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Analysis of Arctic Cod Movements in the Beaufort Sea Nearshore Region, 1978-79

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ABSTRACT. A study was conducted to investigate distribution and abundance of arctic cod in the nearshore region of the Beaufort Sea. Data collection methods included 3 m otter trawl and hydroacoustic surveys. Temperature and conductivity measurements were taken throughout the study area on a regular basis. The results indicated that arctic cod are associated with a transition layer between a surface water mass, characterized by low salinity and high temperature, and a bottom water mass, characterized by high salinity and low temperature. Arctic cod apparently oriented to the shoreward edge of the marine water mass and redistributed themselves depending on the location of the shoreward edge. It is hypothesized that the transition layer concentrates food organisms, and this abundance of food may be one factor that induces shoals of arctic cod to utilize this transition layer.

Key words: arctic cod, Alaskan Beaufort Sea, nearshore movements, temperature/salinity association, coastal habitat use, *Boreogadus saida*

RÉSUMÉ. Une étude a été menée afin de déterminer la distribution et l'abondance de la morue arctique dans la zone côtière de la mer de Beaufort. Les données ont été recueillies à l'aide d'un chalut à plateaux de 3 m et de relevés hydro-acoustiques. Des mesures de température et de conductivité ont été prises de façon régulière, dans toute la zone étudiée. Les résultats ont indiqué que la morue arctique est associée à une couche de transition entre une masse d'eau de surface, caractérisée par une faible salinité et une haute température, et une masse d'eau profonde, caractérisée par une forte salinité et une basse température. La morue arctique se dirigeait apparemment vers la limite côtière de la masse d'eau de mer et sa distribution suivait cette limite côtière. On peut avancer l'hypothèse que la couche de transition est très riche en éléments nutritifs, et que cette abondance de nourriture est un des facteurs qui amènent les bancs de morues arctiques à se servir de cette couche de transition.

Mots clés: morue arctique, mer de Beaufort de l'Alaska, déplacements près des côtes, association température/salinité, utilisation de l'habitat côtier, *Boreogadus saida*

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INTRODUCTION

Arctic cod (*Boreogadus saida*) is a dominant species in the arctic marine ichthyofauna, yet little information has been published on the distribution and abundance of this species in the North American Arctic (Craig *et al.*, 1982). A number of recent studies have established the numerical abundance of arctic cod in the Alaskan Chukchi and Beaufort Sea region (Quast, 1974; Wolotira *et al.*, 1979). Craig and Haldorson (1981) noted large variations in arctic cod abundance that were not explainable with available data. Griffiths and Gallaway (1982) reported an unusual pattern of fluctuating arctic cod abundance in the nearshore region of Prudhoe Bay but did not address factors that might lead to such a pattern.

The present study was undertaken to assess arctic cod distribution and abundance in the Beaufort Sea nearshore region in the vicinity of Prudhoe Bay. The objectives of the study were to 1) measure daily and seasonal changes in environmental parameters, 2) identify daily and seasonal patterns of arctic cod distribution and abundance and 3) relate observed changes in fish distribution to changes in environmental conditions.

METHODS

Field Studies

Field investigations were conducted from 16-21 August 1978 and 18 July-1 September 1979. Five subareas, extending from the western end of Stump Island to the east side of Prudhoe Bay, were sampled primarily with otter trawling and hydroacoustic transects (Fig. 1). Trawling was conducted throughout all five subareas, while hydroacoustic surveys were conducted in the offshore subarea.

Sample stations were located utilizing a Motorola Mini-Ranger III navigational positioning system. Transponders were positioned at the end of Dockhead No. 3 and on Stump Island 3000 m from the dock transponder.

A 3 m semi-balloon otter trawl with 13 mm square mesh in the body and 3 mm square mesh cod end was used at each trawl station. The trawl data provided information to ground-truth the hydroacoustic sampling. All trawls were made on bottom. With a few exceptions, towing time was 15 min. Trawling effort consisted of 33 samples in August 1978, 43 samples in July 1979 and 32 samples in August 1979.

All fish captured by net sampling were identified and counted. Subsamples of arctic cod (*Boreogadus saida*), kelp snailfish (*Liparis tunicatus*), capelin (*Mallotus villosus*), rainbow smelt (*Osmerus mordax*), Pacific sand lance (*Ammodytes hexapterus*) and fourhorn sculpin (*Myoxocephalus quadricornis*) captured by otter trawl were preserved in 10% formalin for laboratory examination.

Hydroacoustic sampling was conducted by R.E. Thorne (University of Washington, Fisheries Research Institute). The primary hydroacoustic equipment used in this study was a Simrad EY-M echo sounder, which transmits a 0.6 $m \cdot sec^{-1}$ pulse of 70 kHz sound, used in conjunction with a wide-angle transducer. The effective angle of detection for this transducer was about 30° under the survey conditions.

Echoes from fish and other targets were printed on a chart recorder as a function of depth and time and were also recorded on magnetic tape for more detailed analysis of echo amplitudes. The pulse repetition rate was 3.2 $transmissions \cdot sec^{-1}$. The hydroacoustic equipment was applied in two modes: fixed location and transecting. In the fixed-location mode, the transducer was suspended just below the surface from a float several

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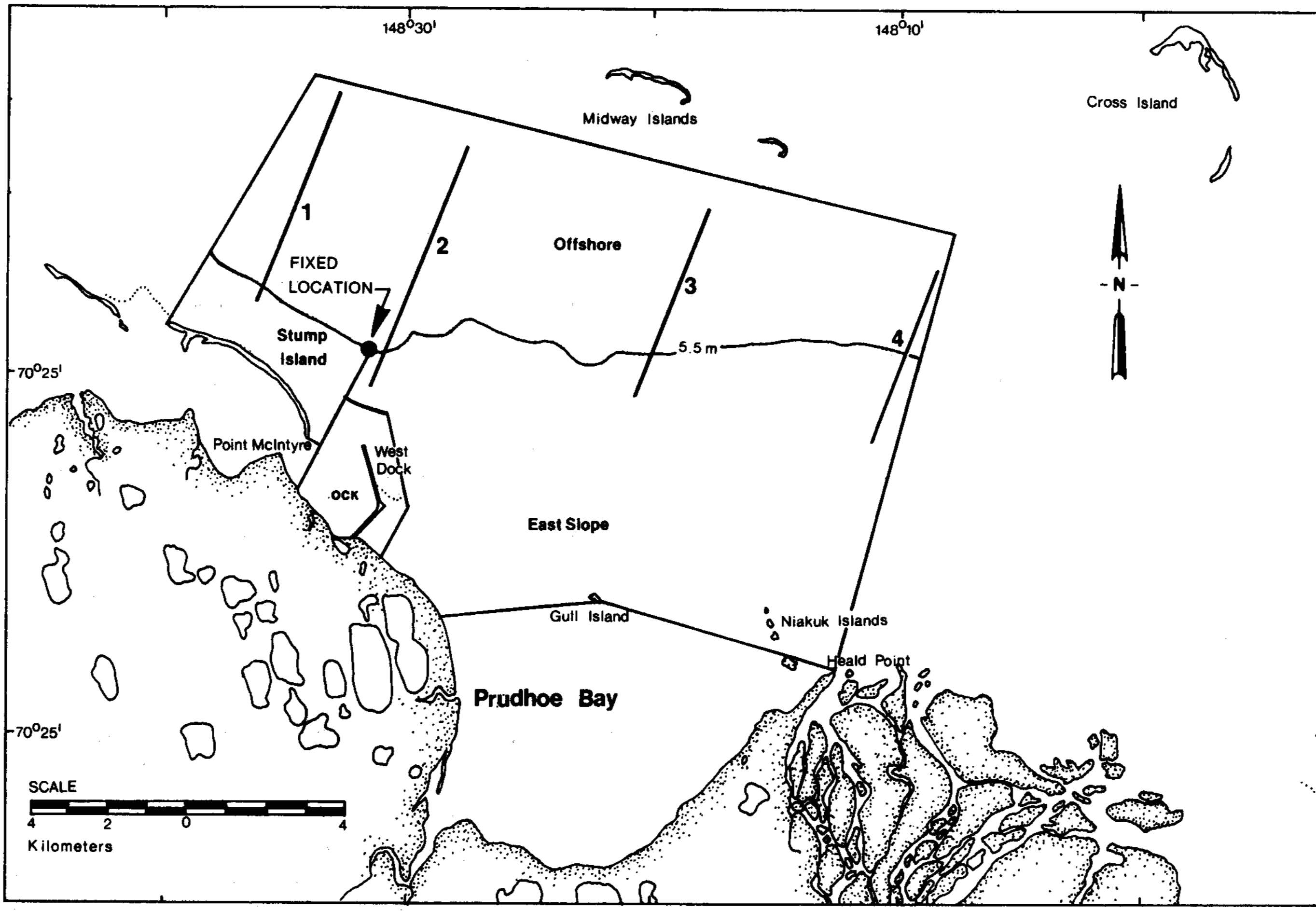

FIG. 1. Location of hydroacoustic transects, fixed location and five trawling subareas (Stump Island, West Dock, East Slope, Prudhoe Bay and Offshore) surveyed during Beaufort Sea fish studies, 1978 and 1979.

metres from the anchored boat. During transecting, the transducer was towed just below the surface from a wood beam projecting in front of the boat. This arrangement was designed to minimize the effects of fish avoiding the boat in shallow water.

Hydroacoustic data were collected during two periods: 23-27 July and 28 August -1 September. The primary transect design consisted of four north-south lines, which were replicated during each survey (Fig. 1). Transects typically were conducted in water depths >4 m. Some east-west transects were also run along specific depth contours (e.g., 6 m). The fixed location was at a 6 m depth along transect no. 2 (Fig. 1) and was monitored for 9½ and 12 hr in July and August 1979 respectively.

In addition to biological and hydroacoustic samples, a series of water quality measurements was taken to characterize the water sampled. Water conductivity and temperature profiles were measured with a Martek Mark VII water quality analyzer. The sensor head contained a temperature probe (–5° to +50°C range; ±0.1°C accuracy) and a five-electrode conductivity cell (0-70 mmho·cm^{-1} range; ±0.07 mmho·cm^{-1} accuracy). Both parameters could thus be profiled on a single lowering. Depth of immersion was measured by counting 0.3 m markings on the handling line. Using the computer reduction algorithm described by Chin *et al.* (1979), the conductivity, temperature and depth data were processed to obtain vertical profiles of temperature and salinity.

Laboratory and Data Analyses

In the laboratory, all preserved fish were sorted, identified, measured (total length) and counted. A random sample of arctic cod from the preserved August subsamples was weighed.

The hydroacoustic analysis procedures consisted of echogram analysis supplemented by detailed analysis of magnetic tape records. Echo counts and amplitude characterization of selected transects were made using a storage oscilloscope.

The number of fish counted by the hydroacoustic system was determined by assuming a mean target strength of –50 decibels (dB), which corresponds to a 10 cm fish target. Echoes were counted if they exceeded a threshold of –60 dB. Fish densities were then calculated from the total number of echoes over the threshold divided by the volume sampled. The volume sampled was determined by the depth interval, the number of transmissions and the sampling angle of the transducer.

RESULTS

Depth and Substrate Features

The offshore subarea (water depths 5.5-10 m) was populated by a typically marine flora and fauna including three species of kelp (order Laminariales), two species of nudibranches, various marine gastropods, soft coral, starfish and sponges. Kelp was collected at 95% (19 of 20) of the 1979 offshore trawl stations. Bottom sediments were apparently composed of fine sand and fine silt (Chin *et al.*, 1979). Scattered patches of sand/gravel and clay deposit were identified during the trawl survey. The East Slope subarea (0.3-5.5 m) was also predominantly soft sediments, with possible sand/gravel deposits. Kelp was collected in 70% (7 of 10) of the 1979 trawl samples in this area. The Stump Island subarea, with a depth range similar to that of the East Slope, was primarily fine sand with areas of gravel. Kelp was taken in 38% (8 of 21) of the 1979 trawl samples. Maximum depths in the West Dock and Prudhoe Bay subareas were 3.0-3.5 m. Sediments in the West Dock area were composed of sand and silt, with mud found in some areas. In the Prudhoe Bay subarea, sediment types also ranged from fine sand to mud/clay. Kelp was not collected in either subarea.

Ice Features

The presence of ice was a dominant feature in the study area. In July the ice had retreated to approximately the 5 m contour, with a periodic inshore movement of floating ice with west winds. Thus, the ability to navigate at and beyond this boundary was severely limited. In August the ice had essentially retreated to depths >10 m and surveying could be conducted farther offshore. Grounded ice was observed as far offshore as the 7 m depth contour.

Water Mass Features

Water movements and temperature and salinity characteristics in the general study were dynamic, with wide fluctuations over a short period of time. Basically, there were two water masses: a warm (2-9°C), low-salinity (6-27‰) surface mass with a cold (<–1°C), high-salinity (28-32‰) bottom mass. The depth to the transition layer between the two water masses (i.e., the interface between the two water masses) fluctuated from 1.5 m to > 10 m (Fig. 2). The two- to three-day period between temperature and salinity measurements was often sufficient for the marine water mass (low-temperature, high-salinity) to mix with the surface during strong winds or return to the study area. Following each influx of the marine water mass, there was usually a period of mixing, with a resulting increase in near-surface salinity (Fig. 3) (Chin, 1980). In general, surface temperatures decreased and surface salinities increased during the study period. A decrease in river discharge and ice melt may also have contributed to this pattern.

The transition layer between the two water masses was visible on the hydroacoustic traces, allowing the temporal and spatial fluctuations in the transition layer to be monitored with the hydroacoustic instrumentation (Fig. 4). The layering effect was particularly visible during July, when the density differences between the two masses were greatest. Temporal and spatial fluctuations were particularly evident between 28 August and 1 September. Based on the hydroacoustic transect monitoring, the marine water mass was apparently offshore at depths > 10 m between 28 and 30 August. This observation was verified by the CTD measurements. During the fixed-location monitoring at a depth of 6 m on 31 August and 1 September, the marine water mass moved inshore to a depth of about 4 m. Again, this onshore movement was also observed in the CTD measurements (Fig. 2). The thickness of the marine water mass at the hydroacoustic fixed location increased from essentially zero to 2.2 m in less than 24 hr, demonstrating the area's rapid response to meteorological changes.

Otter Trawl Catch

The otter trawl catch was dominated by arctic cod (98% of the catch), with minor catches of kelp snailfish, fourhorn sculpin, Pacific sandlance, capelin, rainbow smelt and least cisco (*Coregonus sardinella*). The length frequency of otter trawl-caught arctic cod in both 1978 and 1979 indicated that primarily one age group, probably age-1 fish, was present; few older fish were captured.

The results of the otter trawling indicate a general offshore movement of arctic cod between the July and August sampling periods. During July 1979, the highest mean catch rate for arctic cod (271 cod/trawl) was recorded in the West Dock subarea,

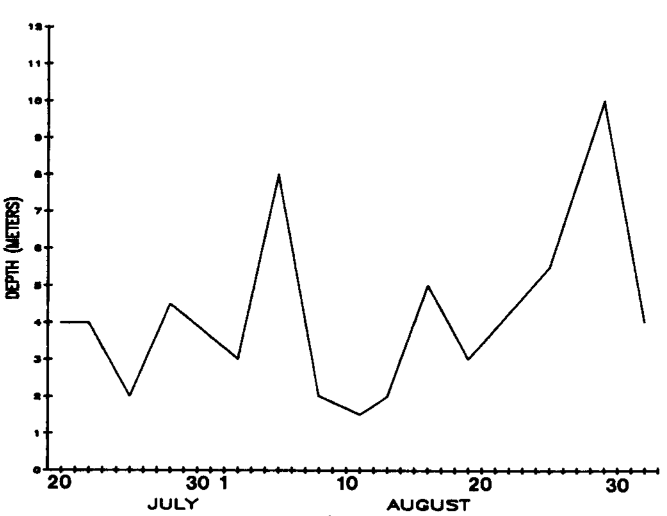

FIG. 2. Location of the transition layer between surface and marine water masses, as determined by CTD surveys 20 July-1 September 1979.

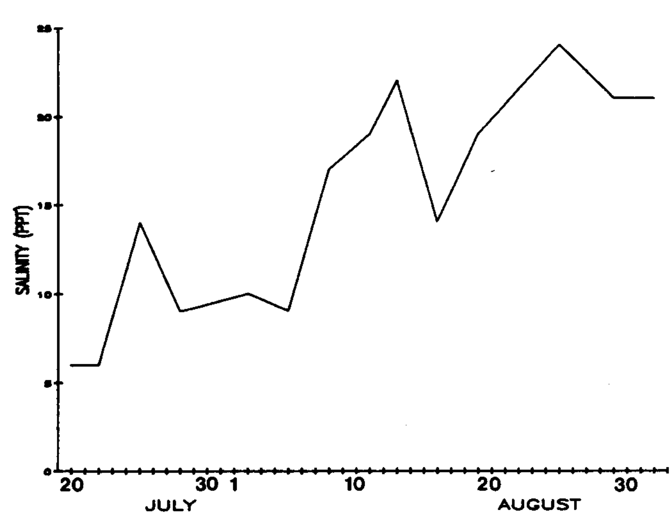

FIG. 3. Summer surface salinity in the study region as determined by CTD surveys 20 July-1 September 1979.

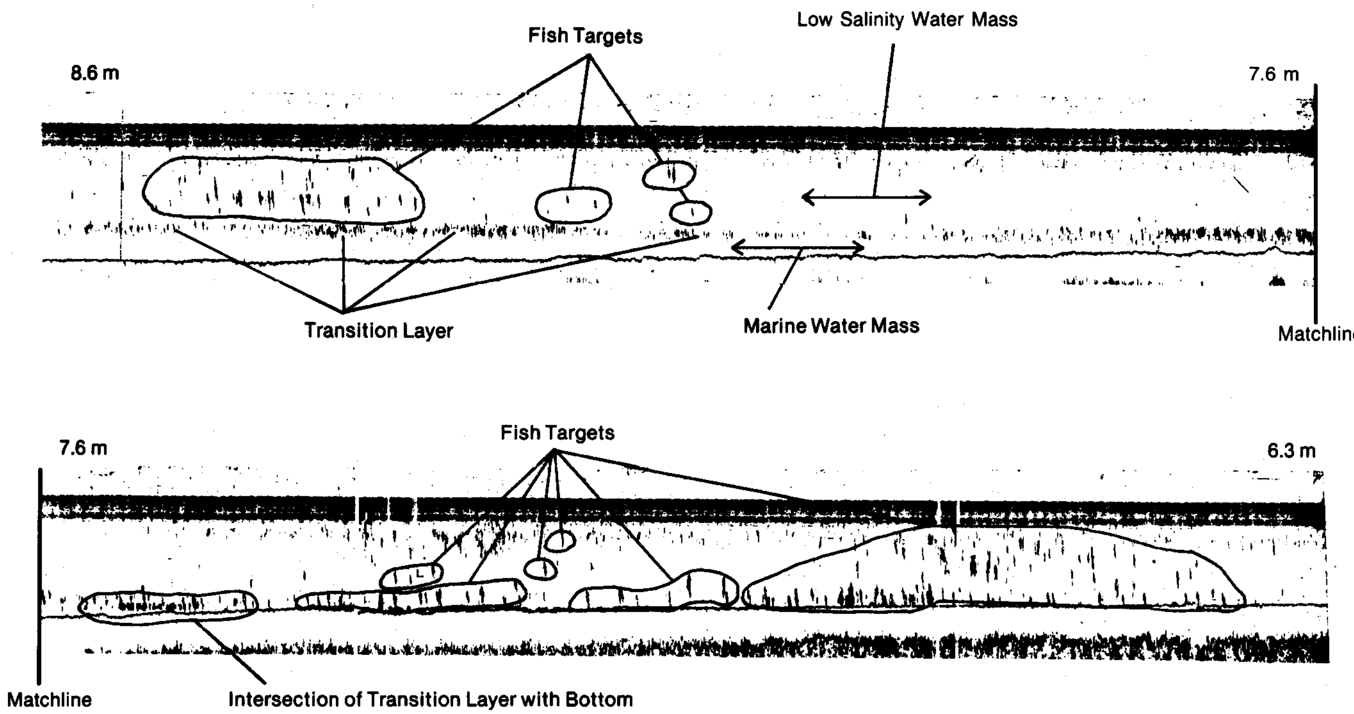

FIG. 4. Intersection of transition layer with seabed along transect 1 on 30 August, illustrating the orientation of pelagic and demersal fish targets to the two water masses and transition layer (bottom strip is a continuation of the top strip).

followed by the Stump Island and East Slope subareas (Table 1). The lowest mean catch rates (0.3 and 0.9 cod/trawl) were recorded in the Prudhoe Bay and offshore subareas respectively. In August 1979 the pattern changed, with the highest mean catch (14.8 cod/trawl) recorded in the offshore subarea and lower catches in the inshore subareas. Prudhoe Bay catches in August 1979 were again the lowest (0.5 cod/trawl) of all five areas. During the August 1978 survey, the highest catches were recorded in the West Dock and Prudhoe Bay subareas respectively, followed by offshore, East Slope and Stump Island (Table 1). During all three trawl surveys (one in 1978 and two in 1979), the mean catches of arctic cod around the West Dock were higher than those in the two subareas on either side of the dock (i.e., Stump Island and East Slope).

The mean bottom depth of capture of arctic cod was 2.7 m (SD = 1.7) in July and 5.8 m (SD = 2.0) in August 1979, a statistically significant increase in bottom depth (t-test, $p < .001$). These data again indicate an offshore movement of arctic cod between the July and August sampling periods. In contrast, neither the mean bottom depth of capture of kelp snailfish (5.5 m in July; 4.8 m in August) nor the mean bottom depth of trawl hauls (4.3 m in July; 4.8 m in August) showed a corresponding significant change between July and August.

Hydroacoustic Measurements

Transect series were run during four days in July; however, one series was obscured by reverberation from rough water. Additional data were collected over a 9.5 hr period during two days of fixed-location monitoring in July. During the August series, data were collected over five days. A total of 15 hr of data were collected during transects, including complete, replicated four-transect series each of the first three days and a replicated run of transect 2 the last day. In addition, 12 hr of data were collected at the fixed location over two days. The length of transects was increased over July because of the improved weather and ice conditions.

TABLE 1. Relative abundance of arctic cod in each subarea based on catches by 3 m otter trawl during 1978 and 1979 trawl surveys

	August 1978			July 1979			August 1979		
Subarea	Mean catch	SD	N	Mean catch	SD	N	Mean catch	SD	N
Stump Island	3.0	2.6	5	19.7	34.5	13	3.4	3.8	8
West Dock	133.0	58.0	2	270.9	615.0	9	6.6	10.9	5
East Slope	3.6	3.2	9	25.8	46.7	5	4.8	10.2	5
Prudhoe Bay	23.9	27.0	9	0.3	0.5	6	0.5	1.0	4
Offshore	8.0	20.6	8	0.9	1.1	10	14.8	17.4	10
			33			43			32

SD = standard deviation.
N = number of samples.

Fish abundance was generally low during July. Results of otter trawlings used to ground-truth the hydroacoustics indicated that most of these fish were arctic cod. Target detection rates for the three series were 6.1, 3.1 and 9.9 targets·hr^{-1} for 23, 24 and 26 July respectively, with corresponding mean fish densities of 2.7, 0.7 and 3.5 fish per $10^4 m^3$. The first two series were mid-day, while the third was during the 1820-2140 period. Neither inshore-offshore nor alongshore trends were evident. Targets in the marine water mass were typically located near bottom, with the mean height above bottom about 0.6 m. Targets in the surface water mass (<2.3 m on 23 and 24 July, <3.8 m on 26 July) could not be detected because of the strong surface reverberation in this layer. During the fixed-location monitoring on 25 and 26 July, 13 fish were observed — a mean rate of 1.9·hr^{-1}, corresponding to 10.5 fish per $10^4 m^3$.

Abundance of fish targets and interference from non-fish backscatter were much greater during the August survey. The estimated target densities ranged from 0 to 329 fish per $10^4 m^3$, with a mean of 55.6 fish per $10^4 m^3$. There was considerable variability in both abundance and inshore-offshore distribution during the four days (Table 2). These changes appeared to be related to changes in water masses. Discontinuity layers could often be acoustically detected, especially the boundary of the cold (<0°C), high salinity (30‰) marine water mass. This water mass was apparently offshore between 28 and 30 August. Fish concentrations were observed during transect monitoring on 28 August, but not on 29 August (Fig. 5A,B). Concurrent otter trawling indicated most of these fish were arctic cod. Transects were extended offshore during 30 August, and high fish concentrations were discovered just inshore of the depth where the cold marine water intersected the bottom on all transects (Figs. 4 and 5C). High fish concentrations in the surface water mass, possibly pelagic species, also occurred above the marine layer offshore from this intersection depth on all transects (Figs. 4 and 5C).

Although daily variability appeared to dominate the August-

TABLE 2. Densities and distribution of fish echoes along hydroacoustic transect 2, 28 August-1 September

Date	Depth range[1] (m)	Sampled volume ($10^4 m^3$)	Fish echoes	Density (fish per $10^4 m^3$)
28 August	4.3-6.1	1.30	105	80.8
	6.1-6.9	2.10	690	328.6
	6.9-7.6	2.78	63	22.7
29 August	4.3-6.1	1.93	2	1.0
	6.1-6.9	2.80	6	2.1
30 August	4.3-6.1	1.61	0	0
	6.1-6.9	2.49	147	59.0
	6.9-7.6	3.26	592	181.6
	7.6-8.2	6.68	517	77.4
	8.2-7.0	3.34	51	15.3
1 September	6.1-6.9	1.47	0	0
	6.9-7.6	3.85	146	37.9
	7.6-8.2	8.67	127	14.6
	8.2-7.0	4.90	63	12.9
	7.0-5.8	2.35	0	0

[1]From Stump Island toward Midway Islands.

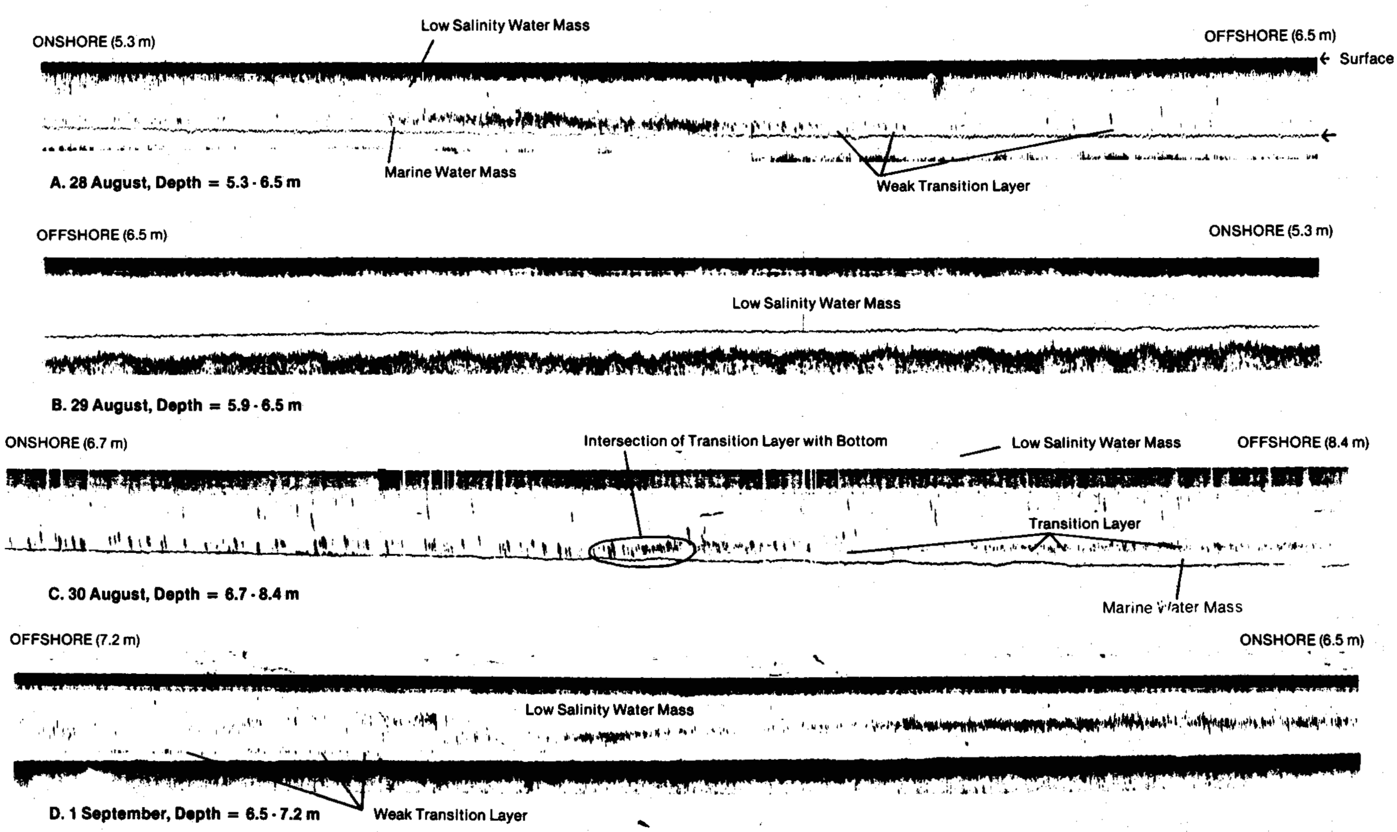

FIG. 5. Representative echograms from hydroacoustic transect 2 during 28 August-1 September 1979, illustrating the association of fish targets with the two water masses and transition layer. On 28 August the transition layer is weak and diffuse, on 29 August it is absent, on 30 August it is strong and continuous and on 1 September the transition layer is weak and appears to be mixing and dissipating (each strip represents approximately 2 km of transect).

September data, some differences between transects within days were noted. During 28 August, the concentration of targets between 4.0 and 5.8 m was strongest along transect 2 and moderately strong along transect 3. The concentration of targets was limited to the nearshore region along transect 1 and completely absent along transect 4, where the scattering was inshore at depths of 2.4-3.7 m. During 30 August, the fish concentration was again greater along transect 2 between 6.7 and 7.9 m bottom depths. The distribution along transect 1 was similar, though less dense and more inshore (Fig. 5). On transects 3 and 4, high fish concentrations were limited to the outer end of the transects, which terminated just as the water depth began to shallow on the barrier island side.

During the 12 hr of fixed-location monitoring in August, a total of 51 targets were observed — a rate of $5.5 \cdot hr^{-1}$, corresponding to 15.8 fish per $10^4 m^3$. Considerable variability was observed between the two days in the depth of the echoes, possibly related to the species present. On 31 August targets were near bottom (6.0-6.4 m), while on 1 September targets were 2.4-3.6 m below the surface. A diel trend was suggested by the lower densities during afternoon.

DISCUSSION

The summer 1979 water sampling revealed a dynamic system with two water masses: a warm, low-salinity water mass on top of a cold, high-salinity water mass. The depth to the transition layer (or interface), as measured by CTD, between the two masses varied from 1.5 m to >10 m throughout the study area during the July and August sampling periods. The depth to the transition layer generally increased during the season, probably as a result of mixing by wind action and reduced ice melt and river discharge. Arctic cod also showed a net offshore movement to deeper water between the July and August trawling periods. The move to deeper water did not appear to be an artifact of the trawl sampling, as the solitary kelp snailfish did not show a change in depth between sampling periods.

An association between the leading edge of the marine water mass and arctic cod distribution is indicated by the hydroacoustic measurements. In general, the highest measured fish densities were at the bottom of the warmer, less saline water mass immediately above the intersection of the leading edge of the marine water mass with the bottom. This association was particularly evident during the 28-30 August transect series. On 28 August high fish densities were recorded near bottom along the transition layer at 6-7 m. On 29 August the marine water mass had either mixed with the low-salinity surface water mass or had moved out of the study area because of changes in wind stress, and high fish densities were not observed. However, on 30 August the marine water mass was again observed in the study area (at 7.6 m on transect 2) and high demersal fish densities in front of the leading edge of the marine water mass were again observed. Pelagic fish targets were oriented above the transition layer, offshore of the leading edge of the marine water mass. During July, when few fish targets were encountered, arctic cod were in shallow water (mean bottom depth of capture = 2.7 m) and could not be detected by hydroacoustic techniques. The transition layer between the two masses was at 2.5-3.6 m; thus both the intersection of the transition layer with the bottom and high fish densities were inshore of the hydroacoustic transects.

Additional support for the hypothesis that arctic cod position themselves shoreward of the transition layer is provided by data in Craig and Haldorson (1981) and Chin *et al.* (1979). A massive influx of age 1-3 arctic cod at Milne Point in Simpson Lagoon and along the west side of the West Dock was reported beginning on 14 August 1978 (Craig and Haldorson, 1981). In addition, the second highest otter trawl catch rate recorded in the present study during 16-21 August 1978 sampling was in the shallow waters of Prudhoe Bay, an area where catch rates were lowest during 1979. On 13 August 1978, the marine water mass approached to within at least 1.5 m of the surface throughout much of the area, including along the Stump Island, West Dock and Prudhoe Bay subareas (Chin *et al.*, 1979). Arctic cod orienting to the area where the transition layer intersects the bottom thus would have entered depths of approximately 1 m or less and would almost certainly have migrated into Simpson Lagoon as well as into Prudhoe Bay. Catches of arctic cod in Simpson Lagoon remained high until 22 August 1978, then declined as cod moved out of the lagoon (Craig and Haldorson, 1981), presumably in response to the reestablishment of a deeper transition layer offshore.

The pattern of arctic cod catches recorded by Griffiths and Gallaway (1982) appear to be similarly influenced by periodic upwelling events. Arctic cod catches in fyke nets placed along the shoreline were typified by sharp peaks in catch rates, lasting 2-3 days, separated by 9-14 days of low or no catch (Griffiths and Gallaway, 1982:Fig. 16). In each case, the sharp increase in catch rate was accompanied or followed by a sharp increase in salinity. Such a pattern would be expected if the arctic cod are orienting to the leading edge of the marine water mass and are moving inshore in advance of upwelling marine waters.

The indication is that demersal species, such as arctic cod, and some pelagic species, possibly arctic char and cisco, position themselves according to the upper edge of the marine water mass and move inshore and offshore in response to the presence of this transition between water masses. The composition of the scattering layer observed at the transition between the two masses was not determined but may contain biological or detrital components. Plankton samples from the vicinity of the transition layer contained significantly more fish larvae than surface samples (Tarbox and Moulton, 1980) and appeared to contain higher densities of copepods and mysids. The concentration of fish larvae and invertebrates may attract arctic cod, which are known to feed on mysids and copepods. Similarly, the presence of arctic cod could attract their predators, i.e., arctic char. Thus the apparent association of fish with water masses may reflect a predator-prey relationship. The reason the biological activity is concentrated at the transition layer between the water masses is as yet unknown. The probable explanation is that there is increased primary production along the front between the marine water mass and the surface water mass, such as is found in the eastern Bering Sea (Goering and Iverson, 1981). The deeper marine water contains higher levels of dissolved nutrients, which stimulates primary productivity when exposed to sunlight at the mixing zone with the warmer surface water. In the Bering Sea, such a transition area is characterized by intense biological activity (Hood and Calder, 1981). It is likely that arctic cod and other fish remain in the warmer surface water mass to maximize energy conversion during the two- to three-month summer feeding period, since metabolic activity in poikilotherms must be minimal in the cold (<–1°C) marine water mass.

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