

Automated monitoring of a large-scale cod (*Gadus morhua*) migration in the open sea

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Abstract: The migration patterns of marine fishes are poorly known, in part owing to the technical limitations associated with tracking the movements of animals in deep water. Here we document a large-scale, directed, migration of Atlantic cod (*Gadus morhua*) off eastern Canada. Our approach was based on the acoustic tagging of 126 fish and the deployment of 69 subsurface receivers, stretching over a 160-km distance along the edge of the Laurentian Channel. After 1 year of automated recording, we found that 65% of the fish migrated out of coastal waters in two distinct runs during the summer–autumn period. The offshore-migrating fish overwintered in deep Laurentian Channel waters, returning inshore in April. Individual migration routes and migration timing were variable, indicating that the cod did not aggregate in large schools during the seasonal migration events.

Résumé : Les patrons migratoires des poissons marins sont mal connus, en partie à cause de limitations techniques reliées au suivi des mouvements d'animaux en haute mer. Cette étude documente une migration dirigée et à grande échelle de morues (*Gadus morhua*) sur la côte est canadienne. Nos résultats sont basés sur le marquage de 126 poissons et le déploiement de 69 récepteurs sur une distance de 160 km le long de la pente du Chenal Laurentien. Après 1 an d'enregistrements automatisés, nous avons trouvé que 65 % des morues ont migré vers le large en deux épisodes distincts en été et en automne. Les poissons qui ont migré vers le large ont passé l'hiver dans les eaux profondes du Chenal Laurentien, pour retourner en eaux côtières en avril. Les trajets migratoires individuels et leur synchronisme étaient variables, ce qui indique que les morues ne se sont pas agrégées en grands bancs durant leurs migrations saisonnières.

Introduction

Since the 1980s, satellite tracking has yielded detailed information on the migration routes of marine organisms ranging from seals to tuna and sea turtles. However, most marine animals remain submerged their entire life, which precludes communication with satellites. In the 1990s, the development of archival phototags was regarded as a significant advance for tracking underwater life. These tags allow a detailed recording of light intensity that can be used to estimate daily position to an accuracy of about 140 km (Welch and Eveson 1999). The study of more localized movement patterns, such as those in coastal waters or over the continental shelf, requires that locations be estimated with much finer spatial resolution. Moreover, most species are simply

too small to be equipped with large and expensive “pop-up” archival tags. The alternative is small archival tags that must be recovered opportunistically, typically by fishermen, and returned to the laboratory. This means that a relatively large number of animals must be tagged to ensure reasonable numbers of tag recoveries over the desired time scale (months to one or more years).

Because of such practical limitations, tracking deep sea life is most often accomplished by active tracking, where an individual is fitted with an acoustic transmitter and followed for as long as possible, usually a matter of days. Longer-term studies have been achieved by returning to the study sites and attempting to relocate the tagged individuals (e.g., Robichaud and Rose 2001). However, recent advances in acoustic technology have made available low-cost, submersible receivers

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that can automatically detect and identify passing fish or other aquatic animals equipped with coded transmitters (Voegeli et al. 1998; Arnold and Dewar 2001). Here we provide the first evidence that this technology can be applied over a large area in the open sea to track the seasonal migrations of fish populations and resolve important fishery management issues.

Experimental design

Our experiment was conducted off the Canadian Atlantic coast (Fig. 1). Of particular interest to fishery managers is whether the Cape Breton cod (*Gadus morhua*) stock (Northwest Atlantic Fisheries Organization (NAFO) Division 4Vn cod) migrates annually to the same offshore winter grounds as the much larger southern Gulf of St. Lawrence stock (NAFO 4T cod, see "4T Winter Schools" in Fig. 1). Such a migration would leave open the possibility of unintended fishing mortality on the Cape Breton stock, which has been under a fishing moratorium since 1993.

In June 2000, we captured Cape Breton cod by performing short trawl sets on their main spawning grounds near the eastern coast of Cape Breton Island. We surgically implanted individually coded transmitters (50 kHz, Vemco Ltd., Shad Bay, N.S.) into their body cavities and released them into their natural habitat. Follow-up acoustic surveys in the vicinity of all release sites after 6, 10, and 14 months indicated that 126 (spatial distribution shown in Fig. 1) sexually mature cod (length 43–72 cm) survived the tag implantation. Soon after the tagging, in July 2000, we deployed automated receivers (single-frequency VR1, Vemco Ltd.) over the ocean bottom in locations designed to intercept any migrants to presumed offshore overwintering locations. Fifty-nine receivers were deployed 2.0–2.5 km apart in deep waters (depth range, 92–185 m; mean, 140 m) at the edge of the Laurentian Channel, creating a 160-km monitoring line separating the inshore from the offshore. Ten additional receivers were moored at inshore locations (depth range, 54–123 m; mean, 85 m) in the event that the tagged cod were nonmigratory and overwintered near the coast. All receivers continuously monitored the passage of any tagged individuals over a 1-year period.

Results and discussion

In August 2001, we recovered 60 of 69 (87%) receivers deployed the previous year. In addition to the lost moorings, six of the recovered units had been subjected to some catastrophic event leading to a power loss shortly after their deployment. This brought to 54 (45 offshore, 9 inshore) the number of units that were recovered and that functioned throughout the experiment.

The stored data indicated that 67 tagged cod had traveled within detection range of the submerged receivers (inshore and offshore receivers combined). Together the 67 fish generated a dataset of 510 000 receptions, each of these consisting of an individually identified cod and date and time stamp. As expected, most (90%) fish transmitted their tag number several times while passing near a receiver unit; a minority (10%) transmitted their identification code between two and five times only, suggesting that these individuals

were near the detection limits of the monitoring stations (Simpfendorfer et al. 2002).

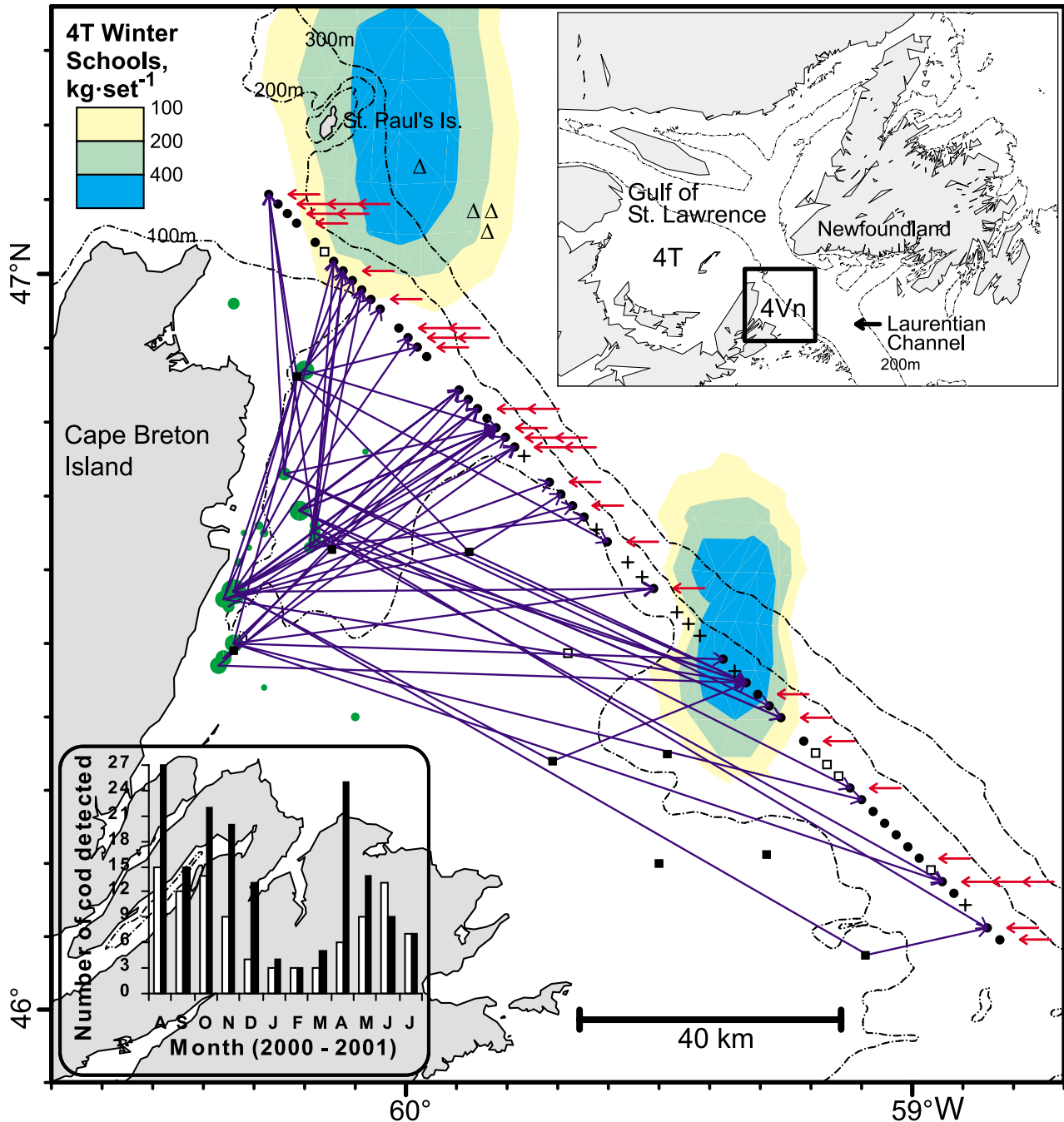
The frequency pattern of detections across months was consistent with an offshore migration during the summer–autumn period of 2000 and a return migration during the spring of 2001 (histogram inset in Fig. 1). During the offshore migration, the receiver line detected 51 cod (blue arrow lines in Fig. 1) moving toward the same wintering grounds as the southern Gulf population. In the spring, the offshore line detected 35 cod (red arrow lines in Fig. 1) returning towards the coast.

Within-season migration timing was recorded with unprecedented resolution (shown graphically in Figs. 2a and 2b). In the spring, the majority (63%) of the returning cod intercepted the monitoring line between 5 April (day of year (DOY) 95) and 26 April (DOY 116). Surprisingly, however, there were two distinctive migration runs across the receiver line during the summer–autumn period. A large proportion (61%) of the offshore-migrating cod reached the receiver line before the end of August (DOY 244), whereas a second group of inshore cod, classified as autumn migrants, started arriving at the receiver line on 15 October (DOY 289). Whether an individual migrated offshore in summer or in autumn was not related to its size, date of release, or point of release. Overall these results imply that there are two distinct migratory groups within the Cape Breton cod population. To our knowledge, differential migration timing within fish populations has never been reported.

The two groups not only initiated migration at different times, but also behaved quite differently in offshore waters. Based on straight-line distance–time rates, summer migrants moved between offshore receivers very slowly, at an average speed of 0.03 body lengths (BL) per second (median; 25th and 75th percentiles were 0.01 and 0.06 BL·s⁻¹, respectively) compared with 0.17 BL·s⁻¹ (median; 25th and 75th percentiles were 0.05 and 0.39 BL·s⁻¹, respectively) for autumn migrants ($p < 0.001$, Mann–Whitney U test). Time spent over the line differed accordingly: summer migrants were detected for 68 days (median; 25th and 75th percentiles were 12 and 106 days, respectively) compared with 21 days (median; 25th and 75th percentiles were 4 and 48 days, respectively) for autumn migrants ($p < 0.05$, Mann–Whitney U test). The reason for the extended stay at the edge of the Laurentian Channel is not known, although it may have been related to the seasonal dynamics in feeding. Cod stocks off the Canadian Atlantic coast feed intensively during the summer period (e.g., Schwalme and Chouinard 1999) to rebuild energy reserves after the main spawning event (spring); accordingly, it is possible that the edge of the Laurentian Channel represents an important feeding area for the summer migrants.

In general, the offshore-migrating cod moved south along the edge of the Laurentian Channel before leaving the monitoring line for winter grounds (Fig. 2c). By comparison, the shoreward-migrating cod in the spring tended to travel north along the edge of the Laurentian Channel (Fig. 2d). This difference in swimming orientation was also apparent from the seasonal changes in speed over the receiver line. Peak southeasterly speeds occurred during the offshore migration (Fig. 2e), whereas maximum northwesterly speeds were re-

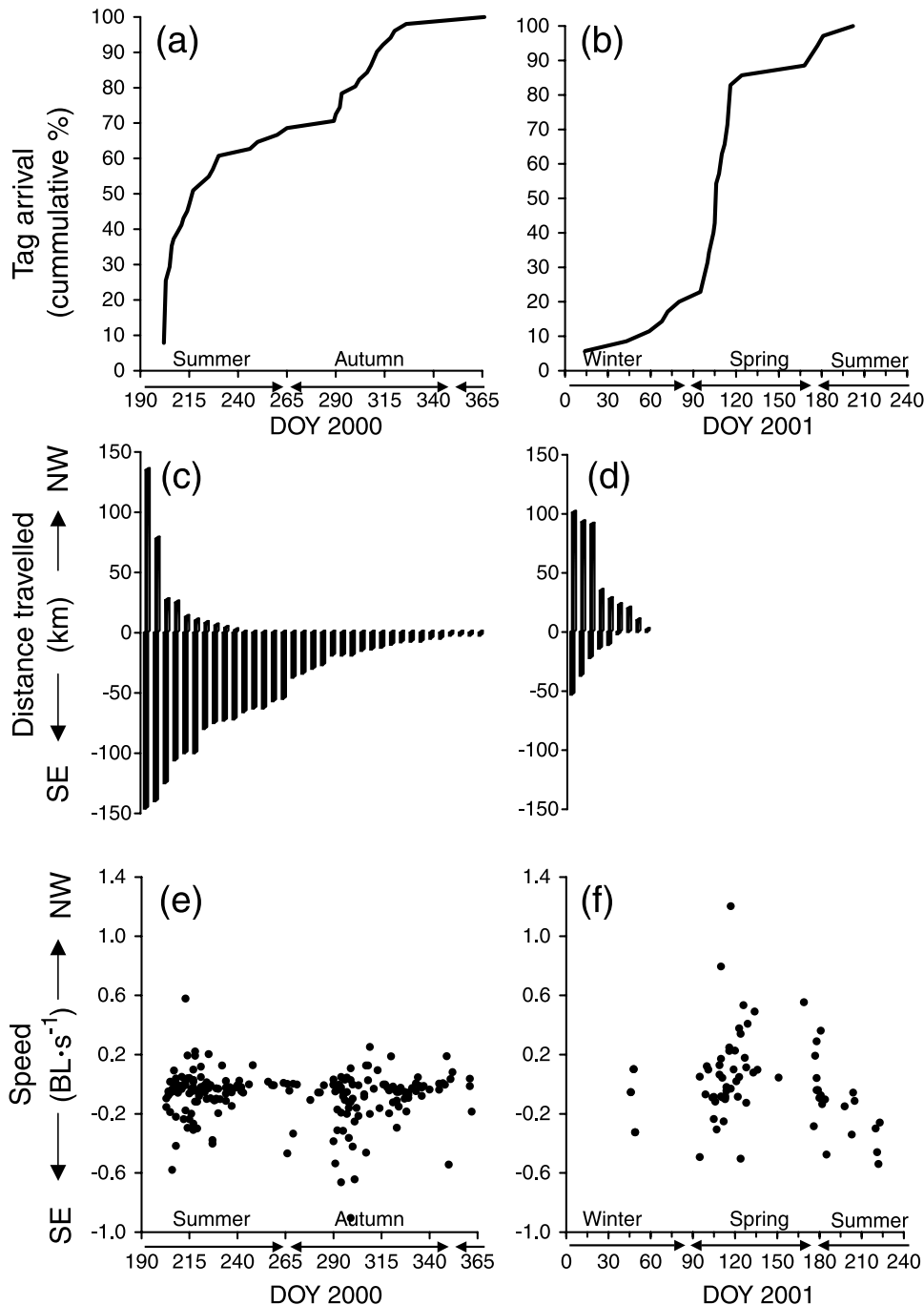
Fig. 1. Map of the study area summarizing the experimental design and the seasonal migrations of tagged Cape Breton cod (*Gadus morhua*). The green circles near the coastline show tagging sites (1 to 22 surviving fish per site, total 126 fish); other symbols show position of moored receivers (● offshore recovered; ■ inshore recovered; + not recovered; □ power failure). The histogram (inset) shows the detection frequency pattern across months for inshore (open bars) and offshore (solid bars) receivers. Each blue arrow line represents a tagged cod detected offshore in 2000; red arrow lines show returning cod in 2001. The large winter schools were identified during January distribution surveys in 1995, 1996 (shown), and 1997 (Campana et al. 1999); the open triangles south of St. Paul's Island show location of tagged cod identified during the January 2001 acoustic survey.



corded during the return migration in the spring (Fig. 2f). We interpret these results as seasonal shifts in swimming orientation for the entire tagged population. Because the evolutionary benefits of migration must outweigh the risks, these results likely reflect a safe and reliable control mechanism ensuring that cod follow the proper migration routes.

In previous work, the observation that large cod led immense migratory aggregations off the Newfoundland coast raised the possibility that migration routes are learned (Rose 1993). In the present study, however, individual migration routes were variable, suggesting that cod need not aggregate in large schools to migrate. Thus, the underlying mechanism

Fig. 2. (a–b) Cumulative percentage tag arrival at the receiver line during (a) the offshore migration in 2000 and (b) the shoreward migration in 2001. (c–d) Distance travelled along the line in (c) 2000 and (d) 2001. Each bar represents one cod (*Gadus morhua*) and the distance separating the first and last point of detection along the line. Positive values indicate northwest heading; negative values indicate southeast heading. (e–f) Speed of travel over the line in (e) 2000 and (f) 2001. The 263 data points shown were generated by 51 individuals. DOY, day of year; BL·s⁻¹, body lengths per second.



responsible for the temporal precision and annual inshore–offshore movements displayed by migratory cod awaits further inquiry.

Because both the offshore migrating cod and the returning cod intercepted the receiver line along its entire extent, it appears that the Cape Breton population was not concentrated in any particular area of the Laurentian Channel during the winter. A winter acoustic survey in January 2001 indicated

that at least some of the tagged Cape Breton cod were well mixed with southern Gulf cod. The survey consisted of towing a four-element directional hydrophone array mounted on a VFIN body and connected to a VR28 tracking system (Vemco Ltd.). The acoustic survey covered approximately 5% of the southern Laurentian Channel area and located four of the acoustically tagged fish (open triangles in Fig. 1). These individuals were in deep water (380 m) close to St.

Paul's Island and were part of an immense cod aggregation, most likely dominated by southern Gulf cod (Campana et al. 1999).

We focused next on quantifying the fraction of the tagged population that migrated across the receiver line in the fall and presumably mixed with the southern Gulf stock. As a first step, we computed the receiver line detection efficiency (RE) using two independent methods, generating RE_1 and RE_2

$$RE_1 = \frac{\sum_{\text{receiver}=1}^{45} \frac{2 \times 1.04}{M_R}}{45}$$

$$RE_2 = \frac{N_{FS}}{N_S}$$

where 45 represents the number of recovered and operational receivers along the offshore line, M_R (2.0–12.5 km) is the distance to be monitored by a given receiver, defined as the sum of the two half distances between a receiver and the two adjacent ones, and 1.04 (km) is an average detection radius based on a series ($n = 18$) of open water tests. These tests of detection radius consisted of deploying two (dead) tagged cod near a moored receiver unit. The tests were conducted under various meteorological conditions (i.e., level of interfering background noise). In future experiments, investigators may wish to continuously monitor the detection radius. For example, deploying a high density of receivers along a few sections of a receiver line would ensure 100% coverage in those sections without too much extra cost and would allow investigators to produce dynamic estimates of detection efficiency for the entire line. With respect to the RE_2 equation, N_{FS} is the number of fish detected by the line in both fall and spring ($N_{FS} = 28$), whereas N_S is the number of fish detected in spring ($N_S = 35$). Although there was no winter fishery for cod in 2001, RE_2 adjusts de facto for losses resulting from natural mortality. Note also that RE_2 is insensitive to bypassed migration pathways as long as the percentage of cod that bypassed the line in fall was similar to that bypassing it in spring. This assumption appears reasonable for Cape Breton cod, although it should be rejected for species that do not migrate along the same pathway in both directions (e.g., Pacific salmonids). RE_1 was estimated as 0.72, and RE_2 was estimated as 0.80. Given the close agreement between the two estimates, we decided to take their mean (0.76) as the RE.

Knowing the RE, the actual number of tagged cod that crossed the line was close to 67 ($N_F/0.76$, with $N_F = 51$), making the proportion that crossed the line (P_F) 65% after adjusting for natural mortality

$$P_F = \left(\frac{N_F/0.76}{0.82 \times \text{tagged}} \right) \times 100$$

where 0.82 accounts for the natural mortality integrated over time (based on $M = 0.4$), and "tagged" is the number of tagged fish (126) that swam away from the release sites. This result suggests that 65% of the Cape Breton spawning stock biomass, or approximately 1625 tonnes (t) based on the most recent stock assessment (Mohn 2001), migrated off-

shore and presumably mixed with southern Gulf cod during the winter. Based on recent biomass surveys, this Cape Breton biomass of 1625 t would have been part of a mean overwintering biomass of 48 250 t in the 4Vn area (Campana et al. 1999), the ratio of the two estimates being equal to 3.4%. Random mixing of the overwintering Cape Breton cod with overwintering southern Gulf cod was not implicated by our results, nor could it be assumed. Nevertheless, the movement of tagged cod along the entire 160-km extent of the acoustic monitoring line suggests that the overwintering distribution was not concentrated near the known southern Gulf aggregations in western 4Vn. As such, any winter fishery targeted at southern Gulf cod would be unlikely to catch a mixture containing a large proportion of Cape Breton origin.

Conventional tags, microsatellite DNA, meristics, and otolith elemental fingerprints have all failed to clearly identify and track the small resident Cape Breton cod stock against the backdrop of the much larger adjacent stocks (Campana et al. 1999; Ruzzante et al. 2000; Swain et al. 2001). The deployment of acoustic arrays appears well suited not only for tracking seasonal migrations, but also for assessing movement in and out of marine reserves and nursery areas (Heupel and Hueter 2001). The ability to use a single array for monitoring multiple species is a notable advantage over other approaches.

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