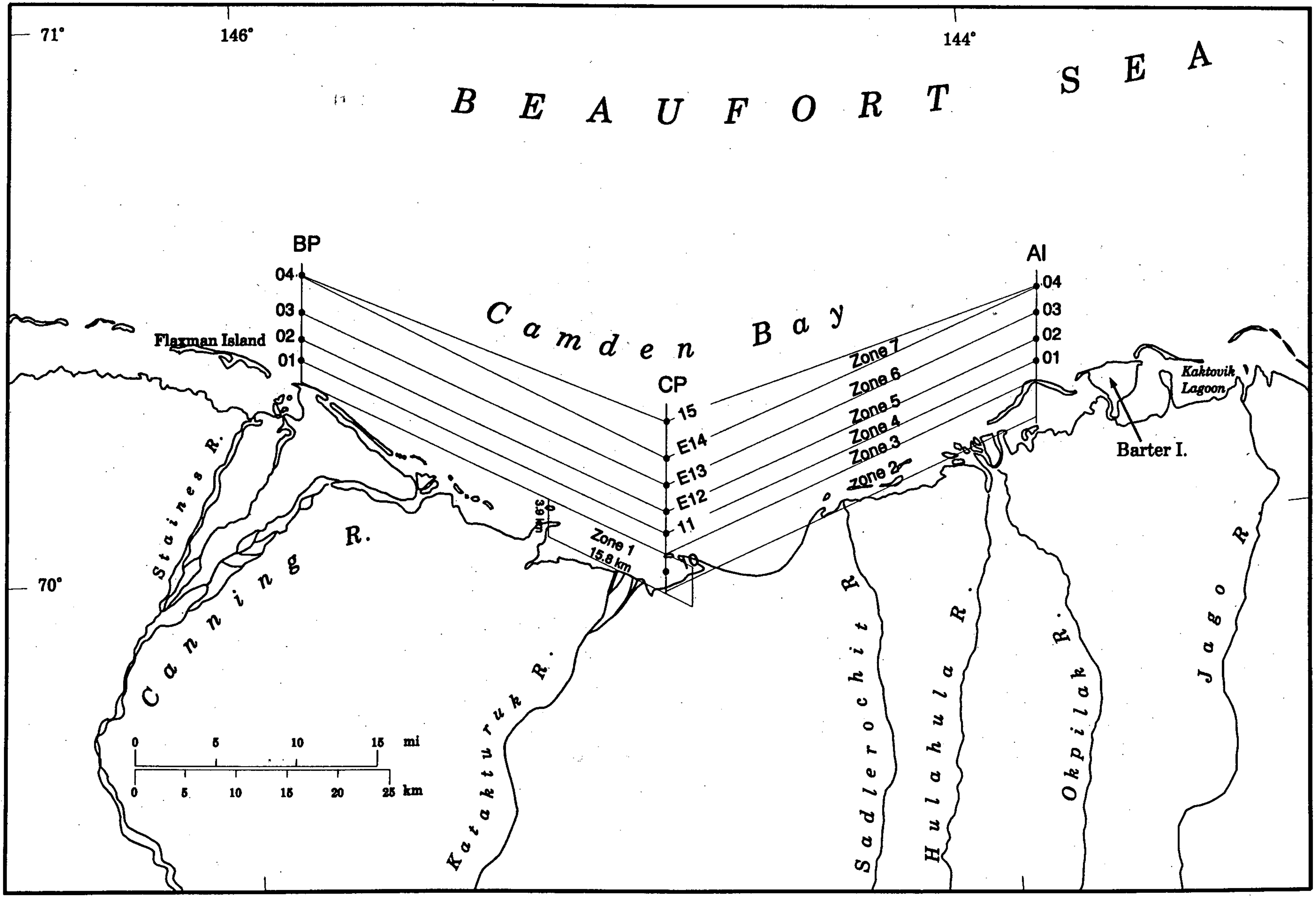


Figure 36.—Zones in Camden Bay.

With the exceptions of Zones 1 and 2, the eastern and western boundaries are defined by the Brownlow Pt. and Arey Island transects, respectively. Zonal areas were approximated using standard geometric relationships when length and width dimensions are known. Volume estimates were derived from area and gear depth characteristics to include only the portion of the water column fished. Most of the zones contained at least three stations where replicate sampling was conducted. The Simpson Cove density estimate is based on replicate sampling at one station. Mean densities (numbers of fish/1,000 m^3) were computed for each zone using similar methods as for the cell blocks (Table 10). Therefore, Arctic cod densities at three stations on the Collinson Pt. transect were determined from mean station data (E12) or from a regression model relating mean cod densities to distance offshore (E13 and E14).

The seven zones encompass a total estimated area of 1,076 km^2 within Camden Bay. The total abundance of Arctic cod was computed within a volume of 2.13×10^9 m^3 of water in the study area. Statistical procedures for estimating CPUE's and their variances, population size and weight and their variances, and corresponding confidence intervals have been described in the previous section.

Table 10.—Zone and station information used to compute population parameters for YOY Arctic cod in Camden Bay, September 2–3, 1990.

Zone	Stations in zone	Number of samples	Area of zone (km^2)	Mean density (fish/1,000 m^3)	Volume ($\times 10^9$ m^3)
1	CP10	2	60	22.5	.12
2	CP10, AI01, CP11	6	160	79.3	.29
3	CP11, BP01, AI01	6	156	72.5	.31
4	E12, BP02, AI02	8	123	118.3	.25
5	E13, BP03, AI03	5	238	46.6	.48
6	E14, BP04, AI04	5	230	45.9	.46
7	CP15, BP04, AI04	6	109	1.5	.22

A CPUE index corresponding to mean fish densities (Arctic cod/1,000 m^3) in each zone was used to enumerate populations within each zone. These are the mean station densities presented in Table 8. The variances associated with these estimates are shown below.

Zone	VAR $\overline{CPUE}_{ik}$ ($\times 10^{12}$)
1	0.0464341
2	91.875424
3	126.80971
4	213.94523
5	351.3299
6	325.29231
7	0.0199113
All Camden Bay	1,109.3188

The relative magnitude of the variances observed in most zones reflects the wide variation in apparent fish abundance that was observed between Barter Island and the Canning River delta.

Population estimates for each zone were calculated next:

Zone	$\hat{P}_{ik}$ (estimated numbers × 10^6)
1	2.7
2	23.0
3	22.5
4	29.6
5	22.4
6	21.1
7	0.3

A total of 121.6 × 10^6 YOY Arctic cod were estimated in Camden Bay representing a mean area-wide density of 57.1 cod/1,000 m^3. Upper and lower 95% confidence limits on the P_{ik} were 194.2 million and 49 million fish, respectively (v = 12). The greatest densities were reported in zonal areas encompassing nearshore waters along the outer coast beaches of Camden Bay. Densities were highest within 9 km of the coast.

Table 11.—CPUE and population weight estimates for YOY Arctic cod in Camden Bay, September 2–3, 1990.

Zone	N	$\overline{CPUE}_{ik}$ (kg/km)	VAR $\overline{CPUE}_{ik}$	$\hat{B}_{ik}$ (kg)	VAR $\hat{B}_{ik}$ (×10^6)
1	2	3.2	0.0008893	2.8235294×10^4	0.0695242
2	6	11.3	0.5029321	2.6588234×10^5	278.43989
3	6	10.3	0.4991602	2.3629411×10^5	262.70679
4	8	16.8	0.7744633	3.0388234×10^5	253.39218
5	5	1.0	7.063252	3.5000×10^4	865.524837
6	5	0.3	6.62207222	1.0147058×10^4	7,575.8565
7	6	0.3	0.0012892	4.8088233×10^3	0.33124
Total	38			88.424995×10^4	17,023.274

The population weight of YOY Arctic cod in each zone was described by expansions relating mean zonal CPUE's (kg/km) and variances to the area (km^2) fished within each zone. Estimates of each are shown in Table 11. The estimated population weight ($\hat{B}_{ik}$) for all Camden Bay, with 9 effective degrees of freedom (v), was 8,842,499.5 kg; 95% confidence limits were 589,119.4 kg and 1,179,380.5 kg. Individual zonal contributions to the total standing stock biomass were:

Zone	Biomass (kg)
1	28,235.3
2	265,882.3
3	236,294.1
4	303,882.3
5	35,000.0
6	10,147.1
7	4,808.8

Density and biomass.—Estimates of $\hat{P}_{ik}$ were converted to mean densities (numbers/m^2) per zone as follows: Zone 1, 0.05; Zone 2, 0.14; Zone 3, 0.47; Zone 4, 0.24; Zone 5, 0.20; Zone 6, 0.20; and Zone 7, 0.01. An overall mean density of 0.11 fish/m^2 was computed for Camden Bay.

Two indices of wet-weight biomass (g/m^2) were developed from the $\hat{P}_{ik}$ and $\hat{B}_{ik}$ abundance estimates for each zone. The computation is the same as was described for similar estimates in the previous section.

Zone	$\hat{P}_{ik}$ Estimate (g/m^2)	$\hat{B}_{ik}$ Estimate (g/m^2)
1	0.5	0.5
2	1.7	1.7
3	5.4	1.5
4	2.8	2.5
5	2.3	0.2
6	2.3	0.004
7	0.2	0.04
All Camden Bay	1.3	0.8

Capelin

Capelin were one of the most abundant marine species captured in 1990. Although they were found nearly 8 km off the coast, most were sampled within 4 km at depths of less than 3 m. Capelin appeared to be most abundant at inner stations along the Collinson Pt. (CP10), Endicott (EC10), and West Dock (WD21) transects. They were also common, but less abundant, in other coastal areas where the net swept most of the water column. The vertical distribution of the capelin may be such that it was not sampled effectively in deeper water habitats by our townet. The mean CPUE of capelin was 11.77 fish/tow (SD = 7.1, range 0–522). Average density was estimated to be 4.3 fish/1,000 m^3 (SD = 22.3, range 0–188.79).

Length Frequencies

Capelin ranged in size from 41 to 95 mm (Fig. 37). The average size was 64.9 mm (SD = 10.5). Using the age–length relationships of Pahlke (1985), these were probably

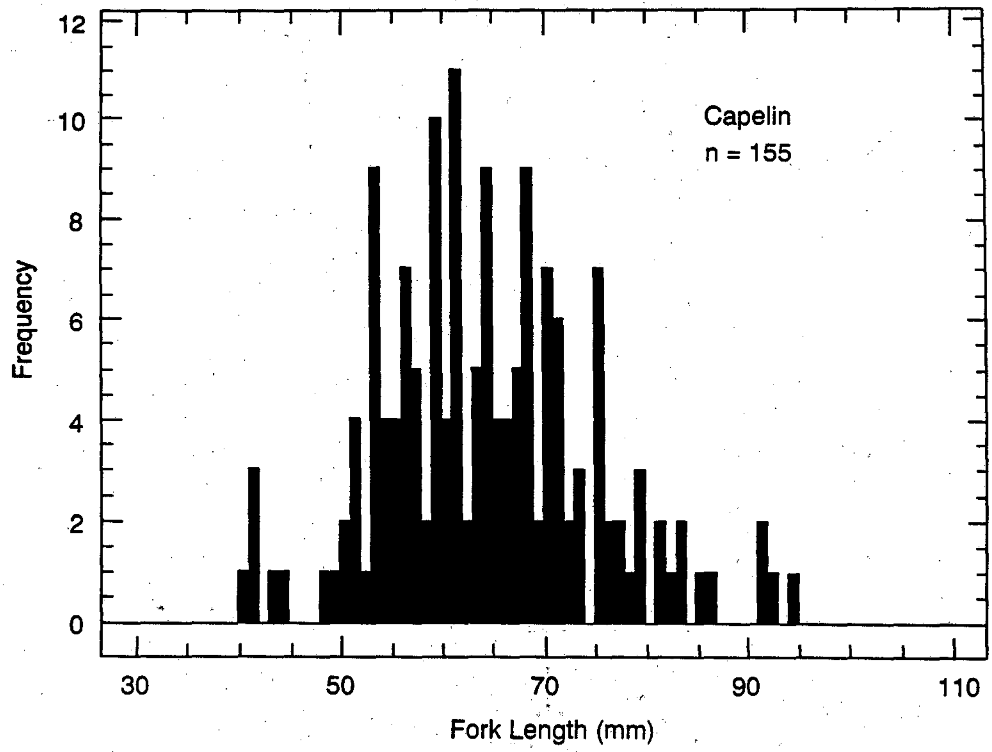


Figure 37.—Capelin length frequencies, all stations.

yearling fish. Several capelin at the lower end of the range (around 40 mm long) could have been YOY fish.

Small differences in size of fish with distance captured from the coast were observed in the catch. Fish captured within 2 km had average lengths of 67.0 mm. Between 2 and 5 km the average length was 63.2 mm. Farther offshore at distances of between 5 and 8 km of the coast the mean capelin size was 73.8 mm.

A trend of decreasing size with time was also observed. The length of capelin reported prior to August 15 averaged 70.8 mm (n = 8). During the second half of the month the mean length fell to 66.1 mm (n = 77) and by early September it was 63.0 mm (n = 70).

Habitat

Capelin were captured in both marine and brackish water habitats in 1990. No strong association with either habitat is apparent in the data. Yearling fish appear to be pelagically distributed in the nearshore waters. They were most frequently encountered in 2–6°C waters between 26 and 31 ppt. The capture of capelin at WD23 (August 21) and at AI01 (August 31) suggests their possible transport offshore in currents being deflected offshore by coastal landforms. At the latter station densities of yearling fish were particularly high (> 30/1,000 m^3), which may suggest close proximity to an important habitat for the species in the Barter Island area.

The average townet catch contained 1.26 ninespine sticklebacks (SD = 3.1, range 0–22 fish). This corresponds to a mean density of 0.33 fish/1,000 m^3 (SD = 0.85, range 0–4.86).

Sticklebacks were most abundant at stations located within 2 km of the coast. They were collected at the inshore stations along all transects except for Brownlow Pt. and Arey Island. Marine conditions existed at all stations on the latter two transects on the dates they were sampled. The farthest offshore capture occurred in Camden Bay at station CC10 on August 2. The greatest abundance was observed at stations CP10 (August 3) and EC10 (August 9) when densities of about 4.5 fish/1,000 m^3 were reported in the catches.

Length Frequencies

Ninespine sticklebacks ranged in size from 26 to 83 mm (Fig. 38). The mean length was 58.0 mm (SD = 10.4). No apparent trend in size could be noted with distance offshore. Inside of 2 km the mean length was 57.9 mm. Between 2 and 5 km from the coast the mean size was 58.3 mm.

Seasonal differences in mean size were apparent but small. Fish sampled prior to August 15 had a mean length of 58.5 mm. Between August 15 and the end of the month the mean size increased to 61.4 mm. In early September the mean size of the sticklebacks was 55.9 mm. Examination of otoliths would be required for age determinations.

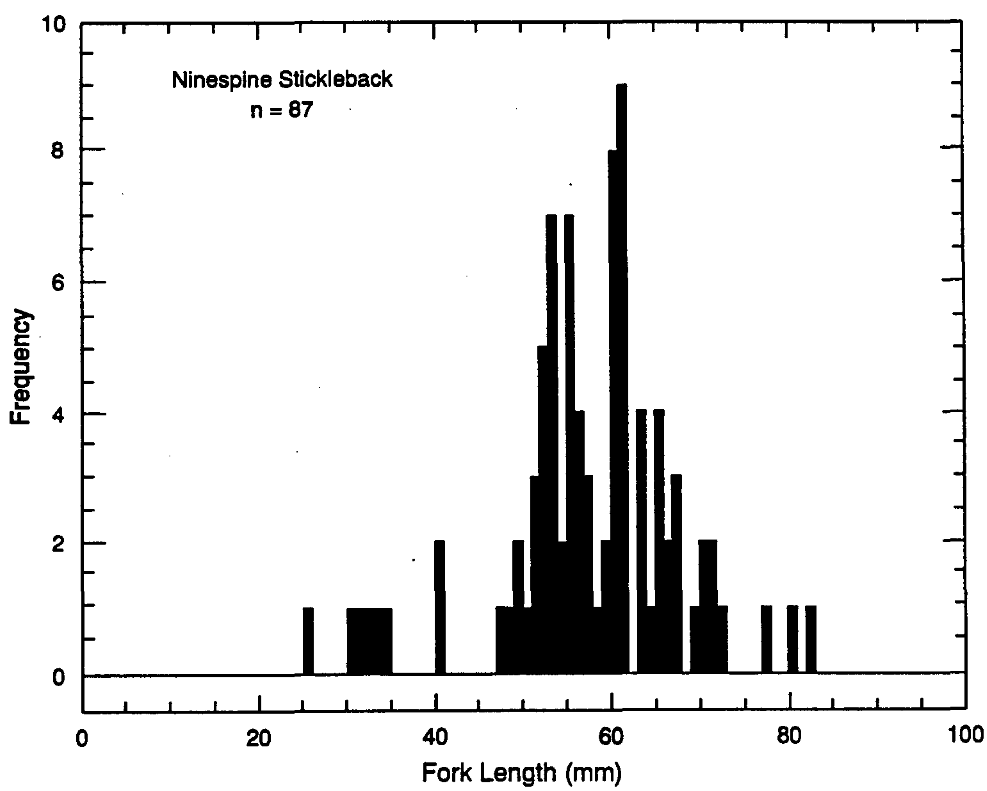


Figure 38.—Ninespine stickleback length frequencies, all stations.

Habitat

The ninespine sticklebacks were most frequently sampled in waters with temperatures ranging between 2 and 4°C and salinities > 27 ppt. The species was found in greatest abundance in areas nearby coastal sources of fresh water such as the Sagavanirktok River near the Endicott Causeway or the Katakturuk River in Simpson Cove. The data indicate that the stickleback is able to tolerate marine conditions.

Kelp Snailfish

With the exception of Arctic cod, kelp snailfish were one of the most common pelagically distributed species of the offshore. They were sampled in mostly marine conditions that overlap those described above for the stickleback. The mean catch per tow was 6.8 fish (SD = 24.3, range 0–151). The mean density was 2.5 fish/1,000 m^3 (SD = 12.4, range 0–90.4).

Length Frequencies

The snailfish ranged in length from 17 to 63 mm (Fig. 39) and averaged 26.4 mm (SD = 6.2). All were juvenile fish and probably young-of-the-year. No apparent differences in mean size were observed with sampling distance from the coast. The mean size ranged between 27.5 and 26.5 mm at distances of 2 km to more than 10 km offshore. Seasonal differences in mean size were less than 1 mm.

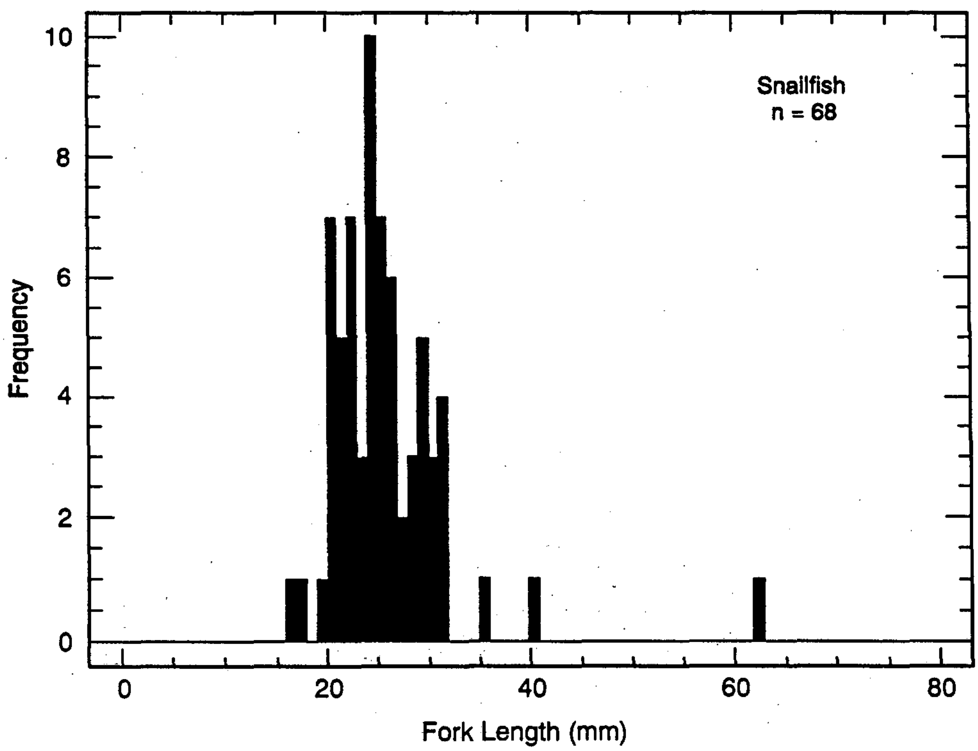


Figure 39.—Snailfish length frequencies, all stations.

Habitat

As was noted above, the environmental conditions observed at the time of snailfish capture were very similar to those of the ninespine stickleback. The juvenile fish were found at offshore stations across the coast from Prudhoe to Camden bays. In the sampling conducted in Camden Bay during early September a very strong association between the juveniles and jellyfish medusae was apparent. Whether or not the relation offers protection to the fish from predators is not known. Their tadpole body shapes and small size do not indicate powerful swimming capabilities.

Other Species

The remaining fishes comprised less than 1% of the total catch. Of these, the fourhorn sculpin was most abundant. Small numbers of arctic staghorn sculpin were lumped into the sculpin group. The average catch of sculpins was about 0.5 fish per tow (mean density = 0.12 fish/1,000 m^3). Sculpins were always captured inshore at shallow stations where the net was able to sample demersal species. The sculpins ranged in length from 25 to 200 mm.

A single Arctic char was captured on August 27 at MS01. This fish measured 230 mm and was apparently unable to avoid the gear.

Five Arctic flounders were collected in Prudhoe Bay when the townet touched bottom at WD21. They ranged in size from 75 to 85 mm. Similarly, two species of eelblennies (12 fish total) were incidentally captured at stations in Prudhoe Bay (WD21) and Simpson Cove (CP10). They ranged from 70 to 80 mm in length.

DISCUSSION

The strong east winds that characterized much of the open-water season effectively reduced the availability of brackish water habitats along the coast. Craig (1984) described a coastal band of brackish water with temperatures of 5–10°C and salinities of 15–25 ppt as being most important to anadromous fishes. Such conditions were rarely encountered in 1990. Nearly isohaline and isothermal conditions were observed at the base of the Endicott transect on August 9. Temperature and salinity were 6.05°C and 23.5 ppt, respectively. A pocket of relatively warm (>5°C), low salinity (24.5 ppt) water was located 7–9 km off the Prudhoe Bay shoreline (WD23) on August 21.

The majority of fish sampling occurred beyond 2 km from the coast. Closer to shore, hydrographic conditions may have been different. Offshore sampling began in early August about midway through the typical open-water season. Thus, the fish habitat conditions of July may have varied greatly from those observed a month later. Regardless, by August any brackish water influences on the nearshore appeared to have been lost and conditions were generally marine.

A major effect of the east winds was the marked lack of hydrographic contrast in the offshore stations sampled in 1990. East winds tend to depress sea level, draw brackish water seaward, and cause upwelling near the land margin (Craig 1984). Only 11 of 77 stations sampled had salinities of less than 28 ppt. Of these, many were greater than 27 ppt. A truly coastal water mass was not evident in the sampling.

Depth-integrated temperatures averaged over the vertical dimension of the townet served as a proxy for environmental temperature of the offshore habitats. Only 18% of the stations sampled had temperatures exceeding 5°C, 18% were between 4 and 5°C, and 31% between 3 and 4°C. Thirty-three percent of the stations had temperatures of less than 3°C. Reynolds (1977) describes the role of temperature as a proximate (cue, guidepost, directing) factor affecting the movement behavior of fishes. The lack of temperature contrast coupled with the sporadic nature of the sampling precluded definitive statements about habitat preference based on disproportionate catches in various habitat types. The catches do, however, provide new information on the modal ranges and offshore distributions of fish not previously available. In the context of existing environmental issues and concerns this is especially true for YOY Arctic ciscoes.

The warmest temperatures were usually found at stations occurring nearest the coast and in close proximity to large river drainages. Thus, they were under greater local influence of freshwater mixing than their offshore counterparts. For example, the station in Simpson Cove (CP10) had consistently higher temperatures than were observed elsewhere in Camden Bay. This station is located about 2 km to the northeast of the Katakturuk River. Similarly, the hydrographic conditions near the base of the Endicott transect were fresher (Sagavanirktok River influences) than those located farther offshore. In each instance, the water properties at each station were most affected during periods of high discharge or westerly winds.

In a review of fish use of coastal waters in the Beaufort Sea, Craig (1984) observed that the use of marine habitats by arctic fishes is poorly known. In fact, little information is available describing the occurrence of fish beyond 200 m of the shoreline at most locations along the coast. The 1990 sampling revealed pelagic fishes to be widely distributed with regular occurrence in catches taken 0.5 to 12 km off the coast seaward over depths of more than 10 m. The mean overall fish density (all species combined) was 67 fish/1,000 m^3 over the 1.8-m depth interval sampled. This is more than twice the density reported for Prudhoe Bay in August 1979 by Moulton and Tarbox (1987), whose estimate was for the entire water column and included pelagic and demersal species alike.

There are other indications that fish use of the offshore may be greater than has previously been described. Rose and Leggett (1989) described low densities of capelin in the northern Gulf of St. Lawrence as fewer than 100 fish/10^5 m^3 and very high densities as more than 400 fish/10^5 m^3. In 1990, we reported a mean capelin density of nearly 12 fish/10^3 m^3. The mean Arctic cod density was almost 5 times higher (58 fish/10^3 m^3). Between 83.6×10^6 (cell block method) and 121.6×10^6 (zone method) YOY Arctic cod were estimated in Camden Bay during early September. The cod biomass was estimated at 1.6×10^6 to 8.8×10^6 kg with respect to the two methods shown. These estimates do not include older cod, which apparently have a different depth distribution than younger fish. The abundance of large numbers of YOY cod late in the season suggests an onshore movement of young from spawning areas removed from the bay.

The cell block method may provide more accurate estimates of relative cod abundance than the zonal method. Assuming that the true distribution of young cod is reflected in the catches, the use of less diverse (more compact spatially in a longitudinal sense) areas and volumes results in reduced variances in the estimation procedure. Similar methods have been used elsewhere to estimate population abundance and standing stocks of demersal fishes (e.g., Bering Sea). In the Bering Sea, population parameters for relative abundance of demersal species are generated from replicate bottom trawls in a network of survey areas (cells) with areas in excess of 1,300 km^2 per cell. By comparison, our estimates of Arctic cod abundance in Camden Bay derive from replicate sampling at 14 stations over a total area of less than 1,100 km^2.

The results of the standing stock evaluations suggest a mean overall YOY cod density of 0.04 fish/m^2 (range 0.0001–0.13/m^2). Craig and Haldorson (1981) estimated a run of 19 × 10^6 Arctic cod into Simpson Lagoon during mid-August 1978. Their estimate was based on various indicators of coastal fish abundance from fyke net catch data and assumptions of equal dispersal of cod throughout the lagoon. The estimate of 19 million fish corresponds to a cod density of 0.12 fish/m^2. This is very similar to the 0.13 fish/m^2 estimated for the central portion of Camden Bay in September 1990. From an ecological perspective, 0.13 fish/m^2 corresponds to a wet-weight biomass of 1.5 g/m^2 or 0.15 g dry weight/m^2 (mean weight of average fish was 11.6 g). Assuming that the daily rate of primary production is 1 gC/m^2 in Camden Bay, and a 10% transfer efficiency between trophic levels occurs, this implies sustainable biomass levels of about 0.1 for L2 (copepods) and 0.01 for L3 (secondary) consumers.

The habitat conditions observed at West Dock between August 21 and 23 indicate the upwelling of cold (<3.5°C), marine (salinity > 31 ppt) water near the coast (WD21). Warmer (> 5°C), less saline (<28 ppt) waters were observed farther offshore. These conditions are not unlike those described for the deflection of the Sagavanirktok River plume by the West Dock causeway under east winds (Hale et al. 1989). Wind data from Beaufort Lagoon indicate that a major storm event (east wind) had occurred just prior to our sampling at West Dock. However, since those data reflect wind conditions 220 km to the east, they cannot be extrapolated to the local conditions in Prudhoe Bay. Without an examination of the local wind record from Deadhorse, the mechanism responsible for the freshening of offshore waters remains speculative.

Existing oceanographic studies of the coastal Beaufort Sea suggest that coastal currents lag behind wind conditions by a period of 3–4 h (e.g., Hale et al. 1989). Data obtained from the eastern Beaufort Sea in 1989 (Hale 1991) show that upwelling occurs and reaches a depth of 2 m within 36 h of a west-to-east wind shift. If similar lag times can be assumed for changes in water properties at Prudhoe Bay, the vertical temperature and salinity sections constructed for the West Dock transect (August 21 and 22) argue for easterly winds at the time of sampling. Under strong east winds a strong onshore current is established along the west side of West Dock as westward-flowing coastal waters replace lagoonal water being displaced offshore. This current could explain the apparent high relative abundance of juvenile Arctic ciscoes inside Stump Island Lagoon (WD21) on August 21. They were the highest reported anywhere all season (32.26 fish/1,000 m^3).

The high relative abundance of juvenile ciscoes in marine waters in the Stump Island Lagoon (WD21) may possibly reflect the passive migration of fish in strong coastal currents. The ciscoes may, on the other hand, be exhibiting a slight deviation from the shoreline dependency suspected of their migration and taking a less circuitous pathway into Simpson Lagoon. The catches at WD21 were among the largest and most diverse reported in 1990. This in part stems from the sampling of the entire water column at this site. Even so, the diversity and abundance of species observed is indicative of heightened biological activity. The catch of juvenile ciscoes in marine conditions may reflect a temporary departure from nearby brackish waters in response to nonthermal habitat factors (Reynolds 1977). Such factors might have included movements in response to prey or predators.

The mean CPUE's of young ciscoes captured at fyke-net stations on the east and west sides of West Dock on August 21 and 22 were 107 fish/d and 29 fish/d, respectively (pers. comm., W. Wilson, LGL, Anchorage, AK). Assuming that the fish were migrating through the area at a constant rate implies mean hourly catch rates of 4.5 fish (east) and 1.2 fish (west). In order to determine whether the inshore concentrations of fish differed greatly from those reported offshore, a regression analysis relating townet CPUE's (expanded to hourly catch rates) and densities was performed. The resultant equation, CPUE1h = –0.042658 + 6.04811 (Density), had an r^2 of 99.63% and SE (estimate) of 1.583. This suggests that the fish densities inshore of WD21 were on the order of 0.75 fish/1,000 m^3 (west) and 0.21 fish/1,000 m^3 (east). Clearly, the indications are that fish abundance was much greater away from the immediate shoreline. The response surface relationship for temperature and fish densities indicates that the mean temperature was about 4°C at the fyke net stations. Apparently, the dispersal of juveniles in the marine waters west of West Dock was not related to thermal factors alone. This concurs with the findings of Bryan (1990) who concluded that currents and not thermoregulatory behaviors were primarily responsible for fish movements through Prudhoe Bay.

The documentation of young Arctic cisco catches at all of the West Dock stations in August provides new information about the offshore distribution of the species in the Beaufort Sea. At first glance, it suggests the possibility of a wider migration corridor through Prudhoe Bay (at least 11 km) than has been described. The lack of offshore sampling to the east and west of Prudhoe Bay negates such a broad generalization. Likewise, whether or not the offshore catches really provide evidence of a causeway effect cannot be unequivocally stated. Importantly, the ultimate fate of the young ciscoes occurring in marine, or near-marine, waters is uncertain. The occurrence of juveniles outside suspected modal ranges raises questions about the physiological tolerances of age 0 fish.

Relatively high YOY Arctic cisco abundances were observed at several of the stations sampled offshore on the West Dock transect. Replicate samples indicated juvenile densities ranging from 5 to 7 fish/1,000 m^3 some 5 km from the coast (WD22), 4–7 fish/1,000 m^3 at 7.5 km (WD23), 0–20 fish/1,000 m^3 at 9.5 km, and 0–1.5 fish/1,000 m^3 at more than 11.0 km offshore. This distribution may reflect the presence of more favorable habitat offshore and the fishes' movement responses to temperature and salinity optima (e.g., Neill et al. 1983). The fish may simply have been moving with optimal conditions found in currents being deflected offshore.

The offshore catches of juvenile Arctic ciscoes in marine, or near-marine, conditions contradicts existing paradigms of the species' tolerance of such temperature and salinity conditions (Fechhelm and Gallaway 1984). Existing experimental data for Arctic ciscoes indicates high mortalities to fish exposed to waters possessing salinities in excess of 25 ppt (Fechhelm et al., in press). The presence of juveniles in marine habitats that were sampled at many locations in 1990 suggests the possibility of acclimation.

The trend of decreasing mean size in juvenile ciscoes with advancing summer has been reported in fish recruiting to the Colville Delta (Moulton 1989). Apparently, larger individuals lead the migration across the coast. This relates not only to size-related differences in the swimming performance of larger fish but may also reflect stock-related differences in size and migration behavior. Instantaneous growth rates were observed to vary between daily increases of 4.95% (early) and 2.54% (late) in mean body weight during August 1990. These values fall within the observed growth ranges for pink salmon during their first few weeks at sea (Taylor et al. 1987). Like the juvenile pink salmon, young Arctic ciscoes move directly from their incubation sites to the sea in spring. Thus, the initial phases of their marine residence, particularly growth, may be comparable. During summer 1986, the instantaneous growth in migrant pink salmon was reported to vary between 2.92 and 9.68% of body weight per day (average 5.09%).

One would expect a diminishing expression of growth if the daily growth increment remains constant with increasing body size of the fish. The temporal difference observed in 1990 is probably related to availability of brackish habitats and greater accessibility to abundant foods early in the season. Presumably, higher growth rates are inherent to these warmer, less saline environs. Widespread marine conditions persisted throughout the study area in August.

English (in press) reported growth rates of 0.08% and 0.83% of body length per day (BL/d) for pen-reared Arctic ciscoes held at Niakuk and Endicott, respectively, in 1988. While interannual comparisons are tempting, it is difficult to compare the growth of free-ranging fish to that of fish held in captivity. Free-ranging fish actively search for patchily distributed prey and are able to respond to environmental changes via a multitude of adaptive behaviors. The occurrence of juveniles some distance away from the coast in temperatures outside what are considered modal may reflect localized dispersals in response to prey or other nonthermal factors (Reynolds 1977; Rose and Leggett 1989). Without knowledge of the abundance of young ciscoes and their prey in adjacent habitats, such inferences cannot be made. Although our estimates are based on small sample sizes, the juvenile length frequencies suggest relative rates of increase of about 1.6% mean BL/d in early August and 0.85% mean BL/d during the late August to early September period. If during 1990, the mean size of juveniles was about 35 mm at entry to the sea, and the coastal migration to Alaska was about 30 d, the implied relative rate of increase is 1.2% BL/d for the average-sized fish.

Preliminary catch data from several fyke-net sites in lagoonal waters of the eastern Beaufort Sea and in Prudhoe Bay provide additional information about the timing and age composition of the juvenile migration. They also provide a measure of how well temporal changes in abundance observed offshore parallel similar estimates made nearer the coast. Small numbers of juvenile Arctic cisco were captured at FWS field stations in Beaufort and

Kaktovik lagoons and in Camden Bay on July 9 (pers. comm., T. Underwood, FWS). More than 50%, or about 3,000, of the fish captured in the lagoons east of Barter Island during the second half of July were age 1 fish (>100 mm). During the same period, a significant but substantially smaller proportion (314 or about 25% of the catch) of the juveniles collected in Camden Bay was age 1 fish.

Season-long catch data of the FWS indicate that YOY ciscoes were consistently more abundant in Beaufort and Kaktovik lagoons than in Camden Bay. Our catches of young ciscoes at coastal stations off Arey Island, Carter Creek, and Collinson Point suggest a significant portion of the migration may bypass Simpson Cove and move directly across the bay. The migration corridor would thus extend approximately 2 km off the outer beaches of eastern Camden Bay. The sampling off Brownlow Point was too light and too late in the season to address fish movements along the western coast of the bay. It seems probable that the fish hug the coast after crossing the bay and migrate directly into Stefansson Sound through the shallow pass to the east of Flaxman Island.

Young-of-the-year Arctic cisco began appearing in Prudhoe Bay on August 4 (pers. comm., W. Wilson, LGL, Anchorage, AK). Catches remained high through August 11, at which time fishing operations were interrupted by a week-long storm. When fishing was resumed the catch rate rose on August 21 and remained high through September 1. All fishing was terminated on September 1. A spike was noted in the CPUE at or about August 30. This spike coincides with the large pulse of juveniles (densities of 5–10 fish/1,000 m^3) observed in townetting conducted in eastern Stefansson Sound (MS01) on August 27.

Both passive and directed migrations in juvenile Arctic ciscoes adequately explain the apparent rates of fish movement observed in 1990. A purely passive migration of fish in wind-driven currents resulted in an estimated migration rate of about 15 km/d. Similarly, if the migrant was always assumed to be moving to the west, a daily migration rate of 18 km was computed. Assuming, that YOY ciscoes enter the Mackenzie estuary by mid-June, their arrival in Prudhoe Bay on August 2 indicates an elapsed travel time of 48 d. The apparent migration rate would thus be about 10 km/d (490 km/48 d). Since we know little about the early residence and movements of the juveniles at sea this estimate may be overly conservative. Our estimates would indicate travel times of between 27 and 30 d for directed and passive transports, respectively, of fish from Canada to Prudhoe Bay.

Neither rate accounts for the numerous adaptive behaviors the fish may employ to reduce losses (i.e., net daily westward movements) during the migration period. Inshore, such behaviors may include the movement of fish to protected areas behind islands and spits. Offshore, fishes might move to greater depths to avoid adverse current conditions. Such behaviors would minimize fish movements to the east, and thus could potentially increase the net migration rate to the west. The use of actual currents from moored instruments might improve this estimate. The probability of a longer migration period would also act to reduce the average daily growth rate in migrating ciscoes.

Both the passive and the directed migration scenarios resulted in a net southerly directional component to the 1990 juvenile migration. This would have the net overall tendency to hold the migration closer nearshore. Nearshore areas may offer greater fish protection from prolonged encounters with the marine waters and hostile currents that may exist offshore. Given that the mortalities of migrant juveniles are probably high, a nearshore migration may increase opportunities for survival simply by proximity to refuge during storms or other periods of duress. A slight dispersal offshore offers abilities to utilize coastal refuges while at the same time avoiding predators common to the coast. Since both u and v current components act upon the fish movements, the inclusion of the cross-shore component is seen as a valid approach. The offsetting effect of a positive v on cisco dispersals offshore warrants greater attention. The degree of offsetting appears to be greatest during open coast migrations such as experienced by fish moving into Camden Bay.

The offshore catches at West Dock do not appear to reflect dispersal patterns of YOY Arctic cisco at other locations along the coast. The occurrence of juveniles off Arey Island (AI01) late in the season represents another area of potential offshore abundance. The geomorphology of the coastline in each area suggests that fish movements in deflected coastal waters (east wind conditions) may be involved. The cluster grouping of catches from inshore stations at Endicott and the offshore stations at West Dock tend to support this contention. The similarity in thermal conditions in the habitats at each area suggests freshwater influences of the Sagavanirktok River.

The offshore survey results demonstrated the outer portions of the coastal band and adjacent marine habitats to be important for arctic fishes. At certain locations, east wind conditions may promote the offshore movements of coastal fishes, including small anadromous species. Sustained westerly winds result in a deepening of the brackish water habitat along the coast. However, this would be offset by a narrowing of the horizontal width of this habitat because westerly winds displace coastal water against the shoreline. The narrowing of the coastal band could act to restrict the fish to areas closer to shore. Conversely, a widening of the coastal band could be expected during periods of sustained east winds. Offshore dispersals of anadromous fishes such as Arctic char and Arctic cisco would be expected under such conditions. Such excursions are indicated by Arctic char catches off the coast in Stefansson Sound in 1988 (Thorsteinson et al. 1990) and 1990 (this study). Factors, other than thermal conditions, should reasonably be expected to account for temporary departures from brackish to marine habitats where potential prey such as young cod and snailfish are abundant.

CONCLUSIONS

The preponderance of east winds in 1990 had a profound effect on the active sampling objectives of the research. The east winds coupled with diminished coastal river runoff resulted in widespread marine conditions throughout the study area. This resulted in a lack of strong contrast in temperature and salinity attributes needed to clearly distinguish habitat use patterns in migratory or coastal fish assemblages. These conditions appear to be atypical of the "average" coastal conditions that occur during summer. Nevertheless, the indication is that anadromous fish continue to use the nearshore habitat for at least brief excursions that may be outside their preferences. One could speculate that the less than optimal conditions may produce higher than average mortalities in species such as Arctic char and Arctic cisco due to reduced fitness for overwintering.

The apparent affinity of the anadromous species for the shoreline may maximize opportunities to encounter warm, brackish or freshwater refugia at river and stream mouths. Such habitats would offer a temporary respite from adverse conditions. Following offshore feeding bouts the use of such refugia would promote rapid assimilation of energy reserves. The abundance of potential prey offshore (e.g., small cods, capelin, and snailfish) argues for such behavioral adaptation in species such as the Arctic char and Arctic cisco.

In years when the coastal band is more expansive the reliance of fish on such refugia may not be evident. The lack of sampling in the offshore Beaufort Sea in such circumstances leaves the question unanswered. Alternative to the refugium hypothesis, the apparent shoreline dependency of migratory fishes could reflect behavioral mechanisms such as searching for home stream odors or other cues that aid navigation. By contrast, the juvenile Arctic cisco migration involves highly motivated young fish that may be utilizing offshore waters to find current conditions that facilitate rapid westward movement. The frequent occurrence of young fish in marine conditions may indicate a greater physiological adaptability than previously considered possible. This hypothesis awaits laboratory confirmation. The near ubiquity of marine conditions in the coastal zone may have foreclosed any options for habitat selection.