The acoustic dead zone: theoretical vs. empirical estimates, and its effect on density measurements of semi-demersal fish

L. G. S. Mello and G. A. Rose

Mello, L. G. S., and Rose, G. A. 2009. The acoustic dead zone: theoretical vs. empirical estimates, and its effect on density measurements of semi-demersal fish. – ICES Journal of Marine Science, 66: 1364–1369.

The height of the acoustic dead zone, the region near the seabed where fish cannot be resolved acoustically, was calculated both theoretically (DZ_t) and empirically (DZ_e). The DZ_e was based on measurements of depth and trawl geometry from sensors (SCANMAR) mounted on a bottom trawl deployed during a survey off Newfoundland and Labrador in winter 2007. Acoustic data were acquired while trawling, using a 38-kHz echosounder (Simrad EK500) with a hull-mounted transducer. The DZ_e was calculated as the difference between the trawl-footrope depth and the corresponding acoustically sensed, seabed depth. EK500 and SCANMAR estimates of seabed depth were significantly different. The fish caught were mostly Atlantic cod (*Gadus morhua*). The estimates of DZ_e ranged between 2.0 and 3.5 m and were greater than DZ_t by 0.1–0.9 m in more than half the cases. Three values of acoustically derived cod densities were estimated for each tow, without dead-zone correction and with corrections for DZ_t and DZ_e. When compared with DZ_t corrections, DZ_e resulted in negative (6–12%) and positive (9–35%) corrections to cod density. A general linear model revealed that the seabed depth gradient, standard deviation of estimated fish density in the dead zone, and wind direction and force explained 85% of the difference between DZ_t and DZ_e estimates. These factors affected the detection of the seabed and biased acoustically derived indices of demersal-fish abundance.

Keywords: acoustic dead zone, bottom trawl, fish-density estimate, *Gadus morhua*, Labrador, Newfoundland.

Received 7 August 2008; accepted 30 January 2009; advance access publication 20 April 2009.

L. G. S. Mello and G. A. Rose: Fisheries Conservation Group, Marine Institute, Memorial University of Newfoundland, PO Box 4920, St John's, NL, Canada A1C 5R3. Correspondence to L. G. S. Mello: tel: +1 709 778 0652; fax: +1 709 778 0669; e-mail: luiz.mello@mi.mun.ca.

Introduction

Combined acoustic-trawl surveys have been used to assess the abundances of demersal-fish resources since the 1980s (Hylen *et al.*, 1986; Godø and Wespestad, 1993; Mello and Rose, 2008). However, the utility of acoustic data for stock assessments of fish located near the seabed is often perceived as limited (Greig, 2004; McQuinn *et al.*, 2005). The main reason for this is the difficulties associated with the detection of fish located in the integrator dead zone (Ona and Mitson, 1996). This is the region near the seabed where fish cannot be resolved acoustically, because of the additive effects of the unsampled volume of a spherical acoustic beam (i.e. from the point of contact with the seabed to the outer edges of the beam), the backstep used to exclude seabed reflections, and the partial integration zone where only a portion of the echo is detected. In this paper, these regions taken together are referred to as the acoustic dead zone (ADZ).

The most common approach taken to quantify the effect of the ADZ on estimates of demersal-fish biomass is to calculate the associated theoretical sampling volume, then to extrapolate the fish density within the ADZ using the acoustic-density measurements from immediately above the ADZ (Mamylov and Ratushny, 1996; Rose, 2003; McQuinn *et al.*, 2005). The sampling volume within the ADZ, resulting from the acoustic beam and the ADZ height, can be calculated readily given knowledge of the seabed depth (d), the acoustic-pulse duration (τ), the sound speed (c), and the transducer beam width (θ).

Generally, the acoustic signal from an echosounder is used to estimate d, which is subsequently used to calculate the ADZ volume. This approach is limited by the accuracy of the estimated d. Furthermore, the ADZ volume is also modulated by factors such as seabed topography and the movement of tow-body or hull-mounted transducers (Kloser *et al.*, 2001; Pedersen *et al.*, 2004).

In this study, data gathered during a combined acoustic and trawl survey conducted off Newfoundland and Labrador were used to estimate the ADZ height following the approach proposed by Ona and Mitson (1996). The seabed depths estimated from the echosounder were compared with those measured simultaneously with a SCANMAR sensor mounted on a Campelen 1800 bottom trawl. The main goals were to quantify and model the uncertainties associated with estimates of the ADZ height and the effect of the ADZ volume on estimates of semi-demersal fish density.

Methods

A survey was conducted between 28 February and 19 March 2007 from the Canadian Coast Guard Ship "Teleost" to estimate the abundance and distribution of Atlantic cod (*Gadus morhua*) overwintering off eastern Newfoundland and southern Labrador. Data were collected with a calibrated echosounder (Simrad EK500) configured with a hull-mounted (6 m deep), 38-kHz transducer (Simrad ES38-B; 7.1° beam width). Echosounder measurements

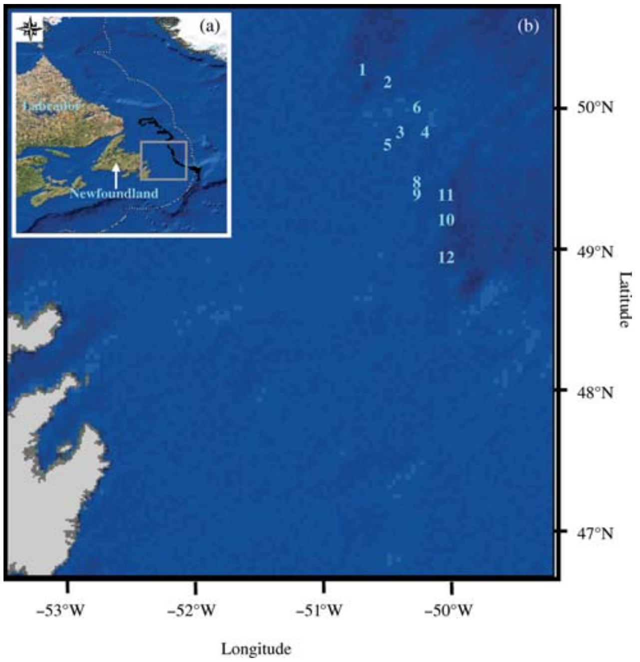

Figure 1. (a) The east coast of North America, illustrating the acoustic tracks (black dotted lines) of the survey off Newfoundland and Labrador in winter of 2007, and the area (grey square) where tows were conducted. (b) Detail of the study area indicating tow locations (1–12).

were recorded 24 h d^{-1}, while the ship followed a triangular track (Figure 1).

In all, 25 fishing tows were conducted with a Campelen trawl. In each case, the trawl was towed on the seabed for a period of 15 min at a speed of 3 knots, resulting in tow lengths of 1389 m. Only 12 of these tows were analysed. Data from the remaining tows were not used, because they were conducted with a different sampling protocol or were recorded with errors resulting from software or operational difficulties, e.g. erroneous or missing acoustic seabed detections or discrepancies between the trawl and the vessel paths. Fishing tows were conducted along bathymetric contours, within and around detected fish aggregations, and in areas with low or no acoustic signal. Catch data were used to verify the species contributing to the acoustic signal and to measure their length, mass, sex, and maturity stage. At each trawl station, the water temperature was profiled using a trawl-mounted CTD (Seabird 19), and time, light level, sea condition, and wind direction and force were also recorded (Table 1).

Metrics of the trawl geometry, door spread, headrope, and footrope depth and clearance from the seabed, were measured continuously using trawl-mounted sensors (SCANMAR, Scantech Group). Constant wire tension was controlled by an auto-trawl system, so maintaining an optimal trawl position. Together, these systems were used to maintain trawl symmetry, compensating for seabed slope and oblique water flow (Stauffer, 2004). Only tows with negligible athwartship warp angle were used in this analysis.

Because the trawl lagged the vessel by various distances dependant on the seabed depth, acoustic data were selected only from the area fished. This was achieved by synchronizing the SCANMAR and the echosounder clocks before surveying and choosing the portions of the echograms, which corresponded to the times when the trawl was on the seabed. The trawl touchdown and liftoff times and positions were calculated from the seabed depth, the warp length, and the vessel's initial and final geographic position.

The echograms were edited and integrated using Echoview (SonarData Pty Ltd) to estimate the area-backscattering coefficient, s_a, for each integration bin (100 m long × 25 m deep) along the trawl track. Account was taken of the average c calculated from the water-temperature profiles. Seabed depth was estimated for each ping as the depth of the maximum volume-backscattering strength (S_v, dB), backstepped to −48 dB. Seabed depths were corrected for the transducer depth.

Echotraces (e.g. echo shapes and colours) and target strengths (*TS*) of single fish were used to separate the S_v from cod from that of the seabed and other fish species. In two tows, it was not possible to separate acoustically the S_v from cod from that of other fish species, mainly redfish, *Sebastes* spp. In those cases, the proportion of cod by mass in the catch was used to partition the s_a. Therefore, not all the acoustic- and trawl-density estimates are totally independent (Hjellvik *et al.*, 2007).

Table 1. Tow-station information (time, light level, sea condition, and wind) recorded during a combined acoustic and trawl survey off Newfoundland and Labrador during winter 2007.

	Time (NST)				Wind	
Tow number	Start	End	Light level	Sea condition	Force (km h^{-1})	Direction (°)
1	23:45	0:00	Dark	4	50–61	293–337
2	10:35	10:50	Bright sunlight	5	20–28	293–337
3	21:14	21:29	Dark	5	39–49	158–202
4	3:39	3:54	Dark	4	20–28	158–202
5	21:38	21:53	Dark	5	39–49	248–292
6	13:43	13:58	Overcast	9	62–74	203–247
7	6:27	6:42	Dusk and dawn	5	39–49	158–202
8	20:30	20:45	Dark	2	29–38	203–247
9	20:54	21:09	Dark	4	39–49	338–22
10	2:38	2:53	Dark	3	29–38	338–22
11	5:25	5:40	Dusk and dawn	4	20–28	338–22
12	0:28	0:43	Dark	6	39–49	68–112

Sea condition and wind force are according to the Beaufort scale. NST, Newfoundland Standard Time (GMT—3:30 h).

Cod s_a were converted to areal densities (AD; kg m^{-2}):

$$\mathrm{AD} = \frac{s_a}{10^{TS/10}}, \quad (1)$$

using a mass-based TS equation (dB kg^{-1}; Rose, 2003):

$$TS = -11.26\ \log(L_\mathrm{T}) - 13.67, \quad (2)$$

where L_T is the total length (cm).

The height of the ADZ, the distance between the echosounder-detected seabed and the actual seabed, was estimated in two ways: first, using a theoretical method as proposed by Ona and Mitson (1996), and second, by comparing the echosounder-detected seabed (d_ek) with the seabed depth estimated from the SCANMAR sensor (d_scan). In both cases, average values were calculated for each 1-min interval (i) of the trawl track.

The theoretical ADZ height ($\mathrm{DZ_t}$) was calculated as

$$\mathrm{DZ}_{\mathrm{t},i} = \left(2404 \times \frac{d_{\mathrm{ek},i} \tan^4 \theta}{\theta^2}\right) + \frac{c\tau}{4}, \quad (3)$$

where $d_{\mathrm{ek},i}$ is the average echosounder-detected seabed depth (m) at time i. In this analysis, c was the average sound speed (m s^{-1}) from the depth of the transducer to the seabed, $\tau = 1$ ms, and $\theta = 3.5°$. The empirical ADZ height ($\mathrm{DZ_e}$) was calculated as

$$\mathrm{DZ}_{\mathrm{e},i} = d_{\mathrm{scan},i} - d_{\mathrm{ek},i}, \quad (4)$$

where $d_{\mathrm{scan},i}$ is the SCANMAR-estimated seabed depth (m) at time i.

Three estimates of AD were derived for each tow:

(i) $\mathrm{AD_0}$ includes only fish above the echosounder-detected seabed;

(ii) $\mathrm{AD_t}$, includes $\mathrm{AD_0}$ plus the cod estimated to be in the $\mathrm{DZ_t}$ by linearly extrapolating the cod densities in the 5 m above d_ek; and

(iii) $\mathrm{AD_e}$, includes $\mathrm{AD_0}$ plus the cod estimated to be in the $\mathrm{DZ_e}$ from the average density in the 5 m above d_ek.

The resulting AD values were compared with estimates of fish density from the trawl catches (TD). The TD values were calculated as the ratio between the catch mass (kg) and area swept by the trawl (m^2). The swept-area was calculated from the door spread multiplied by the tow distance. Door spread was used rather than wingspread to give the best estimate of the effective swept-area for cod in deep water (Walsh, 1996; McCallum and Walsh, 2002).

At all times of the day during the survey, cod were typically patchily aggregated within 3 m of the seabed (Figure 2). Therefore, most cod were probably available to the ~5-m vertical opening of the trawl, and any diel bias in TD was probably negligible. This situation allowed comparisons between AD and TD values.

A general linear model (GLM) was used to study the variability in the heights of the ADZ vs. 1-minute, trawl-track intervals (i):

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_p X_{ip} + \varepsilon_i, \quad (5)$$

where $Y_i = ((\mathrm{DZ}_{ei} - \mathrm{DZ}_{ti})/\mathrm{DZ}_{ei})$; $X_{i1}, \ldots, X_{ip}$ the p predictors, $\beta_o, \ldots, \beta_p$ the variable coefficients, and ϵ_i the random error.

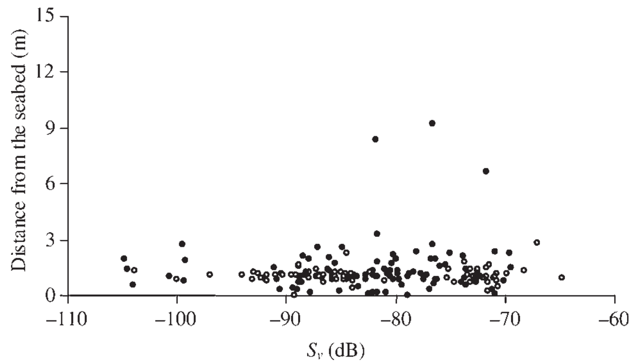

Figure 2. Vertical distribution in relation to the seabed of the acoustic-backscattering strength (S_v) of targets detected during tows (1–12) during daytime (open circles) and night-time (dots).

Predictors initially included were the average d_scan during the tow; the difference between d_scan at the start and end of the tow (tow-depth gradient); TD, $\mathrm{AD_0}$, $\mathrm{AD_t}$, $\mathrm{AD_e}$, their standard deviation (s.d.), the sea condition, and the wind direction and force. Interactions among predictors were also investigated. Ultimately, only predictors that were statistically significant ($p < 0.05$) were used.

Results

The $d_{\mathrm{scan},i}$ differed significantly from the corresponding $d_{\mathrm{ek},i}$ (ANOVA, $p < 0.0001$, $F = 4998$, $n = 359$). The average $d_{\mathrm{scan},i}$ and corresponding average $d_{\mathrm{ek},i}$ varied from 309 to 523 m and 308 to 520 m, respectively. Most $d_{\mathrm{scan},i}$ values ranged from 340 to 440 m (Table 2). Generally, the $d_{\mathrm{scan},i}$ were less variable (s.d. < 5 m) than corresponding $d_{\mathrm{ek},I}$ (s.d. > 5 m in eight tows).

The average $\mathrm{DZ_t}$ and $\mathrm{DZ_e}$ ranged between 2.0 and 2.8 m and between 2.0 and 3.5 m, respectively. $\mathrm{DZ_e}$ was more variable and larger than $\mathrm{DZ_t}$ in 8 of 12 tows (by 0.1–0.9 m; Figure 3).

There were no significant differences in door spread among fishing tows ($p > 0.05$, $F = 11$, and $n = 149$). The average door spread ranged from 54 to 58 m (Table 2). These statistics indicate that swept-areas were similar among tows. For all but one tow, the

Table 2. Average depth of fishing tows estimated using data from an echosounder (Simrad EK500 with hull-mounted transducer) and a trawl-mounted depth sensor (SCANMAR) and the trawl-door spread.

	Depth (s.d.)		
Tow number	Echosounder (m)	Trawl sensor (m)	Trawl-door spread (s.d.) (m)
1	413 (7)	408 (2)	56 (4.5)
2	434 (2)	434 (3)	55 (3.9)
3	520 (8)	523 (5)	58 (3.5)
4	308 (1)	309 (2)	55 (4.7)
5	430 (7)	423 (3)	57 (4.1)
6	344 (4)	343 (4)	56 (6.4)
7	409 (11)	406 (3)	56 (8.1)
8	391 (11)	399 (10)	59 (6.5)
9	377 (7)	383 (1)	55 (3.3)
10	391 (3)	400 (2)	54 (2.6)
11	410 (15)	422 (2)	56 (3.1)
12	406 (9)	417 (1)	55 (2.4)

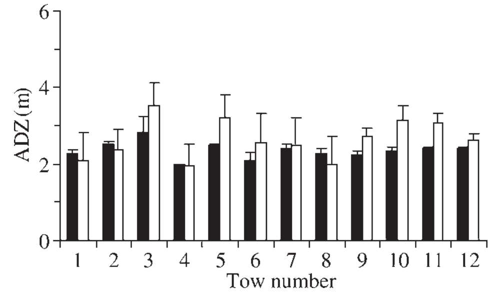

Figure 3. The mean ADZ height during tows calculated using a theoretical approach (DZ_t) as described by Ona and Mitson (1996; black bar) and empirically (DZ_e; white bar). T-bar equals 1 s.d.

L_T distributions of cod overlapped (Figure 4). The average L_T of the cod was 46 cm (s.d. = 9 cm).

Predictably, AD_0 values were always less than AD_e and AD_t (Figure 5). By a large margin, the largest AD values were observed in tows 1, 2, and 10–12. The TD displayed similar trends, but were greater than AD for high-density tows and less than AD for low-density tows. Correcting for DZ_t and DZ_e, AD_e was greater than AD_t in seven tows (10–35%) and less than AD_t in three tows (6–12%). The variance was high, regardless of the method used.

Ultimately, *Y* was highly significant ($p < 0.004$) and explains as much as 85% of the variances in estimates of the ADZ heights (Table 3). Depth gradient and wind direction explained most of the variance, followed by the s.d. of AD_e, and wind force. The coefficients were all positive, except for that associated with wind direction.

Discussion

These results were consistent with those of previous studies that revealed that seabed slope (Kloser *et al.*, 2001; Pedersen *et al.*, 2004), variations in the angle of incidence of the acoustic beam relative to the seabed (Ona and Mitson, 1996; Pedersen *et al.*, 2004), and fish density (Rose, 2003) affect the acoustic detection of the seabed, and therefore bias acoustically derived indices of demersal-fish abundance (Mamylov and Ratushny, 1996; McQuinn *et al.*, 2005). Windspeed and sea condition were directly related to each other (e.g. Beaufort scale), affecting the pitch and roll of the ship and consequently the movement of the hull-mounted transducers. It is logical that ADZ height should increase with windspeed. However, this analysis indicated that wind direction was inversely related to the ADZ height and explained a larger proportion of the variance in the ADZ height than did wind force. This could be explained by the fact that, in many areas, sea condition improves or worsens according to the direction of the predominant wind.

Mello and Rose (2005, 2008) found that for cod, variability in acoustic-density estimates (measured as the coefficient of variation, and standard error, s.e.) was directly related to high densities of patchily distributed fish. Other studies of groundfish have yielded similar results (Walsh, 1996; Hjellvik *et al.*, 2003; Gauthier and Rose, 2005). The reasons for this are uncertain, but include potential herding by the trawl (Hjellvik *et al.*, 2007) and underestimation of the densities in the ADZ because of non-linear increases in densities approaching the seabed (Gauthier and Rose, 2005). When fish are many, density estimates from the trawl swept-area may exceed those generated from acoustics. In contrast, acoustic measures tend to be greater than trawl catches at low densities with either of the ADZ-height corrections applied. These differences could be caused by random variation or misinterpretation of very low backscatter.

Bias and differences between estimated densities from acoustic and catch data can also result from changes in catchability because of trawl asymmetry (McCallum and Walsh, 2002; Weinberg and

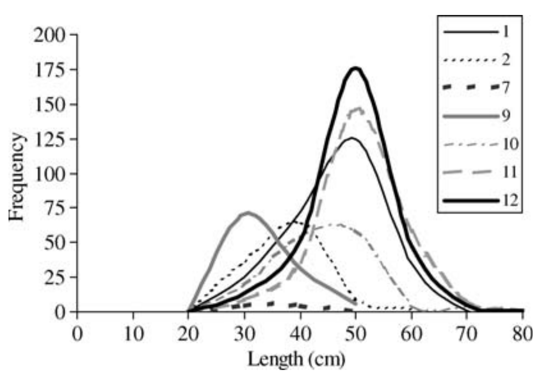

Figure 4. Distribution of cod total lengths (L_T) caught by a Campelen 1800 bottom trawl during tows (1–12). Tows 3–6 and 8 are not plotted because they caught <10 fish.

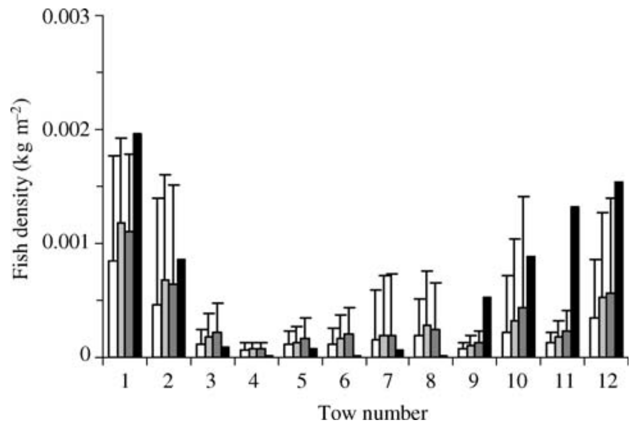

Figure 5. Estimates of the average cod density per tow from acoustic data without dead-zone correction (AD_0, white); with dead-zone correction using DZ_t (AD_t, light grey); with dead-zone correction using DZ_e (AD_e; dark grey); and trawl swept-area (TD; black). T-bar equals 1 s.d.

Table 3. Results of the GLM (5) used to explain variability in the ADZ height.

Source	r^2	d.f.	*F*	*p* > *F*	β (s.d.)
Model	0.85	11	10.2	0.004	−0.30[a] (0.14)
s.d. of AD_e		1	9.2	0.01	0.19 (0.09)
Wind direction		1	12.7	0.009	−0.02 (0.01)
Wind force		1	4.7	0.05	0.05 (0.02)
Tow-depth gradient		1	14.2	0.007	1.24 (0.33)

Parameters include the average d_{scan} (and s.d.), difference between d_{scan} at the start and end of the tow (tow-depth gradient), the density indices AD_0, AD_t, AD_e, and TD (and their s.d. values), sea condition, and wind direction and wind force. Only significant ($p < 0.05$) parameters are presented. β refers to the regression coefficients.
[a]Intercept.

Somerton, 2006) or fish availability (Aglen *et al*., 1999; Godø *et al*., 1999; Hjellvik *et al*., 2004). However, the auto-trawl system and the monitoring of trawl parameters indicated that the gear was operating optimally. Most of the fish detected acoustically were found near the seabed and were available to the trawl. Overall, the gear performance, availability of fish to the trawl, and catch-size compositions suggest that the trawl catchability was similar during fishing tows and was not, at least in this study, an important source of bias in TD.

Fish-density estimates have been independently validated to estimate correction factors using acoustic and catch data (Hjellvik et al., 2002; Simmonds, 2003; Neilson *et al*., 2003; Bez *et al*., 2007) and other stock assessment techniques (Somerton *et al*., 1999; Kloser *et al*., 2001; Savereide and Quinn, 2004). For the same reason, this study used a similar approach to estimate corrections of seabed depth and semi-demersal fish-density measurements.

Differences between d_{scan} and d_{ek} can be the result of error in estimates of the trawl position relative to the vessel track. Perhaps, the differences could be reduced with the use of currently available trawl-mounted sensors that provide real-time measurements of the gear position in relation to the vessel, in addition to monitoring gear geometry to d_{scan}. In addition, accounting for transducer motion (pitch, roll, and heave) in the d_{ek} should be considered.

Corrections to AD values, using theoretically derived ADZ heights, have been used for a number of fish stocks (Siwabessy *et al*., 2000; Stensholt *et al*., 2002; Rose, 2003; McQuinn *et al*., 2005). As additional independent measures of ADZ height become available, stock- or survey-specific correction factors could be developed by the incorporation of various oceanographic and biological variables into the estimation process. Estimates of ADZ height at trawl locations could be extrapolated to larger survey areas.

Conclusion

Acoustic estimates of seabed depth are biased by seabed slope and vessel motion. This biases estimates of the volume of the ADZ and semi-demersal fish density. For a winter survey of Atlantic cod, the empirically estimated ADZ height differed from theoretical values by −0.2 to 0.8 m and resulted in negative (6–12%) and positive (9–35%) corrections to cod density, particularly for tows with the highest catch densities.

A GLM indicated that the variability in the estimated ADZ height was largely related to the seabed depth gradient, the s.d. of estimated fish density in the ADZ, and wind direction and force. These results were consistent with those of previous studies that demonstrated that seabed slope, transducer motion, and fish density affect the acoustic detection of the seabed, and therefore bias acoustically derived indices of demersal-fish abundance.

Acknowledgements

We thank D. Power, C. Stevens, C. Lang, S. Fudge, C. Knickle, A. Olafsdottir, and technical personnel from DFO, and the crew of the CCGS "Teleost" for their logistical support and expertise, as well as three anonymous reviewers for their valuable comments. We also thank D. Demer for his comments and edits of the manuscript. Financial support for this study was provided by the Department of Fisheries and Aquaculture, Government of Newfoundland and Labrador, and the Canadian Department of Fisheries and Oceans.

References

Aglen, A., Engås, A., Huse, I., Michalsen, K., and Stensholt, B. K. 1999. How vertical fish distribution may affect survey results. ICES Journal of Marine Science, 56: 345–360.

Bez, N., Reid, D., Neville, S., Vérin, Y., Hjellvik, V., and Gerritsen, H. D. 2007. Acoustic data collected during and between bottom trawl stations: consistency and common trends. Canadian Journal of Fisheries and Aquatic Sciences, 64: 166–180.

Gauthier, S., and Rose, G. A. 2005. Diel vertical migration and shoaling heterogeneity in Atlantic redfish: effects on acoustic and bottom-trawl surveys. ICES Journal of Marine Science, 62: 72–85.

Godø, O. R., Walsh, S. J., and Engås, A. 1999. Investigating density-dependent catchability in bottom-trawl surveys. ICES Journal of Marine Science, 56: 292–298.

Godø, O. R., and Wespestad, V. G. 1993. Monitoring changes of abundance of gadoids with varying availability to trawl and acoustic surveys. ICES Journal of Marine Science, 50: 39–51.

Greig, T. 2004. Fish in the dead zone: are there any whispers from the bottom? ICES Document CM 2004/R: 17.

Hjellvik, V., Godø, O. R., and Tjøstheim, D. 2002. Diurnal variation in bottom trawl survey catches: does it pay to adjust? Canadian Journal of Fisheries and Aquatic Sciences, 59: 33–48.

Hjellvik, V., Godø, O. R., and Tjøstheim, D. 2004. Diurnal variation in acoustic densities: why do we see less in the dark? Canadian Journal of Fisheries and Aquatic Sciences, 61: 2237–2254.

Hjellvik, V., Michalsen, K., Aglen, A., and Nakken, O. 2003. An attempt at estimating the effective fishing height of the bottom trawl using acoustic survey recordings. ICES Journal of Marine Science, 60: 967–979.

Hjellvik, V., Tjøstheim, D., and Godø, R. 2007. Can the precision of bottom trawl indices be increased by using simultaneously collected acoustic data? The Barents Sea experience. Canadian Journal of Fisheries and Aquatic Sciences, 64: 1390–1402.

Hylen, A., Nakken, O., and Sunnanå, K. 1986. The use of acoustic and bottom trawl surveys in the assessment of north-east cod and haddock stocks. *In* A Workshop on Comparative Biology, Assessment and Management of Gadoids from the North Pacific and Atlantic Oceans, June 1985, pp. 473–498. Ed. by M. Alton. Seattle, Washington.

Kloser, R. J., Ryan, T. E., Williams, A., and Lewis, M. 2001. Development and application of a combined industry/scientific acoustic survey of orange roughy in the eastern zone. CSIRO Marine Research. Final Report, December 2001. FRDC Project-99/111. Uniprint, Hobart, Tasmania. 211 pp.

Mamylov, V. S., and Ratushny, S. V. 1996. On method of estimation of acoustic shadow zone when assessing groundfish stocks. NAFO SCR Document, 96/92.

McCallum, B. R., and Walsh, S. J. 2002. An update on the performance of the Campelen 1800 during bottom trawl surveys in NAFO Subareas 2 and 3 in 2001. NAFO SCR Document, 02/32.

McQuinn, I. H., Simard, Y., Stroud, T. W. F., Beaulieu, J-L., and Walsh, S. J. 2005. An adaptive, integrated "acoustic-trawl" survey design for Atlantic cod (*Gadus morhua*) with estimation of the acoustic and trawl dead zones. ICES Journal of Marine Science, 62: 93–106.

Mello, L. G. S., and Rose, G. A. 2005. Using geostatistics to quantify seasonal distribution and aggregation patterns of fishes: an example of Atlantic cod (*Gadus morhua*). Canadian Journal of Fisheries and Aquatic Sciences, 62: 659–670.

Mello, L. G. S., and Rose, G. A. 2008. An acoustic-trawl survey of offshore over-wintering northern cod, Feb–Mar 2007. Canadian Science Advisory Secretariat Research Document, 2008/048.

Neilson, J. D., Clark, D., Melvin, G. D., Perley, P., and Stevens, C. 2003. The diel-vertical distribution and characteristics of pre-spawning aggregations of pollock (*Pollachius virens*) as inferred from hydroacoustic observations: the implications for survey design. ICES Journal of Marine Science, 60: 860–871.

Ona, E., and Mitson, R. B. 1996. Acoustic sampling and signal processing near the seabed: the deadzone revisited. ICES Journal of Marine Science, 53: 677–690.

Pedersen, G., Ruben, P., and Ona, E. 2004. Direct measurement of the effective deadzone volume on sloping bottom from split beam phase angles. ICES Document CM 2004/R: 34.

Rose, G. A. 2003. Monitoring coastal northern cod: towards an optimal survey of Smith Sound, Newfoundland. ICES Journal of Marine Science, 60: 453–462.

Savereide, J. W., and Quinn, T. J. 2004. An age-structured assessment model for Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences, 61: 974–985.

Simmonds, E. J. 2003. Weighting of acoustic- and trawl-survey indices for the assessment of North Sea herring. ICES Journal of Marine Science, 60: 463–471.

Siwabessy, P. J. W., Penrose, J. D., and Kloser, R. J. 2000. A comparison between acoustically derived s_A estimates and those derived from nets. ECUA 2000 (European Conference on Underwater Acoustics), Lyon, France, 11–13 July 2000.

Somerton, D., Ianelli, J., Walsh, S., Smith, S., Godø, O. R., and Ramm, D. 1999. Incorporating experimentally derived estimates of survey trawl efficiency into the stock assessment process: a discussion. ICES Journal of Marine Science, 56: 299–302.

Stauffer, G. 2004. NOAA protocols for groundfish bottom trawl surveys of the nation's fishery resources. US Department of Commerce, NOAA Technical Memo, NMFS-F/SPO-65. 205 pp.

Stensholt, B. K., Aglen, A., Mehl, S., and Stensholt, E. 2002. Vertical density distribution of fish: a balance between environmental and physiological limitation. ICES Journal of Marine Science, 59: 679–710.

Walsh, S. J. 1996. Efficiency of bottom sampling trawls in deriving survey abundance indices. NAFO Scientific Council Studies, 28: 9–24.

Weinberg, K. L., and Somerton, D. A. 2006. Variation in trawl geometry due to unequal warp length. Fishery Bulletin US, 104: 21–34.

doi:10.1093/icesjms/fsp099