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Diel variation in the catchability of gadoids and its influence on the reliability of abundance indices

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Present management of the north-east Arctic cod and haddock stocks is based on scientific assessments of stock abundance. The assessment procedures apply acoustic and bottom-trawl survey indices of abundance for tuning of the VPA (virtual population analysis). The reliability of the survey indices is strongly dependent on the precision and accuracy of the fish sampling conducted with trawls. Variation in bottom trawl catches and vertical distribution of cod and haddock from a small area were studied with the aim of finding environmental factors of explanatory importance for the observed variation. Data were obtained over a period of three days from two vessels trawling in parallel, one of which simultaneously collected acoustic information on vertical distribution. Variation in catch size and length composition was analysed and related to the observed vertical distribution. The results show that tidal currents affect the vertical distribution of cod and haddock and, hence, the availability to the bottom trawl. On the other hand, light intensity apparently affects the catch efficiency of the sampling trawl. Consequently, the abundance estimates from acoustic and bottom-trawl surveys are affected by the interaction of diel rhythms in tidal current and light intensity. This illustrates the importance of monitoring the environmental factors that influence fish behaviour in order to increase the reliability of the abundance estimates.

Key words: catch efficiency, diel variation, fish distribution, gadoids, light intensity, tidal currents.

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Introduction

The management of the stocks of north-east Arctic cod (*Gadus morhua* L.) and haddock (*Melanogrammus aeglefinus* L.) is based on abundance estimates from virtual population analyses (VPA) (ICES, 1992). This method, which uses both commercial fisheries statistics and data from scientific surveys, is very sensitive to changes in fishing strategy and efficiency (Shepherd, 1988) as well as to changes in migration patterns (Ulltang, 1977). Since such changes are shown to have taken place in the Barents Sea cod fishery in the last decades, fisheries-dependent data have become less reliable, while results from the standardized scientific surveys have increased their importance in the assessment procedures (Hylen *et al.*, 1986).

The Institute of Marine Research in Bergen has carried out combined bottom trawl and acoustic surveys for cod and haddock in the Barents Sea and Svalbard area since 1981. The indices of abundance from bottom trawl and acoustic surveys are used independently for tuning of the VPA (ICES, 1992). The two methods cover different fractions of the true stock, i.e. the acoustic measurements perform best on pelagic recordings, while the representativeness of the species and length distribution of fish caught by the bottom trawl is restricted to the catching height of the trawl opening. Combining the information from the two estimates would probably increase the reliability of the survey results, particularly in the cases where fish migrate vertically (Godø, 1994).

Vertical migration is in most cases described as an optimization of the relation between predation risk and food consumption, triggered by changes in light intensity (Neilson and Perry, 1990; Helfman, 1993). Water currents are also known to influence the vertical distribution of fish; some species avoiding increased

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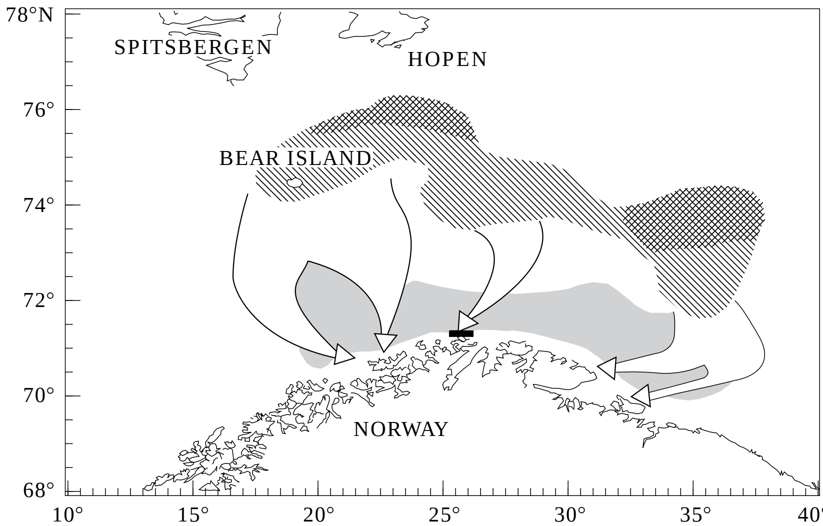

Figure 1. Areas of immature cod concentrations (from Hylen *et al.*, 1991) are shown by grey shading, while the experimental area is indicated by a black rectangle. Mature and immature capelin concentrations (hatched and cross-hatched shading) with the main routes of spawning migrations to the coast of Norway (open arrows) from February to March (from Ozhigin and Luka, 1985).

current speed, others utilizing them for transport, either by passive or by modulated drift (Arnold, 1981; Arnold *et al.*, 1994).

This study is based on acoustic records and bottom-trawl catches collected during a survey in the Barents Sea in March 1991. The survey was originally designed to provide detailed information on the rhythms of food consumption by cod. Because of the intensive sampling and the restricted geographical sampling area, data from this survey are appropriate for studying the importance of light and tidal currents on the vertical distribution of cod and haddock. Furthermore, we discuss the influence of these environmental factors on the reliability of abundance estimates.

Material and methods

The survey was conducted in the area 71°N and 26°E (Fig. 1) from 3 to 5 March 1991. Two vessels trawling in parallel were used in order to compensate for possible differences in small-scale aggregation. The RV ''Johan Hjort'' (65 m – 3300 HP) and the MT ''Anny Kræmer'' (50.7 m – 2400 HP) conducted side-by-side trawling, one vessel being two to three cables behind the other one, in alternating order. Trawling was performed on bottom depths between 267 and 290 m.

A standard Norwegian sampling trawl, Campelen 1800, with rockhopper ground gear (see Engås and Godø, 1989), 6.4 m^2 V doors (3.65 × 2.02 m, 1750 kg), and 40 m sweeps was used by both vessels. The duration of a tow was 30 min at a speed of 3 knots (Doppler-log), giving a trawl distance of 1.5 nautical miles. Trawl geometry (i.e. headline height, wing- and doorspread) was measured with acoustic trawl instruments (SCANMAR).

On-deck sampling was carried out as in routine surveys in the Barents Sea, i.e. by sorting fish species from the total catch and measuring fish length to the nearest centimetre below.

The acoustic data were sampled and analysed with the Bergen Echo Integrator (BEI) system (Knutsen, 1990). Instruments were calibrated according to the standard target method (Foote *et al.*, 1987). Acoustic data were only collected by RV ''Johan Hjort''. The average area backscattering coefficients per unit sea surface (s_A; square metres per square nautical mile) represents the fish density (Knutsen, 1990). The combined area back-scattering coefficients for cod and haddock are presented as mean values per hour and the vertical distribution is given in five, 2 m high, bottom related channels as well as from the surface to the bottom in 20 m layers. When referring to the bottom channel density, the sum of s_A values in the five bottom related channels is used. The proportion of cod and haddock close to bottom was calculated as the density in the bottom channel ($s_{A10\ m}$) divided by the total density (s_{Atot}).

A tidal atlas for the Barents Sea was used to elucidate the current regime in the measurement area during the sampling period, giving mean current speed and direction from the bottom to surface (Gjevik *et al.*, 1990). Diel changes in light levels were based on the height of the sun above the horizon. UTC (Universal Time Coordinates) represent time of day in all calculations and presentations.

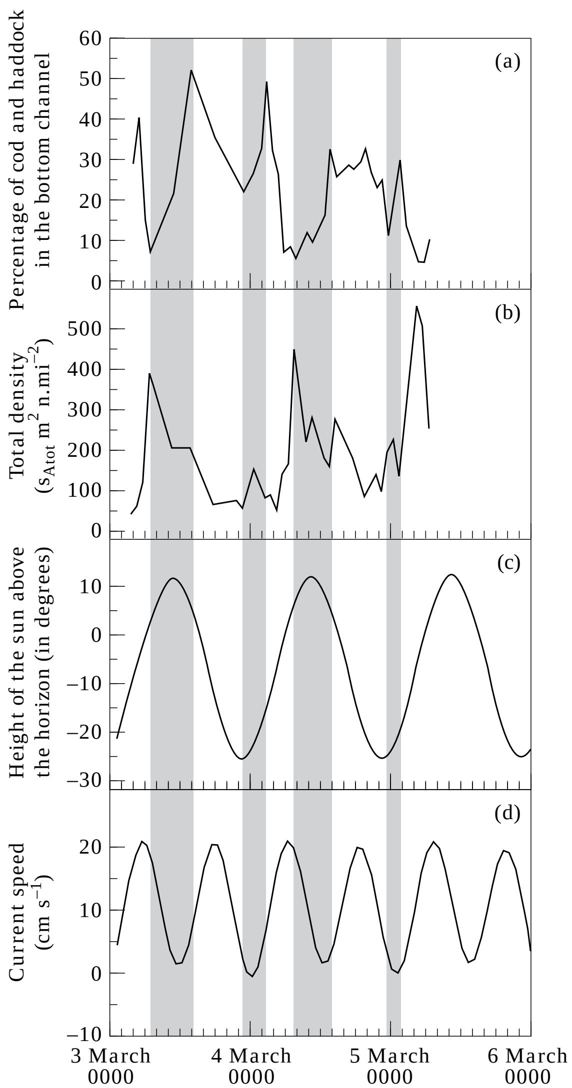

Figure 2. Vertical distribution of cod and haddock expressed by (a) the percentage of fish in the bottom channel, related to (b) total densities of cod and haddock as s_{Atot}, square metres per square nautical mile (m^2 nmi^{-2}), (c) light intensity expressed as the height of the sun above the horizon, and (d) tidal currents. Shaded areas indicate periods of fish descents.

Results

Vertical distribution

The proportion of cod and haddock in the bottom channel varied substantially, giving rise to two peaks in the distribution per day (Fig. 2a). Even though the total density of cod and haddock also varied during the sampling period (Fig. 2b), this could not explain the observed semi-diel variation. During the survey the sun was above the horizon from 05.35 to 15.18 UTC, which is defined as day-time, while the twilight period lasted for about 60 min (Fig. 2c). On two occasions, fish descent could be explained by increasing light levels, but still two others remain unexplained. In this area the tidal ellipse undulates between a south-east and a north-west tidal flow of 10 cm s^{-1} (Gjevik *et al.*, 1990). Along the coast of Finnmark a residual current (coastal current) goes south-east with a speed of approximately 10 cm s^{-1} (H. Loeng, Inst. of Mar. Sci., pers. comm.). Consequently, the north-western tidal current is almost neutralized, leading to a continuous south-eastern flowing current, undulating between a maximum level of 20 cm s^{-1} to a minimum level of zero (Fig. 2d). Direct comparison of the changes in vertical distribution and current speed indicates that fish descend to the bottom in periods of decreasing or at low levels of current speed, while they leave the bottom during times of increasing or at maximum current speed.

Variability in bottom-trawl catches

Since cod dominated the catches, it was natural to use only this species when examining variability in trawl efficiency. The catches of cod from both vessels were higher during the day than at night (Fig. 3). Under normal operation, the headline height was around 4 m for both vessels and the wingspread approximately 19 m. Trawl geometry measurements showed unstable bottom contact for two of the trawl stations by the ''Johan Hjort'' (indicated by an x in Fig. 3). Excluding these hauls, the catches of the two vessels varied synchronously ($r=0.87$, $p \leq 0.001$) with the best fit for high catches. The catches from ''Anny Kræmer'' peaked twice, once at sunrise and once at mid-day.

The mean length of cod caught by the RV ''Johan Hjort'' and MT ''Anny Kræmer'' varied synchronously during day and night (Fig. 4, $r=0.84$, $p \leq 0.003$) with a clear minimum at dawn and another less pronounced one at night. Mean lengths of around 55 cm indicated a substantial proportion of immature cod (4 to 5 years of age, Hylen *et al.*, 1991) in the catches.

Because of low sampling rates it was not possible to relate variations in catch size and mean lengths to changes in current speed.

Comparisons of acoustic records and bottom-trawl catches

In order to examine a possible diel variation in sampling efficiency, summarized cod and haddock catches were compared with the combined s_A values for the two species, as mean values per hour (Fig. 5). The acoustic recordings up to a height of 10 m above bottom were used to compare these two relative density measurements (see discussion). This is also the vertical range used to elucidate diel rhythms in the vertical migrations.

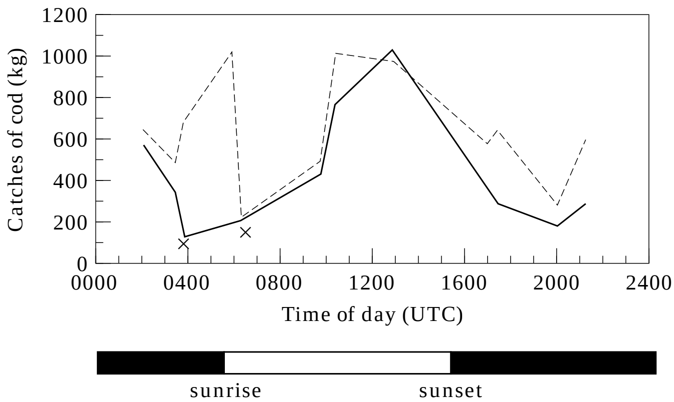

Figure 3. Catches of cod from RV ''Johan Hjort'' (continuous line) and MT ''Anny Kræmer'' (broken line). × indicates trawl stations with unstable bottom contact. Time of sunrise and sunset, given as Universal Time Coordinates (UTC), defines the day (open bar) and night (black bar) period.

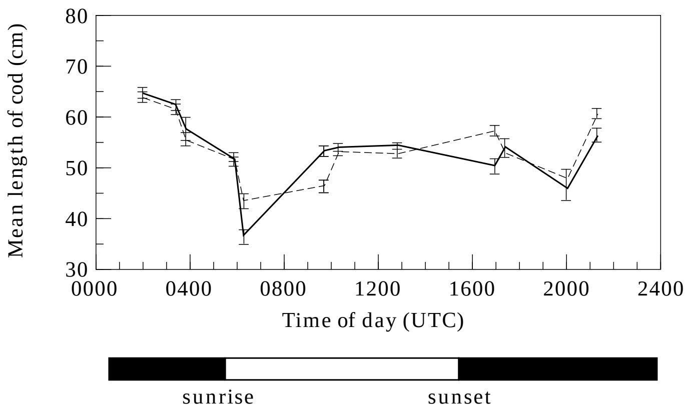

Figure 4. Mean length (± s.e.) of cod caught from RV ''Johan Hjort'' (continuous line) and MT ''Anny Kræmer'' (broken line). Time of sunrise and sunset, given as Universal Time Coordinates (UTC), defines the day (open bar) and night (black bar) period.

The plot of the trawl catch was above the acoustic index during the day and below it at night.

Discussion

Vertical distribution

Bottom-trawl surveys are based on the assumption that catch (n) and abundance (N) are related by $n = q f N$, where q is the catchability coefficient and f the fishing effort. For scientific surveys f is set equal to one. The coefficient, q, can be split into two components; availability, q_a, and efficiency, q_e (Godø, 1994). Availability is the proportion of the fish stock within reach of the trawl, while catch efficiency is the proportion of the available fish actually caught by the trawl, so selection can be defined as a relative change in the relationship between q_a and q_e. If q_a is assumed to be directly related to the vertical distribution of the fish, then it can be expressed as the proportion of acoustic fish density in the bottom channel relative to the total value in the water column.

The vertical migration observed in this study appeared to follow the tidal rhythm. Fish ascent was related to periods with relatively strong east-going currents, while fish descent was observed when the current speed was decreasing. Stomach analyses conducted during this survey showed that cod mainly prey on capelin (Michalsen, 1993). The echograms also indicated that when cod were pelagic they often mixed with capelin.

The observed rhythms in the vertical distribution of cod may be the result of individual adaptation to environmental variations. Since immature cod are in the western part of their distributional area at this time of year (Nakken and Raknes, 1987), the observed ascent from the bottom at the time of strong east-going currents could be an adaptation to a modulated drift used during migration to their north-eastern wintering

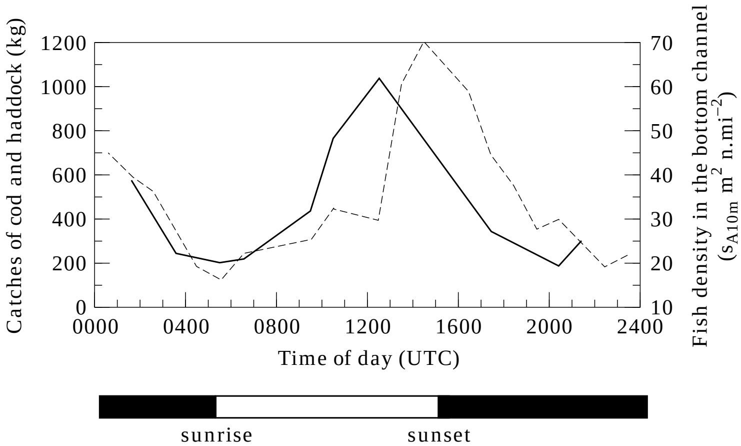

Figure 5. Fish density in the bottom channel as $s_{A10\ m}$, square metres per square nautical mile ($m^2\ nmi^{-2}$) (broken line) and catches (kg) of cod and haddock (continuous line), presented as mean values per hour. Time of sunrise and sunset, given as Universal Time Coordinates (UTC), defines the day (open bar) and night (black bar) period.

areas, as demonstrated for several other fish species (see Arnold *et al.*, 1994). In addition to saving energy, this migration strategy, starting in the west and ending in the east, maximizes the overlap between immature cod and mature capelin, both in time and space. As illustrated in Figure 1, the influx of mature capelin to the coast of Finnmark can be considered as a continuous process in time, starting in the west and ending in the east, with the main influx coming from the east and being directed westwards (Ozhigin and Luka, 1985). The duration of the overlap between cod and capelin has been estimated to last between 45 and 60 days (Bogstad and Gjøsæter, 1994).

As pointed out earlier, the vertical migration of cod and haddock seemed to follow a semi-diurnal rhythm set by changes in tidal currents. However, the onset of sunrise appeared to advance and expand the period of fish descent (see Fig. 2c). Since the day-time period interacts with the time of high but gradually decreasing current speed, it is difficult to distinguish which of the two factors, light or currents, has the greatest impact on migration patterns. Possibly, the co-occurrence of decreasing current speed and sunrise have a more pronounced effect on fish descent than either factor alone.

Variability in bottom-trawl catches

The two vessels showed diel variations in catch rates of cod. In addition to the observed changes in the availability of fish to the bottom trawl, this can be a result of changes in trawl efficiency. Because of visual herding, the trawl with its doors and bridles is more effective during the day than during the night (Wardle, 1993), leading to an overestimation of fish abundance during the day compared with the catch rates at night (Engås and Soldal, 1992). In addition to the herding effect, current speed and direction may influence the performance of the trawl such that trawl efficiency is affected.

Apparently, there was a difference in trawl efficiency between the two vessels. The catches from the “Anny Kræmer” were almost always higher than those from the “Johan Hjort”, which may have been caused by minor differences in the rigging of the trawls (Carrothers, 1981) or differences in noise patterns generated by the vessels (Mitson, 1993).

Because of the high correlation in catch rates and in mean lengths of cod between the two vessels ($r=0.87$ and $r=0.84$ respectively), it is assumed that the observed diel variation was a result of changes in catchability (q_a and q_e) and not of small-scale aggregation in the fish distribution close to bottom.

Diel variation in the mean length of cod was observed. As a result of reduced reaction distances to the trawl during periods of low light levels, small fish, which have poorer swimming ability than older and larger individuals, will not be herded into the mouth of the trawl, thus giving rise to a length-dependent trawl selection (Wardle, 1993). This bias in the length distribution at night will cause an overestimation of the acoustic target strength that is used to convert acoustic values to total numbers, thereby leading to an underestimation of abundance and erroneous age composition (Engås and Soldal, 1992). Mesh selection by the sampling trawl has been assumed to be minimal, with the fish length for 50% capture being about 15 cm. This will not have any significant influence on the catch composition observed here because of the low proportion of such small cod in this area at this time of year.

Stomachs sampled during the survey showed that cod greater than 30 cm in length were mainly preying on capelin, while smaller cod, less than 30 cm, had a much wider diet (Michalsen, 1993). Since swimming capacity also changes with fish length (Wardle, 1993), it is possible that the observed variations in the mean length of cod, in addition to the size-dependence of trawl efficiency, were caused by size differences in vertical migration patterns.

Comparisons of acoustic records and bottom-trawl catches

A comparison of the acoustic recordings and the bottom-trawl catches revealed diel changes in the relationship between the two measurements of relative abundance. Acoustic recordings up to a height of 10 m were correlated with the trawl catches, as fish are known to be scared downwards into the trawl from about that depth (Godø, 1994), although this could depend on environmental conditions (Aglen, 1996). The apparent time delay of the highest acoustic values in relation to the highest catches of cod and haddock (Fig. 5) may be an artifact of too few trawl stations and low sampling frequency. However, the vertical migrations are found to be closely related to changes in the tidal currents with a rhythm of 12 h and 25 min, while the trawl efficiency is related to light intensity and thus has a period of 24 h.

Other factors might also influence the relation between the two sampling methods. High availability of the fish to the bottom trawl causes low availability for acoustic detection, since it is difficult to separate fish and bottom echoes because of the dead-zone problem (Mitson, 1983). The target-strength function (TS) is based on the assumption that the swimbladder, which is responsible for 90–95% of the reflected acoustic energy, acts as an ideal buoyancy organ with volume and shape independent of depth changes (Foote, 1980a). The process of gas secretion and resorption is slow, and the compensation for depth change is likely to lag behind the rate of vertical migration (Tytler and Blaxter, 1973).

Consequently fish are probably in a neutral buoyancy state only at the top of their vertical range (Arnold and Greer Walker, 1992) which, in addition to the dead-zone problem, will lead to a masking of the proportion of fish in the bottom channel. Changes in pressure levels, exceeding 50–70% of that to which the fish is adapted, cause a reduction in target strength (Tytler and Blaxter, 1973; Ona, 1990). In addition, a compression of the swimbladder because of heavy feeding and gonad maturation, as well as a change in the tilt angle, can bias the acoustic estimates of abundance by as much as 20–70% (Foote, 1980b; Ona, 1990). The vertical range of migrations by fish in this experiment caused pressure changes of no more than an order of 2:3 (migrating between 200 to 300 m). However, since most of the examined stomachs were fully expanded (Michalsen, 1993) it is possible that a reduction in target strength occurred as a result of the combined effect that food consumption and vertical migrations has on swimbladder compression.

The two components of the catchability coefficient, the availability and the efficiency, were shown to be influenced by changes in both tidal currents and light levels. As a consequence, the reliability of the abundance estimates is dependent on variations in these environmental factors. In order to increase the reliability of abundance estimates, further investigations on fish behaviour in response to changes in the environment should be carried out and the effects quantified. To adjust abundance estimates for changes in the vertical and horizontal distribution of fish, we need more knowledge of the mechanisms controlling migrations, from both large-scale and small-scale perspectives.

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