Variations in the target strength of Atlantic cod during vertical migration

George A. Rose


Experiments conducted at sea in June 1999 and January 2000 indicated that the mean target strength (TS) of Atlantic cod (Gadus morhua) varies not just with length, but also with pressure (depth) and fish orientation, particularly during vertical migration. In June, when fish were migrating and spawning, vertical migration was pronounced, extending up to 150 m off the seabed, and the associated TS declined by as much as 5 dB. In January, when the fish were located nearer the seabed, mean TS was more stable and matched a conventional model of TS vs. length [L, cm; i.e. TS = 20 log(L) − 66] based on measurements of ex situ fish orientated horizontally and positioned at close range. This paper demonstrates that mean TS is inversely related (p < 0.05) to the range off the seabed (r, m), which includes 90% of fish. Based on this finding, a new multivariate TS model is proposed: TS = 20 log(L) − 65 − 0.05 r. In this model, r is a proxy for swimbladder volume and fish orientation. A survey in May 2007 found that cod (mean L = 63 cm) dispersed in such a way that single targets could be resolved up to 100 m from the seabed. Measurements of TS of in situ individual fish (TS_individual) and mean TS inferred from a comparison of area-backscattering coefficients (sa) and count-based densities (TS_indirect) were positively correlated with a slope not different from unity. Means of these TS estimates were −32.4 and −32.2 dB, respectively, or ~2.3 dB less than that predicted by the conventional model. In contrast, the new multivariate model predicts TS = −32.5 dB, which is nearly identical with the means of TS_individual and TS_indirect.

Keywords: acoustic surveys, Atlantic cod, Smith Sound, target strength, vertical migration.

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Introduction

Many marine fish surveyed using acoustic methods undertake vertical migrations that move them from the seabed well into the pelagic zone (Harden-Jones, 1968; Levenez and Petit, 1990; Rose, 1993). Such migrations may vary with season and the physiological cycles of the fish. It has been known for many years that vertical migrations in fish may have strong effects on the acoustic-scattering properties of both individuals and aggregations of fish (Foote, 1980), as a consequence of several factors: (i) swim-bladder volume vs. pressure (Harden-Jones and Scholes, 1981; Arnold and Walker, 1992), (ii) fish orientation while swimming (Nakken and Olsen, 1977; McQuinn and Winger, 2003), and (iii) fish physiology and condition (Ona, 1990; Thorne and Thomas, 1990). Some of these factors reduce and others increase the acoustic target strength (TS). Despite such known variations, mean TS with fish size is still commonly used to scale area-backscattering coefficients (sa) to estimate fish density or biomass. In fact, the literature is replete with empirical and theoretical models of TS vs. size (typically length; L) relationships for many species (Simmonds and MacLennan, 2005).

In the coastal waters of Newfoundland and the Gulf of St Lawrence, Atlantic cod (Gadus morhua) have been surveyed and researched acoustically for many years (Rose and Leggett, 1989; Rose, 1993, 2003; McQuinn et al., 2005). Despite ample evidence of variation in TS measurements of in situ cod, fish biomass or numbers have been estimated using empirical TS vs. L models (e.g. Rose and Porter, 1996). The same has been true in the Barents Sea, where cod are surveyed using acoustic methods (Hjellvik et al., 2004). Recent surveys of cod conducted during different seasons and under different conditions of vertical migration have highlighted the uncertainty (systematic and random error) introduced in estimates of biomass when using simple TS vs. L models. These surveys also provided an opportunity to conduct experiments to quantify variation in TS. In particular, diel and seasonal variations in the vertical distribution and swimming behaviour of cod were studied, as well as their effects on sa and TS.

In theory, fish moving to shallower depths should exhibit increases in TS because of pressure decreases and the resultant increases in swimbladder volumes, as per Boyle’s Law (Harden-Jones and Scholes, 1981). Vertical movements might also cause decreases in TS because of non-horizontal swimming behaviour. Traditionally, this variability and the resulting uncertainty has been accepted (Hjellvik et al., 2004) or mitigated by restricting surveys to the same season each year and the same time of day (Rose, 2003). However, the recent requirement of year-round acoustic surveys for ecosystem-based studies of cod disallows these approaches, and stresses the need for more accurate and precise TS models, perhaps with more variables. The purpose of this research is to quantify the influences of vertical migrations of cod in coastal Newfoundland waters on their TS.
Methods

Surveys of spawning and overwintering cod were conducted in Smith Sound, Trinity Bay, Newfoundland, from the CCGS “Teleost” in June 1999 and January 2000, respectively. Measurements of volume-backscattering strength ($S_v$) and $TS$ were made with a calibrated 38 kHz echosounder (Simrad EK500) and a hull-mounted, split-beam transducer (ES38B; see Table 1 for settings). The echosounder transmitted once per second. Once during each survey, the ship remained stationary for a period of 24–30 h directly over a large concentration of fish. Before and after these periods, the ship surveyed a larger area surrounding and including the fish. The surveys indicated that the fish aggregation did not move much horizontally during the periods that the ship was stationary. Cod were caught after each experiment using a Campelen 1800 research trawl (McCallum and Walsh, 1996). All catches were 100% cod.

Another survey of cod in Smith Sound was conducted with the 15 m vessel “Coastal Explorer” in May 2007. Again, $S_v$ and $TS$ were measured with a calibrated EK500 and a hull-mounted ES38B (see Rose, 2003, for details of the survey design). During this survey, most of the acoustically detected cod could be resolved individually at distances up to 100 m off the seabed. There were only a few fish located near the seabed, suggesting that there were also only a few fish in the dead zone (Ona and Mitson, 1996). These data provided good measurements of $TS$ of in situ cod ($TS_{\text{individual}}$) and fish tracks that allow measures of their numerical densities. Comparison of these density estimates with those derived from the echo-integration method give indirect estimates of mean $TS$ of in situ cod ($TS_{\text{indirect}}$). Fishing on acoustic targets was done during this survey, but mean fork lengths are reported for cod caught in a January 2007 survey in Smith Sound.

The acoustic data were analysed using Echoview software (Myriax Inc., Hobart, Australia). The seabed was identified in the echograms by experienced personnel. For the first two stationary experiments, the volume-backscattering coefficients ($S_v$) were integrated in 5 m deep 10 min long bins. The $S_v$ from the May 2007 survey were integrated in 5 m deep 100 m long bins. Following Ona and Mitson (1996), the $S_v$ were corrected for the dead zone by extrapolating the mean $S_v$ in the 5 m above the detected seabed throughout the depth of the dead zone. Following Gauthier and Rose (2001), if the volume density of fish ($N_v$) exceeded empirically determined thresholds, $TS$ were omitted from those bins (Sawada et al., 1993). Additionally, the depth distributions of cod were calculated by weighting the mid-depth of the bins by the associated $S_v$ for each hour. Statistical analyses were performed using Systat (Systat Inc., San Jose, USA).

Results

In June 1999, the distribution of cod $L$ was bimodal with a mean $L = 65$ cm; the dominant mode ranged from 40 to 95 cm (Figure 1a). These fish moved 50–150 m vertically (Figures 2a and 3a and b). From these data, 13,887 $TS_{\text{individual}}$ measurements were grouped into 2,939 bins; of these, 1,354 were acceptable with $N_v, 0.1$ fish m$^{-3}$ (Figure 2b). Grouped by hour, mean $TS_{\text{individual}}$ were averaged in bins of the same size.

For all three studies, the respective $TS$ measurements were averaged in bins of the same size. Following Ona and Mitson (1996), the $S_v$ were corrected for the dead zone by extrapolating the mean $S_v$ in the 5 m above the detected seabed throughout the depth of the dead zone. Following Gauthier and Rose (2001), if the volume density of fish ($N_v$) exceeded empirically determined thresholds, $TS$ were omitted from those bins (Sawada et al., 1993). Additionally, the depth distributions of cod were calculated by weighting the mid-depth of the bins by the associated $S_v$ for each hour. Statistical analyses were performed using Systat (Systat Inc., San Jose, USA).

Table 1. Settings for the echosounder (Simrad EK500) with 38 kHz, split-beam transducer (ES38B) during June 1999 and January 2000.

<table>
<thead>
<tr>
<th>Setting</th>
<th>June 1999</th>
<th>January 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transducer depth (m)</td>
<td>6 (1)</td>
<td>6 (1)</td>
</tr>
<tr>
<td>Absorption coefficient (dB km$^{-1}$)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Pulse length (ms)</td>
<td>Medium = one</td>
<td>Medium = one</td>
</tr>
<tr>
<td>Bandwidth (kHz)</td>
<td>Auto</td>
<td>Auto</td>
</tr>
<tr>
<td>Maximum power (W)</td>
<td>2 000</td>
<td>2 000</td>
</tr>
<tr>
<td>Two-way beam angle (dB)</td>
<td>$-20.6 (-20.5)$</td>
<td>$-20.6 (-20.5)$</td>
</tr>
<tr>
<td>$S_v$ transducer gain (dB)</td>
<td>25.8 (-26.5)</td>
<td>25.8 (-26.5)</td>
</tr>
<tr>
<td>$TS$ transducer gain (dB)</td>
<td>26.0 (-26.3)</td>
<td>26.0 (-26.3)</td>
</tr>
<tr>
<td>Angle sensitivity alongship</td>
<td>21.9</td>
<td>21.9</td>
</tr>
<tr>
<td>Angle sensitivity athwartship</td>
<td>21.9</td>
<td>21.9</td>
</tr>
<tr>
<td>3 dB beam width alongship (°)</td>
<td>7.0 (6.9)</td>
<td>7.0 (6.9)</td>
</tr>
<tr>
<td>3 dB beam width athwartship (°)</td>
<td>6.8</td>
<td>6.8</td>
</tr>
<tr>
<td>Alongship offset (°)</td>
<td>$-0.16 (0.06)$</td>
<td>$-0.16 (0.06)$</td>
</tr>
<tr>
<td>Athwartship offset (°)</td>
<td>$-0.16 (-0.02)$</td>
<td>$-0.16 (-0.02)$</td>
</tr>
<tr>
<td>Bottom minimum threshold (dB)</td>
<td>$-48$</td>
<td>$-48$</td>
</tr>
<tr>
<td>$TS$ minimum (dB)</td>
<td>$-60$</td>
<td>$-60$</td>
</tr>
<tr>
<td>Minimum echo length factor</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Maximum echo length factor</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Maximum gain compensation (dB)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Maximum phase deviation (°)</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Some settings (in parentheses) differed in May 2007.

Figure 1. Length distribution of cod sampled during (a) June 1999 and (b) January 2000 in Smith Sound.
largest during the daytime when the fish were within 25 m of the seabed, and closely matched model predictions (Figure 2c). At night, the fish were much more pelagic, and mean $TS_{\text{individual}}$ declined as much as 5 dB. The mean $TS_{\text{individual}}$ for tracked fish, weighted by the number of measures in each track, was very similar to the mean $TS_{\text{individual}}$ and they too declined up to 5 dB as the fish migrated vertically (Figure 4a). The numbers of tracked fish were much larger by night than by day (Figure 4b). The vertical distance that individual tracked fish moved was larger and more variable as the fish moved farther from the seabed (Figure 4c).

In January 2000, the unimodal distribution of cod $L$ ranged from 30 to 100 cm, with a mean $L = 55$ cm (Figure 1b). These fish moved only 25–40 m vertically (Figures 3c and d and 5a). From these data, 10,203 $TS_{\text{individual}}$ measurements were grouped into 2275 bins; of these, only 157 were acceptable, with $N_v$ between 0.04 and 1.0 fish m$^{-3}$ (Figure 5b). The lower limit rejected $TS$ values obtained from large zooplankton, later confirmed in images from a camera deployed on an ROV. Grouped by hour, mean $TS_{\text{individual}}$ were largest by day and matched model predictions (Figure 5c). Measurements of the mean $TS$ of tracked fish were too few by day to be reported.

The mean $TS$ values for tracked fish, weighted by the number of measures in each track, were very similar to the mean $TS_{\text{individual}}$ and model predictions of $TS$, except during daylight, when only a few fish were tracked and measurement uncertainty was large (Figure 6a). As with solitary measurements of individual targets, the numbers of tracked fish were much larger during the hours of darkness (Figure 6b). Tracked fish moved vertically only 2–3 m in January compared with 10–20 m in June (Figure 6c).

The range above the seabed that encompassed 90% of the cod backscatter ($r$, m) was significantly correlated with the mean $TS_{\text{individual}}$ in June 1999 (Figure 7). Using $r$ as a proxy for the combined effects of $\theta$ and changes in swimbladder volume with
pressure, the regression slope (Figure 8) was added to the TS vs. \( L \) equation from Rose and Porter (1996):

\[
TS = 20 \log(L) - 65.
\]

resulting in a new multivariate TS model:

\[
TS = 20 \log(L) - 65 - 0.05r.
\]

The data supporting Equation (2) were not extrapolated if \( r \) was in the range 20–100 m.

Equation (2) was used to estimate cod biomass from a survey on 8 May 2007 where the cod were pelagic and had low \( s_\nu \) (Figure 3e). Estimates of \( TS_{\text{indirect}} \) were highly variable throughout the survey, but the slope of the regression of \( TS_{\text{indirect}} \) on \( TS_{\text{individual}} \) did not differ significantly from unity, and their means were virtually equal (mean \( TS_{\text{indirect}} = -32.2 \) dB; mean...
TS of Atlantic cod during vertical migration

Discussion

This analysis confirms that the TS of Atlantic cod is modulated by fish behaviour. Therefore, models of TS vs. L (Rose and Porter, 1996; Simmonds and MacLennan, 2005, and references therein) do not account for these variations and may contribute uncertainty, generally negative bias, in estimates of abundance reaching, perhaps, 4–5 dB or >300% negative bias. In one example in this study, the use of Equation (1) resulted in an underestimation of cod biomass of 40–45%. Similarly, Hjellvik et al. (2004) established declines of up to 50% in the Barents Sea biomass during night-time for estimates derived using TS vs. L models for cod and other species. Notwithstanding these provocative findings,
Typically, uncertainty is managed in any time-series of cod abundance measurements by standardizing the survey timing and $TS$ model (Simmonds and MacLennan, 2005; Kalikhman and Yudanov, 2006). This is true for surveys in coastal Newfoundland, which inspired this study. They are traditionally conducted only in January and February, when the vertical fish distribution is most stable (Rose, 2003). Recently, however, ecosystem-based studies of cod required surveys to be conducted throughout the year. Also, for surveys in the Barents Sea, intra-survey or inter-year variations in vertical distributions of cod could introduce significant uncertainty (bias and imprecision) in the acoustically derived, cod-biomass estimates (Hjellvik et al., 2004).

This study demonstrates that in addition to cod size, $TS$ is modulated by fish-swimbladder volume and orientation during vertical migrations. This conclusion could be relevant to other vertically migrating species with swimbladders that exhibit pronounced acoustic directivity at the survey frequency. Use of a multivariate model could account for temporal and spatial variations in $TS$, thereby reducing uncertainty in the biomass estimates. This study constitutes a step in that direction by providing a model of $TS$ vs. cod length and range from the seabed, a proxy for fish-swimbladder volume and orientation during vertical migrations.

References


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