

# Using acoustic technology to improve the modelling of the transportation and distribution of juvenile gadoids in the Barents Sea

Geir O. Johansen, Olav R. Godø, Morten D. Skogen, and Terje Torkelsen

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Transport of the juvenile stages of gadoids by oceanic currents in the Barents Sea is governed by interactions between the vertical positioning of the fish and the horizontal movement of the water masses. The resulting geographical distribution is important for growth and survival. There is need for observations at proper temporal and spatial scales to improve the representation of vertical distribution in models of the transport process. Stationary acoustic systems are suitable for this purpose. We use such a system to quantify the vertical dynamics of 0-group gadoids with reference to a conceptual model of the temporal variation. The vertical distribution from the conceptual model is applied within a Lagrangian, particle-tracking model. This approach performs better in predicting the geographic distribution of the 0-group during the first 10 months after hatching than a model with random, vertical distribution. The potential of stationary acoustic systems to provide high-quality vertical distributions that improve the predictive power of the transport model is demonstrated. Extensive sampling programmes based on the principles presented here can provide the observations needed to obtain more realistic recruitment–prediction models.

**Keywords:** advection, cod, 0-group, haddock, hydrodynamic model, recruitment, stationary acoustics, vertical distribution.

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G. O. Johansen, O. R. Godø, M. D. Skogen and T. Torkelsen: Institute of Marine Research, PO Box 1870 Nordnes N-5817, Bergen, Norway. Correspondence to G. O. Johansen: tel: +47 55 23 53 78; fax: +47 55 23 85 31; e-mail: geir.odd.johansen@imr.no.

## Introduction

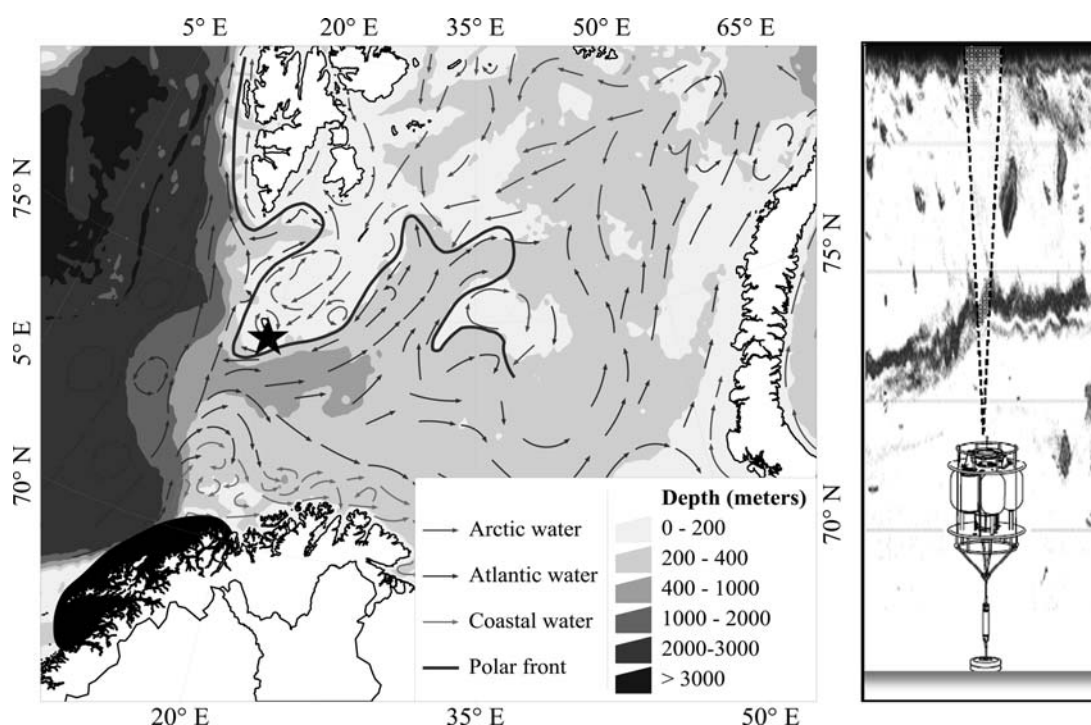
Northeast Arctic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) migrate annually from the nursery and feeding areas in the Barents Sea–Svalbard region to the spawning grounds off the Norwegian coast (Godø, 1984; Bergstad *et al.*, 1987). Eggs and early larvae are carried by the ocean currents towards the nursery areas (Bergstad *et al.*, 1987; Figure 1). The transport of eggs and juvenile fish is governed by the vertical and horizontal oceanographic features that interact with the vertical distribution and migration of the fish (Stenevik *et al.*, 2001). Cod is the gadoid in the Barents Sea for which there is most information about the factors influencing early survival, and the current study focuses on it.

Environmental conditions, such as temperature, windstress, and food availability, influence the spatial distribution and survival of eggs and larvae during the first six months of the drift phase (Ottersen and Sundby, 1995; Sundby, 2000). The geographic distribution resulting from the transport is important for growth and survival during the first winter in the Barents Sea (Helle *et al.*, 2002; Ottersen *et al.*, 2002; Ciannelli *et al.*, 2007). Therefore, realistic modelling of the geographic distribution is important for predicting recruitment.

The transport of juvenile fish by ocean currents is an example of physical–biological interactions that have been extensively modelled (Hannah, 2007). Such models require detailed information about the vertical distribution and migration of eggs and juveniles,

which determine the interaction between vertical positioning and horizontal transport (Vikebø *et al.*, 2005; Vikebø *et al.*, 2007). Recent drift models for juvenile fish rely on assumptions about the vertical distribution in the drift phase (Vikebø *et al.*, 2005, 2007; Fiksen *et al.*, 2007; Daewel *et al.*, 2008). There is an urgent need for better field observations of vertical distribution and its change with ontogeny to improve predictions of the geographic distribution of juvenile fish resulting from oceanic transport (Vikebø *et al.*, 2007).

The general characteristics of the vertical distribution of cod eggs and larvae along the Norwegian coast are known from field observations (Bjørke and Sundby, 1984; Ellertsen *et al.*, 1989). The long time-series of 0-group surveys in the Barents Sea (Dingsør, 2005) and associated studies (Godø *et al.*, 1993; Høyen *et al.*, 1995; Nakken *et al.*, 1995) also provide some information about the vertical distribution and migration of age-0 cod in autumn. These observations are based on trawl samples and records from hull-mounted echosounders on moving vessels. They do not provide correct information about the diel variation in the vertical distribution because they are confounded by location. They are also scattered through the season and are thus effectively snapshots of the seasonal variation. This lack of temporal representation can be overcome using new stationary acoustic technology that provides vertical-distribution data with high temporal and spatial resolution. Several studies have demonstrated the application of stationary acoustics to the vertical distribution



**Figure 1.** Map of the spawning area (black shaded area in southwestern corner) and general ocean currents (black arrows) defining the drift routes of juvenile gadoids in the Barents Sea. The black star is the location of the acoustic “Lander”. The right panel illustrates the Lander anchored to the bottom with the acoustic beam pointing upwards and an echogram added as an illustration.

and the associated behaviour of fish, with both vessel-based (Torgersen and Kaartvedt, 2001; Kaartvedt *et al.*, 2008) and autonomous systems (Axenrot *et al.*, 2004; Mehner, 2006).

Stationary acoustic methods can provide data on the vertical distribution of juvenile fish during the pelagic drifting phase. The integration of such data into particle-tracking models greatly improves their predictive power. The primary goal of this paper is to demonstrate the potential of vertical distributions obtained from advanced stationary acoustic systems as input data for such models, resulting in better predictions of the geographic distribution of fish. The use of autonomous equipment to record the vertical distribution and migration of juvenile cod and haddock is described. With cod as an example, it is further demonstrated how such data can be applied within an existing particle-tracking model to predict the 0-group distribution in the Barents Sea at the time of larval settlement. In this case, the conceptual model compensates for the lack of observations over the complete drifting phase, but the principles remain the same. Two vertical-distribution scenarios are provided for use in a particle-tracking model that predicts the transportation of 0-group cod into the Barents Sea.

## Material and methods

The data presented here were collected in the Barents Sea during a cruise of the RV “G. O. Sars” from 9 to 13 October 2006. The study area was a square of  $5 \times 5$  nautical miles near  $74^\circ\text{N}$   $19^\circ\text{E}$ , south of Bear Island, with an average bottom depth of 136 m. A stationary acoustic platform, the “Lander”, was moored on the seabed in the centre of the square, with the transducer at 120 m depth (Figure 1). Acoustic observations were obtained between 08:48 (UTC) on 12 October and 06:54 (UTC) the next day. An upward-looking Simrad 38 kHz, split-beam echosounder with an ES38DD transducer was mounted on the Lander. The pulse

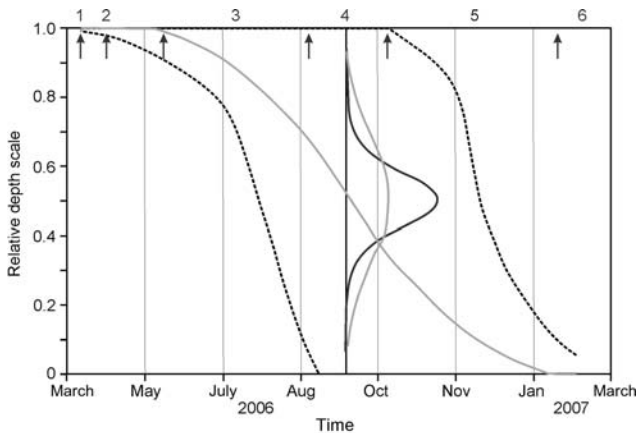
length was  $256 \mu\text{s}$ , and the ping interval was 1 s. The echosounder was calibrated before the experiment in accordance with Foote *et al.* (1987). Fish were sampled within the square, at depths from 30 to 126 m, using a pelagic trawl with a 22 mm mesh codend. Details of the experimental setup are given in Johansen *et al.* (2006). The Lander data were rerun in a simulated survey at 10 knots to obtain nautical-area-scattering coefficients ( $s_A$ ;  $\text{m}^2$  nautical mile $^{-2}$ ) for fish above the transducer. The  $s_A$  values from the Lander were then aggregated in 1 m depth channels, and averaged over one hour time-steps and four diel periods. The latter were based on nautical twilights, i.e. the times when the sun was  $0$ – $12^\circ$  below the horizon; see <http://www.sunrisesunset.com>. The four periods were day (06:07 to 14:58), dusk (14:58 to 17:43), night (07:43 to 03:22), and dawn (03:22 to 06:07). All times are UTC. The mean depth of the observed fish, referred to as the  $s_A$ -weighted mean depth, was calculated as the average of the 1 m channel depths, weighted by the average within-channel  $s_A$  values for the hourly time-steps.

A conceptual model of the drift phase of 0-group cod is presented in Table 1 and Figure 2. The model describes how the vertical distribution of juvenile cod develops through their first year of life, and it is built on existing knowledge at specific times during the life cycle reported in the literature (Table 1). The dominant components of the model are associated with temporal dynamics, that is to say, the season representing the ontogenetic development and the time of day representing the diel variation in fish behaviour. The drift phase is partitioned into six important events concerning the vertical distribution and migration associated with growth and habitat association (surface, midwater, and bottom). The ontogenetic change in average depth is represented by a sigmoid curve, which illustrates a descent from the surface to the bottom over a period of 10 months. The depth range expands to

**Table 1.** Characteristics of the development and behaviour of cod from spawning to bottom settlement.

Time	Approximately 1 April	Approximately 25 April	Approximately mid-May (2.5 months)	Early August (2 months)	Early October (3–4 months)	February–
Process/stage	Spawning/eggs, no active migration	Hatching/larvae, no active migration	Functional swimbladder feeding/larvae, limited migration	0-group, extensive migration, diel variation	0-group, extensive migration, diel variation	Limited migration
Association	Surface associated	Surface associated	Surface associated (upper 75 m)	Surface or midwater associated	Bottom associated	Bottom settled

Approximate start time and duration of the process are indicated. Synthesis of information in Bjørke and Sundby (1984), Bergstad *et al.* (1987), Ellertsen *et al.* (1989), Sundby *et al.* (1989), Nakken (1994), Høyen *et al.* (1995), Nakken *et al.* (1995) and Von Herbing *et al.* (1996).



**Figure 2.** Conceptual model of the vertical distribution of juvenile cod from spawning to bottom settlement. Average relative depth is indicated by the solid grey line moving from the surface (relative depth = 1) in April to the bottom in the following January. The dotted lines indicate the range of the depth distribution. Numbers at the top indicate the seasons of spawning (1), hatching (2), development of functional swimbladder (3), change from surface to midwater association (4), change to bottom association (5), and settled (6). Arrows indicate the approximate times of transitions between different seasons. Examples of vertical distributions in mid-September are represented by the grey (night) and black (day) normal distributions in the centre of the figure.

a maximum throughout the surface and midwater phases, then it contracts as the juvenile fish become more bottom-associated. The vertical distribution at each time is modelled as a normal distribution, where the mean is the average depth according to the sigmoid curve and the variance corresponds to the depth range. In the surface and bottom phases, the normal distribution is truncated at each of these boundaries. The diel variation follows the method described in Hjellevik *et al.* (2004). The average depth is the same, but the variance is higher at night than by day.

The drift of juvenile cod was studied using a Lagrangian, particle-tracking model with ocean-current fields input from an ocean model. The latter (Norwegian Meteorological Institute; <http://www.met.no>) was a version of the terrain-following Princeton Ocean Model (POM) (Blumberg and Mellor, 1987; Engedahl, 1995). This model (MI-POM) provides daily forecasts of oceanic conditions with a horizontal resolution of  $20 \times 20$  km, covering the North Sea, the Nordic Seas, and the Barents Sea. The predicted ocean-current fields at 0, 3, 10, 30, 50, 100, and 250 m depth were stored hourly and used as input to the particle-tracking model, which was run offline with a one hour time-step. Horizontal advection of the particles was calculated using a simple “forward Euler” method, where no diffusion was

assumed. Four simulations were done with different vertical behaviours of the particles. These are referred to below as Simulations 1, 2, 3, and 4, respectively.

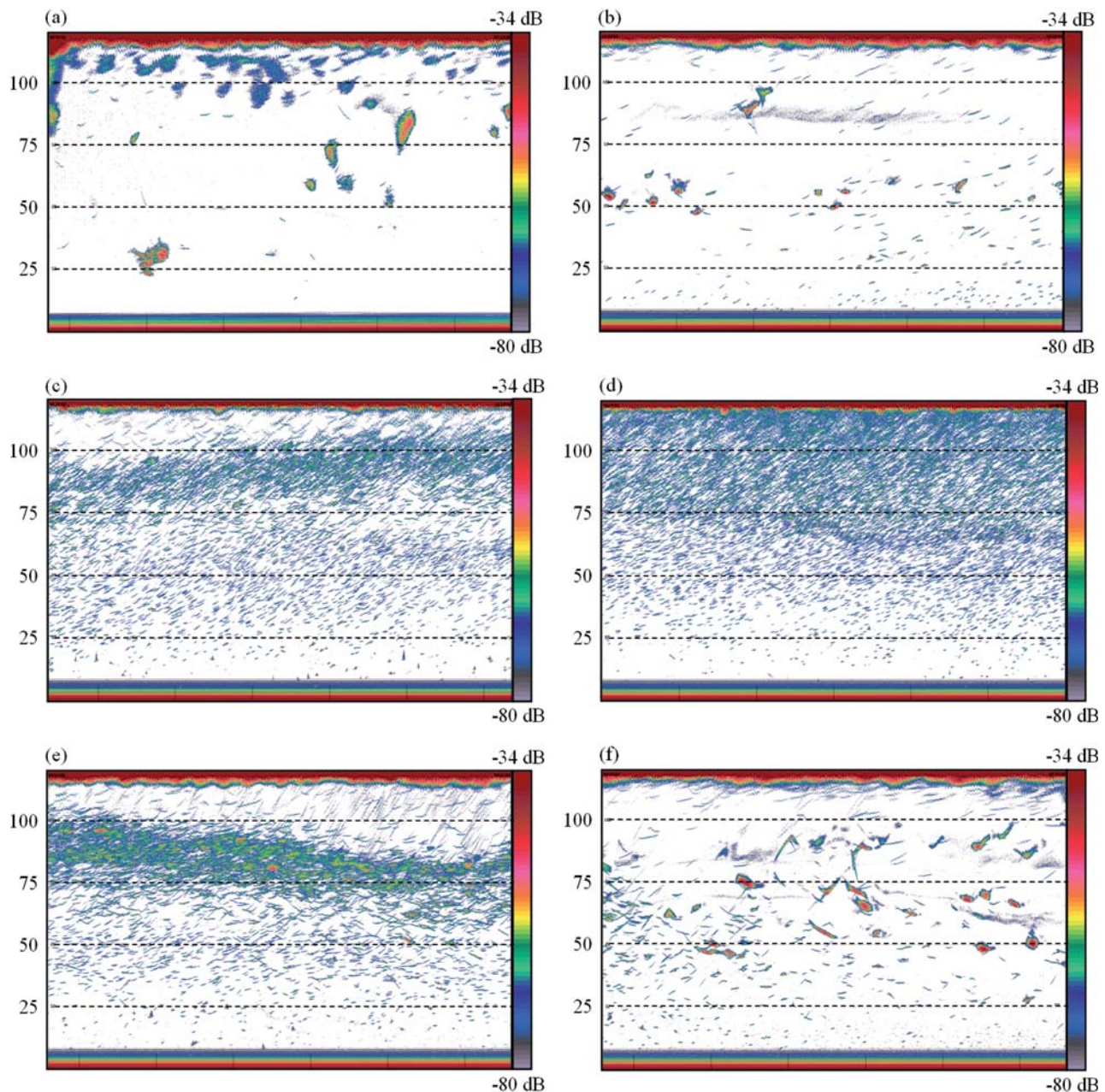
In Simulation 1, the particles adjusted their vertical positions as a function of age and time of day. During the first 45 days after the particles were released, their depths were randomly chosen within the upper 30 m and thereafter from the conceptual model described in Figure 2, except that the maximum depth was set to 250 m. In Simulation 2, the depth of each particle was randomly chosen in the upper 30 m throughout the entire period. Simulation 3 is identical to Simulation 1, except that different day and night distributions were each used for a nominal 12 h, that is to say, not the actual daylength. In Simulation 4, all the particles were permanently at 20 m depth. In all simulations, the vertical position of each particle was updated at every time-step according to the model criteria noted above. To simulate spawning, all the particles were released on Røstbanken, near Lofoten, during the two months from 1 March to 1 May 2006. The spawning intensity followed a normal distribution, with peak spawning around 1 April. In total, approximately 32 000 particles were released.

## Results

The trawl catches were mainly young-of-the-year cod and haddock, which constituted about 98% of the total by numbers. The average ratio of cod to haddock numbers was 10:1. The acoustic data varied throughout the 24-h period with respect to both the depth distribution and the aggregation of targets (Figure 3). Time variations in the  $s_A$ -weighted mean depth and the  $s_A$  of the 1 m channels are presented in Figure 4. Most of the time the  $s_A$ -weighted mean depth was around 45 m, but it was much greater at dawn and, to a lesser extent, at dusk.  $s_A$  tended to be higher at night than by day, with the highest variation at dawn. The high variation between 08:00 and 09:00 is probably due to the small sample size, because the experiment started at 08:48. The hourly distribution of  $s_A$  was skewed with some extremely high values in daytime when compared with night-time values. The depth profiles of  $s_A$  from the Lander were more variable during the twilight periods than at other times (Figure 5). The night-time profile was smoother than the daytime one. The temporal variation seen in Figures 4 and 5 reflects the more aggregated distribution of fish in daylight and the transition periods at dusk and dawn evident from the echograms in Figure 3.

The particle distributions on 1 July and 1 November for Simulations 1 and 2 are presented in Figure 6. The geographic distributions resulting from the drift models were influenced by the vertical distribution of the particles. The ontogenetic dynamics in Simulation 1 gave a more northerly and westerly distribution of juvenile cod than Simulation 2, where the particles were always in the upper 30 m. On 1 July when the particles in Simulation 1





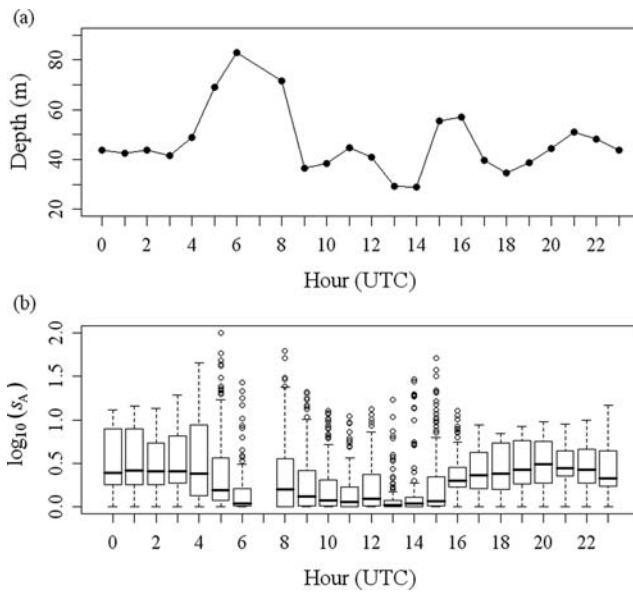
**Figure 3.** Echograms illustrating the vertical distribution of 0-group fish south of Bear Island 12–13 October 2006. The colour scale indicates the volume-backscattering strength,  $S_v$  (dB). The panels are successive 30-minute recordings starting at (a) 08:44, (b) 15:50, (c) 16:58, (d) 18:10, (e) 03:53, and (f) 04:43 (UTC). The depth scale on the left of each echogram is the distance above the transducer in metres.

were still close to the surface, the differences were small, but this was not the case on 1 November. The distributions from Simulations 3 and 4 were almost identical with those of Simulations 1 and 2, respectively, and are therefore not included in Figure 6.

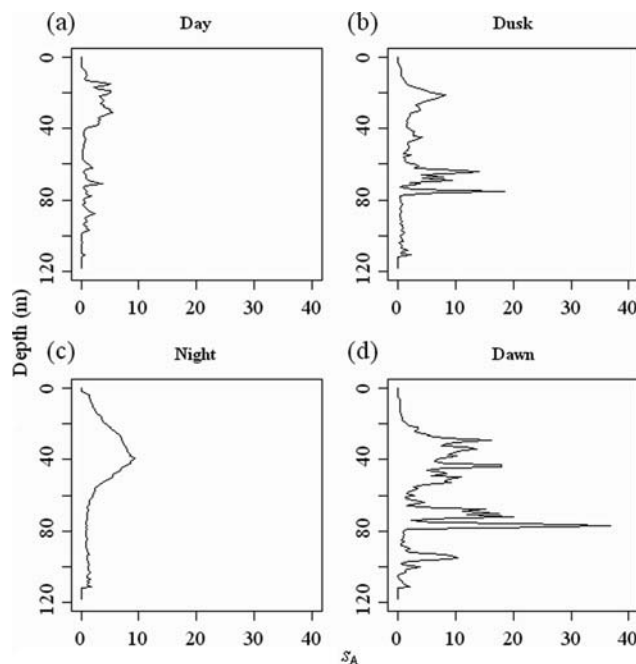
## Discussion

The vertical distribution of the gadoid 0-group in October is characterized by a diurnal cycle of aggregation and dispersion, not only of vertical migration. The echograms reveal that the 0-group fish form dense aggregations during the day and they disperse throughout the water column at night. The higher  $s_A$  values

in the daytime arise from the formation of schools. The twilight periods exhibit a gradual transition between the typical daytime and night-time patterns commonly observed in fish behaviour (Helfman, 1993). Therefore, the vertical profiles are more variable during twilight. Around dawn, the  $s_A$ -weighted mean depth of the fish distribution is approximately 35 m deeper than the diel average, whereas the depth change at dusk is less clear. This indicates a stronger behavioural response to increasing compared with decreasing light. This vertical migration was transient, and fish aggregated at the diel average after a short time. A similar interplay between light levels and anti-predator behaviour has been reported



**Figure 4.** (a) Mean  $s_A$ -weighted depths and (b) box-and-whisker plot of  $\log_{10}(s_A)$  against time from the Lander observations. (b) Illustrates the medians (bold horizontal lines), first and third quartiles (vertical limits of boxes), and  $\pm 1.58$  times the interquartile range divided by  $\sqrt{N}$  (where  $N$  is the number of 1 m depth channels) at the ends of the whiskers. The small circles denote observations outside the range of the whiskers. The data from 07:00 UTC are missing.



**Figure 5.** Depth distribution of 0-group gadoids from the Lander observations given as  $s_A$  (m<sup>2</sup> nautical mile<sup>-2</sup>) by 1-m depth channels averaged over four periods. The periods are: (a) day 06:07 to 14:58; (b) dusk 14:58 to 17:43; (c) night 17:43 to 03:22; and (d) dawn 03:22 to 06:07. Times are UTC.

for aggregations of 0-group cod in the West Atlantic (Anderson *et al.*, 2007).

The trawl samples reveal that both cod and haddock contributed to the acoustic backscatter, although cod was by far the most abundant species in the study area. The current results cannot distinguish the relative influence of these two species. The distribution and drift of haddock are not fully understood and, therefore, our study focused on cod. We have demonstrated the potential of stationary acoustics for evaluating models of the vertical distribution of 0-group gadoids. The same principles should apply even when the two species are mixed. Future studies should evaluate differences in the vertical dynamics between species through more extensive sampling, and the consequent effects on the geographic distribution.

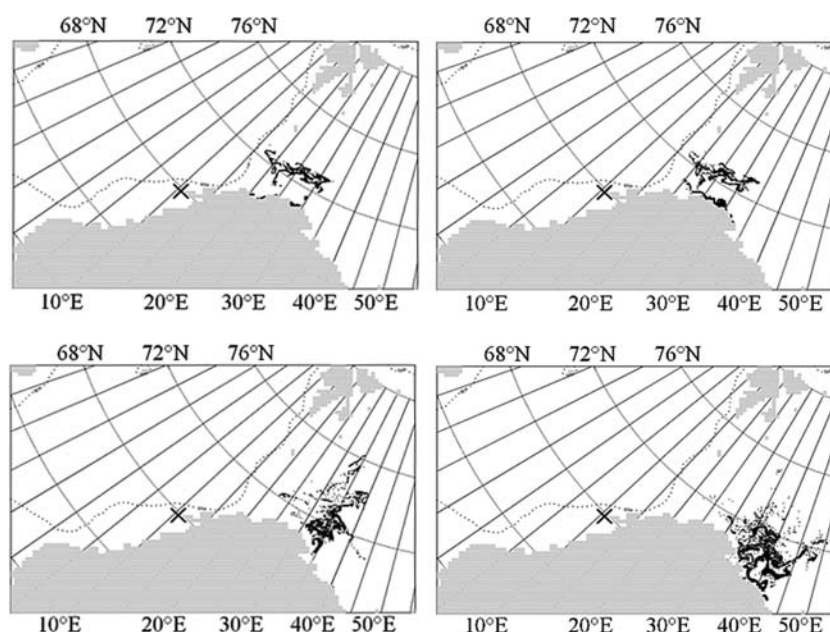
The acoustic observations corroborate the general pattern in the diel variation predicted by the conceptual model, displaying a wider depth range at night than during the day. The peak of the observed vertical distribution is shifted towards the surface when compared with the more symmetrical distribution indicated by the conceptual model. It must be emphasized that the acoustic observations are limited with respect to both time and space. They provide only an indicative validation of the model. A rigorous test of the conceptual model would require considerable amounts of data on larger temporal and spatial scales. Such data could provide a more realistic description of the ontogenetic and diel dynamics of the vertical distribution, making the conceptual model a more useful predictor of the vertical distribution to be combined with a drift model. The current results demonstrate the potential of new acoustic systems to provide high-quality data for the precise quantification of the vertical distributions of marine organisms, as well as their temporal variation.

The simulation results from the drift model demonstrated a significant effect of the assumptions about the vertical distribution of the particles. Similar results have been reported for other drift models (Vikebø *et al.*, 2005, 2007; Fiksen *et al.*, 2007). Inclusion of ontogenetic dynamics in Simulation 1 clearly gives a more northerly and westerly distribution at the end of the simulations than Simulation 2, where the particles were randomly placed in the upper 30 m. This emphasizes the importance of integrating models and observations to obtain a realistic description of the vertical dynamics of the simulated particles. The assumptions about the vertical distribution of the 0-group fish, based on the conceptual model (Simulation 1), seem to be more realistic than those of Simulation 2. In Simulation 1, the 0-group ends up closer to Bear Island and the study area where acoustic abundances of 0-group gadoids were high. Simulation 1 also results in a geographic 0-group distribution better matched to that observed in the joint Norwegian–Russian ecosystem survey from 8 August to 5 October 2006 (Anon., 2006).

There are several advantages of using stationary acoustics rather than vessel-based systems. The Lander provides data on the temporal variation of the vertical distribution and fish behaviour at a single location. This is difficult to achieve with a moving vessel covering a large area. The Lander also provides near-surface acoustic recordings not accessible to a vessel with a hull-mounted transducer. Furthermore, vessel avoidance can be important once the 0-group is large enough for proactive behaviour.

The use of acoustic Landers as stationary platforms is a step forward in understanding important processes in the dynamics of marine ecosystems. The current results, although limited in





**Figure 6.** Geographic distribution of particles from Simulations 1 (conceptual model for vertical distribution, left panels) and 2 (random positioning in the upper 30 m, right panels), using a Lagrangian, particle-tracking model. The top and bottom panels refer to 1 July and 1 November, respectively. The crosses indicate the release location of the particles at “Røstbanken”.

time and space, provide new and valuable information about the vertical structuring of 0-group gadoids in the Barents Sea. This is a promising approach to the integration of observations and models to improve predictions of how ecosystems respond to physical variability. The Lander is now operational; it is compact, durable, and easy to launch. There should be a more intensive observation programme to describe and quantify the vertical distribution of 0-group gadoids in the Barents Sea. To cover the complete drift route, the Landers should be moved and deployed according to the geographic distribution of the 0-group. The true spatial variation in the vertical dynamics should be evaluated by concurrent observations with two Landers. In addition, the possibility of combining Lander and vessel data should be explored. This observation programme should provide the observations needed to obtain models of recruitment to fish stocks that are more realistic than those currently at our disposal.

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