DENSITY DISTRIBUTION OF JUVENILE ARCTIC COD, *BOREOGADUS SAIDA*, IN THE EASTERN CHUKCHI SEA IN THE FALL OF 1970

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ABSTRACT

The Arctic cod, *Boreogadus saida*, is a key element in the ecosystem of the Arctic Ocean. Juveniles, principally young-of-the-year, were taken by Isaacs-Kidd mid-water trawl at night during September and October 1970 in the eastern Chukchi Sea. Their average concentration was about 28/1,000 m^3 and their average biomass about 0.7 metric ton/km^2 of ocean surface. In 20 stations (representing about 30 x 10^3 km^2, or 8,714 square nautical miles), the number of juvenile cod (N) per standard haul (about 8,223 m^3 of water filtered per haul) increased with depth in meters (D) at about the same rate [$\log_{10}(N + 1) = 0.0669D$]. Yet the depth at which equivalent concentrations occurred varied over a range of 38 m between stations. The zone of increased concentration with depth, called a density structure, appears to be the nighttime relict of a graded negatively phototactic response to sunlight by the juvenile cod during preceding daylight. Apparently the structure was vertically displaced after dark by wind-induced upwelling and downwelling. The juvenile cod may have originated in the northwestern Bering Sea, off Arctic Siberia, or within the Chukchi Sea, and probably had recycled in the Chukchi Sea prior to capture.

This study of biomass and distribution of juvenile Arctic cod, *Boreogadus saida* (Lepechin), in the Chukchi Sea is an outgrowth of the Western Beaufort Sea Ecological Cruise of 1970 (WEBSEC-70) sponsored by the U.S. Coast Guard. My original objective was to explore the fishes of the marine ecosystem in the Arctic Ocean east of Point Barrow, Alaska, and if possible to quantify the occurrence of important forms. Because of an early southward shift of the arctic ice pack, the study was moved to the eastern Chukchi Sea. The sampling schedule—date, location, depth of water, and number and types of hauls—is given in Table 1 and Figure 1. The species of fish and where they occurred are summaried in Quast (1972).

Juvenile Arctic cod and Pacific sand lance, *Ammodytes hexapterus* Pallas, were virtually the only fish species trawled in the surface and mid-depths at night. The cod occurred at every station; also they were more numerous and had a larger biomass than the sand lance—a subjective estimate suggests a minimum 10 fold difference in both respects. Although sand lance were chiefly taken at the surface, the number of Arctic cod usually increased with depth. Because of the apparent importance of the Arctic cod in the off-bottom marine ecosystem of the eastern Chukchi Sea during WEBSEC-70, I further analyzed their data to estimate their numbers and biomass over the study area.

General life history, distribution, and literature on Arctic cod are summarized by Andriyashev (1954:195-198). The species is circumpolar and occurs to or nearly to the North Pole. Off Alaska, it occurs along the Arctic coast, in the Chukchi Sea, and in the Bering Strait; it also has been recorded in the winter from Norton Sound and the Gulf of Anadyr. Although most authors term the species "pelagic," "demersal" is probably better because adults appear to be associated with a shallowwater substrate, whether it be ocean bottom over the continental shelf or the undersurface of ice. Maximum size is about 320 mm total length (TL). Association with low temperatures is an important characteristic: Rass (1968: 136) gives the thermal environment of eggs as 0° to 2°C, of larvae as 2° to 5°C, and of fry as 5° to 7°C and probably higher. During WEBSEC-70, specimens of 0-age fish occurred at −1.5° to 3.5°C. According to Andriyashev (1954), Arctic cod mature when about 4 yr old and 190 mm TL; they spawn near coasts, principally in January

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TABLE 1.—Station data for trawl collections in the eastern Chukchi Sea during WEBSEC-70.

Station	Date and inclusive time (Bering Standard)	Approximate position		Depth of water (m)	Hauls		
		Lat. N	Long. W		No.	Type[1]	Depths (m)[2]
10	27 Sept. (1917-2207)	70°04′	165°57′	44	4	R	11
14	29 Sept. (0518-0817)	70°17′	165°02′	51	4	R	11
16	29 Sept. (1721-2002)	70°16′	163°58′	53	4	R	11
20	30 Sept. (1740-2025)	70°20′	163°24′	42	4	R	12
22	1 Oct. (1734-2103)	70°20′	163°25′	35	4	R	12
25	2 Oct. (1731-2036)	70°07′	163°14′	33	4	R	12
30	4 Oct. (1756-2137)	69°58′	164°07′	31	5	M	2,5,10,13,19
32	5 Oct. (1831-2104)	69°48′	163°49′	26	4	R	12
37	6 Oct. (1727-1956)	70°07′	167°36′	49	4	R	12
41	7 Oct. (1752-2014)	69°57′	167°31′	44	4	M	10,10,12,22
45	8 Oct. (1816-2058)	69°57′	168°38′	44	4	M	2,9,13,20
51	9 Oct. (1744-2024)	69°36′	167°36′	48	4	M	2,7,14,20
56	10 Oct. (1940-2229)	69°14′	166°53′	44	4	M	2,9,18,23
61	11 Oct. (1755-2015)	69°05′	166°13′	29	4	M	8,13,16,23
65	12 Oct. (1755-2016)	69°21′	166°45′	36	4	M	8,13,16,22
70	13 Oct. (1735-1958)	69°12′	167°38′	39	4	M	8,13,18,22
74	14 Oct. (1723-1946)	69°35′	164°29′	22	4	M	2,8,13,18
80	15 Oct. (1814-2055)	69°27′	164°43′	30	4	M	2,8,13,22
88	16 Oct. (1917-2205)	68°55′	166°47′	45	4	M	2,11,24,40-45
92	17 Oct. (1733-2014)	68°36′	167°41′	54	4	M	2,13,17,33

[1]M = multidepth hauls with 1.8-m (6-foot) Isaacs-Kidd mid-water trawl, and R = replicate hauls at single depth.
[2]Depth at depressor.

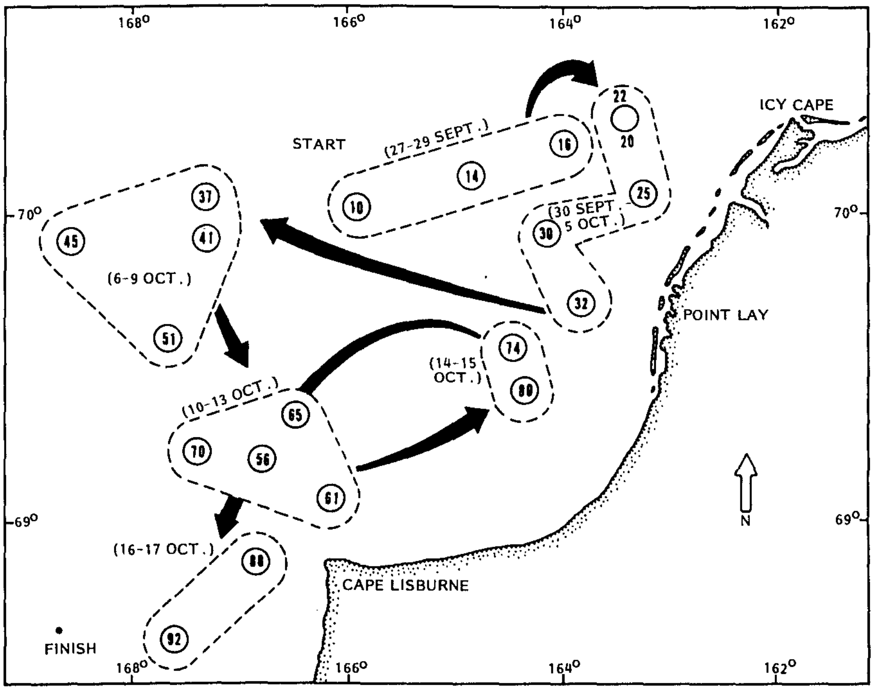

FIGURE 1.—Sequence and position of IKMT stations (circles) in the eastern Chukchi Sea in 1970. Dashed lines indicate time spans for groups of stations.

and February, and their eggs are large—approximately 1.5-1.9 mm in diameter. Rass (1968:136) adds that the first larvae appear in the sea in May-July; the larval stage (5.4-15.0 mm) lasts about 2 mo (in the Barents and Siberian Seas through June-July); and transition to juveniles is at 30-50 mm, in August.

Arctic cod appear to be a key species in the ecology of the arctic seas. They are widespread, locally abundant, and probably are a major element of the secondary consumer level in the trophic pyramid. Ponomarenko (1967:8) found that cod larvae and fry fed successively on copepod eggs, nauplii, and copepodites, and

Hognestad (1968:130) reported that adults trawled from the eastern Barents Sea in September 1966 fed principally on the copepod *Calanus finmarchicus*. In turn, Arctic cod are important as forage for higher level consumers. Andriyashev (1954:194-198) cites literature records for predation on Arctic cod by a long list of species, including char, saffron cod, flounders, sculpins, seals, walrus, beluga, sea gulls, alcids, and skuas. Tuck (1960:166) stresses the importance of Arctic cod in the diet of common and thick-billed murres of the polar basin, whose total populations contain at least 15 million birds (p. 51).

METHODS

Studies with the 1.8-m (6-foot) Isaacs-Kidd midwater trawl (IKMT) involved 81 30-min tows (at depth) at 20 stations (Table 1). All stations were occupied for periods of about 2 h or more, and all but one started at late dusk or dark. The IKMT was similar in dimensions to the trawl tested and figured by Friedl (1971); it had a section of coarse mesh (3.8-cm bar) preceding 0.6-cm bar mesh. The cross-sectional area at the mouth was calculated as 2.87 m^2 and at the beginning of the 0.6-cm mesh as 1.55 m^2. To compensate for the possibility that fish would be herded into the small-mesh section by the coarse anterior mesh, a middle value between the two cross-sectional areas, 2.21 m^2, was arbitrarily used as the effective cross-sectional area of that portion of the net that captured juvenile cod. Calculation of the horizontal and vertical dimensions of the net swath was simplified by treating the effective cross-sectional area as a square—1.49 m on a side. Tows were standardized at 2 nautical miles (3,704 m) at depth by maintaining a vessel speed of 4 knots (estimated by engine revolutions) over 30 min. The resulting horizontal swath was calculated as 5,519 m^2 and the volume filtered as 8,223 m^3. At least four tows were made at each station, either at the same depth or at four different depths (Table 1)—two on one bearing and the remainder on its reciprocal.

Sampling followed a zigzag pattern (Figure 1) before a southward-advancing ice front. Because blocks of ice are sometimes difficult to see or become too abundant to avoid, mid-water trawling at night even in the presence of light pack ice is hazardous. The trawl can be seriously damaged or lost outright if a large block of ice becomes trapped beneath a trawl warp and causes the trawl to be lifted to the surface where the ice would be fed into its mouth at trawling speed. Consequently, trawling was usually done in the relatively open water of broad leads or ahead of the ice pack.

Two types of IKMT station were occupied. In one type (eight stations), nektonic organisms at a single depth within stations were sought by conducting four "replicate" hauls at 11 or 12 m (Table 1). In the other type (12 stations), the vertical distribution of nektonic organisms was sought by making four or five hauls at different depths (Table 1); the depths, which were usually verified with a bathykymograph, were selected after study of a Simrad[2] echogram (Model ER2—38 kHz). No reliable association was detected between presence or absence of bands on echograms and catch at those depths.

Data obtained on juvenile Arctic cod in the IKMT hauls included counts, range of standard lengths, and volumes. When large numbers of cod were captured, usually the total volume was measured and the number of cod was estimated from the average volume per individual in a subsample. When there appeared to be negligible differences in size of cod between hauls, the average volume per individual in one haul was used to estimate the number of juveniles in a volume taken in another haul at the same station.

RESULTS

The juvenile Arctic cod appeared to be principally of 0 age-class (young-of-the-year), based on a comparison between length frequencies of the Chukchi specimens and age-length data reported in the literature. For the comparison, the Chukchi data were converted from standard to total length by a regression based on data from the Chukchi Sea specimens (Table 2), because the measurement employed for data in the literature was not specific and therefore was assumed to be total length (the measurement usually used in fishery studies). Modal size of the Chukchi Sea specimens was 44 mm, slightly higher than the average size for age 0 cod, 35 mm, from the Barents Sea and Spitzbergen cited by Hognestad (1968:130). The

[2]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

TABLE 2.—Regressions of total length and volume on standard (body) length (X) in juvenile Arctic cod from eastern Chukchi Sea. Least squares fit to power equation, $Y = aX_b$, for 83 specimens over sizes 30<SL mm<74.

Measurement (Y)	a	b	Correlation coefficient
Total length (mm)	1.4429	0.9478	0.996
Volume (ml)	0.4454×10^{-4}	3.1678	0.984

upper limits of nearly all size distributions by haul from the Chukchi Sea, 35 of 40, were below the mean size for age I cod cited by Hognestad. Because the cod from the Chukchi Sea were captured in September and October, at a later date than Hognestad's specimens, there is little doubt that most specimens captured in the eastern Chukchi Sea were age 0.

Homogeneity of sampling variance was then examined in the data on frequency of occurrence of juvenile cod in the hauls by comparing within-station (single depth) standard deviations from the replicate stations. Three hauls also were included from one multidepth station because they were taken at about the same depth, 11 m, as the hauls at the replicate stations. Standard deviation appeared to be proportional to the mean in the comparisons (Table 3), strong evidence that the sampling variance was not homogeneous. The variance appeared to be stabilized by logarithmic transformation of the frequencies [$\log_{10}(N + 1)$] which then passed Bartlett's test (Table 3). As a result, the logarithmic transformation was applied to the analysis of frequencies.

The frequency data were examined by analysis of variance to determine the significance of between-station differences in population density. Data from multidepth stations were not used because these stations were not standardized for depth. Significant between-station differences were present (Table 4), evidence that there were important horizontal differences in density of Arctic cod over the sampling area, at least at depths of 11-12 m.

TABLE 4.—Analysis of variance of numbers (transformed) of juvenile Arctic cod in IKMT hauls at eight replicate stations in eastern Chukchi Sea.

Source	d.f.	S.S.	M.S.	F
Among stations	7	10.60984	1.51569	8.84; $P<0.001$
Within stations	24	4.11693	0.17154	—
Total	31	14.72677	—	—

Capture rate of juvenile cod consistently increased with depth and the slope of regressions of number of captures on depth was similar among the multidepth stations. Also, regressions at the stations appeared to bear no direct relationship to salinity structure nearby (Figure 2). Significance of differences between the regressions was tested by analysis of covariance with the result that differences in slope were judged as insignificant. Differences in level, however, did appear to be significant (Table 5). Apparently concentration of juvenile Arctic cod increased at about the same logarithmic rate (0.0669) with depth, but the depth at which a given concentration occurred varied between stations. This triangular area on the plots (Figure 2), with its apex toward the surface, was regarded as the graphic analog of the relationship between concentration and depth in the juvenile cod; it was termed a "density structure." Evidently the density structure was relatively stable relative to the time span of sampling at a station (about 2 h) because the structure was always evident despite the depth sequence of hauls (Figure 2).

TABLE 3.—Comparison of means, standard deviations, and variances for raw and transformed frequencies of occurrence [$\log_{10}(N + 1)$] of juvenile Arctic cod between replicate stations in eastern Chukchi Sea. Data arranged in order of increasing means in the transformed data.

	No. replicate	Raw data			Transformed data		
Station	hauls	Mean	SD	Variance	Mean	SD	Variance[1]
37	4	3.3	4.0373	16.3	0.4758	0.4273	0.1826
32	4	6.3	5.4406	29.6	0.7751	0.3079	0.0948
14	4	20.8	22.0681	487.6	1.0397	0.7333	0.5377
25	4	23.3	31.9312	1,019.6	1.1380	0.5011	0.2511
20	4	51.8	47.7169	2,276.9	1.6159	0.3260	0.1063
22	4	57.0	56.3090	3,170.7	1.6399	0.3516	0.1236
16	4	62.5	28.2436	797.7	1.7612	0.2347	0.0551
41	[2]3	277.7	202.5075	41,009.3	2.3101	0.4795	0.2299
10	4	258.0	87.2221	7,607.7	2.3954	0.1453	0.0211

[1]Bartlett's Test for Homogeneity (Sokal and Rohlf, 1969:370, 371): $\chi^2 = 4.004$, $P>0.5$.
[2]A multidepth station in which three hauls were at approximately 11 m.

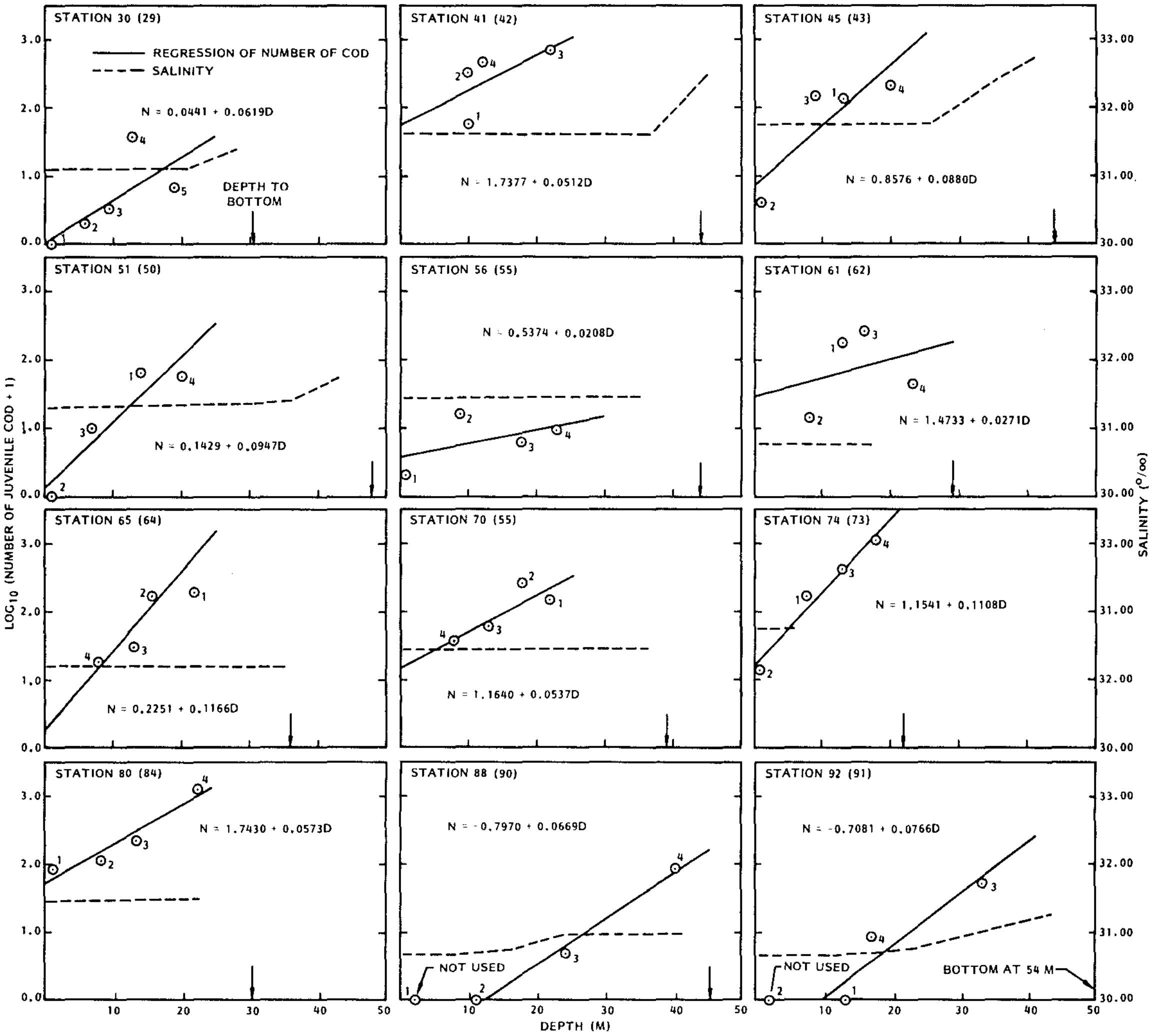

FIGURE 2.—Depth distribution of juvenile Arctic cod and salinity at the 12 multidepth stations. Salinities from the nearest oceanographic station (number in parentheses) from Ingham and Rutland (1972) and U.S. National Oceanographic Data Center. Numbers on points indicate sequence of hauls. Regressions of number of cod (N) on depth in meters (D) fitted by least squares. Pooled slopes for all data = 0.0669.

TABLE 5.—Analysis of covariance on data for abundance and depth of juvenile Arctic cod at 12 multidepth stations in eastern Chukchi Sea.

Source	*d.f.*	*S.S.*	*M.S.*	*F*
1. Individual regressions	23	3.91335	0.17015	—
2. Difference between 1 and 3 for testing slopes	11	1.48432	0.13494	(2)/(1) = 0.79; n.s.
3. Individual regressions fitted with a common slope	34	5.39767	0.15876	—
4. Difference between 3 and 5 for testing levels	11	23.56263	2.14206	(4)/(3) = 13.49; $P<0.005$
5. Regressions fitted to a single line	45	28.96030	—	—

DISCUSSION

Possible Causes of the Density Structure and Its Vertical Displacement

The steady increase of number of cod in the density structure with depth indicated a graded rather than a threshold response to some environmental factor, because if the response depended on a threshold, one would expect a sudden increase in density of juvenile cod when that threshold was reached. Salinity relationships in the water column did not appear to be a cause of the density structure because the water column was usually nearly isohaline through the region of greatest change in concentration of juvenile cod (Figure 2)—the density structure evidently persisted despite forces that contributed to oceanic mixing. Predation by aquatic predators did not seem to be a reasonable cause because the only evident potentially effective fish or invertebrate predator on the cod was large jellyfish, which occurred in approximately equal numbers throughout the water column. Reaction of the juvenile cod to a pressure gradient also was dismissed, for reasons discussed below.

A graded negative phototaxis either in the juvenile cod or, possibly, in the prey they were following seemed to offer the best hypothesis for the cause of the density structure and its variations. A gradient of increasing darkness with depth could coincide closely with the gradient for increase in number of cod. This type of gradient is illustrated in Figure 3 (shown here for the English Channel—the slope in regard to perception by the cod should be dependent on turbidity as well as the spectral sensitivity of the juvenile cod). Under this hypothesis the density structure of juvenile cod found at night was a relict of earlier daylight hours, during which the density structure was maintained despite turbulence, upwelling, and downwelling. With onset of darkness the means of orientation by the fish was removed and the density structure was elevated or depressed, depending on whether it occurred in cells of upwelled or downwelled water. The density structure presumably persisted into the early night when most hauls were made because of the short period of time elapsing before trawling began and also because the cod were relatively inactive at the low sea temperatures

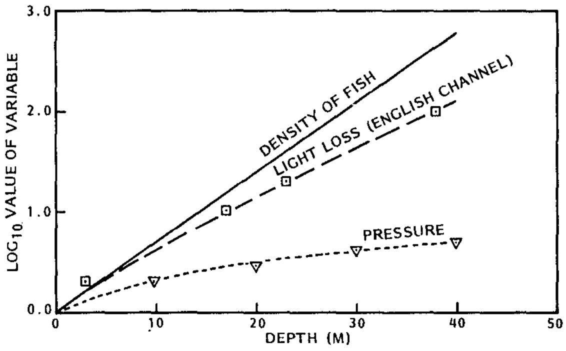

FIGURE 3.—Conformity of the variables—density of juvenile Arctic cod, loss of light (blue-green, English Channel), and pressure at increasing depths. Regression of fish with depth (D), $\hat{N} = 0.0699D$, where $\hat{N}$ = most likely number of fish in a trawl swath (see text); index of light loss based on $I = \log_{10} (1/p \times 100)$, where p = percent of illumination at surface, from data of Nicol (1960:22); and pressure (atmosphere) based on an increase of 1 atm/10-m depth, after Nicol (1960:22).

(−1.5° to 3.5°C). The freshly trawled specimens were markedly inactive. The validity of the gradient hypothesis possibly could have been evaluated further had trawl data been available for daylight hours. Data on vertical distribution of zooplankton were not available because sampling was entirely by vertical tows (Wing, in press).

Orientation by the cod to a pressure gradient was dismissed as an explanation of the density structure for two reasons: the shape of the curve of pressure on depth differs from that of the density structure (Figure 3), and orientation to a pressure gradient should be the same during the day as at night and should not allow the density structure to be elevated or depressed.

If the density structure were a result of behavior in the juvenile cod, it may have been evolved in response to predation by birds. Undoubtedly, such predation is a factor of tremendous ecological importance to juvenile cod, primarily during summer when bird populations are at their peak. Arctic piscivorous birds form a spectrum of depth capabilities, and because their feeding is based at the surface, intensity of predation should decline with depth, i.e., complement the density structure. Watson and Divoky (1972) give an extensive list of bird species observed in the Chukchi Sea during WEBSEC-70, the majority of which are either recorded as predators or are assumed to have, and to make use of, the potential for predation on juvenile Arctic cod. Included are loons, slender-billed shearwater, pelagic cormorant, red phalarope, glaucous gull, herring gull, ivory gull, black-legged kittiwake, Ross's gull, Sabine's gull, murres, guillemot, Kittlitz's murrelet, parakeet auklet, and horned puffin. Swartz (1966:674) estimated a population of about 600,000 piscivorous birds (adults and fledglings) at Cape Thompson, which is south of Cape Lisburne, in 1960; murres and kittiwake gulls accounted for 90% of the population. He estimated that the birds consumed approximately 13.5×10^3 metric tons of food during their breeding season. Tuck (1960:166) found that Arctic cod were the most important fish in the diet of murres, as did Swartz (1966:667) in his studies at Cape Thompson. Tuck cited depth records for murres which indicate that they are able to feed throughout the entire water column over the shelf portion of the Chukchi Sea. Since the birds at Cape Thompson are undoubtedly only a small fraction of the birds that utilize the southern Chukchi Sea, predation on fishes by birds must be intense over the entire region. However, bird predation could not have been a direct cause of the density structure during WEBSEC-70 because most birds appeared to have left the region prior to the time of our visit.

The hypothesis of negative phototaxis in juvenile Arctic cod had further appeal—it seems congruent to presumed needs for lowering vulnerability to predation by birds during summer when subsurface illumination is high while allowing for vertical foraging by the cod when illumination is low. Because piscivorous birds undoubtedly are visual feeders, directed or passive movement toward the surface by juvenile cod at night should not be counterselective. During the prolonged periods of low illumination of arctic winter, and under ice cover, juveniles presumably would be able to occupy the entire water column over the continental shelf. However, because larger juveniles, about 15 cm TL, were commonly seen in daylight near ice that had been broken by the icebreaker, negative phototaxis of the juveniles, if present, must decrease with growth in favor of life near a substrate. Changes from a pelagic to demersal existence during early growth stages is a commonplace in fishes.

Upwelling and downwelling seemed a plausible explanation of the differences in depth noted for the density structure. Salinity of the upper water column and an index of elevation or submergence of the density structure, explained below, showed good correlation (Table 6). The index was obtained for each station by algebraically projecting the pooled value for slopes of all regressions of number vs. depth, multidepth and replicate stations, through the station data, to the hypothetical apex of the density structure at the station. If the apex lay above the ocean surface (e.g., Figure 2, stations 41 and 70), the converted amount in meters was negative and was taken as the amount the density structure was elevated. If the apex lay below the ocean surface (e.g., Figure 2, stations 88 and 92), the converted amount in meters was positive and was taken as the amount the density structure was submerged. For each replicate station the regression was based on a point determined by depth of trawling and the average number of juvenile cod captured at the station. All indices for salinity were based on data for 10-18 m because this zone was the common depth of the replicate hauls; however, the water column was usually nearly isohaline from the surface to considerably below this depth (Figure 2).

Two sources of upwelling seemed possible—an accelerated current around the Cape Lisburne-Point Hope headland and wind over the sampling

TABLE 6.—Comparison of hypothetical elevation of the density structure of juvenile Arctic cod at the trawl stations taken at late dusk or after dark, based on density distribution of cod at each station, with surface salinity at a nearby station. Stations in order from greatest submergence (positive values) to greatest elevation (negative values) of the density structure. Projections for the multidepth stations were based on the data of Figure 2 fit to the standard slope of 0.0669; methods for obtaining projections from the replicate data are explained in the text.

IKMT station and type [1]	Indicated level of apex in meters	Closest oceanographic station	Average salinity at 10-18 m
88(M)	11.9	90	30.72
92(M)	10.5	91	30.67
37(R)	4.9	36	31.65
32(R)	0.5	31	30.85
30(M)	-0.7	29	31.11
51(M)	-2.1	50	31.32
65(M)	-3.4	64	31.19
25(R)	-5.0	24	31.00
56(M)	-8.0	55	31.43
20(R)	-12.2	19	31.72
22(R)	-12.5	19	31.72
45(M)	-12.8	43	31.76
16(R)	-15.3	18	31.11
74(M)	-17.3	73	31.77
70(M)	-17.4	55	31.43
61(M)	-22.0	62	30.76
10(R)	-24.8	9	31.56
41(M)	-26.0	42	31.63
80(M)	-26.1	84	31.47

$r = -0.514$; $P<0.05$

[1]M = multidepth station; R = replicate station.

area. Both should produce transient cells of upwelling and downwelling, but the wind-caused cells should have broader distribution.

Currents apparently flow predominantly northward in the southern Chukchi Sea and accelerate around headlands (Fleming and Heggarty, 1966: 744). Therefore, at an early stage in analysis, it appeared that the density structure of juvenile cod encountered during WEBSEC-70 may have been a result of bird predation off the Cape Lisburne-Point Hope headland or in Kotzebue Sound with subsequent vertical displacement of the density structure in an eddy north of Cape Lisburne. However, this hypothesis was rejected because, as mentioned previously, birds were not abundant during WEBSEC-70; most of them had probably left the region at least a month previously. Moreover, oceanic mixing should quickly dissipate a density structure that formed near the cape. The apparent occurrence of the structure over the entire sampling area indicated that it 1) was quite permanent, 2) was probably maintained by the juvenile cod, and 3) was not in very large measure induced by currents around Cape Lisburne. These requirements were satisfied by the hypothesis of negative phototaxis and wind-induced upwelling.

Horizontal Density Distribution of Juvenile Cod

Regardless of possible origins of the density structure or reasons for its vertical displacement, it was necessary to take the vertical elevation of the density structure (Table 7) into consideration when estimating the concentration and biomass of juvenile cod at each station. This correction was accomplished by regarding the density structure as a unit that extended downward 47 m (the depth equivalent on the density structure of the highest number of cod sampled) in undisturbed water. The structure would be truncated in its upper part by the ocean surface when raised, or truncated in its lower part when it intersected the ocean bottom because of lowering of the structure or shallowness of the sea. Thus, for a structure that appeared to be raised 10 m in the water column, the number of cod remaining in the structure was taken as the number that occurred between 10 and 47 m in an entire structure. If a structure appeared to be truncated by the ocean bottom for 17 m, the number of cod remaining in the structure was taken as the number between 0 and 30 m in an entire structure. Estimation of the density of

TABLE 7.—Reconstruction of numbers of juvenile cod beneath a standard swath at the IKMT stations, eastern Chukchi Sea.

Station (type)	Depth of tows (m)	Average $\log_{10}(N + 1)$	Indicated level of apex in meters[1]	Density structure: Depth of base (m)	Density structure: Juvenile cod (no.)	Depth of water (m)	No. cod below density structure	Total for column beneath swath
10(R)	11	2.3954	-24.8	22.2	4,698	44	7,883	12,581
14(R)	11	1.0397	-4.5	42.5	5,184	51	3,222	8,406
16(R)	11	1.7612	-15.3	31.7	5,138	53	8,073	13,211
20(R)	12	1.6159	-12.2	34.8	5,179	42	2,729	7,908
22(R)	12	1.6399	-12.5	34.5	5,176	35	(2)	5,366
25(R)	12	1.1380	-5.0	42.0	2,462	33	(2)	2,462
30(M)	—	regression	-0.7	46.3	1,268	31	(2)	1,268
32(R)	12	0.7751	0.5	47.5	547	26	(2)	547
37(R)	12	0.4758	4.9	51.9	4,162	49	(2)	4,162
41(M)	—	regression	-26.0	21.0	4,595	44	8,717	13,312
45(M)	—	regression	-12.8	34.2	5,173	44	3,714	8,887
51(M)	—	regression	-2.1	44.9	5,181	48	1,175	6,356
56(M)	—	regression	-8.0	39.0	[3]5,190	44	1,895	7,085
61(M)	—	regression	-22.0	25.0	4,891	29	1,516	6,407
65(M)	—	regression	-3.4	43.6	2,798	36	(2)	2,798
70(M)	—	regression	-17.4	29.6	5,088	39	3,563	8,651
74(M)	—	regression	-17.3	29.7	2,681	22	(2)	2,681
80(M)	—	regression	-26.1	20.9	4,586	30	3,449	8,035
88(M)	—	regression	11.9	58.9	1,492	45	(2)	1,492
92(M)	—	regression	10.5	57.5	3,968	54	(2)	3,968

[1]Negative values indicate apex above the surface.
[2]Stations at which hypothetical depth of bottom of density structure is deeper than the bottom. The number of juvenile cod represented by the overlap is subtracted from the total.
[3]In some instances the number of juvenile cod estimated for a density structure that was truncated at the surface was slightly higher than the theoretical number in an entire density structure. This discrepancy seems to be due to rounding errors in the integrations about the point where the parabolic equation approaches and forms a small angle with the x-axis. Since very few juvenile cod were present in the apex of the density structure, the error is small and probably unimportant.

juvenile cod below the presumed density structure was a problem because data from near bottom were not available for many stations. Therefore, the density of juvenile cod below the structure was assumed to be the maximum calculated for the density structure (i.e., that at 47 m in an entire structure). The possible error in estimating biomass of juvenile Arctic cod at the stations under this assumption was not judged to be serious because the sampling area was so shallow that the bottom of the density structure was usually close to the ocean bottom.

Although the transformed data on cod abundance vs. depth were useful for analyzing the density structure at the stations, back transformation of the estimates offered problems of interpretation. At present there appears to be no practical procedure for back transforming the variance and estimates of a logarithmic-arithmetic regression. Consequently, the density structure was redescribed from the untransformed data by fitting a parabolic regression with least squares (Figure 4). The variables were

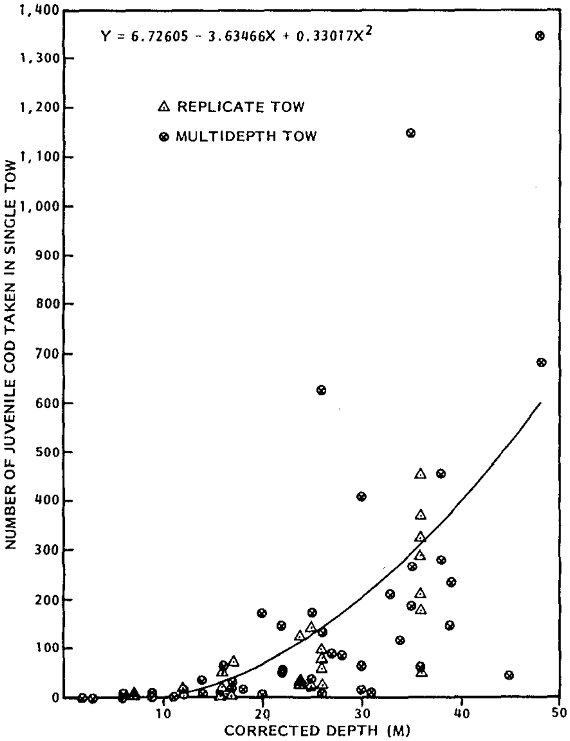

FIGURE 4.—Number of juvenile Arctic cod per Isaacs-Kidd tow, the depths corrected for apparent emergence or submergence of the density structure (Tables 6 and 7). Weighted regression ($1/X^2$) fitted by least squares.

weighted by the inverse of the corrected depth squared because the variance of number of cod vs. depth appeared to be linearly related to the square of the corrected depth. The result was

$$Y = 6.72605 - 3.63466X + 0.33017X^2$$

and its integration

$$Y^* = \int_U^L Y\ (X)\, dX$$

$$= 4.51413\ (L - U) - 1.21968\ (L^2 - U^2) + 0.07386\ (L^3 - U^3)$$

where Y = most likely estimate of number of cod in a tow at corrected depth.
X = corrected depth in meters.
Y^* = most likely estimate of the number of cod over the depth interval U-L in a trawl swath.
U = upper (shallower) level of depth interval, where $0 \leq U \leq L \leq 47$.
L = lower (deeper) level of depth interval.

Accordingly, the density structure contained approximately 5,186 juvenile cod over its depth range (0-47 m) over the area of a trawl swath. The most likely estimate of maximum density, at 47 m, was 379 cod/m of depth over the area of a trawl swath (5,519 m²).

Under these assumptions, composite estimates of the number of juvenile Arctic cod in the water column beneath a standard trawl swath was calculated for all IKMT stations (Table 7). Totals for each station were obtained by adding the number of juvenile cod estimated for that section of the water column occupied by the density structure—5,186 over 47 m of depth except when the structure was truncated by the surface or bottom—to the hypothetical number in the column below the structure, or 379/m of depth. For the replicate stations, where only one depth was sampled, the hypothetical depth of the structure was obtained by comparing the average catch (log transformed data) at the trawling depth with the catch (log transformed data) that would be expected at that depth if the apex of the density structure coincided with the ocean surface. If this comparison indicated that the apex of the hypothetical structure was projected above the ocean surface (indicated by minus values for level of apex in Tables 6 and 7) or below the ocean bottom, then the appropriate adjustments, discussed previously, were made. As a result, estimates of juvenile cod at the IKMT stations were influenced by both an inferred height of the density structure and the depth of water beneath the structure. Stations in relatively shallow water and with a deeply submerged density structure had the lowest estimates, and stations in water deeper than average and with density structures that reached to the surface had the highest. The average for all stations was 28.5 juvenile cod/1,000 m^3 (Table 8).[3]

Biomass of juvenile Arctic cod in the area surveyed by WEBSEC-70 was estimated by converting the overall average concentration to volume and weight. Average volume of individuals in samples was 0.618 ml, with no apparent size segregation with depth (Figure 5). If we assume that the specific gravity of the cod approximated unity (actually they were heavier),

[3]This compares with an arithmetic average of 7.3/1,000 m^3 for the replicate hauls and 19.5 for the multidepth hauls—an average of 13.4 for all hauls. Thus, simple arithmetic averaging would seriously underestimate the value obtained under the hypothesis of density structure with upwelling and downwelling. Even higher values would be obtained if it is assumed that the density structure continued to increase at the same logarithmic rate below its depth of 47 m until the bottom was reached, instead of having the increase truncated at 47 m. This approach would require extrapolation well beyond all observed values for fish densities and would not be fully consistent with the welling part of the hypothesis.

TABLE 8.—Estimated volume of water and number of juvenile cod beneath a standard swath at the IKMT stations, eastern Chukchi Sea.

Station	Volume of water beneath trawl swath (m^3)	Juvenile cod/1,000 m^3
10	242,836	51.8
14	281,469	29.9
16	292,507	45.2
20	231,798	34.1
22	193,165	27.8
25	182,127	13.5
30	171,089	7.4
32	143,494	3.8
37	270,431	15.4
41	242,836	54.8
45	242,836	36.6
51	264,912	24.0
56	242,836	29.2
61	160,051	40.0
65	198,684	14.1
70	215,241	40.2
74	121,418	22.1
80	165,570	48.5
88	248,355	6.0
92	298,026	13.3
Weighted average	—	28.5

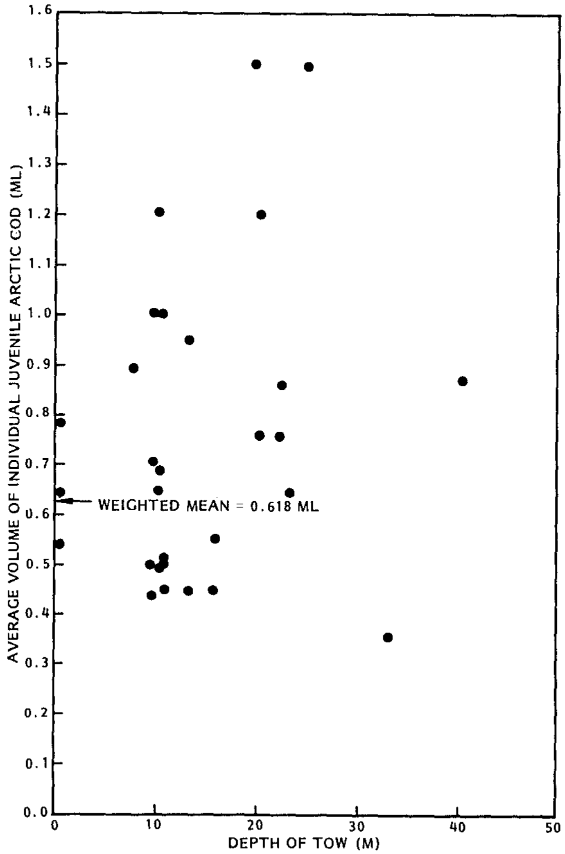

FIGURE 5.—Relation of average volume (milliliters) of individual juvenile Arctic cod in IKMT tow to depth of capture, eastern Chukchi Sea.

then the stations averaged 17.6 g of juvenile cod/1,000 m^3. If we take the area surveyed in the eastern Chukchi Sea as approximately 30 x 10^3 km^2 (8,714 square nautical miles) and the average depth as 40.0 m (the average for the 20 IKMT stations), then approximately 12 x 10^{11} m^3 of ocean were contained in the sampling area. Thus, it appears that 211.2 $\times$ 10^8 g of fish were represented by this volume, or 211.2 $\times$ 10^2 metric tons, for an average of 0.7 metric ton/km^2 of ocean surface.

Where did the juvenile cod originate? Likely sources appear to be the Bering Sea, the East Siberian Sea, or the Chukchi Sea itself. The northwestern part of the Bering Sea has particularly low temperatures (Zenkevitch, 1963:824, 825) and water from the Gulf of Anadyr tends to flow northeastward (Zenkevitch, 1963:821). The East Siberian Sea, of course, also has low temperatures and apparently has an eastward-flowing current into the Chukchi Sea (Zenkevitch, 1963:262). The near absence of high-arctic zooplankton in the eastern Chukchi Sea (Zenkevitch, 1963:268), verified during WEBSEC-70 by Wing (in press), is only weak evidence that the cod did not originate in the East Siberian Sea: the cod probably spawned in January and February (Rass, 1968:136), approximately 8 mo before WEBSEC-70, and it seems possible that the juveniles could have lost their arctic ecological associates over that period of time. In any event, the apparent short time that cod spent in some sections of the Chukchi Sea—about 10 days in the southeastern part according to the oceanographic data of Fleming and Heggarty (1966: 724)—and the time elapsed between spawning and capture at our IKMT stations is evidence that the juvenile cod either originated at considerable distances from the Chukchi Sea or had been cycled in the Chukchi Sea. Since there is reason to believe that a portion of the Chukchi Sea circulates in a counterclockwise gyre (Zenkevitch, 1963:262), similar cycling of eggs and larvae seems possible.

SUMMARY

1. Twenty stations in the eastern Chukchi Sea between Icy Cape and Cape Lisburne were sampled with a 1.8-m (6-foot) Isaacs-Kidd mid-water trawl (IKMT) during September and October 1970.

2. Only two species of fish occurred in any abundance in the middle and upper water column at night, juvenile Pacific sand lance and juvenile Arctic cod (mostly age 0). Because the Arctic cod were most abundant and were distributed through most of the water column, their occurrence was given a detailed analysis.

3. Two types of IKMT stations were occupied; one in which hauls were replicated at the same depth, and another in which hauls were made at several depths. All stations but one (a replicate station) were occupied starting at late dusk or at night.

4. The standard deviation in frequency of juvenile cod occurrence at the replicate stations seemed to be proportional to the means. The variance was stabilized by $\log_{10} (N + 1)$ transformation of the data.

5. Analysis of variance of the transformed data from the replicate stations disclosed significant between-station variation in number of cod occurring at 11-12 m.

6. Number of juvenile cod per unit volume of water increased with depth at all multidepth stations.

7. Analysis of covariance on regressions of cod abundance ($\log_{10}$ transformed) vs. depth disclosed no significant differences in slope of the regressions between stations but significant differences in level.

8. The characteristics of slope and level in the regressions for multidepth stations described a depth region of logarithmic increase in concentrations of juvenile cod. This region was at a different depth at some stations than at others and was called a density structure.

9. It appeared that the density structure resulted from a graded rather than a threshold response to subsurface illumination. Such a response seems to be a suitable behavioral strategy for lessening predation by piscivorous birds.

10. The hypothesis is presented that the density structure was formed during daylight hours and that differences in its vertical displacement between stations at night were caused by wind-induced upwelling or downwelling.

11. Average number of juvenile cod calculated for the stations was 28/1,000 m^3 or approximately 0.7 metric ton/km^2 of ocean surface.

12. The origin of juvenile cod could have been in the northeastern Bering Sea, the East Siberian Sea, the Chukchi Sea, or all three. Regardless of origin, a cycling of eggs and larvae within the Chukchi Sea seems likely.

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