ICES J. mar. Sci., 52: 925–939. 1995

Understanding mackerel migration off Scotland: Tracking with echosounders and commercial data, and including environmental correlates and behaviour

Martin Walsh, David G. Reid, and William R. Turrell

Walsh, M., Reid, D. G., and Turrell, W. R. 1995. Understanding mackerel migration off Scotland: Tracking with echosounders and commercial data, and including environmental correlates and behaviour. – ICES J. mar. Sci., 52: 925–939.

The characteristics of mackerel schools are described from the results of an acoustic survey carried out in January 1994. Schools were typically found in midwater, over bottom depths of >100 m to just beyond the shelf break. They were of deep vertical spread (up to 105 m) with a mean estimated width of 200 m, with packing densities of up to 9 fish m^{-3} and a mean biomass of 640 tonnes. Schools were aggregated into discrete patches of high biomass (up to 12 000 tonnes) which were confined to relatively small areas and separated by distances of up to 50 miles. With this type of distribution it is possible to make repeated surveys over aggregations to determine direction and speed of migration. Spatial distribution from the acoustic survey was compared to that of the main commercial fleet to evaluate how well the latter reflected the distribution and migration of the stock. Using the fleet data, estimated migration rates were 13.0 cm s^{-1}, 17.8 cm s^{-1} and 25.9 cm s^{-1} for the months of December, January, and February, respectively. The distribution of catches in January 1994 was compared with that of previous years and showed no reversal of the northward shift of recent years. The relationship between sea temperature, salinity conditions, shelf edge current measurements, and the distribution of schools is described for the first time.

Key words: mackerel, migration, hydrography, commercial data.

Received 9 December 1994; accepted 22 April 1995.

Martin Walsh, David Reid, and William Turrell: SOAFD Marine Laboratory, PO Box 101, Victoria Road, Aberdeen AB9 8DB, Scotland, UK.

Introduction

The western mackerel (*Scombrus scombrus*) is known to undertake large-scale migrations between summer feeding grounds in the North and Norwegian Seas and its spawning areas south and west of Ireland. Previous studies have shown that the timing and pattern of the post-spawning northerly migration have been relatively stable. The return southerly migration, however, has changed dramatically in both timing and route over the last 20 years (Walsh and Martin, 1986; Anon., 1981, 1986, 1988a,b). During the 1970s and early 1980s this migration occurred in late summer and early autumn, with the fish moving through relatively shallow waters and giving rise to a very substantial fishery in the Minch (west of Scotland 57–58°N 6°W). Since then the migration has occurred progressively later in the year, but has stabilised since 1992. The fish do not now cross the 4°W line until mid-January, with the fish being found west of Scotland and Ireland in February. The timing of migration across the 4°W line is of considerable importance to commercial fishermen since this latitude separates two management areas, and fishing to the east of it is subject to severe quote restrictions. The later the arrival, therefore, the shorter the fishing season for many fishermen. Walsh and Martin (1986) suggested, based on commercial catch data, that this change may have been related to changes in the hydrography of the area following the 1970s salinity anomaly.

The present paper describes the results of a combined acoustic and hydrographic survey of the western mackerel near to the time of the start of their southerly migration (9–26 January 1994). This survey forms part of the EC AIR (Agriculture and Agro-Industry, including Fisheries) funded cooperative research project SEFOS (Shelf Edge Fisheries and Oceanography Study) into the interactions of the hydrography of the European shelf break area and the associated fisheries. The original aim was to map the distribution of the fish in the Shetland/Tampen Bank area, where they were

1054–3139/95/060925+15 $12.00/0

believed to aggregate prior to the start of migration. Fish mapping was integrated with a hydrographic survey of the area to determine the prevailing conditions prior to migration. Previous commercial catch data had indicated that the migration started in mid-January in recent years. Thus, the survey was timed to cover the periods both before and immediately after the start of migration. The second half of the survey was intended to cover the main areas of distribution mapped in the first half, monitor the start of migration, and determine which, if any, hydrographic parameters had changed that might be triggers for the start of migration.

One of the major hydrographic influences in this area is the Shelf Edge Current (SEC). Changes in the behaviour of the SEC are believed to be implicated in the changes in the pattern of mackerel migration. Accordingly, a current meter mooring, with associated CTD recorders was deployed in the fringe of the SEC at the southern end of the survey area. The instrument was intended to record any changes in the SEC during the period of the survey which might have been correlated with changes in fish distribution.

Materials and methods

Acoustic survey

Equipment

The survey was carried out from the Scottish Office research vessel RV "Scotia". Acoustic data were obtained using a SIMRAD EK500 38 kHz split beam echosounder. Calibration of the acoustic equipment was carried out during the survey using a tungsten carbide target following the procedure outlined in Foote *et al.* (1987). The transceiver was mounted in a catamaran that was towed from a boom alongside the vessel. Under survey conditions (10 knots) the catamaran flew at a depth of approximately 4 m. The range was maintained at 250 m throughout the survey with a pulse interval of 1.5 msec. Echosounder output was recorded continuously as hard-copy and in digital form. The hard copy of the echogram was printed out in colour using a Hewlett-Packard paintjet interfaced to the echosounder. Digital data were transferred by ethernet to a SUN SPARC IPC computer and recorded transmission by the transmission of 0.5 m depth samples on to Digital Audio tapes (DAT). Echo integration (MacLennan and Simmonds, 1991) was carried out over 15 min intervals (2.5 nautical miles at 10 knots) by the echosounder and recorded on the printout.

The survey

The survey was carried out in three parts: Part 1, 10–15 January 1994, covering an area north of 61°N and from 0°–2°E of the shelf area west of Shetland; Part 2, 15–20 January 1994, the same area plus the area north of Shetland missed during part 1; Part 3, 24–26 January 1994, covering the shelf area from 3°–5°W (see Fig. 1). The survey was designed as a zig-zag with 10 nm transect spacing. The general movement of the survey was NE to SW in part 1, SW to NE in part 2 and NE to SW in part 3. The mackerel are known to migrate through this area in a generally NE to SW direction. The transects were designed to cover the known depth range of the mackerel in this area, between 100 and 200 m contours. The transects were continued into deeper and shallower water to confirm the assumption of depth range restrictions. The coverage of the northern sector of the survey area was severely curtailed by bad weather during part 1. The survey concentrated on an area from 0°–2°E and the main survey area west of 1°W. The timing and location of the transition from part 1 to part 2, allowing a second complete coverage of the main part of the survey area, was based on observations made during part 1. No mackerel were observed on the last transects in part 1, and the commercial fleet were all positioned north and east of the vessel at this time. It was concluded that the south western edge of the distribution had been located, and that the survey should be continued back over the known areas of mackerel concentration. Again, due to bad weather, part 3 was restricted to the south western sector of the survey area, where fishing activity was reported.

Eight trawl hauls were made during the survey, although only two contained significant numbers of mackerel. The remainder were made on marks attributed to other species or were unsuccessful. Length/frequency and weight/length relationships were derived from the trawl hauls.

Mean length = 36.3 cm
TS/individual = − 53.7 dB
TS/kilogram = − 49.9 dB
Weight/length relationship, $W = 9.56 \times 10^{-4} \cdot L^{3.61}$

Further evidence for the assignment of schools to species was obtained from the commercial vessels operating in the same area. In many cases commercial vessels were actively fishing on schools seen on the echograms, in all cases these were confirmed as mackerel. It should also be noted that the only other pelagic species found in any concentration in this area at this time was herring. Herring and mackerel have very different target strengths and the schools are easily separable using the echogram.

Data analysis

The acoustic data were analysed by two methods. In the first a distribution map of the mackerel biomass in the area was developed using echo-integration data. In the second a data-base of all the mackerel schools seen during the survey was extracted with related structural, temporal and positional information.

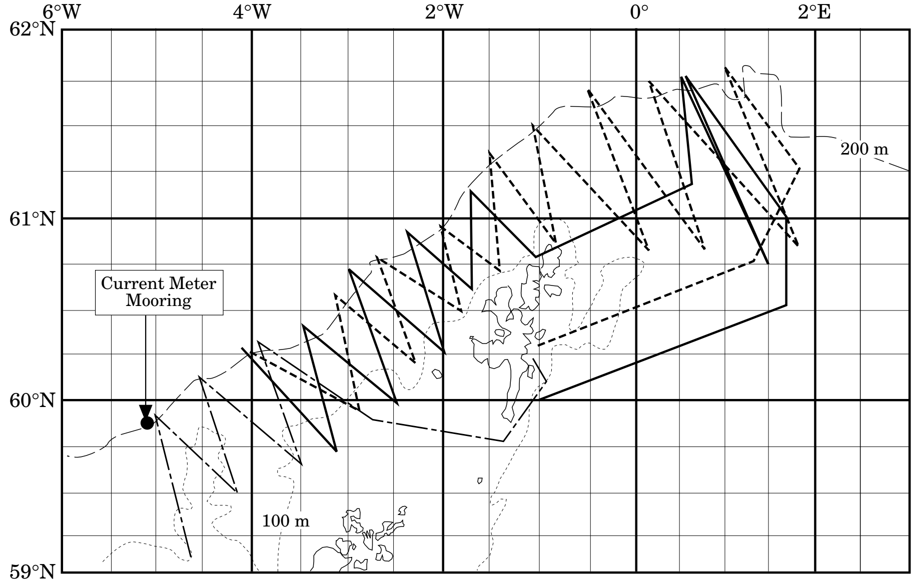

Figure 1. Cruise track for RV "Scotia", 7–27 January 1995. The survey was in three parts indicated by different line styles (——) Part 1; (· · ·) part 2; (– – –) part 3. Thin dotted line represents 100 m depth contour; thin dashed line represents 200 m depth contour.

The first approach followed that recommended by Simmonds *et al.* (1992) and was used during the North Sea herring acoustic surveys. Echo integrals were summed every 15 min. The integrals of mackerel and other sources were separated by visual examination of the echograms and by using the data from fishing exercises. The partitioning of integrals of mackerel and other species was relatively straightforward. Mackerel marks were easily identified and there was very little interference from other scatterers in the water column. The echo-integrals were converted to fish density and hence biomass using the Marine Laboratory's PC-based analysis programme (MILAP). The target strength to length relationship used was that recommended for North Sea acoustic surveys in Anon. (1994): $TS=20 \log L - 84.9$ dB per individual (L, length in cm). The fish density derived from the echo integration was raised to quarter ICES rectangles (approx. 15×15 nm). The data are presented as a circle plot, with the diameters of the circles representing four biomass levels (0, <50, 50–100 and 100+ ktonnes).

In the second approach, a data base was collected from the echograms for all mackerel schools. Each school was recorded with date, time, position, water depth, and echo-integral. The size and position of the school in the water column was also recorded. Parameters recorded were: height and width, range from the surface to the top, mid-point and bottom of the school. The data base was analysed after the survey. Two types of correction were required for the height and width parameters recorded from the echogram. First, the beam pattern was corrected, because this makes the image on the echogram appear larger than it really is. In brief, a school appears taller on the echogram by half a pulse length and wider by a single beam width. Effective beam width is modulated by the TS threshold of the average mackerel school; this is approximately -52 dB, calculated from the dB value of the average sample (single transmission and half metre depth layer) within the schools. Beam width also increases with depth. Second, the school width is corrected for bias resulting from most school crossings being off centre. For a fuller discussion of this problem see Reid and Simmonds (1993).

The biomass of each school was calculated. First, the fish density per square kilometre of sea area was calculated using the school echo-integral, the acoustic cross section of the average mackerel caught, and the calibration constant for the equipment (MacLennan and Simmonds, 1991). The biomass in each school was calculated as the plan area of the school (cross sectional area viewed from above) multiplied by the fish density by area. The density of fish by volume was obtained by first determining the volume of the school from its height and width. It was assumed that schools were cylindrical in shape. The cylinder model was used as most of the schools seen during the survey appeared rectangular on the echogram, with relatively vertical sides. A circular plan cross section was assumed based on work on herring (Pitcher, 1976) and sonar observations of mackerel schools. Previous studies have assumed a square cross section (Walsh and Armstrong, 1975), but this was mainly for simplicity. Other suggestions have been made that mackerel schools are elliptical in plan, the long axis aligned to current or to the vessel. No data were available to substantiate this and the circular plan model was adopted as the simplest. It is, however, clear that more work on the 3D structure of fish schools in the wild is required. One further parameter included in the database was the mid-point of the school, standardised for water depth.

The school parameters were then plotted in scattergrams against depth and day/night.

Hydrographic survey

Sea surface salinity and water temperature (SST) were monitored and recorded continuously during the survey using an Ocean Data model TSG 103 thermosalinograph connected to the vessels non-toxic sea water supply. Data were recorded for subsequent analysis on a BBC microcomputer. Vertical salinity and temperature profiles were produced using an Applied Microsystems CTD model STD12. CTD stations were carried out at the turns between transects and at a minimum of 20 nm intervals along the transects. At each station the water column was profiled down to within 10 m of the seabed. Water samples were collected for calibration every five stations. The CTD and thermosalinograph data were contoured separately for each of the three parts of the survey.

A current meter mooring consisting of three Anderaa RCM7 current meters was deployed at 59°52.28′N 05°02.87′W in 251 m of water, from 20 November 1993–25 January 1994 (Fig. 1). The current meters were placed at 53 m, 141 m and 226 m below the surface. (Data analysis was carried out using programmes written by Marine Laboratory staff.)

Commercial data

A small number of Dutch, Irish, and Scottish fishing vessels provided exact fishing postions during, before and after the period of the SEFOS acoustic survey. These are believed to be representative of their respective fleets which usually work together over relatively small areas. Several of the given catch locations were verified by sightings from the survey vessel and the fishermen who provided the data were selected for their reliability. Official catch statistics were not used because they are less precise and known to be unreliable when mackerel are distributed in areas subject to quota restrictions (as in December 1993 and January 1994). Observations of actively fishing vessels made during the acoustic survey itself were also used in the analysis.

Results

Acoustic survey

Three major patches of mackerel schools were observed during parts 1 and 2 of the survey (Figs 2, 3). Two of these were around the meridian, one between 61°15′N and 61°30′N and the other around 61°00′N. The third patch was seen around 2°W. Figure 3 shows a plot of these three patches with the times and locations at which they were seen during the survey. The two patches of schools close to the meridian were first seen around 10–12 January, east of 0°, during part 1. During part 2 two patches of schools were again seen in this area, one between 61°15′N and 61°40′N and west of 0°, the other around 61°00′N, just east of 0°. No fish were seen at the previous locations of either patch. It is likely that the patches seen in part 2 were the same two patches of fish seen in part 1 which had migrated westward. The patch seen at 2°W on 13 January was being actively fished. The fleet remained with these fish and they were seen together again on 15 January, further south and west. It is almost certain that these were the same fish, as no others were seen at the second location during part 1 or the first location in part 2. The last patch of schools seen was located at 3–5°W. It seems likely that these were the same fish last seen on 15 January, but no certainty can be attached to this assumption, as there was a nine day gap between sightings. It should be noted that the fishing fleet (after stopping for bad weather) was working on this patch again, and also in another area north of Shetland. No fish were reported between these areas. It is suggested that the marks around 4°W are those last seen on 15 January. The style of hatching on the plot is intended to indicate which patches may have been the same fish seen in different locations.

Analysis of the database showed a number of interesting relationships between the schools, location, and time of day. Figures 4–6 show plots of school parameters against water depth and time of day. These data are summarised in Table 1. Taking all the parameters together, it can be seen that, during the day, the schools were deeper in the water column, had a greater vertical spread and a higher fish density fish per cubic metre. There was no significant difference in school width.

The day/night differences in apparent density may be partially the result of changes in target strength due to tilt angle, rather than actual changes in fish numbers. Cage experiments have shown changes of 5 dB in target strength per kilogram between day and night – lower at night (Edwards *et al.*, 1984). Such changes reduce the apparent biomass of night-time schools. A day/night TS change of 4 dB would explain the reduction in fish density, without assuming any systematic change in school volume, i.e. the schools spreading out. Mean school volume by day was 4.8 million m^3, and 7 million m^3 by night. If it is assumed that this represents

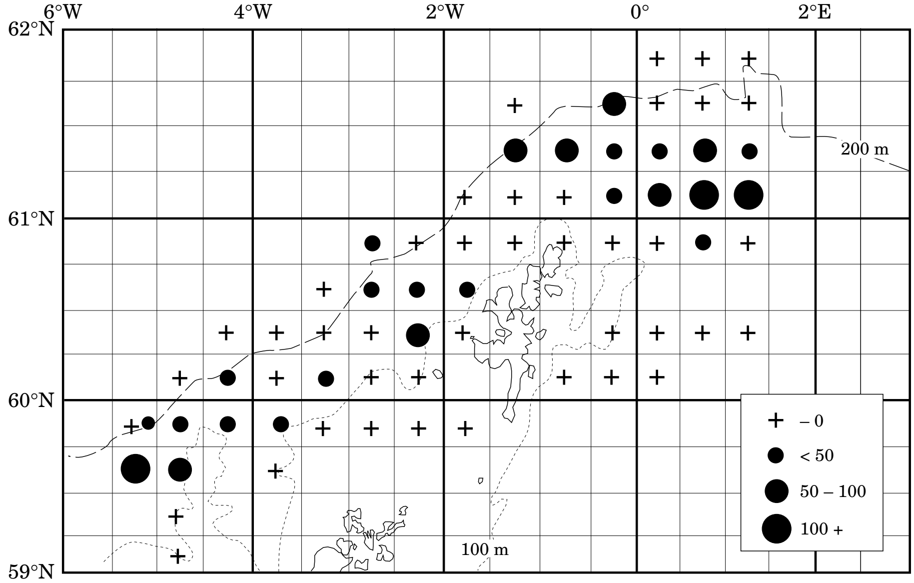

Figure 2. Circle plot of mackerel biomass distribution by quarter ICES statistical rectangle in four categories.

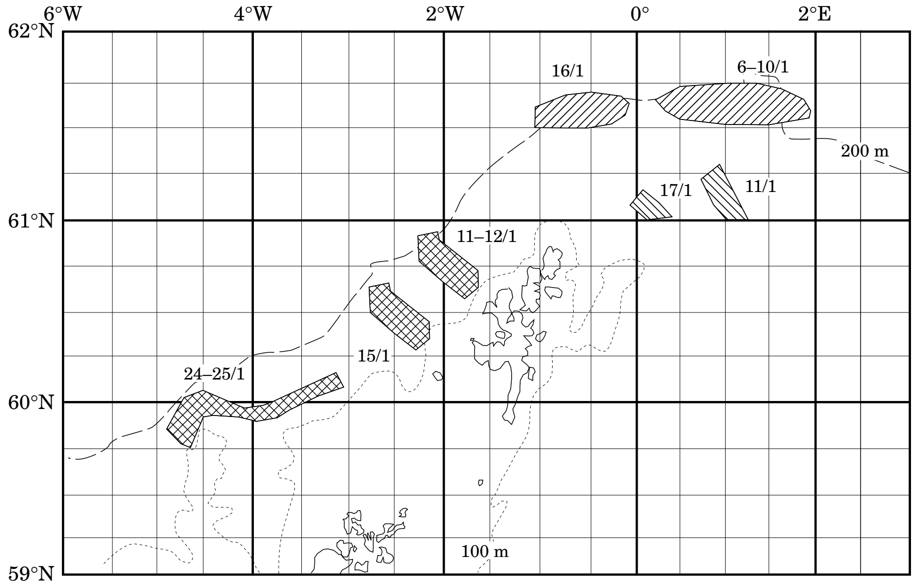

Figure 3. Locations and dates of mackerel concentrations observed. Arrows indicate probable migration of fish between observations. The different cross hatchings represent three different schools.

the schools spreading out at night, the reduction in apparent fish density can be explained by a TS change of 2.4 dB. It is difficult to determine exactly what is happening, but it is probably reasonable to assume that both effects were occurring, and that the schools were more dispersed at night and there were systematic tilt angle changes affecting the true TS value. The main purpose of this study was to examine distribution and migration, and, in this context, the day/night changes in TS are not important, although they may well be for stock assessment purposes.

In general, the school mid-point was found in the upper half of the water column at night and in the lower half during the day. It is interesting to note that, during the night and over the bulk of their water depth range, the schools appeared to occupy a predictable position in

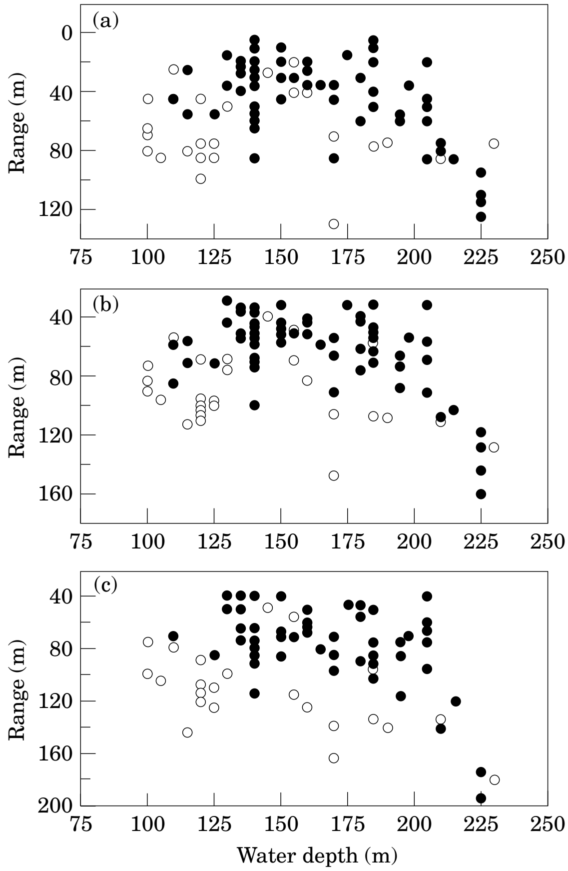

Figure 4. Mackerel school position parameters plotted against water depth (m): (a) range to top of school; (b) range to mid point of school; (c) range to bottom of school. Open circles represent day-time observations, closed circles represent night-time observations.

the water column (approx. $\frac{1}{3}$ the water depth, Fig. 6a). In shallower water (100–125 m), the schools were found relatively deeper in the water column, particularly during the day but also at night. In water depths greater than 200 m the fish were seen much closer to the bottom than in shallower areas; however, there are relatively few observations at this depth and most of these were seen in one 15 min period. It is not possible to draw any general inferences from this small number of schools.

Distribution of mackerel in relation to oceanographic factors

Figures 7–9 show the distributions of observed mackerel schools in relation to sea surface temperature and salinity during the three periods of the acoustic survey. Throughout the survey the waters were unstratified (confirmed by CTD stations) and therefore surface temperatures and salinities can be considered as representative of the water column as a whole.

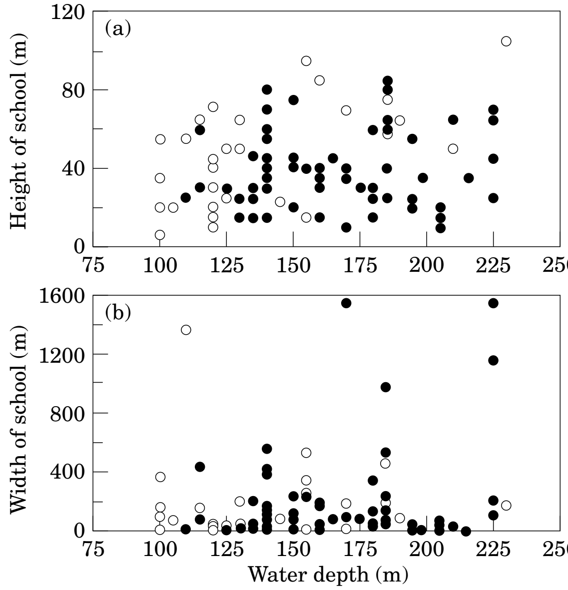

Figure 5. Mackerel school shape parameters plotted against water depth (m): (a) height of school; (b) width of school. Circles as in Fig. 4.

Taking the three parts together all the schools were observed with the temperature range 7.75–9.00°C with the majority at 8.00–8.75°C. There was no evidence of any association of the schools with a very narrow temperature range but no schools were observed in cooler waters (<7.75°C) inshore from the shelf edge.

From Figures 7 and 8, it is evident that the schools were further west in the north-eastern part of the survey area in part 2 than in part 1. At the same time in this region, colder water advanced in a north-westerly direction towards the shelf edge, reducing the area of >7.5°C water in this region. During part 3 there was no overlap in area with parts 1 and 2 so it is not possible to chart this process any further. The schools seen in part 3 were associated with slightly higher temperatures than in the preceding periods.

Within the area surveyed the salinity range was <35.00–>35.40 ppt. Mackerel schools were only observed in waters of >35.15 ppt, i.e. in mixed Atlantic/Shelf water associated with the outer areas of the continental shelf (the majority were found in water with salinities of 35.25–35.40 ppt). As in the case of the temperature data there was some evidence of a change in salinity between parts 1 and 2. The change was again most obvious in the north-eastern part of the survey area, where a north-westerly shift of the isohalines resulted in a reduced area of high salinity water in part 2. This occurred at the time when the mackerel schools appeared to be shifting westwards.

The area covered by the acoustic survey concentrated on the relatively restricted region of expected high

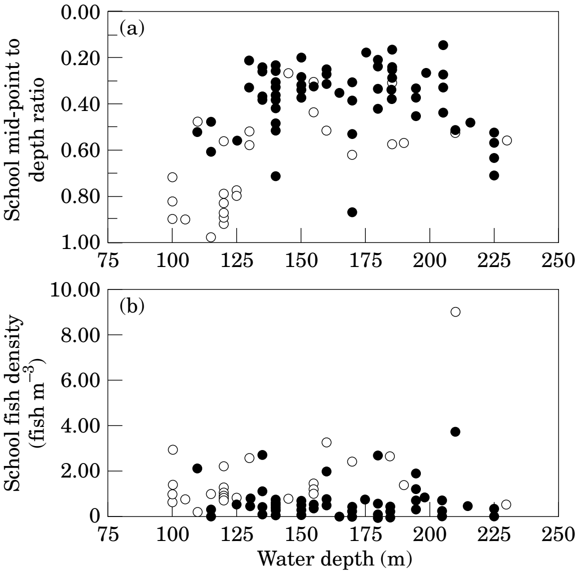

Figure 6. Mackerel school parameters plotted against water depth (m): (a) ratio of school mid point to water depth; (b) fish density of schools (fish m^3). Circles as in Fig. 4.

mackerel abundance. To set the mackerel distribution data in a wider hydrographic context the distribution of catches in January were compared with sea surface temperature data over a wider area (Fig. 10, Meteorological Office Data). These data were taken at the beginning of January and are of low precision. However, they serve to illustrate that the known area of the fishery lay within a tongue of relatively higher temperature water flanked by cooler water to the east and west.

Current measurements (Fig. 11) were successfully obtained at the mooring position described. This was just offshore of the western boundary of the observed distributional area of mackerel schools and slightly inshore of the core of the current. Measurements indicated a fast, persistent north-easterly direction of flow along the line of the shelf edge (i.e. counter to the direction of migration of mackerel at this time) with a mean residual speed of 17.1 cm s^{-1} and a maximum value of 40 cm s^{-1}.

Distribution of international commercial fishing activity to relation to stock distribution

The acoustic survey was divided into three parts. For comparative purposes fishing vessel positions were plotted during the same periods and additionally during the five-day period immediately preceding the first acoustic survey (Fig. 12). The data indicate a relatively steady progression of the fleet towards the south-west throughout January. When fleet activity was compared with the distribution of mackerel schools (Figs 7–9) it is evident that, although the fleet was usually associated with good concentrations of mackerel, it did not necessarily cover the whole or even the major concentration of fish. Thus, during part 1 of the study, the highest concentrations of mackerel were observed at the north-eastern end of the survey area around 1°E in an area where no fishing vessels were observed. The nearest recorded catch during this period was some 30 miles to the south-west while most fishing activity was 80–120 n.mi to the south-west. The high concentrations observed around 1°E during part 1 were located very close to the area fished by the commercial fleet some 4–5 days earlier.

During part 2, the fleet continued to concentrate its activity at the south-western extremity of the distribution although substantial quntities of mackerel were observed 60–80 miles north-east of the fleet.

Insufficient sea area was covered during part 3 to allow any valid comparisons between fleet and mackerel school distribution. Most of the fleet was working within the acoustic survey area south-west of the Shetlands but some vessels were also reported north-east of the Shetlands during this time.

Figure 13 shows the distribution of fishing activity plotted by month of the three-month period around the acoustic survey (December–February). The data suggest that the return migration from the summer feeding grounds to the spawning grounds was already under way

Table 1. Diel differences in mackerel school parameters.

Parameter	Mean value: Night	Mean value: Day	t-test	p
Range to top of school (m)	42.5	62.0	3.08	<0.01
Range to bottom of school (m)	79.5	112.5	5.35	<0.01
Range to school mid point (m)	61.0	87.0	4.73	<0.01
Height of school (m)	37.0	50.5	2.34	<0.05
Width of school (m)	211.5	178.0	− 0.52	n.s.
Density (fish m^{-3})	0.6	1.5	2.87	<0.01
Mid-point/depth	0.37	0.64	6.9	<0.01

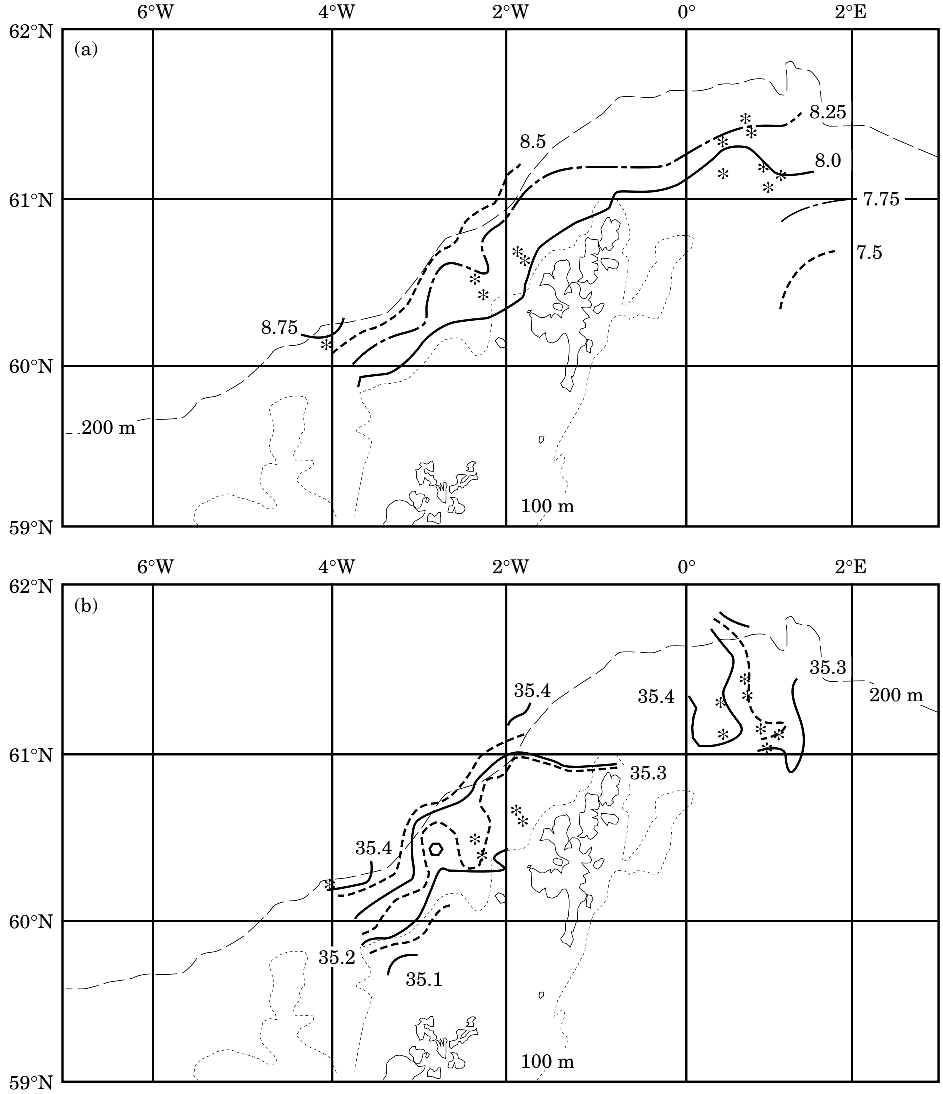

Figure 7. Mackerel school distribution (asterisks) plotted with (a) sea surface temperature contours, and (b) sea surface salinity contours for part 1 of the survey (9–14 January 1994).

in December and gathered speed between successive months. During the preceding two months, unpublished catch data indicate that no catches were taken west of 0° and there was no clearcut pattern to the movements of the fleet. There was therefore no indication that the return migration began before December.

Using the data in Figures 10 and 11 it is possible to make tentative estimates of migration speed. In the case of Figure 10 it is assumed that the most south-westerly catch in each of the four time periods gives some indication of the location of the leading edge of the patches of migrating schools. Mean daily distance travelled and speed have been estimated by calculating the straight line distances between these points (values are therefore minima). In the case of Figure 11, the nearest dates to the beginning, middle, and end of each month were selected to estimate mean daily distance travelled and migration speed. Again, the straight line distances between points were used. Where more than one catch was taken on the same date the mean point between catch positions was used.

The results of these calculations are summarised in Table 2. In December, the migration appeared to be relatively slow, following a north-westerly course up around the shelf-edge from the western fringe of the Norwegian deeps to Tampen bank, and then west to a point north of the Shetlands (the most westerly catch were taken here at the end of the month). Mean

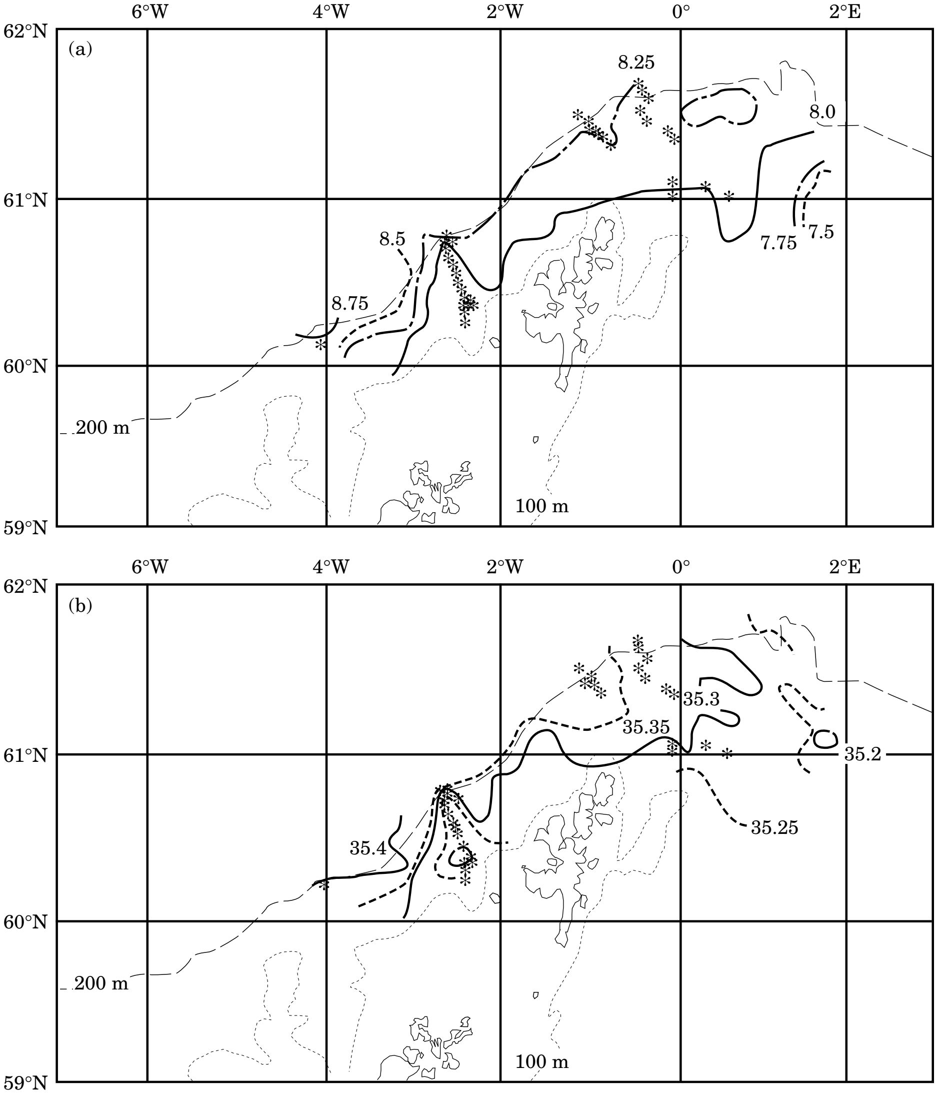

Figure 8. Mackerel school distribution (asterisks) plotted with: (a) sea surface temperature contours; and (b) sea surface salinity contours for part 2 of the survey (15–19 January 1994).

minimum daily distances travelled appeared to be similar at around 6 n.mi d^{-1} during both halves of the month. In January, there are some differences between the results calculated using different dates, and slightly different methods were applied to Figures 10 and 11. In the former, 3 successive periods of about 6 days gave migration estimates of 9–12.8 n.mi d^{-1} while in the latter, 2 half-month periods gave sequential values of 4 and 12.1 n.mi d^{-1}. The two data sets are consistent, however, in indicating a faster migration in the second half of the month than in the first half and both indicate a faster mean migration rate in January than in December.

In February migration rate appeared to be similar to that at the end of January at around 12 n.mi d^{-1} with no marked difference between the first and second halves of the month.

Discussion

The present study is one of several undertaken in recent years which have used a combination of acoustic survey techniques, simultaneous hydrographic observations, and commercial catch data to provide new insights into fish migration. It is the first of its kind on mackerel in the north-east Atlantic and may be set in the context

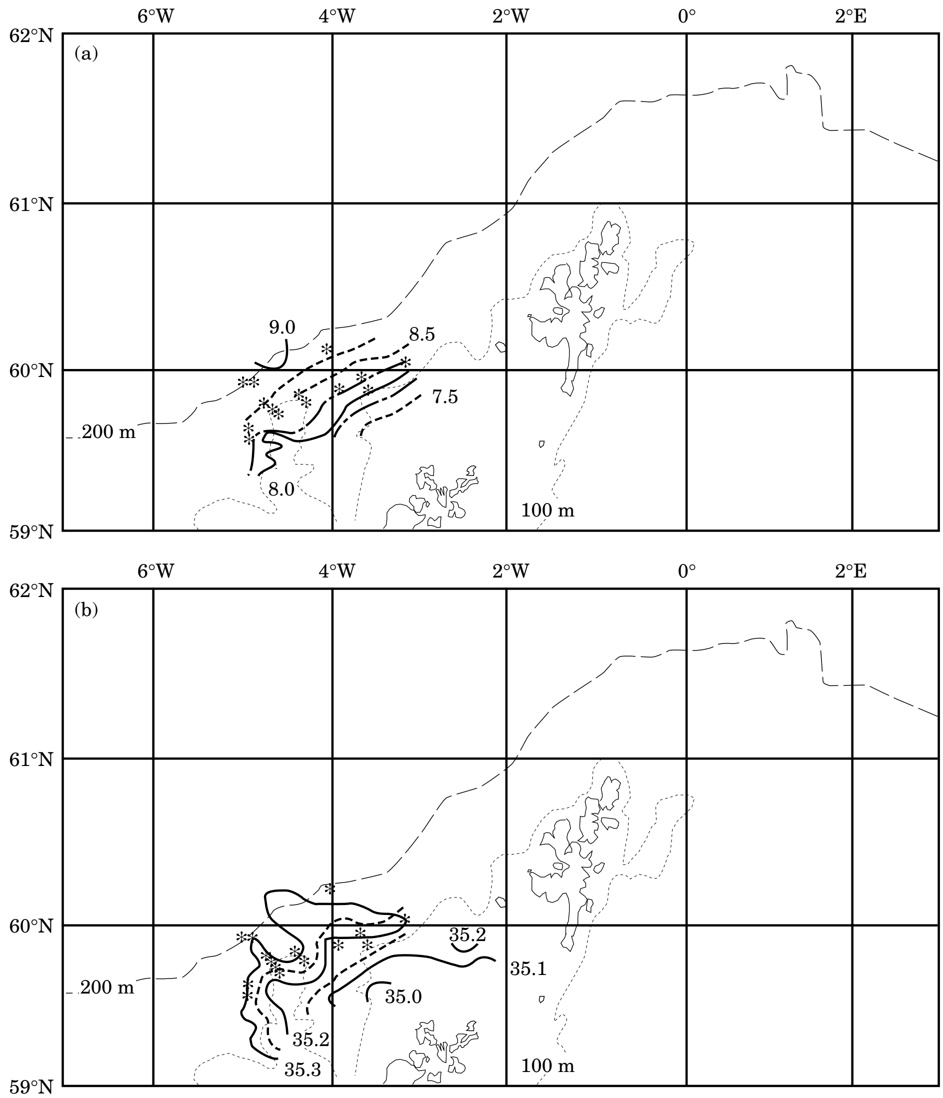

Figure 9. Mackerel school distribution (asterisks) plotted with: (a) sea surface temperature contours; and (b) sea surface salinity contours for part 3 of the survey (24–26 January 1994).

of related work on cod (*Gadus morhua*) by Rose and Leggett (1988) and Rose (1993), mackerel by Castonguay *et al.* (1992) in the north-west Atlantic and blue whiting (*Micromesistius poutassou*) in the north-east Atlantic by Hansen and Jakupsstovu (1991).

The initial expectation, based on commercial vessel data, was that the mackerel would be aggregated in the Shetland area prior to migration which started in mid-January. The findings of this study show that the fish appear to have started their migration from further east and earlier than anticipated, possibly in mid-December. The fish did not appear to migrate as one mass, as a continuous stream of schools, or as a spread of independently migrating schools. The migration would appear to have taken place in a small number of discrete patches, each made up of a fairly large number of schools. It would appear that these patches retain their integrity, at least within the period of the survey. In this particular year these patches could be separated by up to 50 miles (or approximately 5 d, assuming an average speed of 10 n.mi d^{-1}, see Table 2). The acoustic survey allowed these patches to be plotted, their biomass assessed, and in a number of cases, their patterns of movement inferred.

The close correspondence between the results of the acoustic survey and the commercial vessel data is very encouraging. It is also important to note that, in a situation where the fish migrate in large, discrete

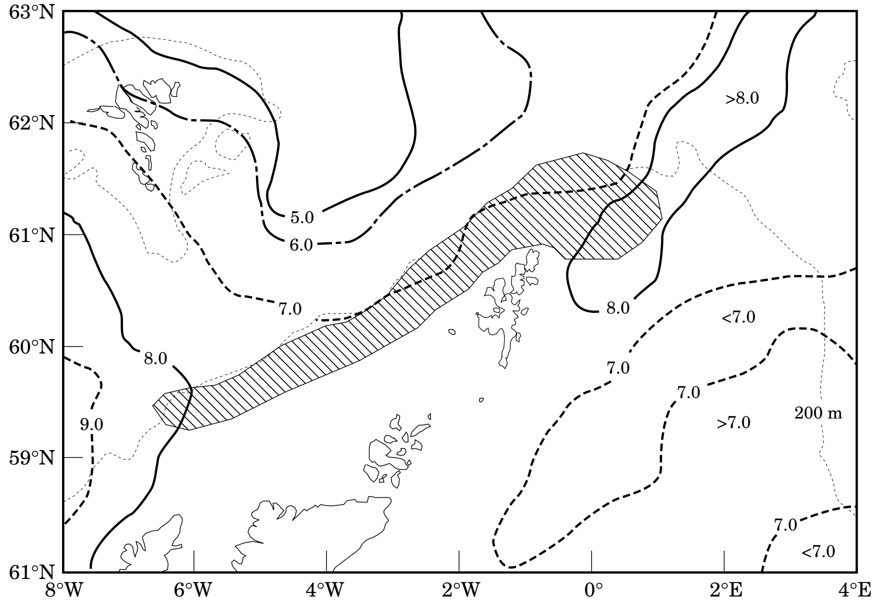

Figure 10. Mackerel fishing fleet distribution in January 1994 plotted with sea surface temperture (SST) contours over a wider geographical area. SST data from Meteorological Office data.

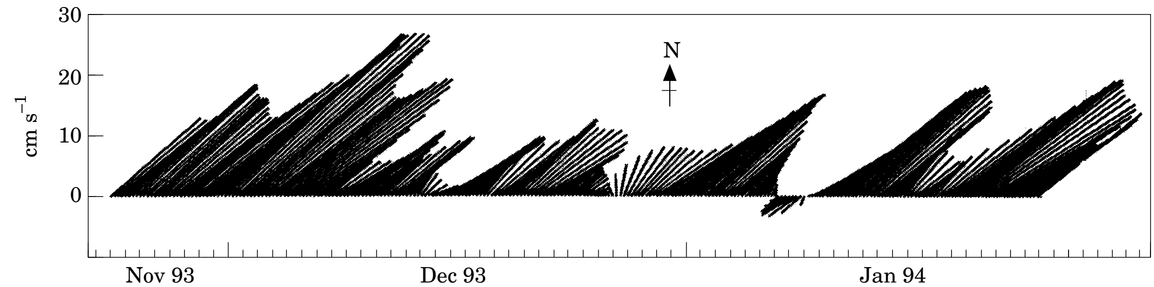

Figure 11. Residual currents recorded at the current meter mooring (see text). Data are plotted showing direction and strength at the current meter nearest to the surface, the other two current meters showed very similar patterns. Deployment was from 20 November 1993 to 29 January 1994.

patches, commercial vessel data can be misleading. In these waters severe weather which stops fishing is common. A fleet of fishing vessels will tend to stay in touch with a patch of schools until contact has been broken by weather. When they are next able to operate the natural tendency will be for the vessels to go to the same area again and then scout for fish. This may result in clustered catch data. It is therefore important to consider the length of time between fishing periods when assessing this type of data. An understanding of the pattern of mackerel movement allows a more sensible appraisal of commercial catch data in the context of a migration study. As an illustration, the catch taken over 24–26 January, east of Shetland and labelled "outlier" in Figure 12, may indicate a new patch coming through the area. The fleet distributions during the period of the surveys probably provide a reasonable reflection of the distribution and migration of the vanguard of the stock.

A comparison of the distribution and migration of western mackerel in 1993/1994 compared to recent seasons (Walsh, unpubl.) indicates a broadly similar pattern to the previous four seasons. The two most recent were very similar whereas, in the two earlier seasons, immigration to the west Shetlands (west of 1°W) appeared to occur before January instead of during the month; distributions at the end of that month, however, were similar. Prior to these four seasons the progression of the fishery south occurred earlier.

The estimated migration speeds may be compared with swimming speeds calculated from tank experiments (He and Wardle, 1988) and tagging experiments (Rankine and Walsh, 1982). The maximum value

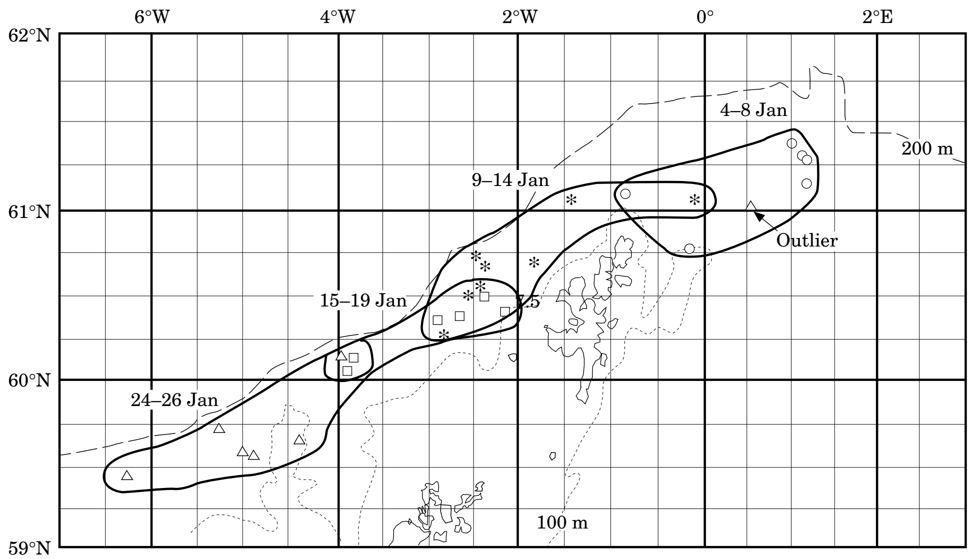

Figure 12. Mackerel fishing fleet distribution in four time periods in January 1994. Boundaries for fishing activity in each period are subjective. ○ = 4–8 January; * = 9–14, survey 1; □ = 15–19, survey 2; △ = 24–29, survey 3.

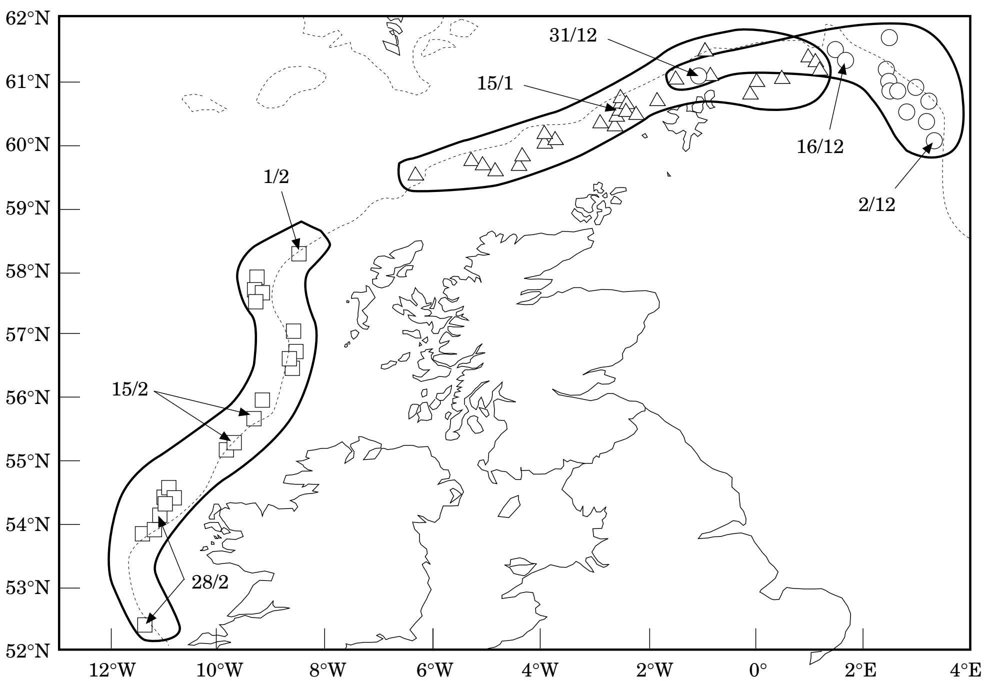

Figure 13. Mackerel fishing fleet distribution between December 1993 and February 1994. Symbols represent positions of catches by individual vessels and vessels observed fishing during the survey. Boundaries for fishing activity in each month are subjective. ○ = December; △ = January; □ = February.

estimated from the catch data (27.5 cm s^{-1}) falls just below the range of preferred swimming speeds from tank experiments (32.4–45.3 cm s^{-1} for a 35 cm fish) and well below the maximum sustainable swimming speed of 122.6 cm s^{-1} for the same size of fish measured over 200 min. It also falls well below the maximum values attained from tagging experiments (51.5–111.2 cm s^{-1} for a 35 cm fish) but well above the average speed of

Table 2. Estimated (minimum) mackerel migration rates based on commercial catch data, during (a) the survey period 7–25 January 1994 and (b) from December 1993–Februrary 1994.

(a) Survey period[1]

Start–end dates	Days	Distance (n.mi)	Distance/Day (n.mi)	Speed (cm s^{-1})
7–14 January	7	69	9.9	21.2
14–19 January	5	45	9.0	19.3
19–25 January	6	77	12.8	27.5
Total	18	191	10.6	22.7

(b) Dec 93–Feb 94[2]

Start–end dates	Days	Distance (n.mi)	Distance/Day (n.mi)	Speed (cm s^{-1})
2–16 December	14	93	6·6	14·2
16–31 December	15	84	5·6	12·0
31 December–15 January	15	60	4·0	8·6
15 January–1 February	17	206	12·1	26·0
1–15 February	14	176	12·6	27·0
15–28 February	13	150	11·5	24·7
Total	88	769	8·7	18·7

[1]Estimates based on straight line distance between most southerly positions of commercial catch during four consecutive time periods.
[2]Estimates based on straight line distance between locations of commercial catches taken on nearest dates to beginning, middle, and end of month.

fish of the same stock tagged in the Minch in 1979 and recovered further south during the same season (10.8 cm s^{-1} for a 35 cm fish). During the latter experiments, a major component of the western stock migrated south earlier in the season and through inshore waters.

The vertical distributions and structure of the mackerel schools agree with previous findings (Walsh and Armstrong, 1985) in the same area. The latter authors also found that schools were denser and lower in the water column during daylight, had greater vertical spread, and showed no evidence of spreading horizontally at night. In the unstratified water conditions observed during the acoustic survey the vertical distribution of schools was predominantly midwater (see above). The schools generally had a wide vertical spread (see Table 1) and the tops of some were close to the surface (Fig. 4a) while the bottoms of others were close to the sea bed (Fig. 4c). Particularly at night, and over most of the water depth range, mackerel occupied a relatively predictable position in the water column, at around one third of the total available depth. At other times of year, for example during the spawning season (Coombes *et al.*, 1979), vertical distribution is known to be affected by stratification of the water column (e.g. egg production above the thermocline). Castonguay *et al.* (1992) also found mackerel associated with the thermocline during the summer feeding period in the Gulf of St Lawrence. At other times of year, notably in March west of the shelf edge, anecdotal accounts suggest schools are found close to the sea bed.

An important element of this study was to be able to place the fish in their hydrographic preferenda. The mackerel were found in water at 7.75–9.00°C and mainly in 35.25–35.40 ppt salinity. Previous unpublished observations (M. Heath, pers. comm.) made during an acoustic survey in November 1983 in the Hebrides region indicated a similar distribution in relation to salinity. The area surveyed covered a salinity range of 34.10–35.40 ppt while identified mackerel schools were only found in higher salinity waters (range 34.8–35.4 ppt), with eight out of nine schools in >35.00 ppt water. Taken in the context of the wider geographical area, it would appear that the mackerel are largely restricted to an intrusion of warmer, more saline water from the south. Given that these values represent the favoured, or at least minimum, values for these fish, it seems likely that migration may be initiated either by a change in the rate of water cooling or by its falling below a preferred salinity threshold.

In relation to temperature threshold, Castonguay *et al.* (1992) found, in the summer, mackerel in the Gulf of St Lawrence in much colder waters than those from which the western stock appear to withdraw in the North and Norwegian Seas in winter. In their investigations, mackerel were most abundant in 4°C water and were even found in temperatures as low at 0°C. These observations do not necessarily invalidate the hypothesis of temperature-initiated emigration but they indicate considerable plasticity of behaviour in different environmental conditions and at different times of year. Although Castonguay *et al.* observed mackerel in greatest abundance in cold water, shoreward feeding migrations of mackerel are positively correlated with the advection of warm (>7°C) surface water. The latter temperature is close to the minimum at which schools were observed during our survey. Their observations, which were all made during daylight, indicated that mackerel were most abundant in cold bottom water overlain by warm surface water. They suggest that thermal preferences may be overidden at certain times of year by physiological needs e.g. during feeding and spawning. During their surveys Castonguay *et al.* suggest the possibility that fish may prefer warm water above the thermocline at night and migrate vertically downward to feed during the day. In our survey, data on stomach contents indicated little or no feeding which appears to be typical at this time of year (Walsh and Rankine, 1979).

The distribution of echotraces and commercial catches described in the present study indicate a southerly migration route along the outer fringes of the continental shelf in water depths of 100–200 m close to the influence of the SEC but inshore of its pathway and in the opposite direction to its flow. The range of estimated minimum migration speeds derived from the catch data (8.6–27.5 cm s^{-1}) may be compared with mean and maximum residual current speed of 17.1 and 40 cm s^{-1}, respectively, measured at the mooring position. The speed of the current is similar to the speed of migration and indicates the likely energetic cost of schools attempting to migrate against its flow and the possibility that it may act as a physical boundary to their distribution as they move south.

Further work is required to study in detail the movement of a single mackerel patch with repeated acoustic coverage. This should be combined with hydrographic and commercial fishing data, to set the survey in a wider temporal and geographical context. A survey of this type is planned for January 1995.

Acknowledgements

This work was carried out as part of the SEFOS project supported by the European Union under the AIR programme and by S.O.A.F.D. The authors would like to thank the following for their assistance: P. J. Copland, G. Slesser, I. M. Gibb, R. D. Adams, M. J. Burns, and E. J. Simmonds of the Marine Laboratory, Aberdeen, and M. Warmerdam of RIVO, IJmuiden, Netherlands. The authors would also like to thank the editor and two anonymous referees for their constructive comments.

References

Anon. 1981. Report of the Mackerel Working Group. ICES CM 1981/H:7.

Anon. 1986. Report of the Mackerel Working Group. ICES CM 1986/Assess 12.

Anon. 1988a. Report of the Norwegian–EEC joint scientific group on migration and area distribution of mackerel (western stock), Bergen, 11–13 November 1987. ICES CM 1988/H:17.

Anon. 1988b. Report on the Mackerel Working Group. ICES CM 1988/Assess: 12.

Anon. 1990. Second report of the EEC–Norwegian joint scientific group on migration and area distribution of mackerel (western stock). Brussels, 12–13 December 1989. ICES CM 1990/H:5.

Anon. 1994. Report of the planning group for herring surveys. ICES CM 1994/H:3.

Castonguay, M., Rose, G. A., and Leggett, W. C. 1992. Onshore movements of Atlantic mackerel (*Scomber scombrus*) in the northern Gulf of St Lawrence: associations with wind-forced advections of warmed surface waters. Canadian Journal of Fisheries and Aquatic Sciences, 49: 2232–2241,

Coombes, S. H., Pipe, R. K., and Mitchell, C. E. 1979. The vertical distribution of fish eggs and larvae in the Eastern North Atlantic and North Sea. ICES/ELM Symp/DA 3, 24 pp.

Edwards, J. I., Armstrong, F., Magurran, A. E., and Pitcher, T. J. 1984. Herring, mackerel and sprat target strength experiments with behavioural observations. ICES CM 1984/B:34 (mimeo).

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Cooperative Research Report, 144.

Hansen, B., and Jakupsstovu S. H. 1991. Availability of blue whiting (*Micromesistius poutassou*) in Faroese waters in relation to the hydrography. ICES 1991/Variability Symp. No. 28/session 3.

He, P., and Wardle, C. S. 1988. Endurance at intermediate swimming speeds of Atlantic mackerel, *Scomber scombrus* L., herring *Clupea harengus* L., and saithe *Pollachius virens* L. Journal of Fish Biology, 33: 255–266.

MacLennan, D. N., and Simmonds, E. J. 1991. Fisheries Acoustics. Chapman and Hall, London and New York. 325 pp.

Rankine, P., and Walsh, M. 1982. Tracing the migrations of Minch mackerel. Scottish Fisheries Bulletin, 47: 8–13.

Reid, D. G., and Simmonds, E. J. 1993. Image analysis techniques for the study of fish school structure from acoustic survey data. Canadian Journal of Fisheries and Aquatic Sciences, 50: 886–893.

Rose, G. A. 1993. Cod spawning on a migration highway in the north-west Atlantic. Nature, 366: 458–461.

Rose G. A., and Leggett, W. C. 1988. Atmosphere–Ocean coupling and Atlantic cod migrations: effects of wind-forced variations in sea temperatures and currents on near-shore distributions and catch rates of *Gadus morhua*. Canadian Journal of Fisheries and Aquatic Sciences, 45: 1234–1243.

Simmonds, E. J., Williamson, N. J., Gerlotto, F., and Aglen, A. 1992. Acoustic survey design and analysis procedure: a comprehensive review of current practice. ICES Cooperative Research Report, 187.

Walsh M., and Armstrong, F. 1986. Investigations of mackerel schools and echotrace characteristics north-west of Scotland in October 1984. ICES CM 1985/H:62 (mimeo).

Walsh M., and Martin, J. H. A. 1986. Recent changes in the distribution and migrations of the western mackerel stock in relation to hydrographic changes. ICES CM 1986/H:17 pp 1–7, 2 tables, 9 figures (mimeo).

Walsh M., and Rankine P. 1979. Observations on the diet of mackerel in the North Sea and to the west of Britain. ICES CM 1979/H:45 (mimeo).