A MODIFIED MIGRATION MODEL FOR ATLANTIC COD, *Gadus morhua*, OFF THE NORTHEAST COAST OF NEWFOUNDLAND

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A modified migration model for Atlantic cod, *Gadus morhua*, off the northeast coast of Newfoundland.

By

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Abstract

Based on observations of cod overwintering inshore and offshore, a modified migration behavior model for northern cod is presented. The existing paradigm of cod migration behavior considers movement between winter spawning locations offshore and summer feeding locations inshore. These migrations were generally thought to remain relatively consistent from year to year.

Sonic tagging and tracking techniques revealed that some adult cod overwinter inshore, enduring water temperatures previously thought to be inhabited only by juvenile cod. The presence of antifreeze proteins in the blood of wild, adult Atlantic cod during winter indicates that some of the cod overwintering inshore had been exposed to temperatures below 0 ^{o}C for at least 30 days. Cod overwintering offshore did not have antifreeze proteins in their blood. Analysis of mitochondrial DNA sequences showed no significant differentiation of genotype proportions between inshore and offshore samples of cod in NAFO division 3L.

The existing migration behaviour model must be revised taking these new discoveries into consideration. The presence of adult cod throughout the year in the Random Island area of Trinity Bay indicates the year round suitability of this habitat for cod. Cod physiology permits individuals to adapt to the winter ocean temperatures and occupy this habitat during the winter months. The new model predicts that not all cod will migrate offshore in the fall. The migration behavior of an individual cod may not be rigid and an individual may overwinter inshore one year and offshore the next.

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INTRODUCTION

Atlantic cod, *Gadus morhua*, is a commercially important, groundfish species found along western Europe from Iceland to the Bay of Biscay and along eastern Canada from Frobisher Bay to as far south as Cape Hatteras (Scott and Scott 1988). Northern cod are defined as those fish which inhabit the North Atlantic Fisheries Organization (NAFO) statistical areas 2J3KL off Labrador and Newfoundland (Fig. 1). The boundaries of these statistical areas are based on documented distributions of fish populations (Halliday and Pinhorn 1990).

Numerous tag and recapture studies have been carried out in the past in an effort to gain a better understanding of the distribution and migration patterns of northern cod (McKenzie 1956, Templeman and Fleming 1962, Postolakii 1966, Templeman 1974, 1979).

From these tagging studies northern cod were divided into a number of fish "stocks", i.e. recognizable units which have certain area occupying and migratory patterns but whose spawning location is different from those of other stocks (Templeman 1979). In 1962 Wilfred Templeman compiled a report of cod stocks in the Northwest Atlantic which summarized the migration routes and spawning areas. There is a general and substantial migration inshore in summer and offshore in winter (Templeman 1962, 1979, Lear 1984). Although the majority of cod move along these migration routes, most tagging studies have shown some fish to be recaptured in other zones at unpredicted times of year (Templeman and Fleming 1962, Postolakii 1966, Templeman 1974, 1979, Lear 1984). These fish tended to compose a negligible portion of the numbers of cod tagged and the authors of these papers concluded that there was some insignificant intermingling between stocks.

The present paradigm of the migration of northern cod off the northeast coast of Newfoundland based on tag and recapture studies is summarized by Templeman (1979) and Lear and Green (1984) and presented in Figure 1. The migratory pattern of northern cod involves an inshore feeding migration in summer. During the winter cod concentrate near offshore banks for spawning (Lear 1984). Larvae drift inshore to nursery grounds in the bays. The immature cod remain inshore until they mature and then move offshore (Lear and Green 1984). By this description, the behavior of adult *Gadus morhua* involves a similar inshore - offshore migration pattern every year.

Tagging studies have shown that cod on the Labrador and Newfoundland shelves intermingle and overlap greatly from north to south in their winter - spring spawning areas (Templeman 1979). Cod that overwinter on the Funk Island Bank arrive inshore from June to September along the Newfoundland coast from southern Labrador to the Avalon Peninsula (Fig. 1) (Templeman 1979). In particular, cod that overwinter on the eastern and southeastern slopes of the Funk Island Bank contribute mostly to the inshore fishery along the coast south of Cape Freels (Lear 1984).

The properties of the stock model of Atlantic cod which Wilfred Templeman (1979) put forth are numerous. Perhaps the factor of greatest importance is that by his definition the boundaries of stocks and local populations are geographically delineated. This, in fact, is one of the advantages of his model. It benefits management because, if it is known where cod should be at specific times of the year, then cod abundance can be better estimated.

The drawback of Templeman's model also lies in its specificity. Set boundaries do not allow for yearly variation in the species distribution as a result of the variable oceanographic environment.

Findings of a sonic tagging and tracking study by Wroblewski et al. (submitted) revealed that some adult northern cod remain inshore in the Random Island region throughout the winter despite cooling of the entire water column below 0 °C. Wroblewski et al. (submitted) were unable to determine the exact temperature of the water where the overwintering cod were located. With the type of transmitter used, the depth of the fish was unknown.

This thesis research investigates physiological, morphological, and behavioral characteristics of adult cod overwintering inshore in the Random Island area. The objective is to extend the existing migration behavior model for northern cod to accomodate recent observations reported in Wroblewski et al. (submitted) and in this thesis. Research reported here demonstrate that adult northern cod can occupy both the inshore or offshore habitat during the winter. There is little documented evidence of adult cod remaining inshore throughout the winter (Templeman and Fleming 1965, Aggett et al. 1987). Literature shows that cod prefer water temperatures of 0 ° - 5 °C in summer (Rose and Leggett 1988, 1989). With wintertime cooling, inshore waters fall below 0 °C, and cod were believed to move offshore to avoid these sub - zero temperatures.

It is important that the biology of northern cod be described as accurately as possible because of its extreme economic importance to the province of Newfoundland and Labrador. The fishing industry has been a long standing traditional way of life. It is important that this resource be scientifically understood as best as possible so that its existence will be ensured for future generations.

METHODS

Inshore expeditions

The purpose of the inshore expeditions was to observe the inshore winter habitat for adult northern cod and compare and contrast this to the offshore winter habitat. During this field research it was discovered that adult northern cod are capable of enduring temperatures as cold as -1.4 ^{o}C in the waters of Random Island, Trinity Bay, Newfoundland during the winter months. These observations were made using sonic tracking technology and temperature recorders. Individual fish were tagged with depth telemetering sonic transmitters so that the fish's location and depth in the water column could be monitored continuously. Based on this information the ocean temperature was monitored to determine if sub - zero temperatures influenced cod movements.

When it was discovered that adult cod in the Random Island region could tolerate these cold temperatures, the means by which they could do this needed to be determined. Caudal blood samples were taken to determine if antifreeze proteins were present. The question then arose whether fish that remained inshore for the winter were genetically distinct from northern cod overwintering offshore. Consequently tissue from cod was collected for DNA sequence analysis of mitochondrial DNA.

Observational methods

The inshore study was carried out in the Random Island region of Trinity Bay because of the active inshore fishery there (Fig. 2a and 2b). The width of Smith Sound, Northwest Arm and Southwest Arm is about 2 nautical miles, a distance within the range of our tracking instrumentation when placed in the center of the channel. The detection of a transmitter was limited to about 1 nautical mile, less with high sea state. Therefore a

search pattern of stopping periodically in the center of the channel to listen for the presence of sonically tagged cod was adopted.

Inshore work was carried out aboard the 55' longliner CFV *Northern Quest*. Three expeditions were undertaken in January, March and April, 1991 to conduct short term tracking studies. To catch experimental animals, trawl lines (longlines) with 250 hooks, baited with frozen herring, were set in Northwest and Southwest Arms of the Random Sound area in all three months (Fig. 2b). In March and April gillnets were used in addition to trawl lines as longline fishing was unsuccessful. These gillnets had 15.25 cm (6 inch) mesh. A fleet of 5 gillnets each 91.5 m (50 fa) long was deployed. As the trawl line or gillnets were retrieved suitable fish were carefully removed from the fishing gear and placed in a holding tank filled with seawater which was replaced frequently with surface seawater. Selection of a fish for tagging with depth sensing sonic transmitters was based on its ability to exhibit apparently normal buoyancy and swimming activity. Cod which were floating ventral side up or were inactive were discarded.

1. Sonic tagging and tracking

The six V3P and V4P sonic transmitters placed in the fish's body cavity for the short term tracking study were manufactured by Vemco Ltd. ™ * and contained silver oxide batteries. They transmit a predetermined, high frequency pulse (between 32 and 76 kHz). Each tag was equipped with a pressure sensor to determine depth. The specifics of the sonic transmitters are given in Appendix A.

A sonically tagged fish had the transmitter surgically implanted into its peritoneal cavity following the procedure given in Templeman and Fleming (1962). An incision approximately 2 - 3 cm long was made lateral and parallel to the ventral midline, anterior to

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* The name Vemco Ltd. ™ is the company that manufactured the sonic tagging and tracking equipment. Its mention is not intended as an endorsement of their company or products.

the anus. The transmitter was gently inserted into the abdominal cavity. The incision was sutured with one or two stitches depending on the length of the incision, and the fish allowed to recover in the holding tank for about 15 to 30 minutes until it was swimming again. Then it was dropped head first or lowered with a dipnet into the ocean.

Monitoring of the fish took place using a Vemco V-10 directional hydrophone, attached to a 6 m long aluminum pole for hand held control or attached to a depressor for towing from a boom amidships of the tracking vessel. A VR-60 receiver was used to process the transmission into data on depth and position. The location and depth of the fish with time were recorded as accurately as possible approximately every 15 - 30 min. By taking concurrent temperature profiles, the temperature of the water in the vicinity of the fish was determined. Any vertical movements that the tagged cod displayed in response to the temperature structure in the water column was recorded. Horizontal movements were more difficult to measure quantitatively. The fish was considered close to the tracking vessel when the signal coming from the receiver was strong and could be detected at a wide angle (or even 360 ^{o}) when turning the directional hydrophone. The position of a fish some distance away from the tracking vessel could only be estimated qualitatively.

2. Morphometric measurements

The forklength (FL) and weight of all the cod caught by longline and gillnets were recorded to the nearest tenth of a centimeter and tenth of a kilogram. Longlines and especially gill nets will select for larger fish. Therefore weight and length from captured fish are not representative of the total group of fish present.

Examination was made of the stomach contents of fish not used for sonic tagging studies. Food items were identified if possible. Index of gut fullness was not recorded. The maturity stage of the gonads was recorded (Appendix B).

To differentiate adults overwintering inshore from adults arriving from offshore overwintering grounds later in the year, the cod trap landings in the Random Island region were monitored from April 26 to September 3, 1991. A subset of cod that were caught was examined. The number of fish examined on a particular day depended on how many fish were actually landed and the time it took the fishermen to clean their catch. The type of gear and the location of the gear was recorded if possible. Fish were weighed, measured for length, examined for stomach contents, sex and maturity stage. Of primary interest was reproductive state.

3. Antifreeze protein analysis

In April, 1991 blood samples were taken from cod for antifreeze protein analysis. The presence of plasma antifreeze would provide evidence whether the fish were physiologically prepared to encounter sub - zero temperatures. Antifreeze proteins in the blood lower the freezing temperature of cod enabling them to survive in sub - zero water.

Methods are as described by Fletcher, King and Kao (1987). Thermal hysteresis is the difference between the melting and freezing points of the blood plasma and is a measure of antifreeze activity (Kao et al. 1986).

4. Mitochondrial DNA analysis

Genetic analysis has been used to detect stock differentiation in many species of marine teleosts (Gyllensten and Wilson 1987, Bickham et al. 1989). Analysis of mitochondrial DNA has been widely used for such purposes (Wilson et al. 1985).

Genetic analysis was performed on cod that were caught but not used for sonic tagging. Hearts were removed, and all samples from a single location were frozen together in a single plastic bag. Date and location of collection were recorded. The hearts were frozen and stored at -70 °C prior to laboratory analysis. Analysis was carried out on a 359 base pair (bp) portion of the mitochondrial cytochrome *b* gene that had previously been used to differentiate cod populations in the north Atlantic (Carr and Marshall 1991a).

The experimental procedures are described in detail by Carr and Marshall (1991a, b) with the following changes. These methods involved a polymerase chain reaction (PCR) and direct DNA sequencing to study the genetic variation. After clearing, samples were extracted with phenol - chloroform. Further removal of impurities in isolated mtDNA took place using ether. For PCR amplification 2 µL of the DNA preparation to be amplified was added to the chemical mixture. The buffer used in gel electrophoresis was TBE (trisma base, boric acid, Na EDTA), pH 7.4, containing ethidium bromide (1 µg/mL). Steps after electrophoresis were modified according to the following procedure:

Millipore purification. The remainder of the amplification product was purified by centrifugation on millipore filters and reconstituted in 100 µL dH2O.

Fluorometer readings. The DNA concentration of the samples was determined in a Hoefer Scientific Instruments TKO 100 Fluorometer. Based on the fluorometer readings an amount of product was used so that it contained 1/3 µg = 1.1 pmol of 1.0 kb ds DNA and used for sequencing.

DNA sequencing. DNA sequences were determined on an Applied Biosystems 373A Automated DNA Sequencer according to standard protocols; details will be reported elsewhere (S. Carr, in prep.). The DNA sequencer uses a standard Sanger sequencing chemistry in which each dideoxy terminator is covalently linked to a different fluorescent

dye. Products of the reaction are separated electrophoretically, and the DNA sequence is read by a scanning laser as a series of chromatographic peaks corresponding to the intensity of one of the dyes, each of which represents one of the four DNA bases (A, C, G, or T) (Carr and Marshall 1991b, Fig. 1).

Offshore expedition

The research plan was to determine morphological, physiological and behavioral characteristics of cod overwintering inshore and then compare these to similar observational results obtained from cod overwintering offshore. The offshore expedition was carried out aboard the *CSS Dawson* in May, 1991. The search for cod was influenced by the extensive pack ice which existed off the northeast coast of Newfoundland at that time (Fig. 2a). A baited trawl was set in the area of Tobin's Point on the northern Grand Banks, a fishing ground located at approximately 49° 30' N, 50° 30' W, and allowed to fish for 5 h at depths of 306 - 324 m. Bottom temperature was 3.0 °C (Fig. 3). Gillnets were not used as the research vessel was not equipped for this fishing gear. Sonically tagged fish were released close to the capture site and tracked with the same equipment used in the inshore study.

Because only 5 fish were caught we requested assistance from the National Sea Products trawler, *Cape Farewell*, which was fishing in the area at the time. They transferred to us at sea a sample of cod from a recent tow. These fish were used for morphometric measurements, mtDNA analysis of heart tissue and antifreeze protein analysis of blood samples, but not for tagging experiments. For the purpose of catching additional cod for sonic tagging studies further inshore, two more baited trawls were set 20 nautical miles off Cape Bonavista (48° 56.71' N, 52° 41.82' W and 48° 49.90' N, 52° 30.72' W) but were not successful in catching any cod (Fig. 2a).

A potential problem was expansion of the swim bladder of cod brought from 300 m to the surface for sonic tagging. It was anticipated that a hypodermic needle could be used to remove gas from the bladder. Not all fish caught appeared to suffer from air in the body cavity due to a decrease in pressure. We were able to tag and release fish apparently swimming normally. Whether the swim bladder of these fish was damaged is unknown.

Tagged cod were tracked continuously for up to 30 h.

RESULTS

Observations of adult northern cod overwintering in an inshore habitat:

A total of 194 cod caught in January and April, 1991 (Table 1) document the presence of cod overwintering in the Random Island region of Trinity Bay in early 1991. No cod were caught during the expedition to Southwest Arm in March. Cod caught in April were taken from < 0 °C water (Fig. 4). Daily summaries of fork length and weight are given in Table 2. The mean fork length of the cod overwintering inshore, sexes combined, was 57.6 ± 9.2 cm with a range of 37.6 to 96.5 cm (Table 3). The distribution of length frequency is shown in Fig. 5 (top). The mean weight, sexes combined was 1.9 ± 1.3 kg with a range of 0.2 to 11.3 kg (Table 3). The distribution of weight frequency is shown in Fig. 5 (bottom). The largest cod captured was 96.5 cm FL and 11.3 kg.

Fleming (1960) determined the age of cod from otoliths and found that they reach 50% maturity at 5.8 years. Ages of the 194 fish overwintering inshore were determined from a length - age relationship calculated from data given in the same report (Fig. 6). Ages for fish larger than 70 cm are highly variable and calculated ages above 14 years may be inaccurate. Cod less than 2 years and greater than 14 years were not extrapolated from the data. The mean age of the cod overwintering inshore was 7.8 ± 2.9 yr. with a range from < 2 to > 14 yr. (Table 4). Not all cod could be sexed. The mean age for males was 7.5 yr. and for females 8 yr. A frequency distribution of ages showed that the majority of cod were 6 yr. and older (Fig. 7, top).

Spawning condition (Appendix B) was determined upon capture and recorded on a scale of 0 to 3 (Table 5). Most of the fish that were captured were either immature (stage 0) or ripening (stage 1). In early April six fish were classified as spawning (stage 2) although two fish were found at stage 2 in January. No spent fish were found in the Random Island region during the months of January and April, 1991.

Examination of stomach contents showed that some of the fish in the inshore study area were feeding. In the Random Island region 30% and 44% of fish examined had some evidence of prey in their stomachs in January and April respectively.

For comparative purposes a total of 994 cod trapped fish was examined from May 29 to September 3, 1991. These cod were generally smaller than those cod found overwintering inshore (Table 3). The length distribution is shown in Fig. 8. The mean length was 50.0 ± 6.0 cm and the mean weight was 1.2 ± 0.8 kg (Table 3). Average length for fish caught during the first two weeks of June was 49.0 ± 6.5 cm and for fish caught during the last two weeks of August was 51.0 ± 5.5 cm.

Ages of cod trapped fish examined were calculated from lengths in the relationship developed in Fig. 6. The mean age for sexes combined of the entire sample was 5.5 ± 1.9 yr. (Table 4).

The stomachs of these fish were generally full, containing a variety of prey types including capelin, shrimp, blackberry (a pteropod), crab, and jellyfish.

Examination of the gonads showed that a 66 cm male fish weighing 3.0 kg was spent on June 11, 1991 (Table 6). The next recordings of spent fish were two males and one female on June 14. Eight spent fish were recorded in July. The bulk of spent cod were landed during the month of August when 79% of that month's sample of mature cod were spent fish (Fig. 9). A small number of immature fish were still in the area during August, and the majority were males.

Tagging and tracking of inshore cod

One goal was to determine the temperatures in which fish overwintering inshore were living. The short battery life (2 - 7 days) of the transmitters did not permit long term tracking of individual cod. Of particular interest was where in the water column these cod

were located: in the warmest part of the water column or on the bottom regardless of the temperature?

Three fish were tagged with depth sensing sonic transmitters in the Random Island region (Table 7). All inshore tagging work was carried out in Southwest Arm. The first fish, designated #1, was tagged on January 29, 1991. The depth track of the fish and the temperature structure of the water in the location of the fish is shown in Fig. 10. The surface water down to 80 m was less than 0 °C, while from 80 - 110 m it was above 0 °C. The fish moved in water both above and below freezing temperatures. Tracking ceased after 30 h because of a storm warning in the area.

The second fish, #2, was tagged on April 7, 1991 (Table 7). On this date the water column temperature was sub - zero. This fish did not go directly to the bottom but descended in steps (Fig. 11). This fish was tracked for 33 h at which point we left to conduct a temperature survey and were not able to relocate it when we returned. Fish #2 was caught in a cod trap on May 22, 1991 off Britannia in Smith Sound.

The third fish, #3, was tagged two days later on April 9, 1991 (Table 7). Upon release this large cod proceeded directly to the bottom (210 m) where it remained for the 8 days it was tracked (Fig. 12). Fish #3 was tracked continuously for 46 h but showed limited horizontal movement. Although we left the area on April 11, we returned on April 13 and 16 to make small excursions in a speed boat to the area to see if fish #3 had moved or had changed its depth. On both occasions we found the fish in approximately the same location and depth as it was on April 11.

Antifreeze protein analysis of inshore cod

Blood samples were collected from 47 cod in the Random Island region in April, 1991. These cod ranged in length from 38 to 89 cm. The thermal hysteresis was

measured directly from the samples and produced a mean value of 0.165 ± 0.079 °C. A thermal hysteresis of less than 0.100 °C indicates very low, if any, antifreeze activity (Sally Goddard, Memorial University, St. John's, pers. comm.).

Results show that 37 of 47 cod (79%) had a thermal hysteresis value equal to or greater than 0.100 °C (Fig. 13, top). Cod with antifreeze had probably been exposed to temperatures < 0 °C for about 30 days (Fletcher et al. 1987). The mean length of these cod was 54.9 ± 11.4 indicating that adult cod overwintering inshore are capable of producing antifreeze. There was no relationship between thermal hysteresis and length (Fig. 14, top).

Of the 47 cod that were sampled for antifreeze in April, fifteen had been marked with Peterson discs by DFO as part of an extensive tagging program in which 2690 cod were tagged in Southwest Arm between January 21 and 28, 1991. Fourteen of these fifteen cod had levels of antifreeze protein in their blood indicating exposure to water temperatures < 0 °C for 30 days. They ranged in length from 39 cm to 57 cm.

Mitochondrial DNA analysis of inshore cod

Direct DNA sequencing of a 307 bp region of the mitochondrial cytochrome *b* gene of cod has revealed more than two dozen genotypes, differing from each other by one to six base pair substitutions (Carr and Marshall 1991b). Of these genotypes 15 are found in 3L. Among the 47 cod examined from the inshore region of Random Island, six genotypes were found. Genotype A, the most common genotype in cod from the western north Atlantic (Carr and Marshall 1991a) was found in 40 (85%) of the fish. The second most common was found in three (6%) of the fish, and four more genotypes were found in a single fish each (2%) (Table 8).

Observations of adult northern cod overwintering in an offshore habitat:

A total of 23 offshore cod were obtained from the *Cape Farewell* and baited trawl. The mean length was 55.0 ± 8.0 cm and the mean weight was 1.2 ± 0.6 kg (Table 3). Lengths ranged from 39.4 to 71.9 cm and weights ranged from 0.1 to 2.7 kg (Table 3).

Age was determined from lengths according to the relationship developed in Fig. 6. The frequency distribution is shown in Fig. 7 (bottom). This sample of offshore cod, sexes combined, ranged in age from 2 to 12 yr. with a mean value of 7.0 yr. (Table 4). As with the inshore sample some immature cod could not be sexed. Of those that were, females ranged from 4 to 12 yr. with a mean of 7.4 yr. while males ranged from 4 to 12 yr. with a mean of 7.3 yr. As previously mentioned, cod aged from otoliths were found to have reached 50% maturity at 5.8 yr. (Fleming 1960).

Spawning condition was determined upon capture and recorded on a scale of 0 to 3 (Appendix B). Out of 18 fish from the *Cape Farewell* that could be sexed, eight were spent (40%) and one cod was immature (Table 5).

Examination of the stomach contents showed that of the 20 fish received from the *Cape Farewell*, five (25%) had been feeding recently on unidentified fish and crab. This low value may have been due to the fact that spawning was underway and the cod were not feeding. Only two of the spent fish were feeding.

Tagging and tracking of offshore cod

Despite the adverse ice conditions, three cod were released with depth sensing sonic transmitters in the offshore region of Tobin's Point on the northern Grand Banks. Bottom temperatures in the area of these fish were 3 °C. Fish #4 was tagged on May 15, 1991 (Table 7), taking 6 hours to reach the bottom (Fig. 15). It is interesting to note that there are two reversals in descent of fish #4. These events occur at 230 m and at 290 m

which seems to correspond to layers of slightly cooler water. A plot of the horizontal movements of this fish on May 16 is shown in Fig. 16.

During tracking of fish #4 on the morning of May 17, 1991 the Fisheries Products International trawler *Zandberg*, crossed the bow of the *CSS Dawson* fishing with an otter trawl. Fish #4 was caught in the towed net. As the *Zandberg* steamed away the signal from the fish became weaker. It was certain that fish #4 had been caught in the otter trawl net. Fish #4 was apparently in an area abundant with cod. The fish escaped from the otter trawl before it was brought on board the *Zandberg*. We picked up the signal at a depth of 80 m about 2 nautical miles from where the fish was caught on the bottom.

Fish #5 was also tagged on May 15 (Table 7). This fish reached the bottom in about 2 h (Fig. 17), less time than it took fish #4 although they were released in the same location. The temperature profile was the same as for the previous fish but the descent of fish #5 showed no hesitation in its descent. After fish #5 was on the bottom the signal was lost and was not picked up again until 31 h later. We found #5 not far from its release position and concluded that when it initially reached the bottom it hid in a crevice or a hole which prevented us from picking up the signal. This fish was tracked for 11 additional hours before the experiment had to be cut short because of the presence of pack ice.

The final fish tagged weighed 1.4 kg and was 54 cm long, the smallest of the 3 tagged cod. Upon release of fish #6 two depth readings were recorded. Then the signal was lost and was not picked up again during the remainder of the cruise.

Antifreeze protein analysis of offshore cod

Blood samples were collected from 19 cod offshore in the Tobin's Point area caught by the *Cape Farewell*. Cod sampled had lengths ranging from 39 to 72 cm. All but two cod were sexually mature and eight were spent. The mean value for the thermal

hysteresis of the offshore cod collected was 0.062 ± 0.009 °C. All values were less than 0.100 °C (Fig. 13, bottom). As previously mentioned any value less than 0.100 °C indicates very low, if any, antifreeze activity. It is likely that these fish were exposed to bottom temperatures > 0 °C during the entire winter and therefore did not produce antifreeze proteins. There was no relationship between thermal hysteresis and length (Fig. 14, bottom)

Mitochondrial DNA analysis of offshore cod

Because of improper storage of collected tissue, mitochondrial DNA could not be successfully sequenced from the offshore samples collected from Tobin's Point. Genotype proportions of the inshore (Random Island) sample were therefore compared with three other series of cod samples taken from 3L (S. Carr, unpublished data). These were 21 fish taken from the northern Grand Banks in June 1988, 47 fish collected from the center of Trinity Bay in March 1990, and 88 fish from a fish plant in Flatrock, Avalon Peninsula, that possibly represent a mixture of inshore and offshore cod processed in June 1989 (Table 8). As with the Random Island sample, the majority of the fish had genotype A. The distribution of genotypes among these four samples was tested for heterogeneity by the Monte Carlo chi - square test of Roff and Bentzen (1989). The calculated chi - square of 44.81 (42 degrees of freedom) was insignificant ($p = 0.33$).

DISCUSSION

The results of this study of northern cod overwintering in inshore and offshore areas are several. The presence of sexually mature fish overwintering inshore is direct evidence that not all adult northern cod move offshore in the fall. Sonic tracking and temperature surveys of the region proved that adult cod can inhabit sub - zero temperature water during the winter months in the Random Island region.

The increase in the presence of spent fish in cod trap landings during August 1991 was probably due to the arrival of offshore fish at the coast. These fish had presumably spawned offshore. A time series of the percentage of spent fish throughout the spring and summer of 1991 clearly shows the appearance of spent fish on 214 Julian day or August 2 (Fig. 8). Spent fish on 189 Julian day (July 8) may be a result of inshore spawning. There is some evidence that spawning takes place in the Random Island region or other areas of Trinity Bay. Unpublished data shows that cod eggs and early stage larvae have been found in Random Sound (E. Dalley, DFO, St. John's, pers. comm.). More research is necessary to determine where in Trinity Bay northern cod spawn. Freshly spawned eggs have been caught in Placentia, Conception, and Trinity Bays between May and September (Thompson 1943).

Cod from the lower part of the northeast coast of Newfoundland reach 50% maturity at 54 cm (Fleming 1960). Table 3 indicates that some cod spending the winter inshore were indeed adults. The sizes of some of the cod sampled from cod traps during the spring and summer are smaller than the size of maturity specified by Fleming but examination of the gonads revealed that 83% of these fish were mature (ripening, spawning or spent).

It was discovered that some adult cod will remain inshore during the winter enduring sub - zero temperatures and producing blood plasma antifreeze proteins. There

is little documented evidence of cod found inshore in sub - zero temperatures during the winter. Those reports which do exist generally describe juvenile cod (Templeman and Fleming 1965, Aggett et al. 1987). The observation that adult cod spend extended periods of time in waters of sub - zero temperatures has not been previously reported, although laboratory experiments have shown that cod are physiologically capable of so doing (Harden-Jones and Scholes 1974, Hew et al. 1981, Fletcher et al. 1987, Kao and Fletcher 1988, Goddard et al. 1992).

There have been cases reported in which large numbers of fish including cod have died due to exposure to sub - zero temperatures (Woodhead and Woodhead 1959, Templeman 1965, Templeman and Fleming 1965). Adult cod will produce antifreeze if the water temperature is 1 ^{o}C, but a temperature of 0 ^{o}C and colder is necessary to maintain antifreeze production (Fletcher et al. 1987). Cod become supercooled if their body temperature falls below their freezing temperature. If a supercooled fish comes in contact with an ice crystal it freezes in a few seconds. Under the same winter conditions adult northern cod produce less plasma antifreeze proteins than juveniles (Kao and Fletcher 1988, Goddard et al. 1992). For this reason it is believed that adult codfish are less able to withstand sub - zero temperatures.

Antifreeze analysis has been carried out on live cod that were caught in cod traps inshore during the summer (Fletcher et al. 1987, Goddard et al. 1992). These fish (likely a mixture of inshore and offshore cod) were kept at sea surface temperatures throughout the winter. Results show that they produce quantities of antifreeze proteins when the water temperature fell below 0 ^{o}C (about the beginning of January).

Wild cod caught in Southwest Arm in January would not be expected to have high levels of antifreeze proteins in their blood because bottom temperatures were still above zero and antifreeze production would not have been induced. Cod captured from the wild

in Southwest Arm in April, 1991 had been exposed to sub - zero temperatures for about one month and had antifreeze levels similar to laboratory cod. In this sense antifreeze activity gives some indication of the fish's temperature history.

Not all inshore cod captured from the same area had comparable antifreeze levels. Some fish which overwintered inshore must have been exposed to > 0 °C water. Although ten or 21% of the fish captured in Southwest Arm in April had insignificant amounts of antifreeze plasma protein in the blood, they were captured in sub - zero water. They had evidently spent some of their time in waters with temperatures which did not induce antifreeze production (above 0 °C) and had recently moved in to sub - zero water. They may have come from offshore areas, or from warmer water existing in deeper parts of Trinity Bay.

The fact that the cod caught offshore did not have any antifreeze does not mean that they are incapable of antifreeze production. It only means that their environment did not induce its production. The offshore bottom temperatures of 2 ° to 3 °C apparently are not low enough to induce antifreeze production.

Evidence that cod overwintering inshore remain close to the coast arises from the returns of transmitters by fishermen (Wroblewski et al. submitted). Two cod tagged for sonic tracking throughout the winter were recaptured five and seven months later 50 nautical miles to the south and north of the tagging site in the Random Island area. A third fish was caught 3 days short of a year later on the south coast of Newfoundland in Fortune Bay, at least 305 nautical miles from the tagging site. This fish was also caught inshore. A fourth sonically tagged cod was caught almost 11 months later near Clarenville, probably spending the entire year of 1991 in Northwest Arm. A fifth was caught 5 months after release in January 1991 in Random Sound.

That fish #2 was recaptured in a cod trap one and a half months later in Britannia, Smith Sound, 30 nautical miles from the release location indicates that it survived after the tracking observations were made. These returns (Wroblewski et al. submitted, this study) are evidence that some overwintering cod will remain inshore into the spring and summer months.

Other evidence for the existence of cod overwintering in bays comes from recent tag and recapture studies by DFO. During the last week of January in 1991 DFO released 2690 cod tagged with Peterson discs and spaghetti T - bar tags in Southwest Arm of Random Sound. From March to May of the same year 319 of these cod were caught by fishermen in the Random Island region (C. Taggart, DFO, St. John's, pers. comm.). indicating that at least some of these cod were still in the region. In addition, 10 of these tagged cod were recaptured on the northern Grand Banks a year later in January and February of 1992. These data suggest that some adult cod may vary their overwintering location from year to year by overwintering inshore in sub - zero temperatures one year and migrating offshore to warmer water the following year.

That 14 of the 15 DFO tagged cod recaptured during this research had significant levels of antifreeze indicates that they remained in Southwest Arm from the time they were tagged in January until they were caught and measured for antifreeze in April. This is another indication that cod have the ability to withstand these temperatures.

Mitochondrial DNA analysis was used to compare cod overwintering inshore and offshore. Significant differences in the genetic sequence of the cytochrome *b* gene would indicate that not enough intermingling occurred between inshore and offshore groups to render them a single population. As no differences were found, there is evidently enough intermixing between inshore and offshore groups to decrease the amount of genetic variability among northern cod in this portion of the Newfoundland coast.

The PCR method has been found to have several advantages for the detection of genetic variation within fish populations, including few problems with the quantity of tissue and its sensitivity to subtle genetic variations within populations (Carr and Marshall 1991a, b).

Ideally tissue samples should have been collected during spawning when separate groups of cod would have been most discrete and the degree of intermingling would have been the lowest. If differences exist between cod which overwinter inshore and offshore, these would be better studied by comparing the two spawning groups. Sampling during fall or summer would have inshore and offshore cod intermixing. Because the mt DNA technique has been successful in the past in detecting differences between populations of cod on the Scotian shelf, western Atlantic and the eastern Atlantic, any significant differences existing between the samples of cod examined should have become evident with this procedure. All the work completed to date on various samples of cod from all over the northeast Newfoundland shelf shows no tendency towards heterogeneity (S. Carr, Memorial University, St. John's, pers. comm.).

The lack of genetic variation found between inshore and offshore samples of cod is consistent with the ability of cod from offshore and inshore to produce antifreeze proteins. The lack of differentiation may be the result of a number of factors. The fragment being analyzed may not be the most variable of the mtDNA strand. In the evolution of these fish there may have been a recent period of strong selection and the population may not have had a chance to rediversify its mtDNA. Or there may indeed be sufficient intermixing of inshore and offshore populations resulting in a lack of differentiation (Carr and Marshall 1991a). The latter is likely the case. Since some DFO tagged cod overwintered inshore in one year and moved offshore the following winter there is evidence of mixing of the northern cod gene pool, perhaps resulting in a loss of heterogeneity.

Results from the present study (antifreeze analysis, tagging and tracking, mt DNA analysis) suggest that not all adult northern cod move to offshore spawning grounds in the fall. Templeman's (1979) migration model was appropriate when overwintering of adult cod inshore was unobserved. The sonic tracking techniques employed here and by Wroblewski et al. (submitted) make possible repeated observation of individual cod through the winter. That some adult cod remained inshore for the winter probably was always true but scientists had no way of observing this directly. The only way in the past to observe cod inshore during the winter was for fishermen to catch them. But fishing on the northeast coast of Newfoundland is greatly curtailed in winter by poor weather and ice conditions. As well, cold water temperatures reduce movement and feeding in cod making them difficult to catch by gillnet or baited trawl (McKenzie 1938). This discovery of adult fish overwintering inshore does not fall within a simple paradigm of cod migration that predicts that all mature cod move according to the time of year toward specific spawning and feeding grounds. Templeman and Fleming (1965) believed that adult fish move offshore in the fall to avoid sub - zero water temperatures.

The revised migration behavior model put forth here focuses on the adaptability of northern cod. It suggests that the behavior of all individuals is not restricted to one migration pattern. Their physiology permits them to manufacture antifreeze proteins and make them cold tolerant. Indications are that all adult northern cod have this ability and will make these proteins if the environmental conditions necessitate it, providing they are permitted to acclimate over a period of time. However if the water is $> 0\ ^{o}C$, and the cod are not in any danger of freezing, then metabolically costly antifreeze proteins will not be produced. Cod in the Random Island region, which lacked high levels of antifreeze, were assumed to have recently been in warmer water, perhaps in the deeper parts of Trinity Bay. Those cod which choose to remain close to shore for the entire winter encounter a

point where the whole water column falls below zero degrees Celsius. In order to adapt to this temperature change, they begin to manufacture antifreeze proteins.

CONCLUSIONS

Based on observations of cod overwintering inshore and offshore a modification of the existing migration behavior model for northern cod is suggested. Adult northern cod can overwinter inshore as well offshore. This research and related studies indicate that the migration behavior of an individual cod may not be rigid. An individual may overwinter inshore one year and offshore the next. The majority of individuals overwinter offshore. Both inshore and offshore cod have the ability to manufacture antifreeze proteins to survive sub - zero temperatures which occur in inshore waters during the winter. Synthesis of antifreeze glycoproteins is not necessary for cod overwintering in above zero water at the edge of the continental shelf. Genetic analysis of mtDNA detected no significant diffferences between cod overwintering inshore and offshore, adding to the evidence that the same animal can exhibit different migration behavior. More research is needed to understand the factors behind the individual's choice to overwinter either inshore or offshore. This behavior may allow northern cod to survive in a constantly changing ocean environment.

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Table 1: Gear type, catch and bottom temperature during experimental fishing carried out in the Random Island region during winter 1991. Trawl refers to baited (herring) longline. Gillnets were 15.25 cm (6 inch) mesh. N/A is not available.

Date Set - Hauled	Location	Depth (m)	Gear	Fishing time (hrs.)	# Fish	Bot. Temp. (°C)
Jan. 28-29	Hatchet Cove	110-165	trawl	18	28	0.4 to 0.7
Jan. 29-30	Hatchet Cove	110-165	trawl	12	27	0.4 to 0.7
Jan. 30-31	Hatchet Cove	110-165	trawl	12	23	0.4 to 0.7
Mar. 13-13	Gooseberry Island	110-165	trawl	8.5	0	-1.3 to-1.4
Mar. 13-14	Hatchet Cove	37-174	gillnets	15	0	-0.8 to-1.0
Mar. 13-14	Hatchet Cove	18-95	trawl	15	0	-0.8 to-1.0
Mar. 14-15	Gooseberry Island	64-128	gillnets	20	0	-1.1 to-1.4
Mar. 14-15	Salmon Cove	183-324	trawl	20	0	N/A
Mar. 15-15	Gooseberry Island	128-155	trawl	5	0	-1.4
Apr. 5-6	Salmon Cove	166	trawl	14	0	-1.3
Apr. 5-6	Random Sound	298	gillnets	14	0	-0.8
Apr. 6-7	Hatchet Cove	42-166	trawl	17	4	-0.9
Apr. 7-8	St. Jones Within	180	gillnets	N/A	10	N/A
Apr. 7-8	Hatchet Cove	238	trawl	12	3	-0.6
Apr. 7-8	Hatchet Cove	152-238	gillnets	12	44	-0.7

Apr. 8-9	Hatchet Cove	181-219	gillnets	17	36	-0.7
Apr. 9-10	Island Cove	219	gillnets	12	11	-0.7
Apr. 10-11	Hatchet Cove	238	gillnets	12	8	-0.7

Table 2: Daily summary of fork length (cm) and weight (kg) of northern cod captured for sonic tracking experiments in 1991.

Date	n	mean Fork Length (cm ± S.D.)	mean Weight (kg ± S.D.)
January 29	26	55.2±6.0	1.3±0.6
January 30	26	54.1±6.9	1.2±0.6
January 31	21	56.0±4.4	1.4±0.5
April 7	2	53.4±9.0	1.9±0.6
April 8	33	58.7±10.6	2.2±1.5
April 9	36	60.3±9.3	2.4±1.3
April 10	11	60.0±9.2	2.2±1.0
April 11	7	59.6±11.4	2.4±1.6
May 15	3	56.4±2.0	1.5±0.2
May 16	20	54.8±8.6	1.2±0.6

Table 3: Fork length (cm) and weight (kg) of northern cod sampled from the Random Island and offshore shelf (Tobin's Point) regions during 1991. W is winter and S is spring and summer.

		n	mean ± S.D.	minimum	maximum
Length (cm)	Random Island(W)	194	57.6±9.2	37.6	96.5
	Random Island (S)	994	50.0±6.0	35.6	111.8
	Tobin's Point(S)	23	55.0±8.0	39.4	71.9
Weight (kg)	Random Island(W)	195	1.9±1.3	0.2	11.3
	Random Island(S)	994	1.2±0.8	0.3	19.0
	Tobin's Point(S)	23	1.2±0.6	0.1	2.7

Table 4: Mean age (years) of northern cod sampled from the Random Island and Tobin's Point regions during 1991. Age was determined from data given in Fleming (1960). W is winter and S is spring and summer.

Location	n	mean ± S.D.	minimum	maximum
Random Island(W)	194	7.8±2.9	< 2	> 14
Random Island(S)	994	5.5±1.9	< 2	> 14
Tobin's Point(S)	23	7.0±2.5	2.2	12.3

Table 5: Maturity condition for northern cod caught during fishing for experimental animals in the Random Island and offshore shelf (Tobin's Point) regions in winter and early spring of 1991. See Appendix B for condition criteria.

Date	Location	Sex	n	Condition 0	1	2	3
January 29	Hatchet	Male	9	2	7	0	0
	Cove	Female	16	8	8	1	0
January 30	Hatchet	Male	10	2	8	0	0
	Cove	Female	15	7	8	1	0
January 31	Hatchet	Male	7	7	0	0	0
	Cove	Female	8	2	6	0	0
April 7	Hatchet	Male	1	1	0	0	0
	Cove	Female	1	0	1	0	0
April 8	Hatchet	Male	11	1	8	2	0
	Cove	Female	21	1	18	2	0
April 9	Hatchet	Male	17	1	16	0	0
	Cove	Female	19	2	15	2	0
April 10	Island	Male	3	0	3	0	0
	Cove	Female	8	2	6	0	0
April 11	Hatchet	Male	1	0	1	0	0
	Cove	Female	6	1	5	0	0
May 16	Tobin's	Male	11	1	0	5	5
	Point	Female	7	0	2	2	3

Table 6: Maturity condition of northern cod sampled from cod traps in the Random Island region from May to September, 1991. Where location says Brook Cove also included are Deer Cove Island, Ford's Head, and Hoppin' Stone. N/A is not available.

Date	Location	Sex	n	Condition 0	1	2	3
May 29	Brook Cove	Male	8	1	1	6	0
		Female	9	4	5	0	0
June 4	Canon Cove	Male	10	6	1	3	0
		Female	11	9	2	0	0
June 11	Island Ledge	Male	14	2	7	4	1
		Female	29	6	14	9	0
June 13	Island Ledge	Male	9	1	0	8	0
		Female	21	8	7	6	0
June 14	Gull Rock Bight	Male	46	7	6	31	2
		Female	56	13	30	12	1
June 25	N/A	Male	5	4	0	1	0
		Female	11	8	1	2	0
July 8	Manuel's Island	Male	8	2	2	1	3
		Female	15	13	2	0	0
July 9	Big Island	Male	10	7	2	0	1
		Female	10	2	8	0	0
July 10	N/A	Male	10	6	3	1	0
		Female	17	4	12	1	0
July 31	Burn Point	Male	7	3	0	1	3
		Female	11	0	10	0	1
August 1	N/A	Male	6	1	1	1	3
		Female	8	0	1	0	7
August 2	Big Island	Male	16	0	0	0	16
		Female	27	0	0	1	26
August 8	N/A	Male	28	15	1	1	11
		Female	36	1	2	3	30
August 16	Brook Cove	Male	32	4	4	6	18
		Female	37	0	15	0	22
August 19	Brook Cove	Male	57	8	1	12	36
		Female	67	1	19	1	46

August 21	Brook Cove	Male	8	1	0	1	6
		Female	23	0	7	0	16
August 22	Brook Cove	Male	31	5	0	2	24
		Female	47	0	3	1	43
August 26	Brook Cove	Male	25	1	0	2	22
		Female	39	0	4	2	33
August 27	Brook Cove	Male	19	2	1	2	14
		Female	32	0		0	26
August 28	Brook Cove	Male	38	6	0	5	27
		Female	50	0	13	1	36
August 29	N/A	Male	9	4	1	1	3
		Female	11	0	5	1	5
August 30	N/A	Male	2	0	0	0	2
		Female	4	0	2	0	2
September 3	Brook Cove	Male	7	2	1	2	2
		Female	5	0	1	0	4

Table 7: Sonic tagging and tracking experiments. Weight (kg) and fork length (cm) of individual cod tagged with depth telemetering transmitters in Southwest Arm, Trinity Bay (January 29, April 7, 9) and Tobin's Point (May 15) during 1991. Holding time (hours:minutes) is the time the fish spent in the holding tank after it was tagged and before it was released. Time to bottom (hours:minutes) is the interval between time of release and time the fish reached the bottom.

Capture Date	Fish #	Temp. Caught	Depth Caught	Weight (kg)	Length (cm)	Holding Time	Time to Bottom	Bottom Depth	Bottom Temp.	Hours Tracked
January 29	1	0.4 °C	140 m	1.5	52.8	0:20	0:32	105 m	0.4 °C	30
April 7	2	-0.9 °C	100 m	2.9	68.6	0:35	0:14 †	74 m	-1.4 °C	33
April 9	3	-0.7 °C	200 m	11.3	96.5	0:12	0:22	210 m	-0.6 °C	192
May 15	4	3.0 °C	324 m	1.8	57.2	0:30	5:45	334 m	3.0 °C	37
May 15	5	3.0 °C	324 m	1.4	57.8	0:55	2:11	334 m	3.0 °C	2+11 ††

† Fish #2 reached 62 m depth in 14 minutes and remained at this depth for 8 hours and 45 minutes. Thereafter it was at a depth of 74 m.

†† The signal for fish # 5 was lost after it reached the bottom in 2 hours. The signal was picked up again 32 hours later and followed for 11 additional hours before the study was ended.

Table 8: Frequency of occurrence of 15 genetic haplotypes in the mitochondrial DNA of four sample sets of cod collected from the Northern Grand Banks, the middle of Trinity Bay, a fishplant in Flatrock and the Random Island area of NAFO division 3L on the northeast coast of Newfoundland.

		Haplotype														
Location	n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Northern Grand Banks	21	19	0	0	1	0	0	1	0	0	0	0	0	0	0	0
Middle of Trinity Bay	47	41	0	0	2	0	0	0	1	0	0	1	1	1	0	0
Fishplant in Flatrock	88	71	1	1	3	3	3	1	3	0	0	0	1	0	1	0
Random Island	47	40	0	1	0	0	0	0	0	1	1	0	0	0	1	3

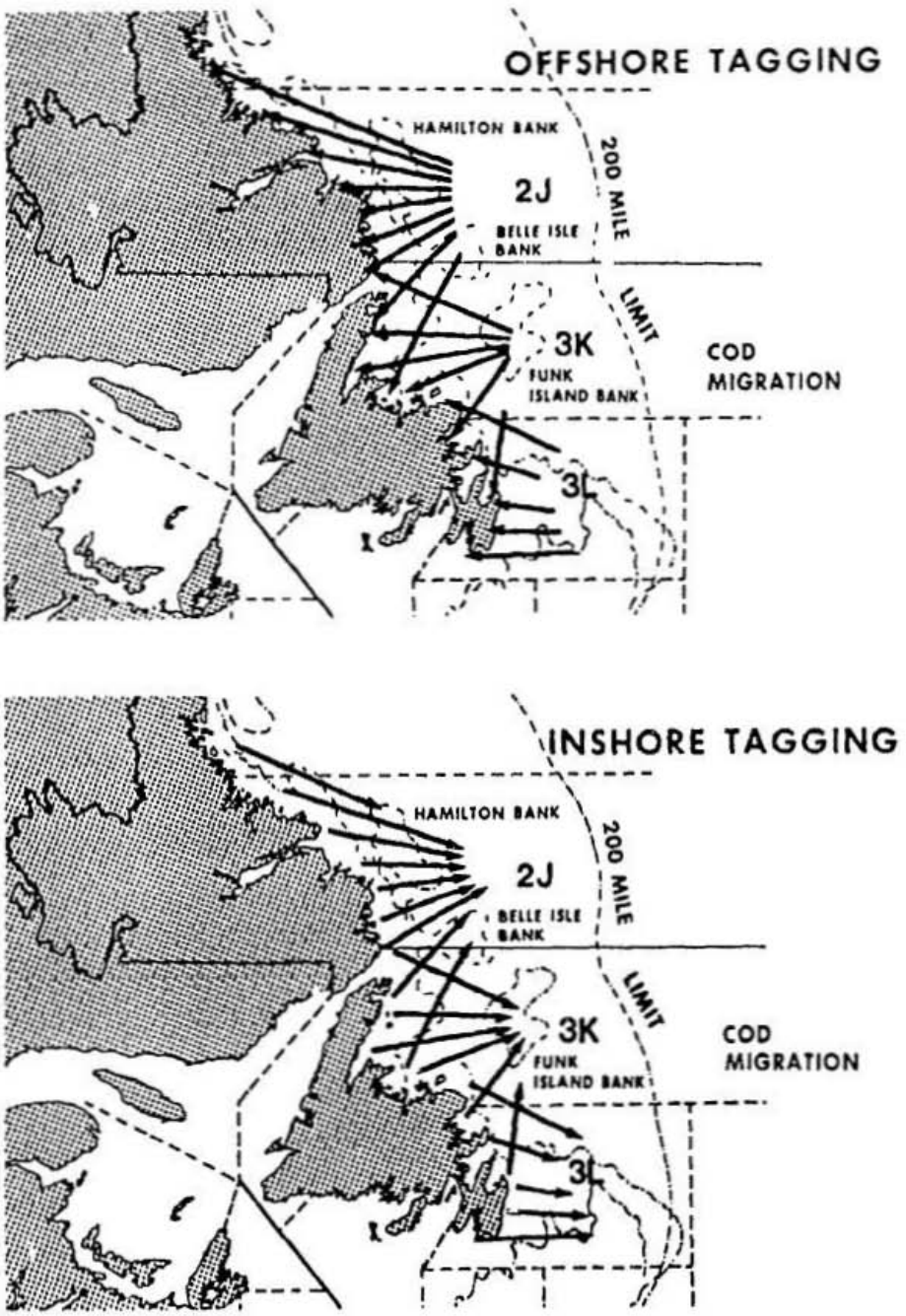

Figure 1: Map of Newfoundland and Labrador showing NAFO statistical areas 2J3KL, place names mentioned in the text and the existing cod migration model based on traditional tag and recapture studies (from Anonymous 1988).

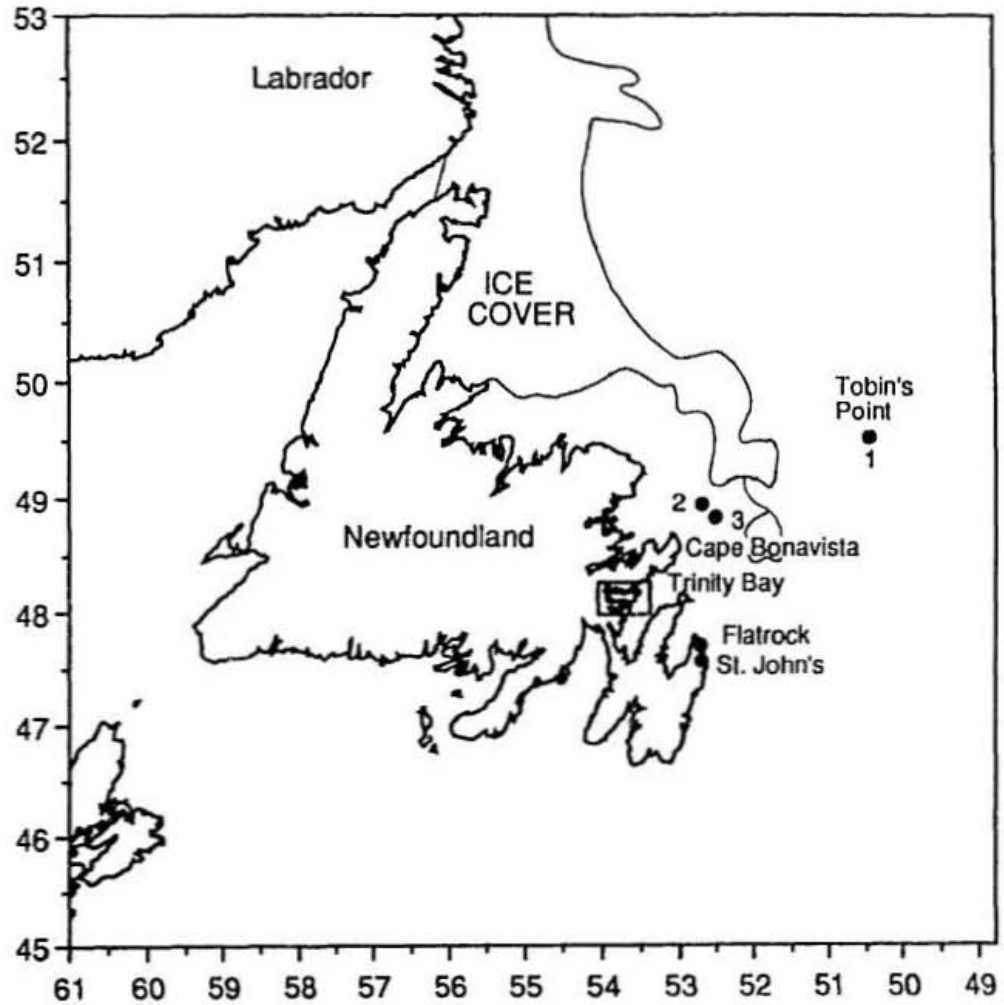

Figure 2a: A map of Newfoundland showing the location where the three longlines were set offshore (site 1 is Tobin's Point), the ice edge for May 16, 1991, and the location of the inshore study site, the Random Island region of Trinity Bay (enclosed in a rectangular box).

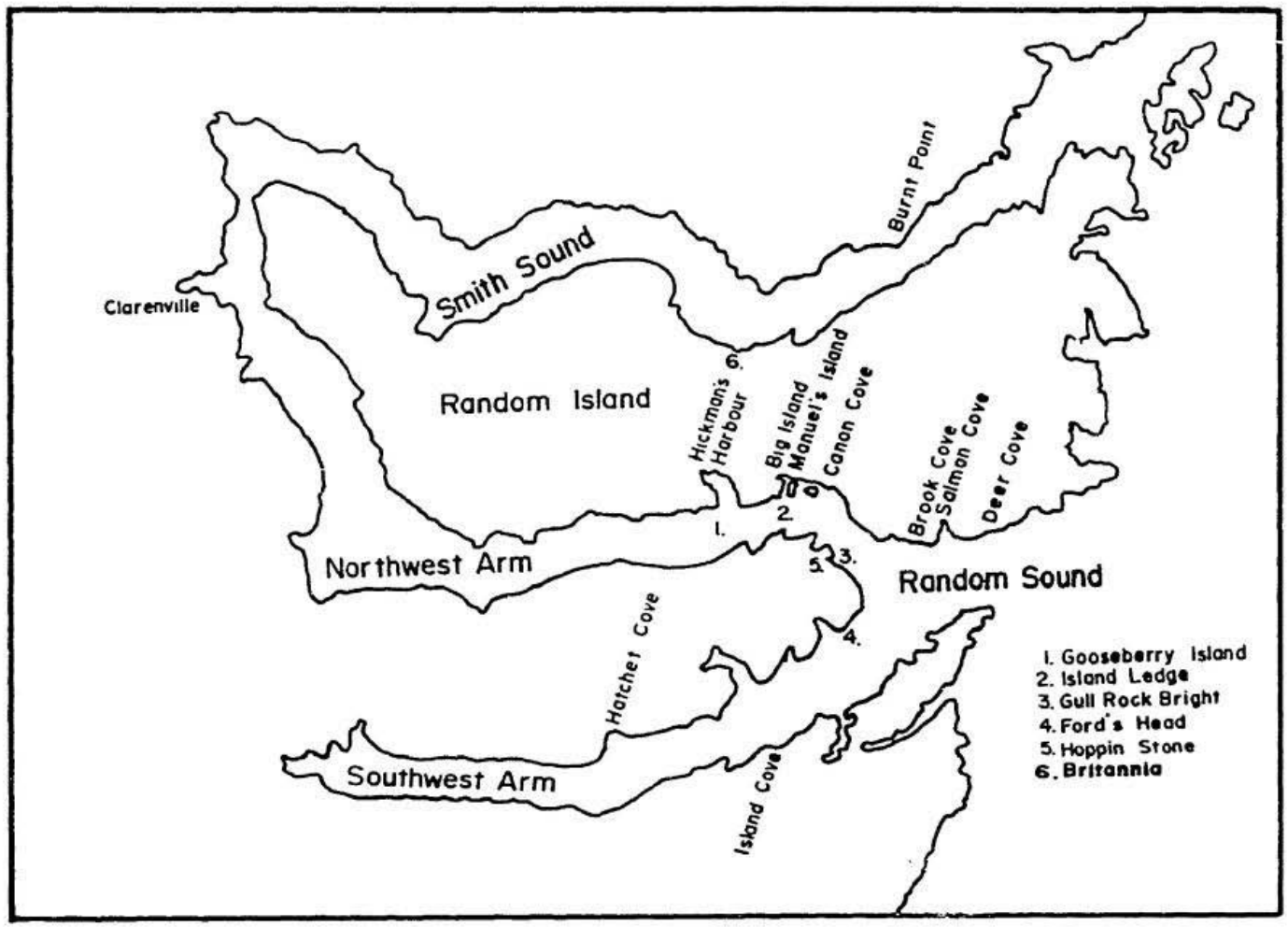

Figure 2b: A map of the Random Island region of Trinity Bay, Newfoundland showing place names mentioned in the text.

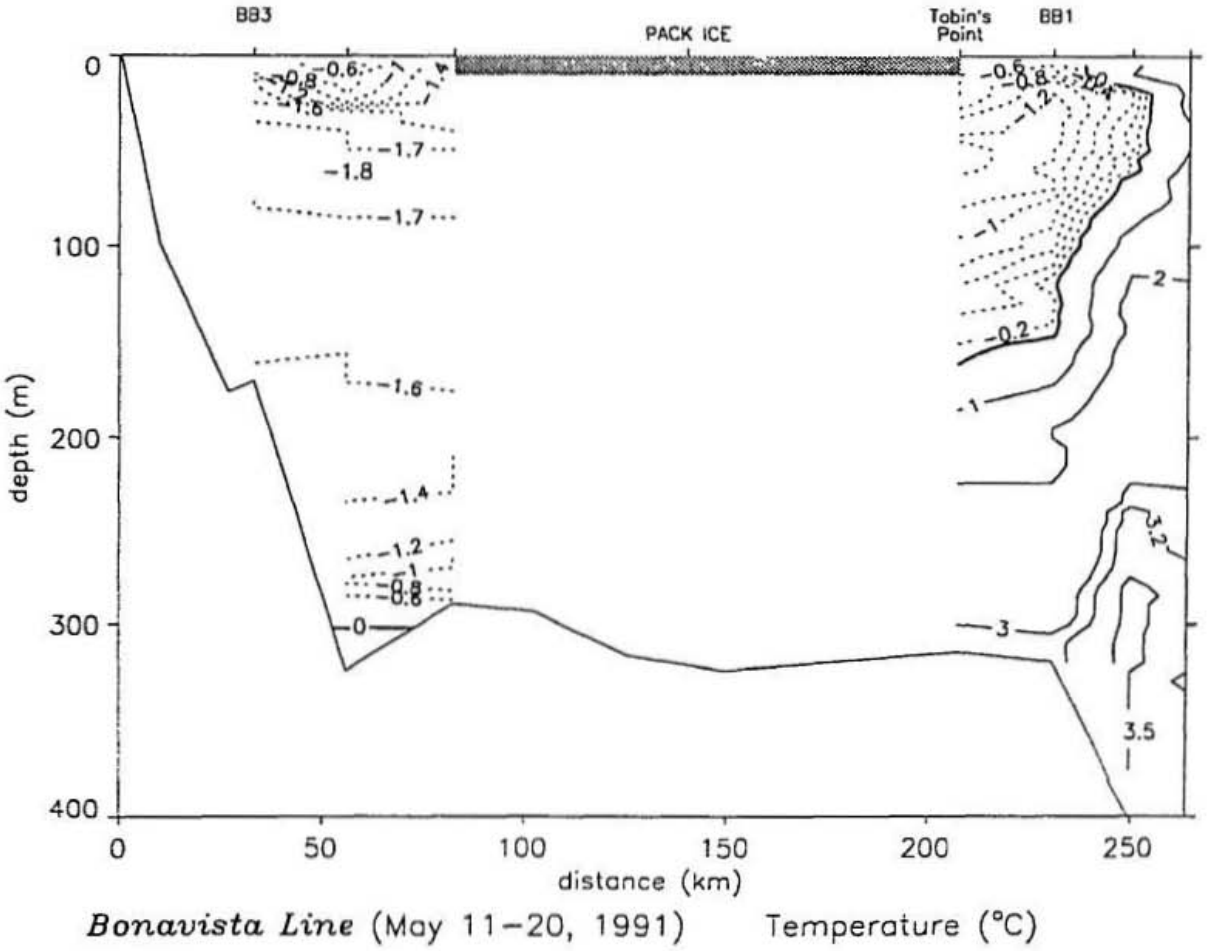

Figure 3: Temperature section of the northeast Newfoundland shelf off Cape Bonavista. Fish #4 and #5 were released at the offshore edge of the pack ice. Dotted lines denote sub - zero temperatures and solid lines denote above zero temperatures.

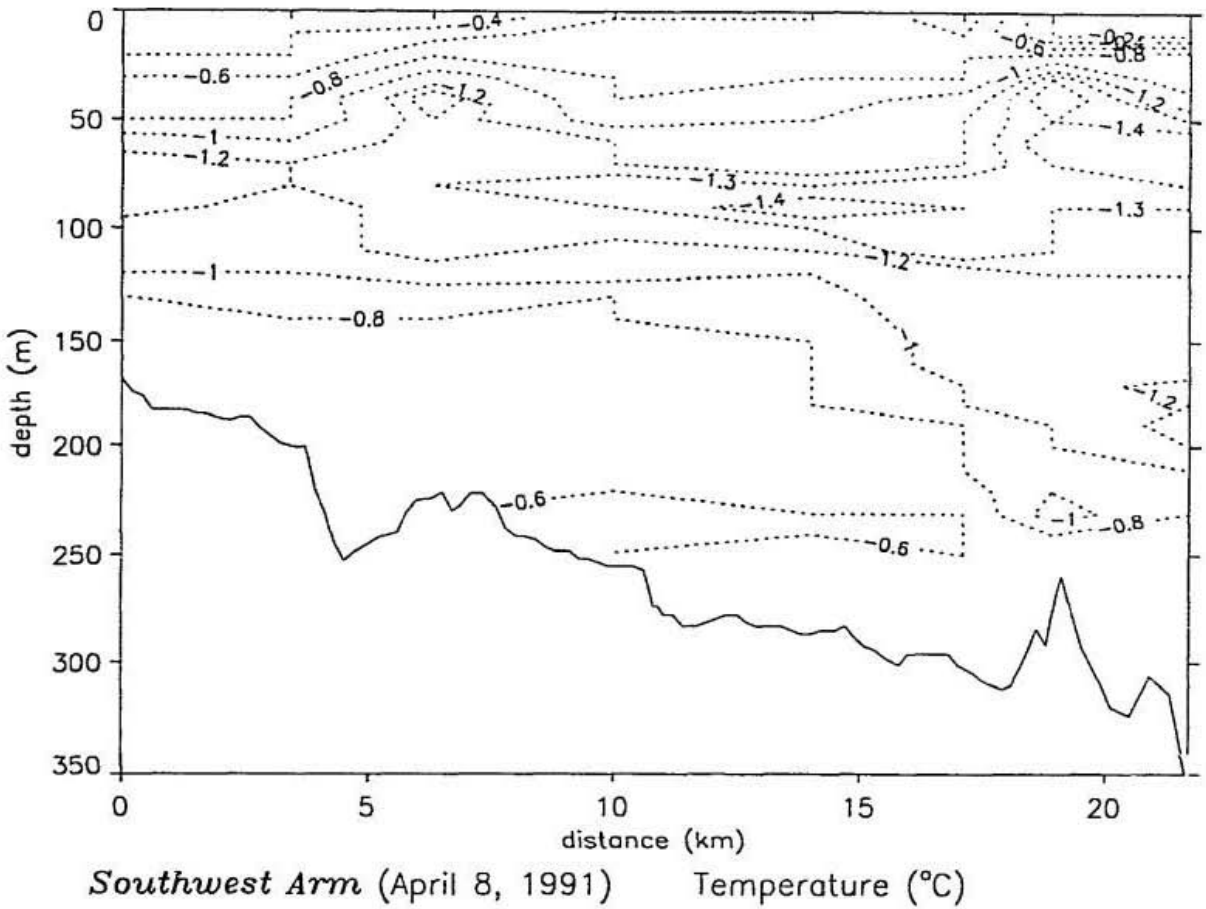

Figure 4: Temperature section of Southwest Arm, Trinity Bay in April 1991. At left is the bottom of the Arm and at right is Random Sound. Dotted lines denote sub - zero temperatures.

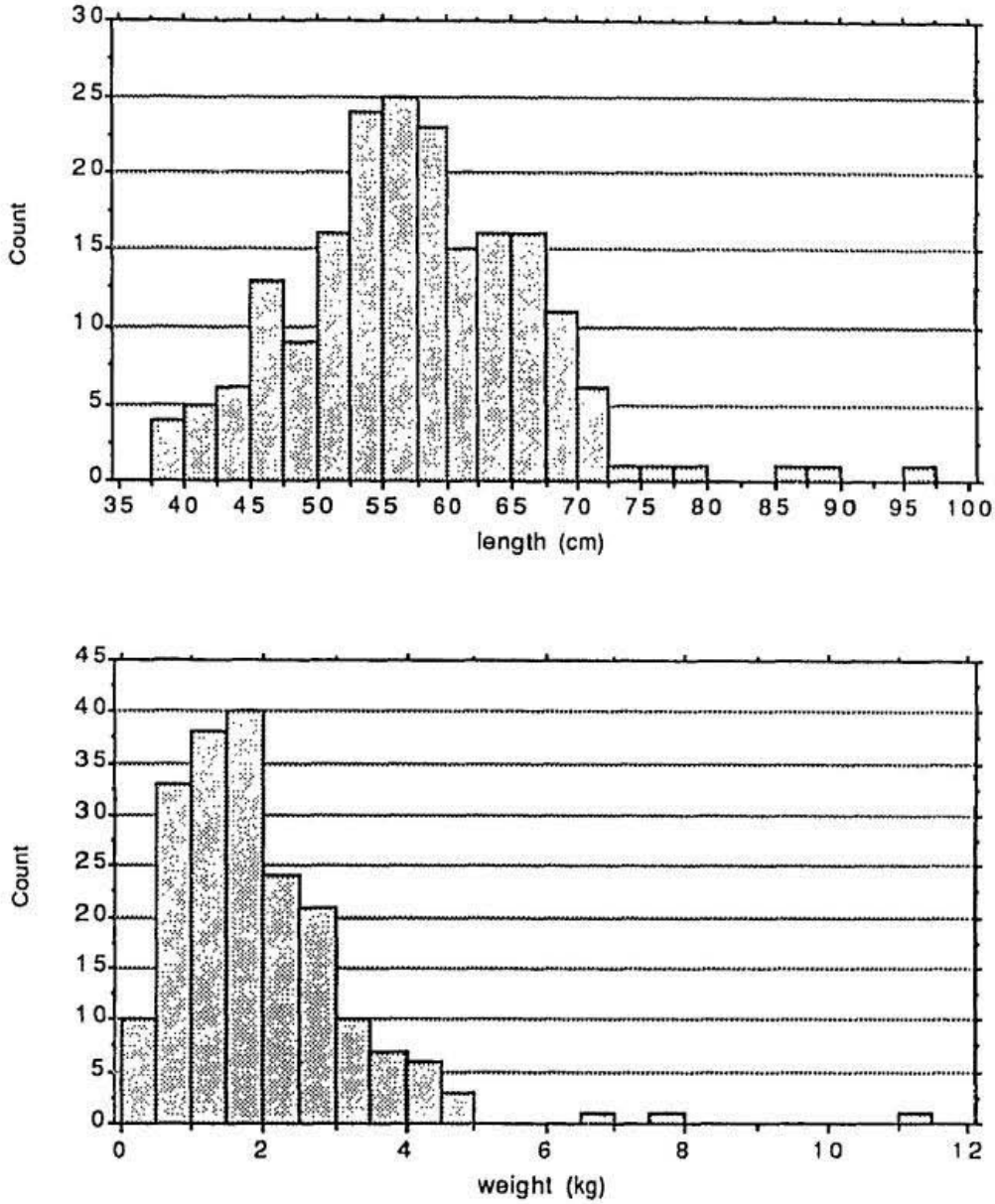

Figure 5: Length frequency distribution (top) and weight frequency distribution (bottom) of northern cod caught inshore in January and April, 1991.

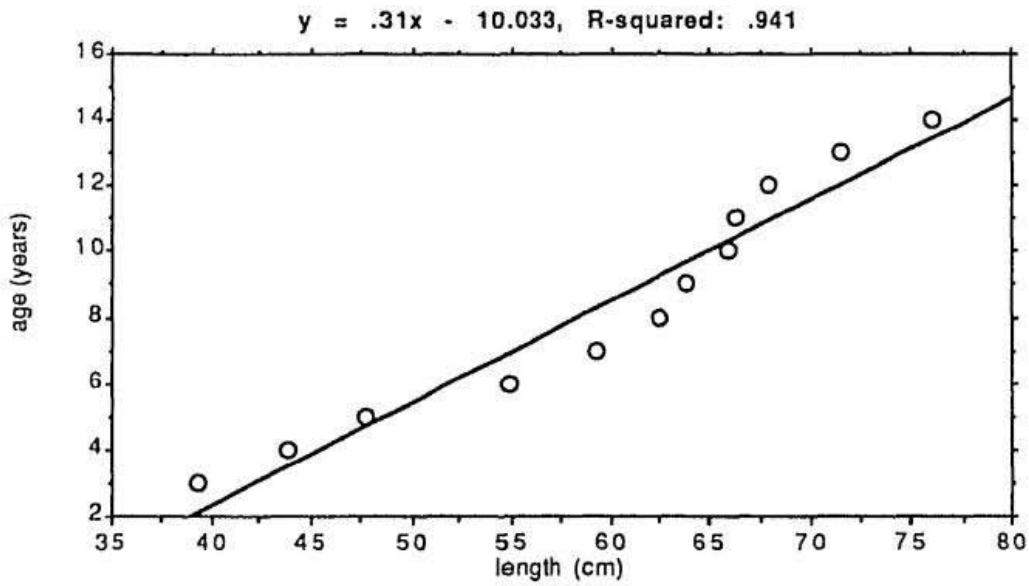

Figure 6: The relationship between age (years) and length (cm) calculated from data in Fleming (1960) for northern cod from the lower 3K and 3L NAFO divisions of the northeast Newfoundland shelf.

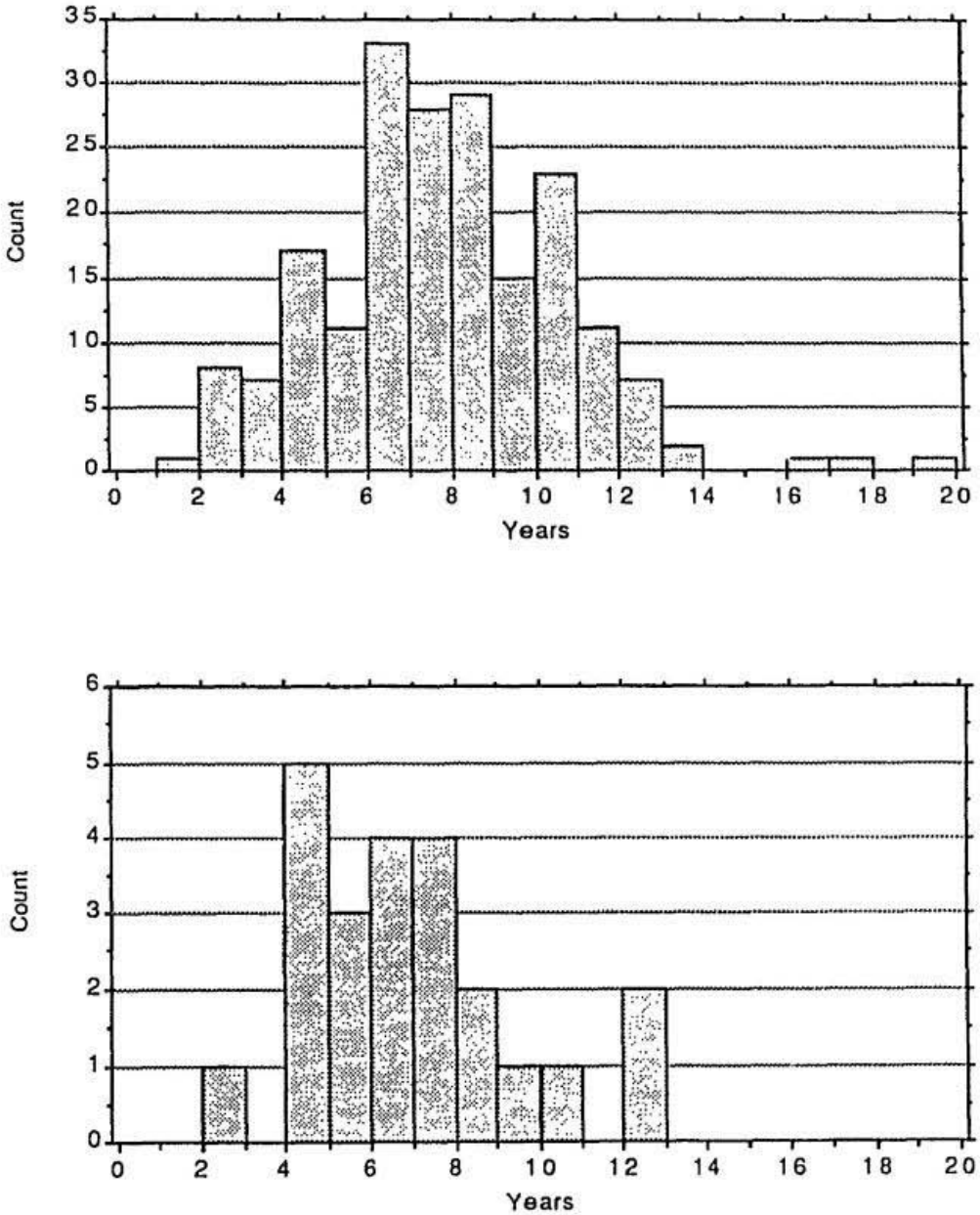

Figure 7: Age frequency distribution of northern cod caught inshore in January and April, 1991 (top) and offshore in May, 1991 (bottom) during fishing for experimental animals.

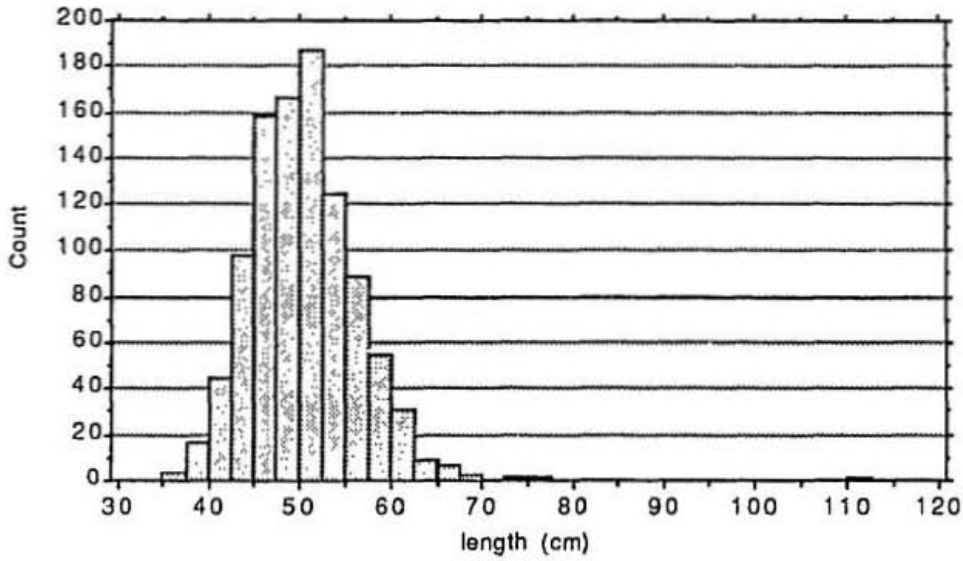

Figure 8: Length frequency distribution of all northern cod sampled from the inshore cod trap fishery in the Random Island region from May to September, 1991.

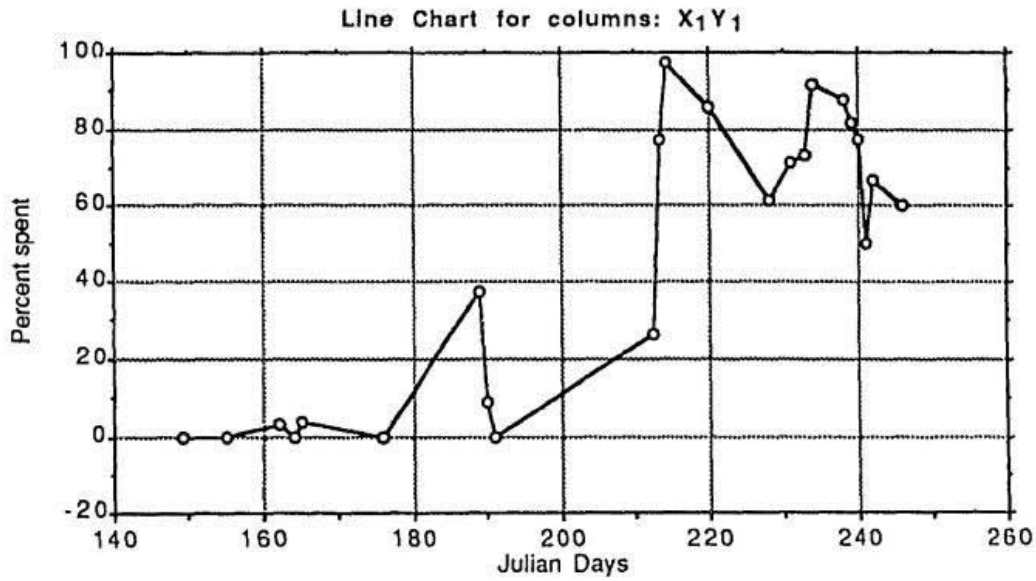

Figure 9: Time series from May to September of 1991 showing the percentage of mature fish that were spent in the Random Island region. Numbers of cod in condition 3 were divided by number of cod in condition 1, 2 and 3 in Table 6.

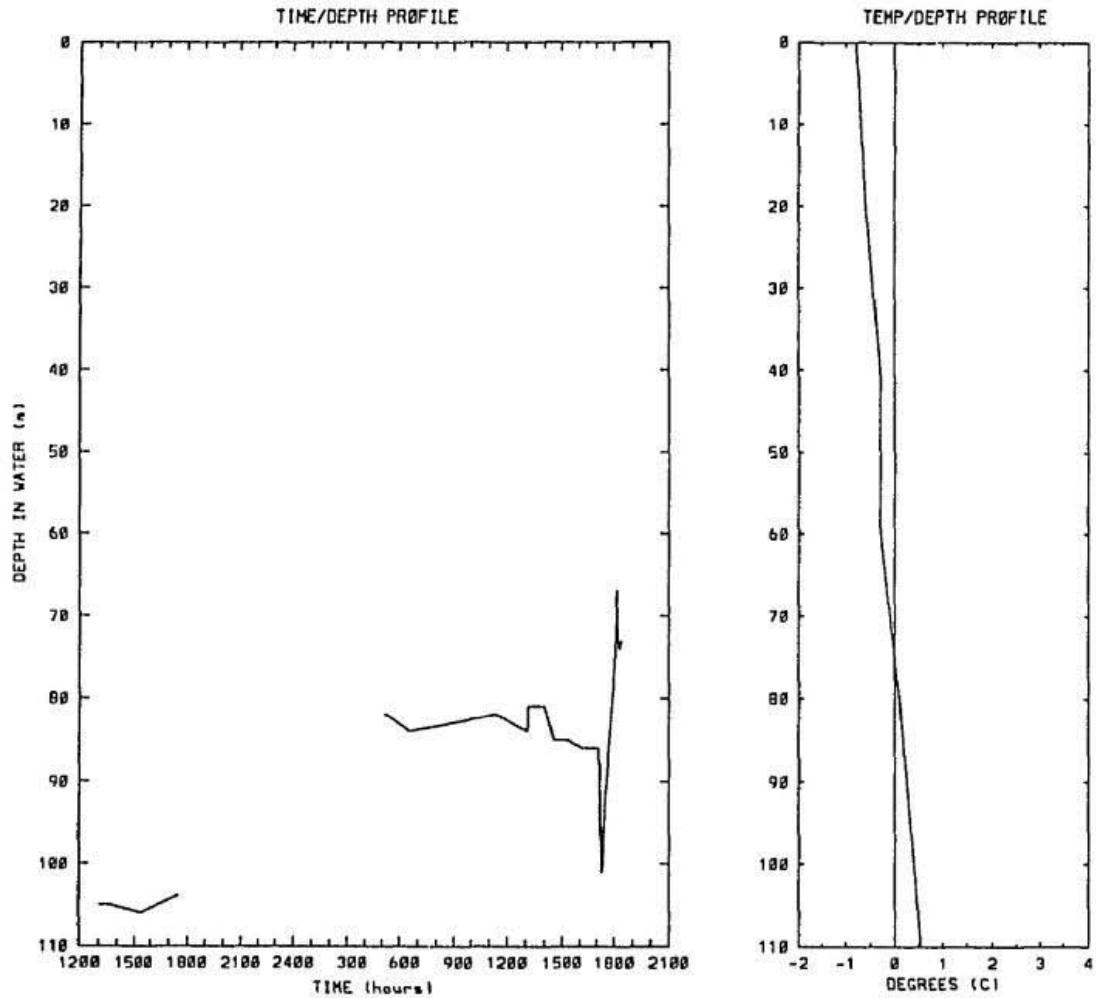

Figure 10: Depth with time of fish #1 and the temperature profile. Fish #1 was 52.8 cm, 1.5 kg, released at Hatchet Cove and tracked January 29 - 30, 1991.

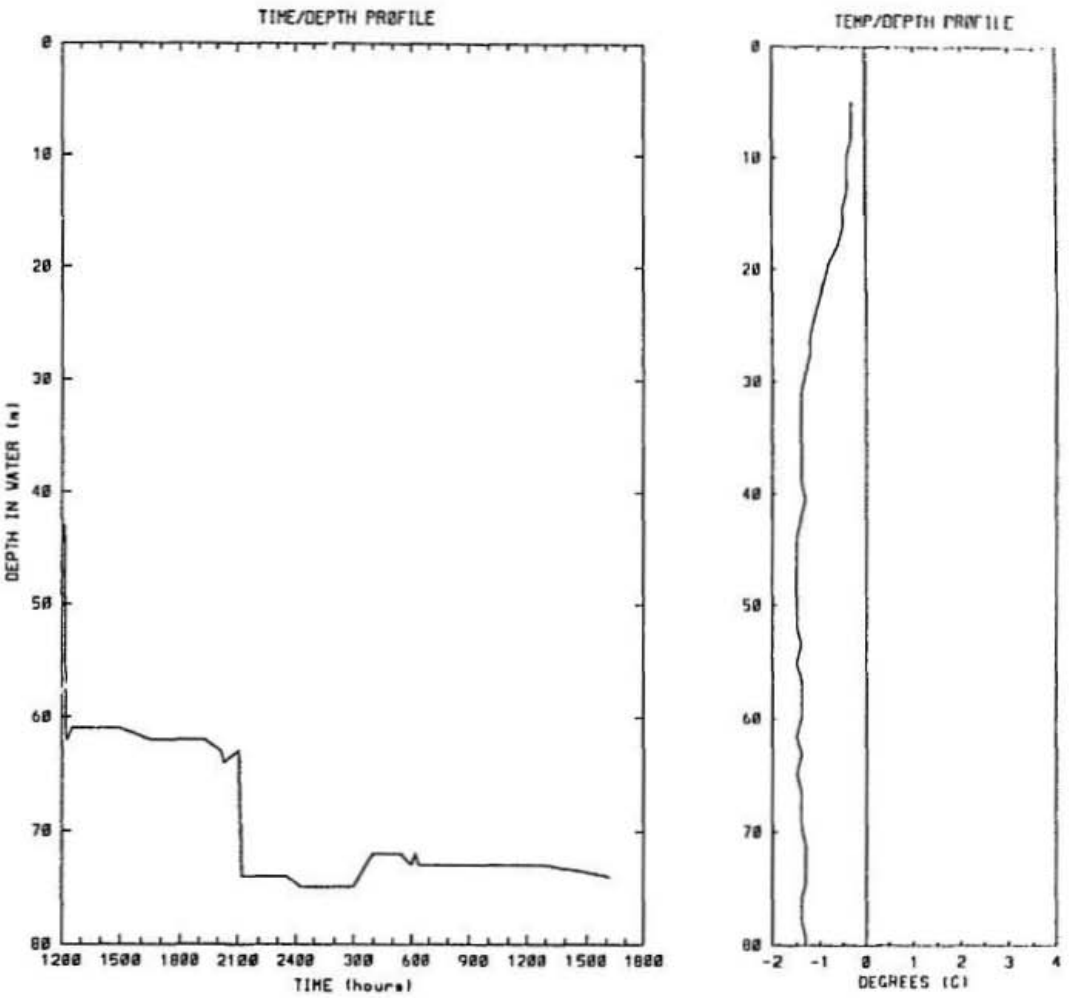

Figure 11: Depth with time of fish #2 and the temperature profile. Fish #2 was 68.6 cm, 2.9 kg, released at Hatchet Cove and tracked April 7 - 8, 1991.

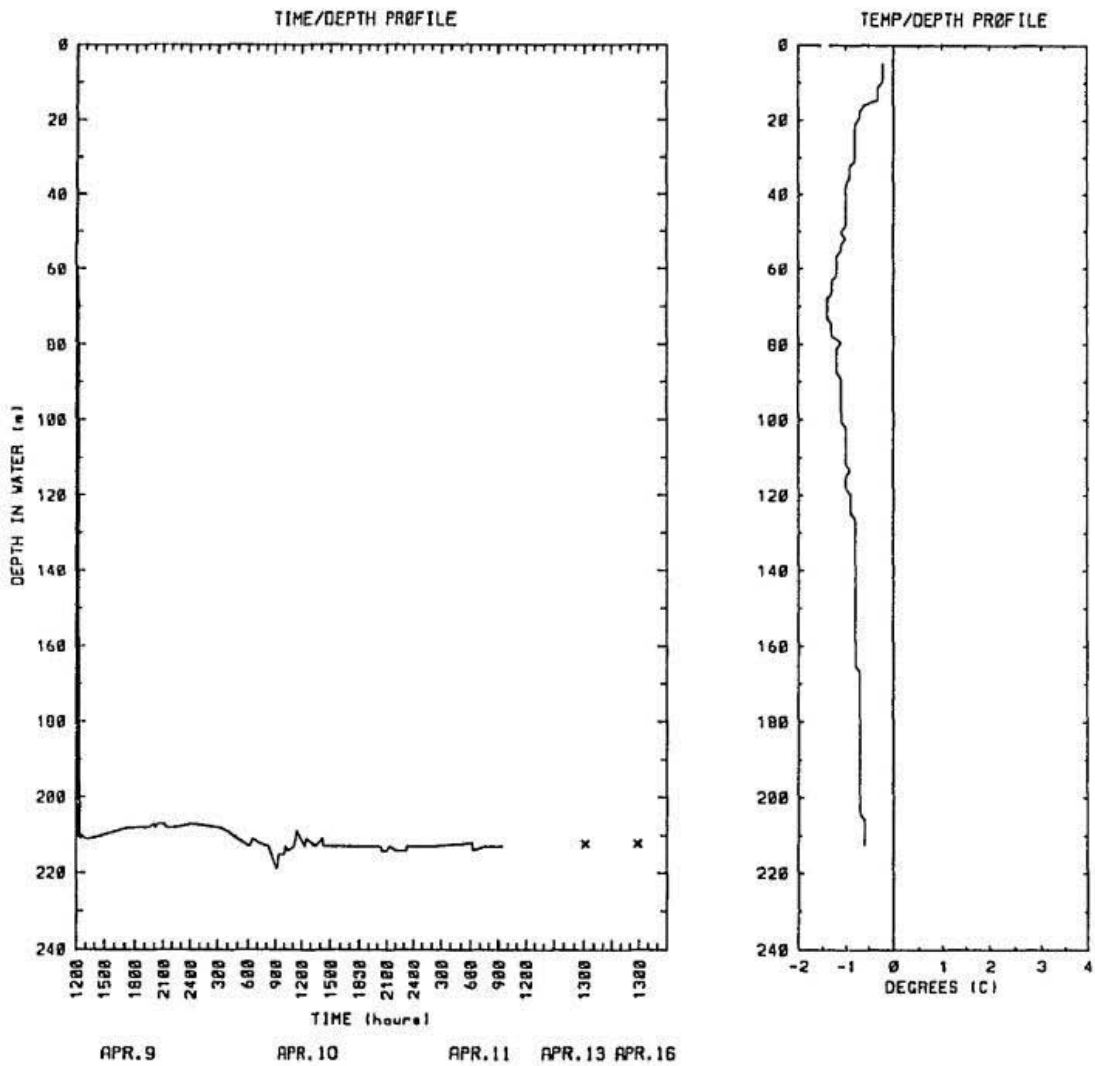

Figure 12: Depth with time of fish #3 and the temperature profile. Fish #3 was 96.5 cm, 11.3 kg, released at Hatchet Cove and tracked April 9 - 16, 1991

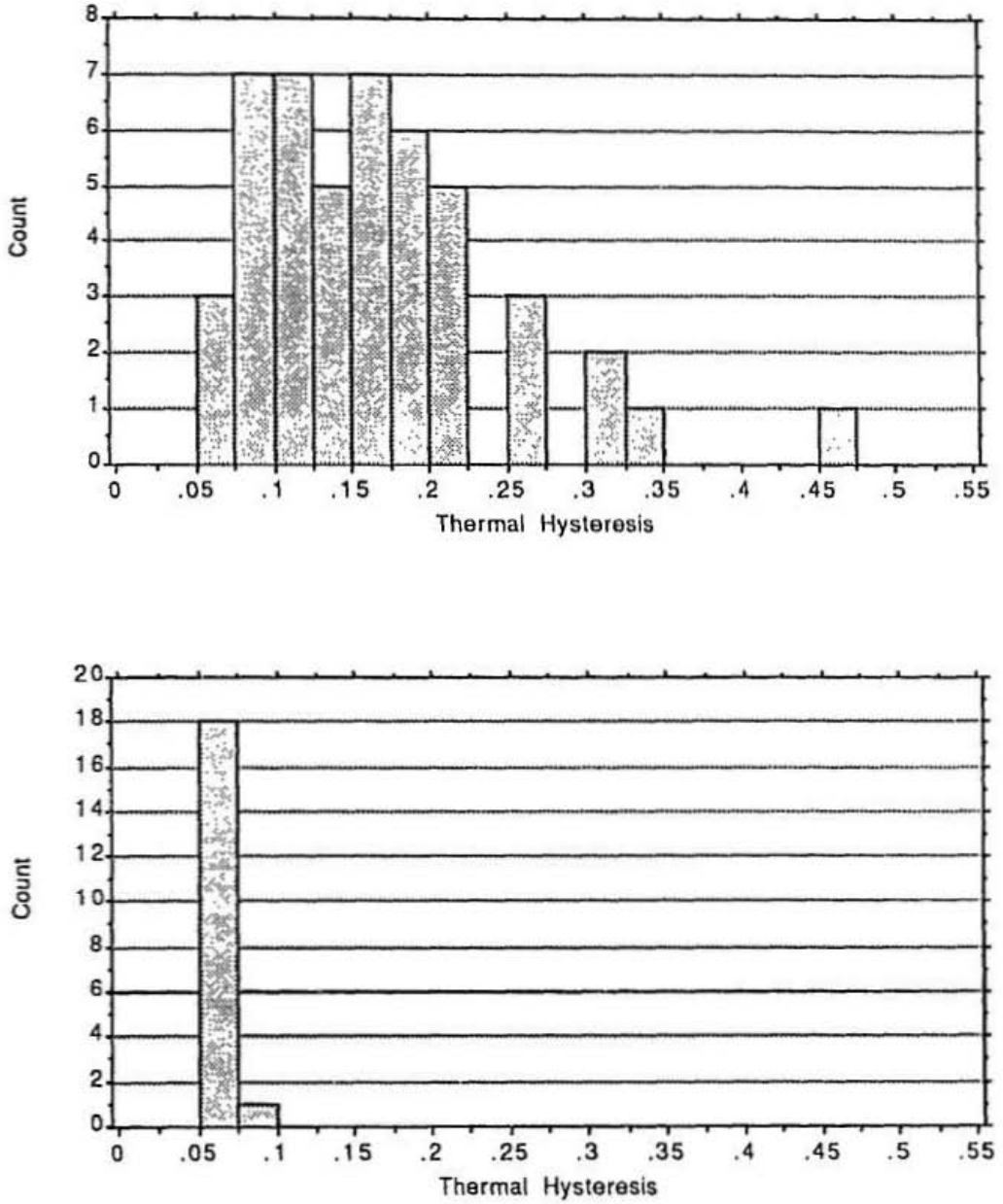

Figure 13: Histogram of the thermal hysteresis for 47 northern cod found overwintering inshore in April, 1991 (top) and 19 northern cod found overwintering offshore in May, 1991 (bottom).

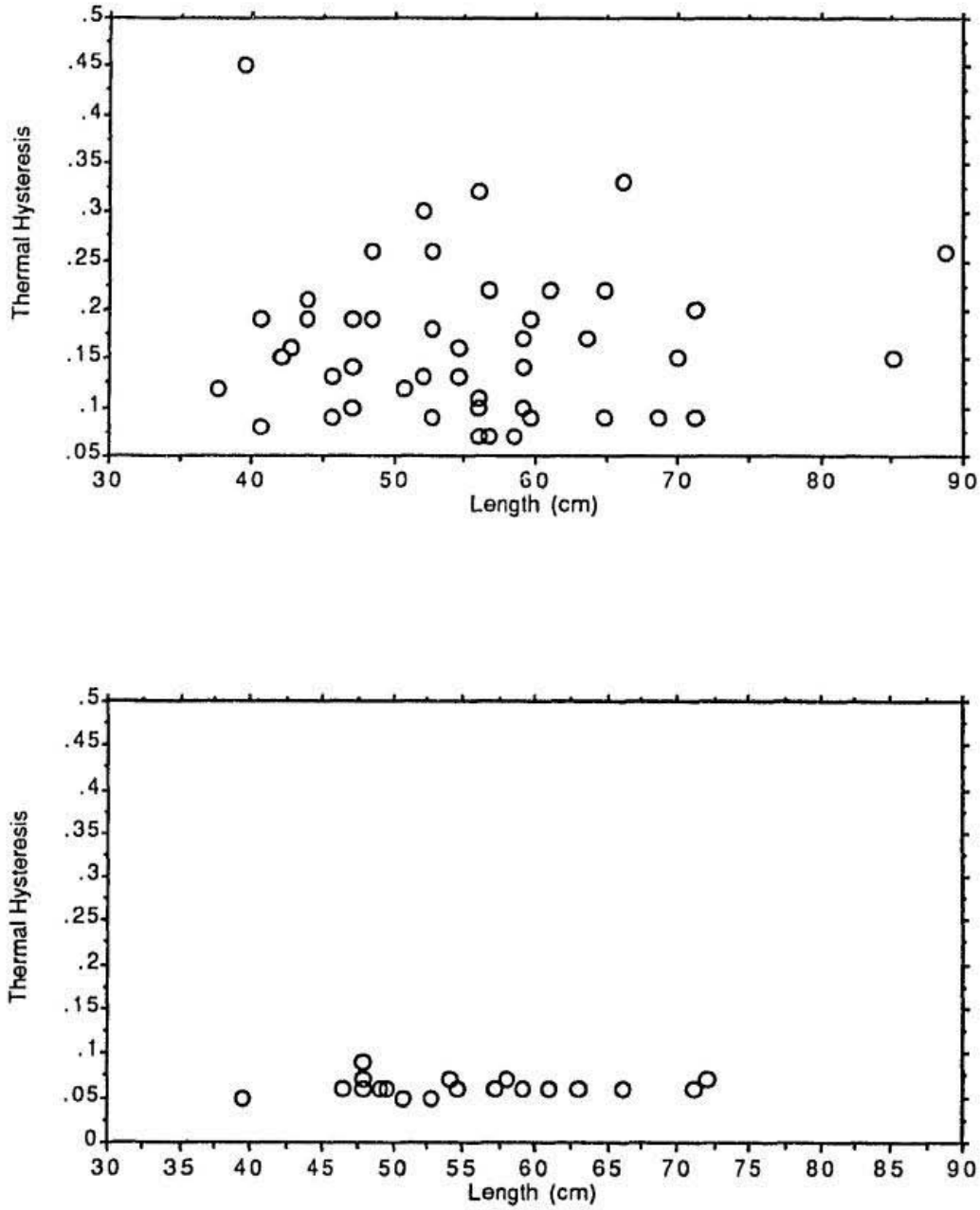

Figure 14: Scatterplot of thermal hysteresis and length for 47 northern cod found overwintering inshore in April, 1991 (top) and 19 northern cod found overwintering offshore in May, 1991 (bottom).

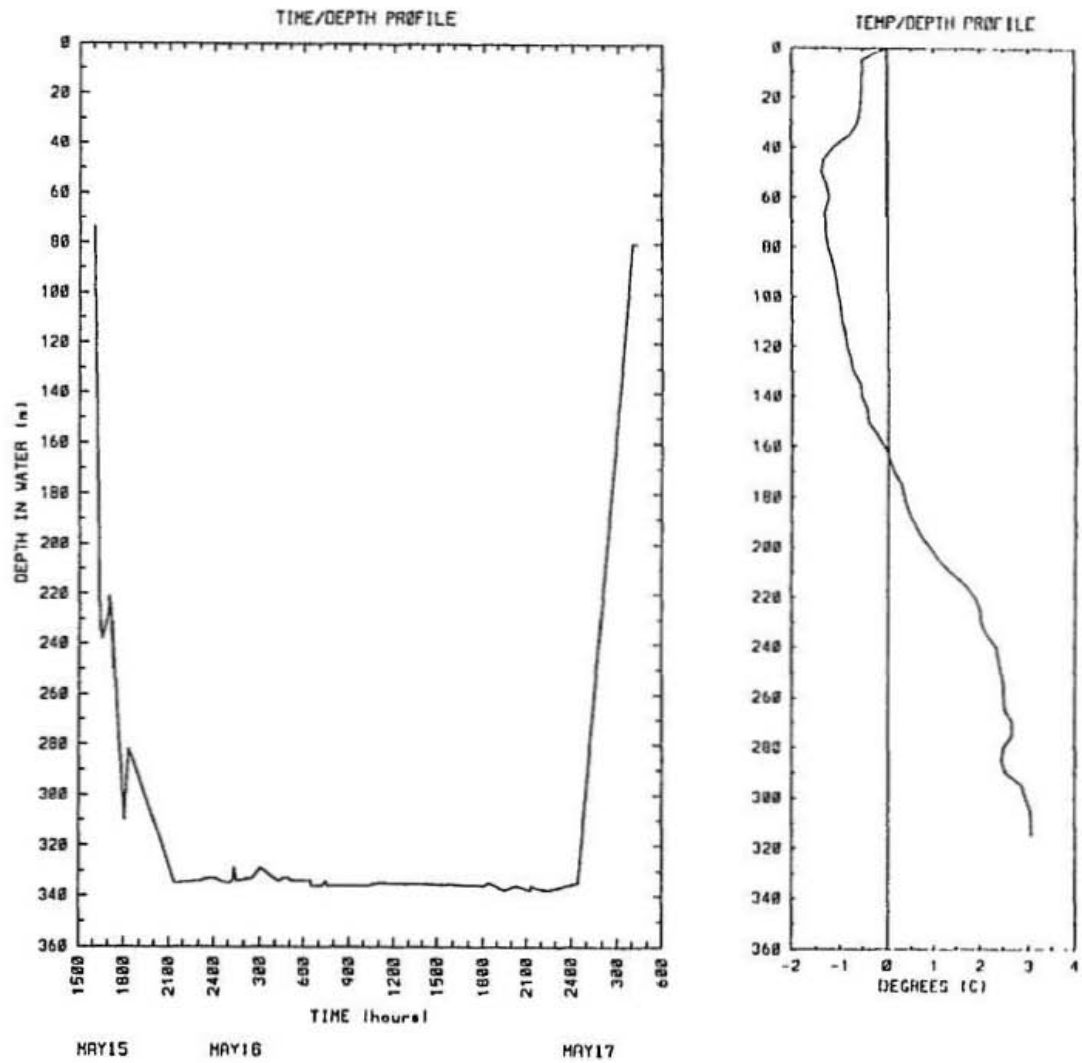

Figure 15: Depth with time of fish #4 and the temperature profile. Fish #4 was 57.2 cm, 1.8 kg, released at Tobin's Point and tracked May 15 - 17, 1991.

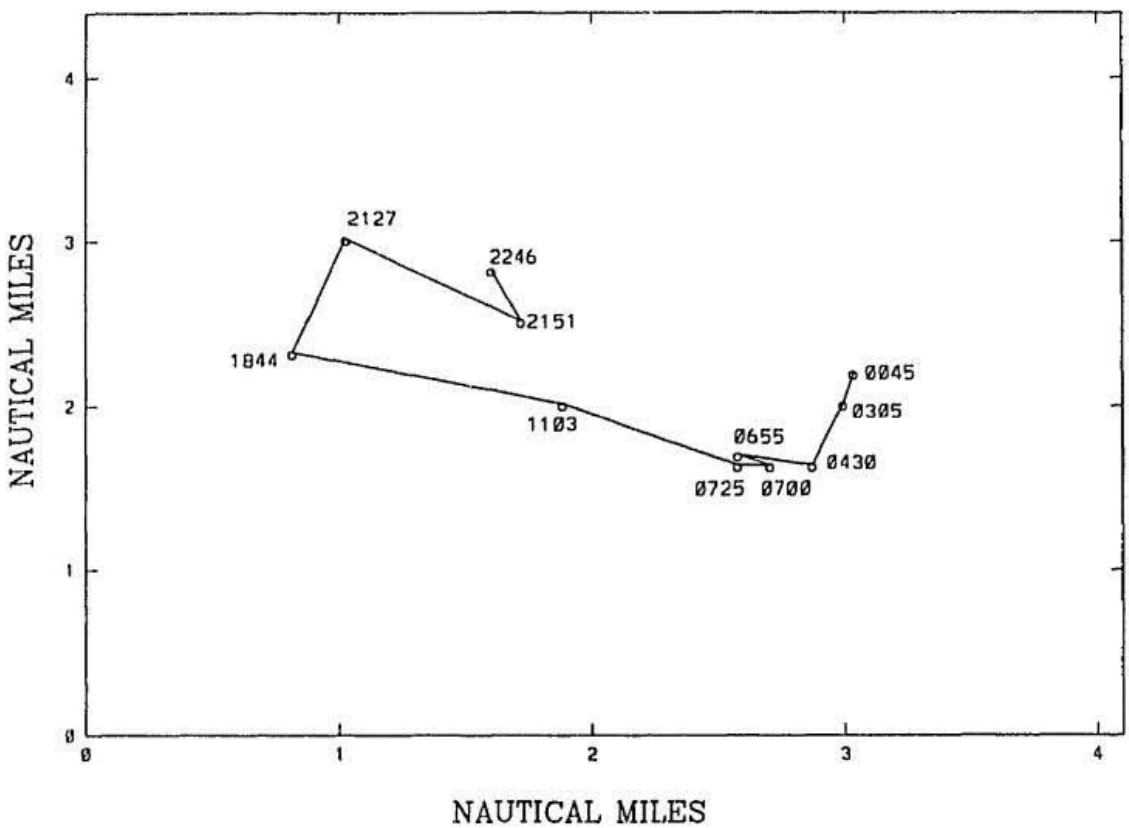

Figure 16: Horizontal movement with time of fish #4 over Tobin's Point on May 16, 1991. The origin of the plot is set at 49° 28.8' N, 50° 31.8' W.

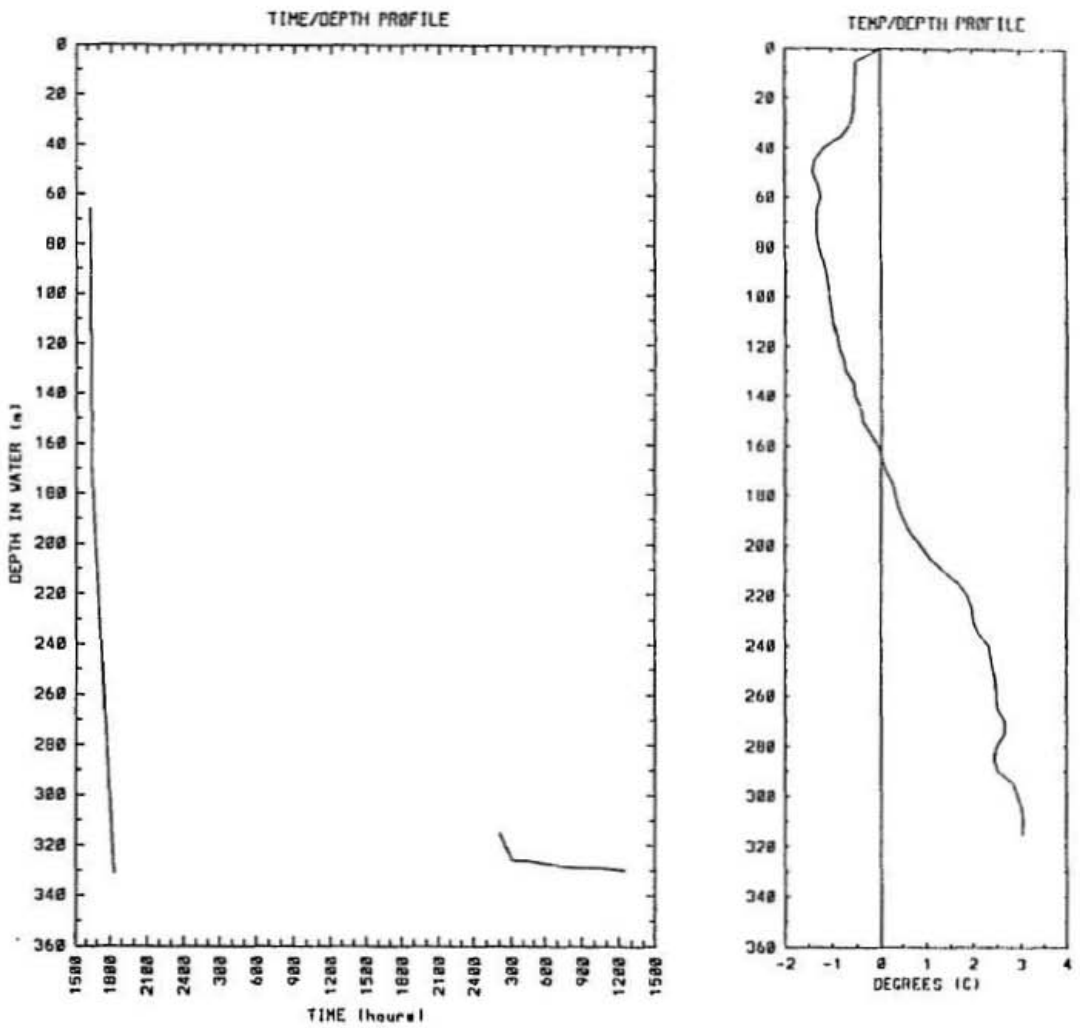

Figure 17: Depth with time of fish #5 and the temperature profile. Fish #5 was 57.8 cm, 1.4 kg, released at Tobin's Point and tracked May 15 - 17, 1991.

Appendix A

Specific information on the sonic transmitters surgically implanted into experimental fish in the Random Island area (7626, 7627, 7624) and in the Tobin's Point area (7907, 7908, 7910) of the northeast Newfoundland continental shelf.

Transmitter number	Fish #	Battery life	Frequency (Hz)	Diameter (mm)	Length (mm)	Weight (g)
7626	1	2 - 3 days	50.0	16	74	30.2
7627	2	"	"	"	"	"
7624	3	7 - 14 days	32.8	32	125	222.5
7907	4	4 - 7 days	50.0	16	62	23.6
7908	5	"	65.5	"	"	"
7910	6	"	76.8	"	"	"

Appendix B

Criteria for determining stages of sexual maturity
(modified from Morrison 1990)

STAGE	FEMALE	MALE
0 - Immature	- Ovary small, translucent in small fish and opaque in larger fish.	- Testis small and translucent, more opaque in larger fish.
1 - Ripening	- Ovary firm, blood vessels visible. Ovary becomes opaque and cream in color, individual eggs can be seen, blood vessels prominent.	- Testis larger and pink in color, begin to turn white and translucent distally.
2 - Ripe and Spawning	- Ovary fills most of body cavity, translucent and opaque eggs, eggs easily released from vent.	- Testis white, spermatozoa easily released from vent in later part of stage.
3 - Spent	- Ovary shrunken, soft and flabby with whitish cast.	- Proximal testis white and flabby, distal testis develops translucent border as ripe spermatozoa are removed.