ICES Journal of Marine Science, 61: 1093–1099 (2004)
doi:10.1016/j.icesjms.2004.06.009

Behaviour of mackerel schools during summer feeding migration in the Norwegian Sea, as observed from fishing vessel sonars

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Godø, O. R., Hjellvik, V., Iversen, S. A., Slotte, A., Tenningen, E., and Torkelsen, T. 2004. Behaviour of mackerel schools during summer feeding migration in the Norwegian Sea, as observed from fishing vessel sonars. – ICES Journal of Marine Science, 61: 1093–1099.

In July 2002, two commercial vessels were used to study the distribution of Northeast Atlantic mackerel (*Scomber scombrus* L.) during their feeding migration in the eastern part of the Norwegian Sea between 62°N and 70°N. Pelagic trawling and school tracking with SIMRAD 24–36 kHz sonar demonstrated that the stock was distributed throughout the study area. Information about time, geographic position, size, depth, speed, and direction was stored for each school during tracking. This study reports analyses of data from 63 schools that were tracked for 30 s or longer. All schools were recorded at depths of less than 100 m, and the majority (65%) were found between the surface and 40 m. The direction of migration (north 0° ± 22.5°, northeast 45° ± 22.5°, etc.) was non-random, with east and west as dominant swimming directions. School size and migration speed varied from 1 to 7000 tonnes and 0 to 6 m s^{-1}, respectively. Methodological improvements are discussed.

Keywords: commercial vessels, distribution, mackerel, migration, school tracking, sonar.

Received 16 March 2003; accepted 3 May 2004

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Introduction

The Northeast Atlantic mackerel stock is distributed from the Bay of Biscay to Svalbard, and performs long seasonal migrations throughout this area (Bolster, 1974; Hamre, 1978; Anon., 1997, 1999; Uriarte and Lucio, 2001; Iversen, 2002), with the feeding migration of the larger individuals towards Svalbard being the most spectacular (Holst and Iversen, 1992). For practical stock assessment and management purposes, information about migration characteristics is important for reliable surveying in general (Godø, 1994) and for Northeast Atlantic mackerel in particular (ICES, 2002).

The northern distribution of mackerel during the summer and autumn has remained unclear owing to the difficulty of making direct observations and surveys of the stock at this time of the year. This is mainly due to the fact that mackerel have no swimbladder and are thus difficult to assess using standard acoustic assessment methods (MacLennan and Simmonds, 1991). Furthermore, some or all the fish are found close to the surface, where they are sensitive to disturbance by moving vessels, and are thus only partially accessible to standard acoustic assessment methods (Aglen, 1994).

This study is part of a more extensive examination of the potential of combining sonar, trawl, and lidar (for details, see Churnside and Wilson, 2001) data for assessing mackerel resources in the Norwegian Sea. We have analysed data collected by commercial vessel sonars during the mackerel summer feeding in the Norwegian Sea, our main goal being to test the potential of automatic collection of sonar data from commercial vessels as a tool for improving stock assessment. We emphasize methodological challenges, geographical distribution, and behavioural patterns, and their potential causes.

Material and methods

Vessels, instrumentation, trawl rigging, and survey design

The investigations were carried out during the period 15–27 July 2002. Two combined purse-seine–mid-water trawlers, MS "Endre Dyrøy" (64.1 m) and MS

"Trønderbas" (68.3 m), both equipped with SIMRAD sonar SP72 operating at 24–36 kHz, systematically sampled the area with large commercial pelagic trawls. "Endre Dyrøy" used a 50 m × 108 m blue whiting trawl while "Trønderbas" used a smaller circular silver smelt trawl. Sampling covered a depth range from 5 m to 40 m. The vessels were required to follow two distinct survey tracks, both covering the same study area from 62°N to 70°N, overlapping each other, but going in different directions (Figure 1). Pelagic trawling was carried out at 91 designated positions (Figure 1) along the survey track. The catches were used for species identification only. Details of length, weight, sex, stage of maturity, as well as otoliths for age determination, were collected for later analysis.

Collection of sonar data

Whenever schools that the officer of the watch judged to be mackerel were observed along the survey track, the vessel reduced speed to 2.0–5.0 m s^{-1} and tracked the school with sonar. The school data were logged on a PC connected to the SP72 sonar. During sonar tracking of the mackerel schools, information about time, geographic position, school area, size, depth, speed, direction, distance, and bearing was stored.

Sonar data processing and analyses

Only the schools that were tracked for at least 30 s were used in the statistical analysis. A total of 63 schools were included in our study, their speed and heading estimated from their first and last recorded times and positions. School size was determined for each ping, and the median size over all pings was taken as the school size. A rough estimate of school size in tonnes can be obtained from a built-in function of the sonar which utilizes a species-dependent relationship between school geometry and size (see, e.g. Misund, 1993).

Several schools were frequently recorded simultaneously on the sonar screen and tended to move in the same direction and at the same speed. Some of these schools were tracked simultaneously and thus may not provide independent information about migration. This is normally a basic demand in many models. Therefore, when several schools were recorded simultaneously, only the track with the longest duration was used.

The schools were separated into eight groups according to their heading. The number of schools in each of the eight sectors was counted, as was their total speed (mean speed multiplied by number of schools), total size, and total speed * size. School movements were studied with respect to three orientations: according to tidal current direction (~45° and ~225°), in relation to vessel cruising direction, and compass heading. These correspond to three hypotheses: that mackerel move in relation to the dominant currents

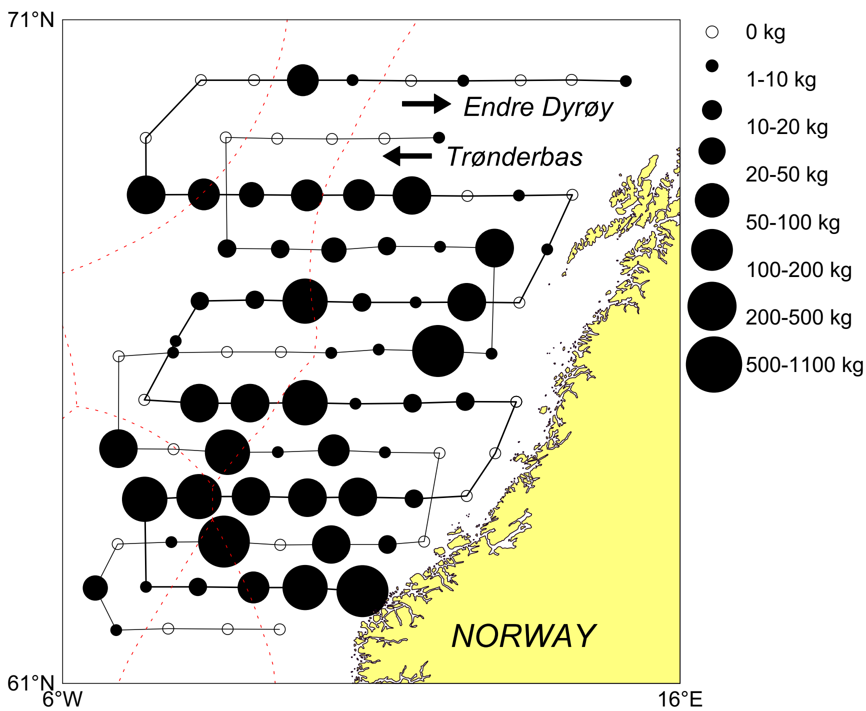

Figure 1. Survey tracks and pelagic trawl stations (30 min) with MS "Endre Dyrøy" and MS "Trønderbas" during 15–27 July 2002. Catches containing mackerel are marked with black bubbles (see scale for amount). National Exclusive Economic Zones are marked.

(rheotaxis), that they are strongly affected by the direction and speed of the survey vessel, or that they move independently of these factors. Under certain assumptions the number of tracks in each of the eight sectors in all three orientations follows a multinomial distribution. However, total speed, size, and speed * size do not. To calculate the probability of obtaining values as high as we did for the dominant direction under the null hypothesis that each direction is equally probable for a given track, a randomization technique was used. Allocating a random direction to each track and calculating the numbers, speed, and size in each direction, correspond to taking one sample under H_0. Repeating this sufficiently often provides an estimate of the probability function under H_0, and empirical p-values and confidence limits can be calculated (see, e.g. Edgington, 1995).

To test for day/night effects, day tracks (observed when the altitude of the sun above the horizon was more than 0°) and night tracks were analysed separately. Tide direction and speed were calculated according to Gjevik *et al.* (1990). To test for tidal effects, the following procedure was utilized. First, the target speed was defined as positive for targets heading eastward (0°−180°), negative for the others. The average target speed was then calculated separately for schools observed when the tide was heading east (0°−180°) or west, respectively, and the difference between the two groups was calculated as $\Delta_V = \overline{V}_E - \overline{V}_W$, where $\overline{V}_E$ and $\overline{V}_W$ are the average target speeds when the tide is heading east and west, respectively. If the target direction is independent of tide direction, one would expect $E(\Delta_V) = 0$. If the targets follow the tide, then $E(\Delta_V) > 0$, and if they swim against it, then $E(\Delta_V) < 0$. Similar Δ_V's were calculated for daytime and night. The procedure was repeated for north−south headings, defining target speed as negative for targets heading southwards (90°−270°) and using the north/south heading of the tide. Confidence intervals under the null hypothesis of no dependence on tidal direction were calculated using standard bootstrap techniques (Efron and Tibshirani, 1993). For each bootstrap replica, the re-sampling was done separately for each tide group and $\overline{V}_E$, $\overline{V}_W$, and Δ_V were calculated. The distribution of Δ_V under the null hypothesis was estimated from the bootstrapped Δ_V's.

Results

Trawl catches (Figure 1) and sonar detections (Figure 2) of schools demonstrated that mackerel were distributed throughout the survey area. Mackerel were caught in 68 of the 91 trawl hauls and had a mean length of 36.1 cm. Catches varied from 1 to 1600 kg. Small catches were mixed with herring and blue whiting, redfish, etc., whereas large catches (> 10 kg) were dominated by mackerel.

The mackerel schools tended to remain close to the surface (Figure 3). All the schools were found at depths of less than 100 m, and the majority (65%) were found between the surface and 40 m.

Analysis of the migration direction showed that the most significant factor tested ($p = 0$) was vessel direction (Figure 4). Current appeared to be insignificant, while the east−west movements were overrepresented compared to other directions ($p = 0.003$). School size varied from 1 to 7000 tonnes, whereas migration speed varied from 0 to 6 m s^{-1} (Figure 5). The migration direction in relation to compass heading was also non-random when tested for the effect of school size ($p = 0.013$), speed ($p = 0.001$), and size * speed ($p = 0.002$). These effects were higher in schools migrating eastward and westward than for other directions (Figure 4). The average north−south component of the track speed is 0.04 m s^{-1} in a northerly direction, whereas the average east−west component is 1.7 m s^{-1} towards the west. The p-value for school size was higher than for number, speed, and speed * size. This is due to the skewed distribution of size, with one school dominating the distribution with a median size 7409 tonnes (the size recordings for this school are highly variable, ranging from 7 to 19 133 tonnes). Since this school was heading eastward, the total size was largest towards the east, whereas west was the dominating direction for number and speed. Speed is more significant than number, since the schools heading north/south tended to move more slowly than those heading east/west (Figure 2).

There were no significant night/day effects on dominant migration direction, and, as stated above, movements also appeared to be random with respect to current direction. However, the directional migration towards the east and west coincided with southwest and northeast flowing tides, respectively (Figure 2). The quantification of possible diurnal and tidal effects was based on the above findings of east−west dominance in migration direction. The observed values for $\overline{V}_E$ and $\overline{V}_W$ were −0.77 and 0.36, respectively, giving a Δ_V of −1.13. The dominant tidal current directions are northeast and southwest, although some geographical variation occurs. In general, it looks as though the mackerel migrated westward when the tide was flowing to the northeast, and eastward when the tide turned towards the southwest. The bootstrapped 95% confidence interval for Δ_V was [−1.45, −0.10], and since 0 is not included in the interval the effect is significant. We made 1000 bootstrap replicates. The north−south migrations were minor and no significant trend emerged. The observed Δ_V was 0.25 and the 95% bootstrapped confidence interval was [−0.63, 0.74]. For day/night, the corresponding confidence interval was [−1.39, 0.56], showing that there was no significant night/day effect on dominant migration direction.

Discussion

Potential improvements in sonar tracking methodology

This study clearly demonstrates that valuable information on migration can be obtained from automatic collection of commercial sonar school detections. This is in accordance

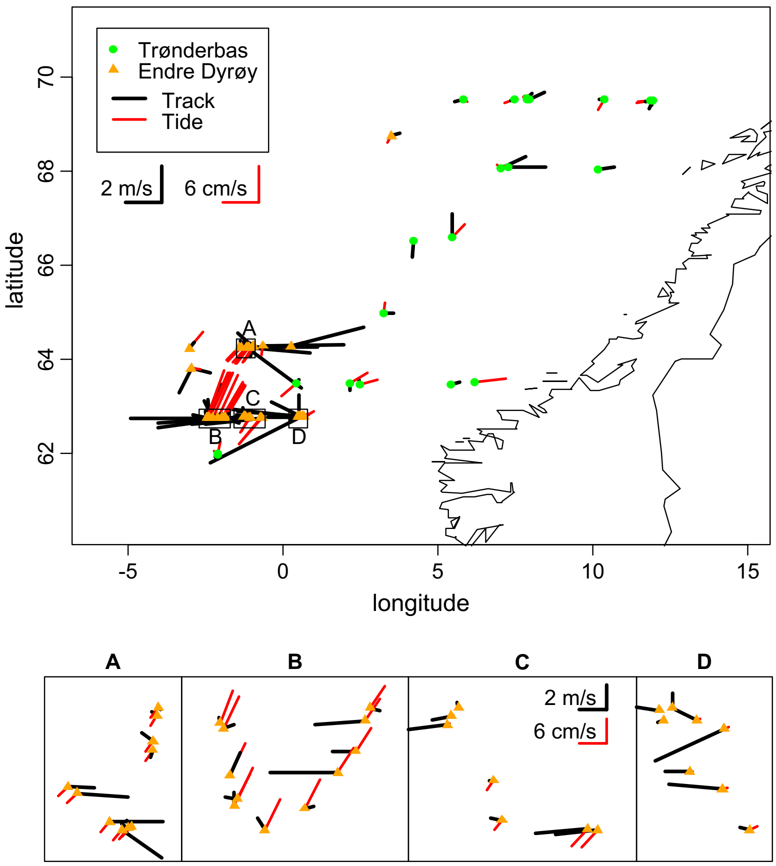

Figure 2. Position, heading, and speed of the tracks and the corresponding tide. The direction of the lines indicates the heading in degrees, and the speed within each category is proportional to their lengths. Reference vectors indicating the speed are given under the legend. Details for areas A, B, C, and D are given in the bottom part of the figure.

with the results of previous work (Misund, 1993; Misund *et al.*, 1998; Melvin *et al.*, 2002) and underlines the fact that large-scale collection of data by the commercial fishing fleet could provide access to important qualitative and quantitative information on the distribution, migration, and behaviour of stocks. The acoustic detection of mackerel without a swimbladder is more difficult than the detection of clupeid species (MacLennan and Simmonds, 1991). Nevertheless, our study shows that the techniques and experience developed during herring studies (Misund, 1993; Pitcher *et al.*, 1996; Misund *et al.*, 1998; Mackinson *et al.*, 1999) can also be used for mackerel studies. A higher frequency, such as that used in most of these studies, would also be preferable for mackerel, as such frequencies produce a better echo from fish flesh. Our analysis also demonstrates that automatic logging procedures must be further developed in the direction of becoming more systematic with respect to the actual action taken when a school is detected on the screen, and, even more importantly, with respect to how to handle multiple targets during tracking.

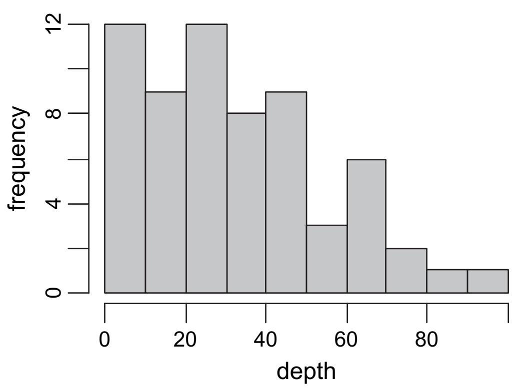

Figure 3. Histogram of median school depths.

A related problem is that any future development of the method will require the identification of optimal data-acquisition strategies. The analysis assumes that the characteristics of each individual school (e.g. migration speed and direction) are independent observations. Due to the similar characteristics of schools that are recorded simultaneously, the essential criterion of independent

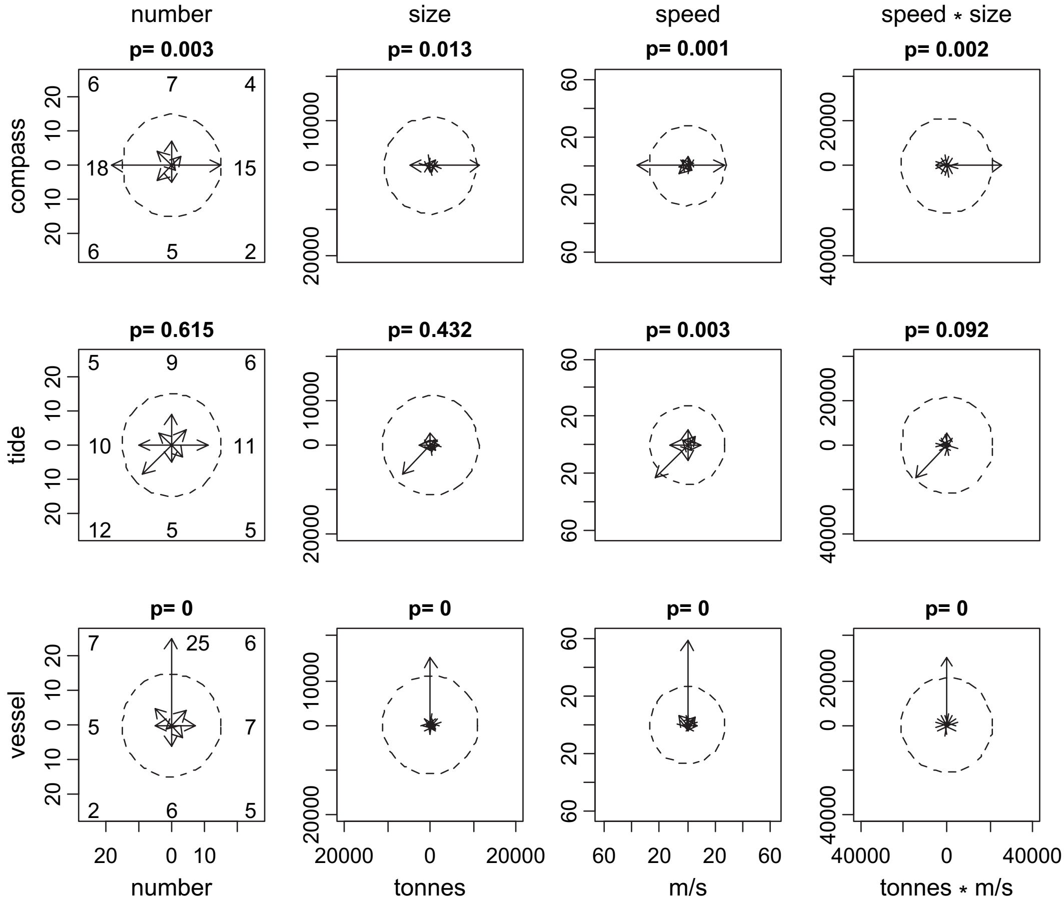

Figure 4. Number of tracks, total size, total speed, and total speed * size moving in each sector direction. The sector directions are defined relative to compass north (top), current direction (middle), and vessel heading (bottom). The probability that one of the arrows in a given plot will transcend the dotted circle, under the null hypothesis that the directions are random, is 5%. The p-value for the length of the longest arrow under H_0 is given at the top of each plot corner. The circles and p-values are calculated from 1000 randomizations. The number of tracks in each sector direction is printed on the inside of the leftmost figure frames.

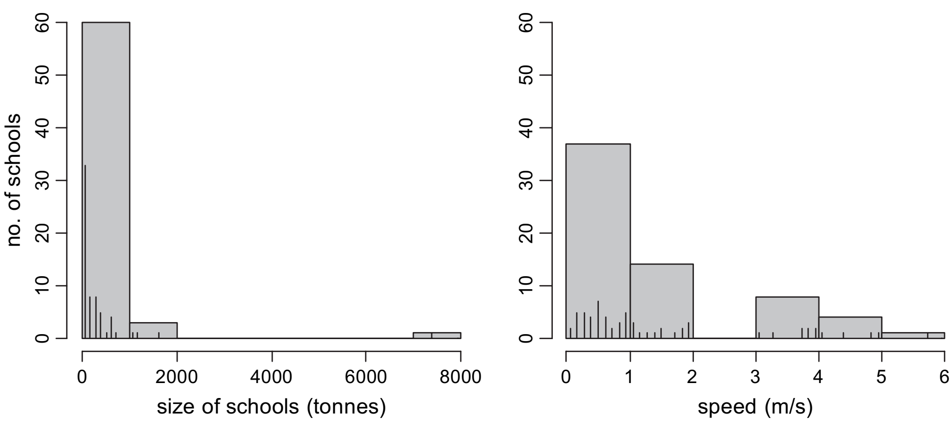

Figure 5. Histograms of school size and school swimming speed. Each bar of each histogram contains a refined histogram of the observations falling within that bar.

observations is not fulfilled convincingly. Adjacent schools may affect each other's speed and direction. On the other hand, if external factors such as the tidal current have a major influence on the characteristics of the schools, such co-occurrence is not unexpected. Two approaches could be further explored. First, when several schools are observed in an area simultaneously, e.g. defined by continuous multiple contacts on the sonar screen, all schools recorded in this area should be associated with a clustering tag. For later analysis, they could be treated as a single unit based on multiple observations. Secondly, when data from several vessels are used, it is essential to define a data-logging strategy, particularly when several targets appear on the screen simultaneously. This was not the case in our experiment and a vessel effect in the results cannot be excluded. Experience so far suggests that we should continue to initiate tracking of new schools as they appear on the screen to the extent that the system can handle them.

Mackerels (Scombridae) are high-performance swimmers (Nauen and Lauder, 2002) and their behaviour may be sensitive to the survey vessel during observation and sampling (see, e.g. Mitson and Knudsen, 2003). The potential effect of vessel avoidance can be studied by looking at the probabilities of non-random distributions of migration direction relative to vessel direction. We tried to minimize the problem by reducing the vessel speed during recording. Nevertheless, at first glance, the significant association between migration and vessel directions suggests a strong vessel effect (Figure 4). On the other hand, we expected that the vessel effect would induce an avoidance reaction to the stimulus source and thus at an angle to the cruise track rather then along it, as indicated by the observations. The maximum swimming speed of nearly 6 $m\,s^{-1}$ (Figure 5) seems unrealistic unless a strong vessel effect is involved. However, it should be kept in mind that we are presenting swimming speeds over the ground, such that intense local currents may strongly bias the observed speed. The data are thus inconclusive and additional actions will be considered for future studies. Only schools within a certain range of bearings and beyond a given threshold distance should be used for migration behaviour studies while the whole track can be used to analyse vessel effects. Local current speeds need to be logged for the study of true swimming speeds through water.

Migration and schooling behaviour

A behavioural response to currents (rheotaxis) is characteristic of fish (Harden Jones, 1968). Castonguay and Gilbert (1995) found that tidal currents affected the migration behaviour of mackerel. We found no direct link between current and migration direction (Figure 4), but the fish apparently turn alternatively east and west, more or less at right angles to the main current system. This may indicate rheotaxis. The schools were detected over bottom depths of several hundreds or thousands of metres and could not have been navigating on the basis of visual bottom clues. If rheotaxis plays a role, the influence of currents on the lateral line (Montgomery *et al.*, 1997) or inertial effects (see, e.g. Sand and Karlsen, 2000) could be important. With the available data it is difficult to determine the net movement, since migration by school size is eastward while the speed and number of schools indicate westward migration. More data and improved logging routines as proposed above will improve our ability to estimate overall net migration. The north–south migration is much less pronounced than the east–west migration, which suggests that the mackerel is at the northernmost limit of its distribution during the summer survey. An alternative explanation is that the feeding strategy of the fish is to move east and west, filtering plankton, letting the North Atlantic Drift carry them to the northern feeding grounds, which may explain the slow average northerly migration speed of 0.04 $m\,s^{-1}$ compared with the east–west component of 1.7 $m\,s^{-1}$ towards the west. The larger size of schools migrating eastward and westward compared to other directions also suggests that these schools are actively searching for prey.

The extensive migration of mackerel is presumed to be linked to physical and biological environmental factors. The fact that most of the mackerel schools tracked in July 2002 were found between the surface and a depth of 40 m could be explained by temperature preferences as well as the availability of prey. This paper does not include any analysis in this respect due to the lack of available data.

Sonar recording of mackerel schools has proved to be a viable methodology for assessing distribution and migration pattern during the summer feeding migration. The methodology needs to be improved with respect to routines and procedures in order to ensure representative evaluation of school distribution and movements. Furthermore, the collection of supplementary information on the physical and biological environment may help to provide a proper base for the development of models capable of explaining variations in the behaviour of this species. July appears to be an optimal time for performing a combined sonar–lidar survey. Initial studies show that lidar is capable of recording mackerel to depths of 40 m (Tenningen *et al.*, 2003) and most of the mackerel that we registered were distributed above this depth.

Acknowledgements

The captains and crews on MS "Endre Dyrøy" and MS "Trønderbas" are thanked for their valuable efforts during the studies. Their cooperative and engaged attitude was essential to the success of this cooperation between scientific and commercial fishing interests.

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