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ACOUSTIC METHODS IN STUDIES OF FISH ECOLOGY

by

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Abstract

Systematic use of echo sounder in fisheries and marine science commenced in the 1930's and developed rapidly after World War II. During the 1950's and 1960's large scale echo surveys were carried out in many regions as a service to fishing fleets and resulting in a substantial increase in knowledge of distribution and migration for many species and stocks. Already in 1958-1968 Russian scientists provided estimates of abundance of Norwegian spring spawning herring based on acoustic surveying and underwater photography.

Acoustic instruments in use in fisheries and plankton research span a frequency range from about 1 kilohertz (kHz) to several megahertz (MHz). At 1 kHz typical ranges and sampling volumes are tens of kilometers and thousands of cubic meters while the corresponding figures at some MHz are ranges of a few meters and sampling volumes of less than a cubic centimeter. The echo ability of fish and plankton varies considerably between species and/or groups of species as well as between acoustic frequencies depending on the material properties and shape and size of targets and particularly on whether or not the organisms contain gas (swim bladders). Integration of echo energy is the most widely used acoustic method for estimating densities and abundance of fish. The basis for the method is the linearity principle, i.e. that the accumulated echo energy per unit volume or area from an aggregation is proportional to actual fish density; the factor of proportionality being the average echo ability (scattering cross section) of the individual fishes. Echo integration was introduced in the early 1960's, and the linearity principle was verified by measurements of live fish in the early 1980's.

Studies of fish behaviour using acoustic instruments have increased in recent years both because of the need to evaluate the reliability in acoustic and swept area estimates of abundance as well as to validate behaviour theory and to increase the knowledge on fish behaviour in general.

Introduction

The use of underwater sound for the purpose of catching marine mammals and fish is probably almost as old as man. People experienced early that noise could herd animals and fish into natural or man made traps. An important part of the fishing operation when using land seines was to herd the schools into bays with inlets narrow enough for the seine to be used. Herding included the use of both visual and sound stimuli; throwing stones into the water and knocking the rail of the small wooden boats. In fact one of the biggest catches of herring ever taken (5300 tonnes) was made 26 December 1932 at my home place, because my relatives and their neighbours succeeded, by splashing and knocking, to herd a large school into a suitable bay.

Leonardo da Vinci (the painter of Mona Lisa) is credited in the scientific literature for the discovery of the existence of sound in the sea. Using a tube with one end in the water and the other in his ear "you will hear ships at great distance" he noted. Remember, it was sailing and/or rowing vessels Leonardo heard. Although the speed of sound in water was measured in the 1820's the practical application of this knowledge had to await the development of electrical transducers and receivers almost a hundred years later. Echo sounders (and sonars) for the detection of sea bottom came into use as a result of research motivated by the First World War. Two decades later Sverdrup Johnson and Fleming (1942) summarized the benefits of this new and efficient tool as follows: "This new method has in a few years completely altered our concept of the topography of the ocean bottom" ... and further ..."The increased knowledge of the character of the bottom topography has greatly facilitated the understanding of the flow of the bottom water, and has helped towards explaining observed differences in hydrographic conditions in neighbouring areas".

During the 1920's captains and scientists applying echo sounders for bottom detection frequently noticed that the instrument also recorded echoes from targets off the bottom. They assumed these targets were from dense schools of fish, and the development and use of echo sounders as fish finders commenced. The first successive trial we know about was made by Ronald Balls who, stimulated by scientists at the Fisheries Laboratory in Lowestoft, installed a so-called echo-meter onboard his herring drifter "Violet and Rose" in 1933 (Balls, 1948). Unfortunately, Balls had no paper recorder on his echo-meter, but in Fig. 1 I have indicated what he read (A) from his observations (B) one evening in August 1933; observations that made a big catch possible for "Violet and Rose". Apart from concluding that the acoustic method would become of great importance for fishermen, Ball's report also included interesting views on herring behaviour; views which were contradicting those held by established marine scientists.

In 1934 two British made echo sounders with paper recorders came into use in Norway; one in the herring and sprat fisheries, the other onboard the research vessel "Johan Hjort". Both instruments proved successfully in use (Sund 1935) and stimulated by the success, scientists started to use the echo sounder systematically in cod and herring investigations. Runnstrøm (1941) included studies of diel behaviour, abundance and distribution in relation to hydrographic conditions in his investigations (Fig. 2).He explained how and why the availability of herring to the fisheries varied from year to year independent of the relative strength of the herring stock. He also suggested that echo surveys of herring with the aim of informing the fishermen would become of great practical importance.

By the outbreak of the Second World War in 1940 only some of the bigger fishing vessels were equipped with acoustic instruments. Extensive research in submarine warfare prior to and during the war brought both theory and technology in underwater acoustics a great step forward, and during the two first decades after the war, 1945-1965, echo-sounders and later sonars came into common use in fisheries and fisheries science.

The main aim of most work carried out in fisheries acoustics in the 1950's and 1960's both regarding the development of instruments and their applications was to achieve an immediate increase in catch per unit of effort in the fisheries. By the end of the 1960's many fishing skippers had available two or more acoustic frequencies in their wheelhouse; a low frequency system (10-50 kHz) for the location of scattering layers and schools at long range and a high frequency system (100-200 kHz) that was used for classification in long line and trawl fisheries as well as behaviour monitoring during the catching process in purse seine fisheries. Already in the 1960's it was well established knowledge among Japanese fishermen and scientists that the echoes from shrimps and certain plankton groups differed very much between low and higher frequencies, (50 and 200 kHz, Shibata 1971).

The amount of information gathered on fish and plankton distribution, fish migration and behaviour due to the use of acoustics during the two-three first decades after the war was enormous. In order to advice the fishing fleets, large scale echo surveys were carried out in many regions with the aim of mapping fish concentrations and studying migrations in relation to environmental factors including prey organisms. Examples of such surveys are The Peruvian Eureka Program (Villanûeva 1971) where up to 21 vessels mapped the geographical distribution of anchoveta in the course of 1 day several times each year, the Icelandic Search and Information Service (Jakobsson 1971), the Japanese service of forecasting fishing conditions in the East China Sea (Ura and Mori 1971) and the Norwegian sonar surveys of herring (Devold 1963). Jakobsson (1971) listed the information that had to be obtained before reliable bulletins could be broadcasted to the fleet:

- the position and extent of herring concentrations
- the average size of the schools
- the stability of the schooling
- the depth and general movement of the schools
- the approximate number of fishable schools
- the state of environmental factors that are likely to influence movements and behaviour of the herring concentrations

Obviously the customers were satisfied with Jakobsson's bulletins because in 1966 the Icelandic fishing industry offered to finance building of a new research vessel for the Institute of Marine Research in Reykjavik.

In the early years quantification of echo density were done according to a system which classified the recordings as they appeared on the paper record into a density scale from 0 to 4 (nothing, very scattered, scattered, dense and very dense (Forbes and Nakken 1972)). Stimulated by Trout et al. (1952) which observed echoes of individual fish, Midttun and Sætersdal (1957) attempted to determine the actual density (numbers per unit volume or area) by counting such traces on the recording paper. One of the earliest series, perhaps the very first acoustic stock estimates reported, are the Russian estimates of spawning stock biomass of Norwegian spring spawning herring (Truskanov and Scherbino 1966). They surveyed the stock in its wintering area southeast of Iceland and estimated the water volumes occupied by herring schools. By multi-plying those volumes with herring densities (numbers per unit volume) obtained from underwater photographs they arrived at figures for spawning stock size. Their results are shown in Table 1 together with the corresponding figures in one of the most recent ICES assessments. The ICES figures are based exclusively on catch at age data so that the two sets are independent. The comparison appear to be quite good in the first part of the series. However, from 1965 to 1968, the period when the stock collapsed, the acoustic estimates were considerably higher than the catch at age based estimates. The reason for the discrepancy is not known, but it is worth noting that estimates of stock size in 1964 and 1965 from tagging experiments are more in line with the Russian figures than with the catch at age based ones.

At present underwater sound is used in marine science for many purposes, such as;

- locating fish and plankton and estimating the size, density and abundance of the animals as well as studying their behaviour and migrations
- monitoring the performance of sampling and fishing gears
- measuring speeds and velocities of vessels, water and particles (fish and plankton) in the water
- bottom mapping
- communicating underwater observations to the sea surface

My presentation will cover the first of these points rather briefly, I am afraid. For those which have particular interest in an overview of the field I recommend a recent comprehensive and well structured review by my colleague Ole Arve Misund with an updated list of relevant literature (Misund 1997). I also strongly recommend MacLennan and Holliday's conclusion of the ICES Symposium on Fisheries and Plankton Acoustics held in Aberdeen a few years ago (MacLennan and Holliday, 1996).

Underwater sound and instruments

Sound is generated by the movement or vibration of an object. For the next 30 minutes my vocal cords will be vibrating - I hope - generating small air pressure disturbances at various frequencies and wave lengths, which when focused by my mouth and amplified through the loudspeakers hopefully should reach your ear drums (Fig. 3). I generate rather low frequency sound, (though not so low as the chairman of the Consultative Committee, Dr. Robin Cooke), while the sopranos operate at considerably higher frequencies. The product of frequency and wavelength is the sound speed, i.e. the movement of the pressure peaks. I can produce a looooong or a short sound pulse by adjusting the time I let my cords vibrate in one transmission. Each pulse contains many waves of various wave length (or frequency) and is hopefully received by you as a word in English.

The vibrating object in underwater acoustics is called the transducer. The words echo sounders and sonars are commonly used for acoustic instruments. Echo sounders have fixed transducers most often pointing vertically (Fig. 1) while sonars have movable transducers so that the sound beam can be pointed in any direction. Electricity is used to set the transducer material into vibrations. Frequency, amplitude, pulse length and beam width are determined by the design of the transducer and by the nature of the electrical signal we feed into it. Any object or target that is "hit" by a sound pulse will reflect some of the energy so that an echo will propagate back towards the transducer. Now the transducer works like our ear converting the reflected pressure disturbance into an electrical signal (Fig. 1B).

The speed of sound in sea water is about 1500 m/sec. It increases with increasing temperature, salinity and depth (pressure). Gradients in temperature and salinity will therefore cause refraction of a sound pulse and thus effect the range at which a given target can be detected, particularly for horizontal ranging sonars.

Fig. 4 displays how range and spatial resolution depend on frequency. High frequencies give good resolution (small sampling volumes) but low range because of the high absorption of energy in the water. At lower frequencies the range is substantially larger, but the spatial resolution is much less because of the larger sampling volume. The choice of operating frequency will always be a choice between resolution and range, and in the figure is indicated the frequency range suitable for observations of schools, individual fish and plankton. It is worth noting that the frequency range in Fig. 4 indicated as the preferred one for studies of individual fish to a large extent coincide with the frequency range the dolphins use.

The echo ability of fish and plankton

It is obvious to all of us that a big target generally will give a stronger echo than a small target of the same shape and material. It is also obvious that the cross sectional area of the target in the sound beam is important. We hear no echo when we shout along a wall that gives a loud echo when we shout directly against it. Hence target size as well as target aspect angle in the sound beam must be of importance. In addition the shape and material properties of the target are factors which affect echo ability. The boundary between water and air is an almost perfect reflector. (If you put your head into the water, you will hear nothing from above the surface!). Fish flesh and bones and other materials having nearly the same density as seawater are poor reflectors. Consequently we would expect

- The echo ability of fish increases with increasing size
- The echo ability depends strongly upon the angle between the target and the incident sound (the tilt angle)
- The echo ability is more dependent upon the size and shape of the swim bladder than on the size and shape of the fish as a whole

Let us look at some measurements:

In fig. 5 and table 2 the echo ability at 38 kHz of three groups of fish is presented as a function of length. The mean curves for gadoids and clupeoids correspond approximately to the established curves for cod and herring. As can be seen there are substantial differences between the three groups. The echo from a cod is more than 2 times that of an equally long herring and 18 times that from a mackerel. These differences are mainly caused by differences in swim bladder size and shape in cod and herring and the absence of swim bladder in mackerel. The last column in table 2 indicate the density of herring and mackerel needed to give an echo equal to that from a density of one cod per unit volume or per unit area. Six mackerels are needed to generate an echo equal to that of one herring; an observation that was made by purse seine skippers using sonar in the North Sea already in the mid 1960's long before any systematic scientific measurements were made. The skippers observed that in order to calibrate their sonars to the catches when changing from herring to mackerel fishing they had to increase the sonar gain by about a factor of 4. In Fig. 6 showing the dorsal aspect reflectivity pattern, i.e. echo ability as a function of tilt angle, the difference between the two gadoid species cod and saithe is substantial, although the two fishes are of equal length. Both fishes have their maximum echo level when tilted head down a few degrees. That is when the long axis of their swim bladder is horizontal. The echo from saithe decreases more rapidly with tilt angle than that from cod. Midttun and Hoff (1962) ascribed this difference to the different shape of the swim bladder in the two species; the cod swim bladder being more ellipsoid or spherical than that of saithe which is cylindrical and more elongated in shape. [Thirty years ago I was convinced that we could use this information to let a computer discriminate between the two species and thus have a real time system for species identification. Seven years and I do not know how much tax payers money thereafter I was convinced that I would not succeed and gave it up].

Scientists and fishermen were early aware that some of the echo recordings obtained were caused by planktonic organisms. During the past two decades regular plankton survey have been carried out (Sameoto 1980) and a considerably amount of knowledge has emerged from systematic and controlled measurements and modelling in plankton acoustics. In table 3 are summarized some results obtained by the group at Woods Hole Oceanographic Institution in USA. Notice the large reduction in density, corresponding to an increase in individual echo ability, between 38 and 120 kHz. Notice also the big difference at higher frequencies between the small sized gastropods and the large salp. At 400 kHz, 6 gastropods will reflect an energy amount equal to that of 300 salps. In terms of echo energy per unit biomass the difference is of course much larger due to the small size of the gastropods. The echo energy from 1 kilo (wet weight) of gastropods is equal to that from 50-100 kilos of siphonophores and shrimps and to that from several tens of tonnes of salps at 200 kHz and higher frequencies.

What are the consequence for survey work?

Clearly, the differences in echo ability between species and/or groups of species both in fish and zooplankton involve that if echo energy measurements at surveys are used to estimate density and abundance then we must know the species- and size composition of the reflecting animals. In some cases this is rather simple as schooling by species and size is a general rule in fish. Stocks of pelagic species like herring, capelin and sardine which often appear in large aggregations within limited areas where the contributions to the echo energy from other fish is insignificant, have been and still are the main targets for acoustic abundance estimation, because it makes the interpretation of echograms easy.

Estimation of density and abundance

Several methods have been introduced for estimating the density in terms of numbers per unit area or per unit volume of the recorded specimens; the most common in use have been echo counting (Craig and Forbes, 1969) and echo integration. When the targets are well separated from neighbours, i.e. only one target in the sample volume, the echoes are counted and the count divided by the area or volume which is being sampled. The technique is useful in the case of which fish is distributed randomly and when the mean density is low. The limiting target density, i.e. the density at which targets appear as individual echoes, increases with decreasing sample volume. Therefore high frequencies permitting small sampling volumes are to be preferred for echo counting. Satisfactory conditions for density and abundance estimation by echo counting are found more often in fresh water than in the sea. The echo counting technique can also be used to measure the echo ability (scattering cross section) of fish and plankton organisms in the wild. Then the measurements are limited to individual fish detected on the edges of dense concentrations. Real time sampling of echo ability of individual targets onboard the survey vessel is an important aid in judging the size of the target and hence in discriminating between layers of plankton and fish as well as between layers of large sized and small sized fish on surveys.

When fish aggregate in schools and layers, the density is usually too high, i.e. several fish per sampling volume, to be estimated by echo counting. The method of echo integration (Dragesund and Olsen 1965) has proved to be more generally applicable as a mean of estimating the density of targets whether or not the received signal contains overlapping echoes. The echo integrator is simply a procedure which accumulates the energy in the received signals. When compensated for range and beam pattern the accumulated echo energy is proportional to the density of targets, the socalled linearity principle. The truth of this principle is not self evident, and for years hot discussions went on also in ICES fora on its validity. In the early 1980's Foote (1983) conducted a definitive test of linearity with live fish (fig. 7). He measured the echo integral from caged free swimming aggegrations of herring and pollock at various frequencies. At the same time he observed the behaviour of the fish by photography so that he was able to correct the echo integral for the actual tilt angle distribution. His estimated and true densities agreed within the bounds of experimental error thus demonstrating that the linearity principle is applicable. The conditions which were tested, cover the range of frequencies, transmitted power levels and fish densities likely to be encountered at sea. At very high densities a shadowing may occur so that accurate density estimation of fish in the lower part of a large dense school is impractible. However, in most surveying work the small equation

$$\text{Integrated echo energy} = \text{Echo ability} \cdot \text{Fish density}$$

or

$$\text{Fish density} = \frac{\text{Integrated echo energy}}{\text{Echo ability}}$$

applies.

However, we learned in the preceding section that different species or groups of fish and animals have quite different echo ability and therefore we have to partition our echo integrals into components associated with particular species or more generally, types of targets. Particular man-machine interface systems are made for this purpose (Knudsen 1990, Foote et al. 1991) which enable the operator to obtain echo energy integrals from any volume (distance and depth) of the sea sampled The system calculates echo energy within any boundaries (distance and depth) selected by the operator and accumulate these values for chosen depth and distance intervals. Species compositions and length distributions from catches as well as measurements of echo ability of individual targets are examined in order to decide to which species or group of species the echo energy from the recorded aggregations should be allocated. It thus appear that a fair amount of subjectivity is involved in the interpretation of the echo recordings and their allocation to species and groups and the question arising is: Can the uncertainty be quantified?

In fig. 9 the mean values of echo energy in four areas are plotted for six species based on the allocations by two teams of observers. The two teams worked independently with exactly the same data sets. Cod was the target species for the survey. Apparently the comparison is reasonably good as can be seen from the scatter of points around the 1/1 line, except for herring in one of the areas.

In the text table below are summarized the errors in acoustic estimates of abundance as indicated by an ICES working group (Simmonds et al. 1992).

	Coefficient of variation (percent)	
	Range	Typical value
Precision	8 - 40	26
Accuracy	13 - 57	35

The estimates are based on an assessment of each individual source of error including instrument calibration, weather and hydrographic conditions, echo ability, species identification, and spatial sampling, and they are an indication of the errors which might occur under typical survey conditions. Some of you may be of the opinion that an accuracy of 35 percent is rather poor. I prefer to think that a precision of 8 percent and an accuracy of 13 percent associated with an estimate of numbers or biomass of fish in the sea is extremely good. Clearly, these small errors are associated with situations where a species for which there is substantial knowledge of echo ability makes up the bulk of the echo recordings and when data is collected under favourable conditions as to weather and the availability of fish.

A comprehensive study of the variances associated with acoustic as well as biological sampling during an acoustic survey was undertaken by Simmonds a few years ago (Simmonds 1995). He explored the effect these variances would have on the overall precision in the estimate of abundance and used North Sea herring as an example. Some of his results are given in Fig. 10. Given the amount of research vessel time available for a herring survey Simmonds question was: In order to maximize the precision how should the available time be divided into time used for acoustic transecting and time used for fishing for identification and biological sampling? The figure illustrates that within a wide range of combinations of sailing time (number of transects) and fishing time (number of trawl stations) the precision was almost constant; the coefficient of variation being about 20 percent. These results are of importance for survey planning and similar analyses ought to be done for other surveys and stocks in order to assure that the allocation of survey effort contribute to optimize the overall precision.

Behaviour and migration

Many studies have been carried out investigating how the fish react to the sounding vessel (Olsen, 1990). Avoidance reactions are described which may effect the reliability of the measured density in different ways; the fish avoid the path of the vessel so that the recorded density is systematically too low, the fish dive when the vessel is passing over it so that its echo ability is less than in the undisturbed situation. Both these types of reactions are typical for near surface layers and schools of many species and ongoing research attempts to quantify the effects on the density esti~~k~~mates. ✓ Sonars are also frequently used to study the behaviour of fish in relation to fishing operations - particularly trawling - in order to determine the sampling efficiency of the gear.

In recent years an increasing amount of information regarding the natural "undisturbed" behaviour of fish has been gained from the use of acoustics (Misund, 1993). Pitcher et al. (1996) studied the behaviour of herring schools in the Norwegian Sea in the feeding season using a high resolution sonar (Fig. 11). They observed that changes in school state occurred surprisingly often, on an average every 5.5 minutes. Reactions which were interpreted as resulting from predator interactions were recorded every 27 minutes, that is between 25 and 30 times per twelve hour daylight. Internal school changes and behavioural interactions between herring schools that encountered one another were also frequent. Such events occurred every 13-14 minutes.

On the basis of their observations the authors suggested that the herrings antipredator behaviour was adjusted to the type of predator attack. Targets identified as individual cod and haddock intimately accompanied the herring schools causing frequent modifications to, but not dispersal of school structure, and most of the herring in the school continued feeding. On the other hand an attacking saithe school impacting at high speed caused the herring school to dive rapidly to 150 m or more, incurring energetic costs for the herring in the form of lost feeding time in addition to depth change costs in diving and surfacing. A rapid approach of the vessel was responded to like the saithe attack. For a rapidly declining herring stock the following question might be asked: Can an increased rate of predator impacts, including fishing operations, disturb herring so often that it effects herring growth negatively?)

Since ancient times the migration of fish has interested humans. People in coastal societies have relied upon the harvesting of fish arriving close to the shore at certain seasons. Unforeseen changes in migration patterns have constituted serious threats to livelihoods. Questions about where and when the fish would arrive have always been posed. The use of acoustic instruments has greatly improved our ability to answer such questions. Fig. 12 shows the migration of cod in eastern Canada as outlined by Rose (1993). In three successive summer seasons 1990, 1991 and 1992 the area was surveyed acoustically indicating what Rose called a "highway" used by the cod concentrations on their way across the Newfoundland shelf. The hatched areas show where fish tagged during the migrations were caught in the fisheries. Cod traversed the outer shelf along the 2°C isotherm until food was encountered. Then migration routes were modified as cod pursued prey. In each year aggregations remained intact until abundant food (capelin and shrimp) was encountered.

This brings us to perhaps the most important fish species in the ecosystems of northern waters, the capelin. It is a small sized plankton feeding pelagic species that utilizes the zooplankton production in the vast areas which become icefree each spring and summer, and it is the main diet of fish, birds and balean whales. For a period of 25-30 years it has been subject to large fisheries, but as our understanding of the role of capelin in the ecosystem has increased a more cautionary approach has been taken in capelin harvesting. The development of the capelin fisheries would not have been possible without sonars and nearly all our quantitative knowledge of seasonal distribution, migrations and fluctuations in abundance are due to information from acoustic surveys. Fig. 13 shows aggregation areas in winter, spawning routes and spawning areas in spring in warm and cold climatic periods in the Barents Sea. Similar east-west shifts between warm and cold periods occur for species which have capelin as their major prey. For hundreds of years people have experienced that the coastal fisheries for cod shifted in a similar way. They also have known that capelin is an important prey item for cod. However, quantification of the cod - capelin interactions has only been possible for about a decade or so. Briefly these interactions are as follows. When capelin is absent or scarce in the ecosystem then the production of cod biomass will suffer in two ways: Cod get lean because of lack of energy rich food and cannibalism in cod increases. Thus there are negative effects both on cod growth and on the recruitment to cod stocks. A main objective for the management of the capelin stock is therefore to reduce the risk of such negative effects on cod production.

An important result in the early days of acoustic surveying was the detailed knowledge obtained on migration routes and - speeds of large concentrations of fish. Numerous examples of spatial displacements and migrations as observed by repeated surveying were reported in the literature in the 1950's and 1960's. Fig. 14 shows the spawning migration of Icelandic capelin. During summer and autumn the fish feed over wide areas in Polar water to the west and north of Iceland. In late autumn early winter the prespawners aggregate north of the country Iceland and start their migration to the spawning fields on the south and southwest coast in the Atlantic waters. The route is much the same each year except for the area in the east where it appears as if the narrow boundary between Atlantic and Polar waters in some years confuses the capelin (Perhaps they want to spawn in Norway?). The speed at which the prespawning capelin migrate varies substantially from one year to another due to reasons "which are far from clear" (Vilhjalmsson 1994).

This presentation has covered only a small fraction of the "space" of acoustic methodology and the results obtained with such methodology. Within a period of a few decades the use of sound has provided information on the spatial distribution and abundance of fish and plankton on large and small scales that could not have been obtained with any other method. Acoustic sensors which actually are underwater ears have become our underwater "eyes", and co-operation within the ICES regime has contributed greatly to this development.

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Table 1.Estimates of spawning stock of Norwegian spring spawning herring (mill. tonnes).

Year	1959	1962	1963	1964	1965	1966	1967	1968
Acoustic surveys (Truskanov and Scherbino, 1966)	6.0	2.5	2.8	3.3	6.8	6.5	4.0	2.0
ICES assessment (ICES, 1996)	6.0	2.8	2.3	2.8	2.9	2.6	1.2	0.2

Table 2. Echo ability of fish at 38 kHz. L is fish length in cm. (Source: MacLennan and Simmonds 1992)

	Target strength dB	Scattering cross section (cm^2)	Relative density
Gadoids	20 logL -67.4	$2.28 \cdot 10^{-2} \cdot L^2$	1
Clupeoids	20 logL -71.9	$0.81 \cdot 10^{-2} \cdot L^2$	3
Mackerel	~20logL -80.0	$0.13 \cdot 10^{-2} \cdot L^2$	18

Table 3. Echo ability of zooplankton. Density (number of animals per cubic meter) required to produce an echo equal to that of ten thousand gastropods at 38 kHz. (Source: Stanton et al 1996)

		Frequency (kHz)			
Animal group	Length (mm	38	120	200	400
Gastropod (elastic-shelled)	1.9	[10000]	133	22	6
Siphonophore (gas inclusion)	37	0.29	0.61	0.94	2.4
Decapod shrimp (fluid like)	16	107	4.6	2.6	4.6
Salp (fluid like)	26	176	368	304	304

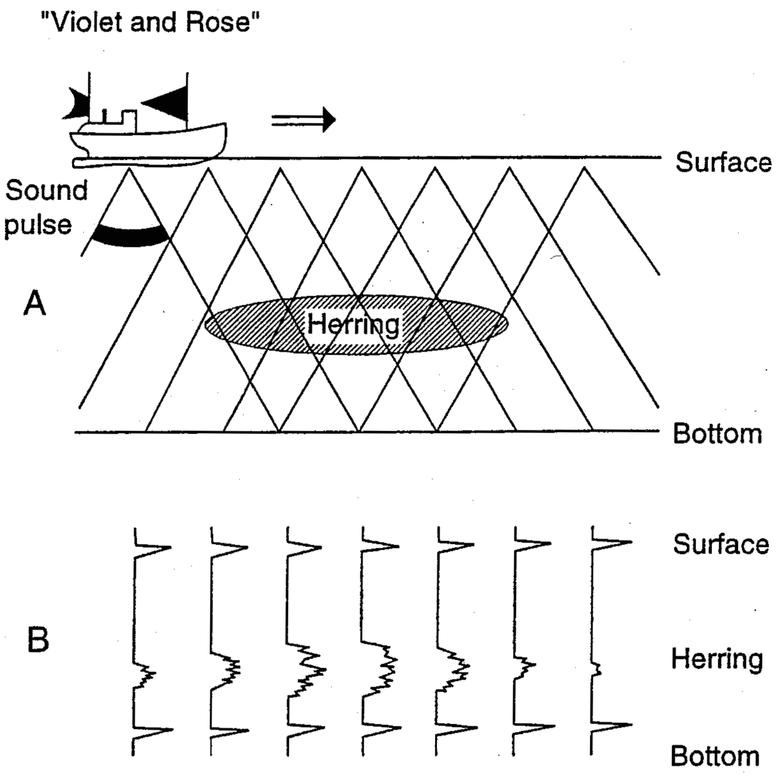

Fig. 1 Seven consecutive soundings while steaming showing echoes from a herring shoal 90 feet in length (Balls, 1948)
A) The actual situation
B) The echometer recordings

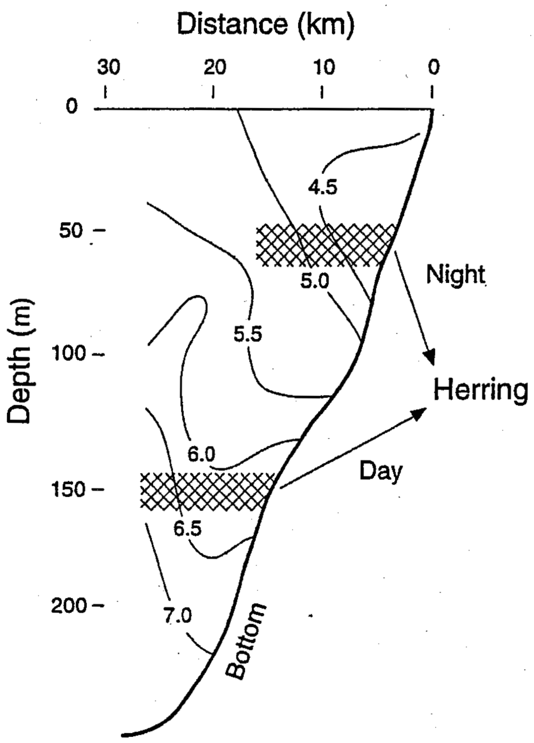

Fig. 2 Distribution of echo recordings of herring and temperature at a spawning ground in Southern Norway in February 1937. (Redrawn from Runnstrøm 1941).

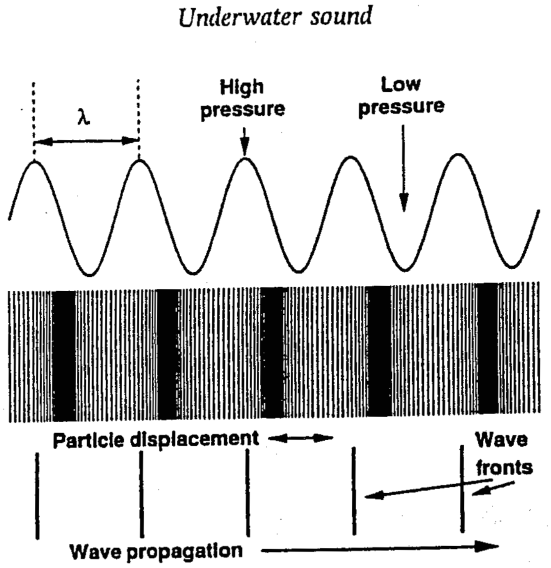

Fig. 3 Sound waves. The pressure (top) varies cyclically as a sine wave; λ is the wavelength. The particle displacement (middle) is out of phase with the pressure. The wave-fronts (lower) are lines which follow the maximum pressure. (From MacLennan and Simmonds 1992).

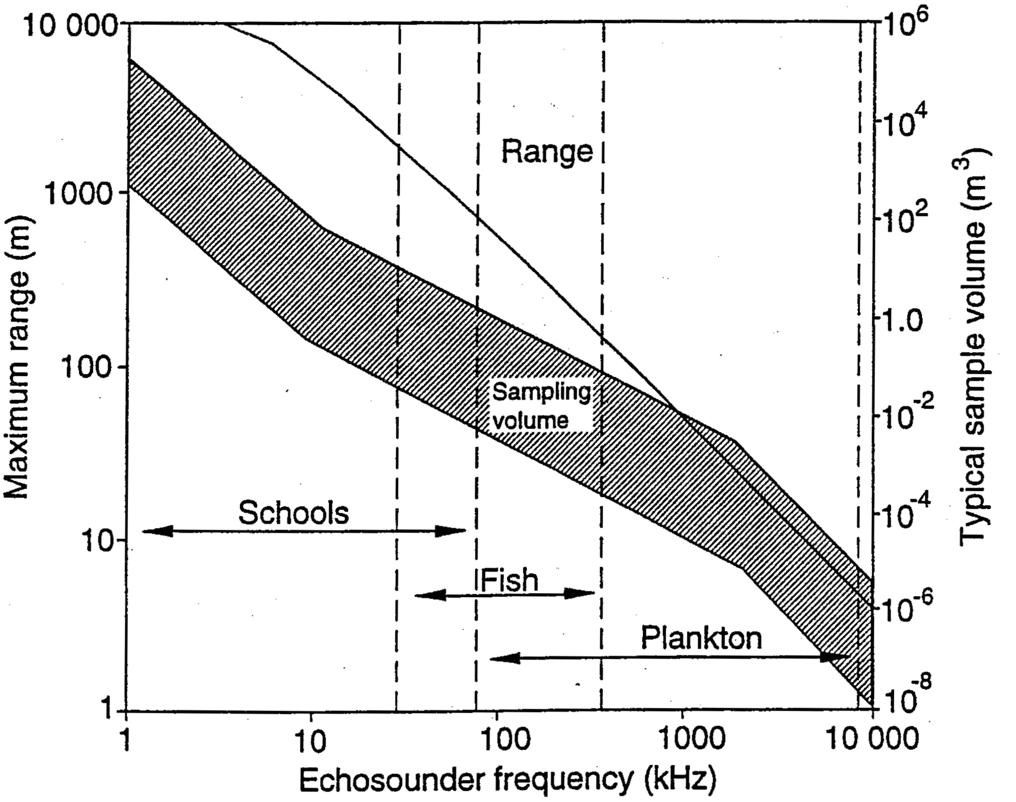

Fig. 4 Range and sampling volume as a function of frequency. Frequency range for various applications are indicated. (From MacLennan and Simmonds 1992).

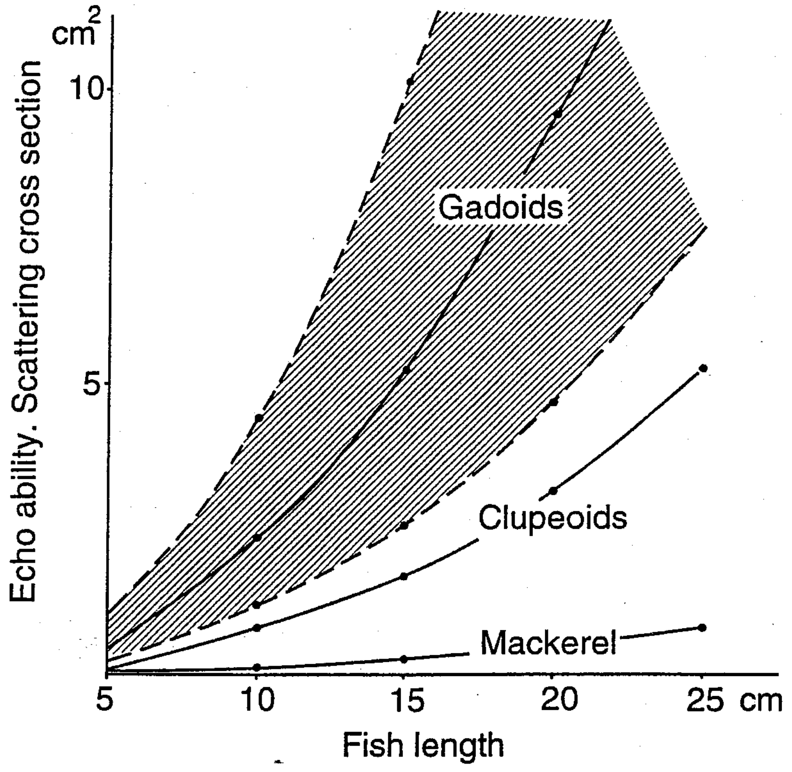

Fig. 5 The relationship between echo ability and length for some fishes. Solid curves: approximate mean value. Hatched area indicate the spread in observations of gadoids. (Source: MacLennan and Simmonds 1992).

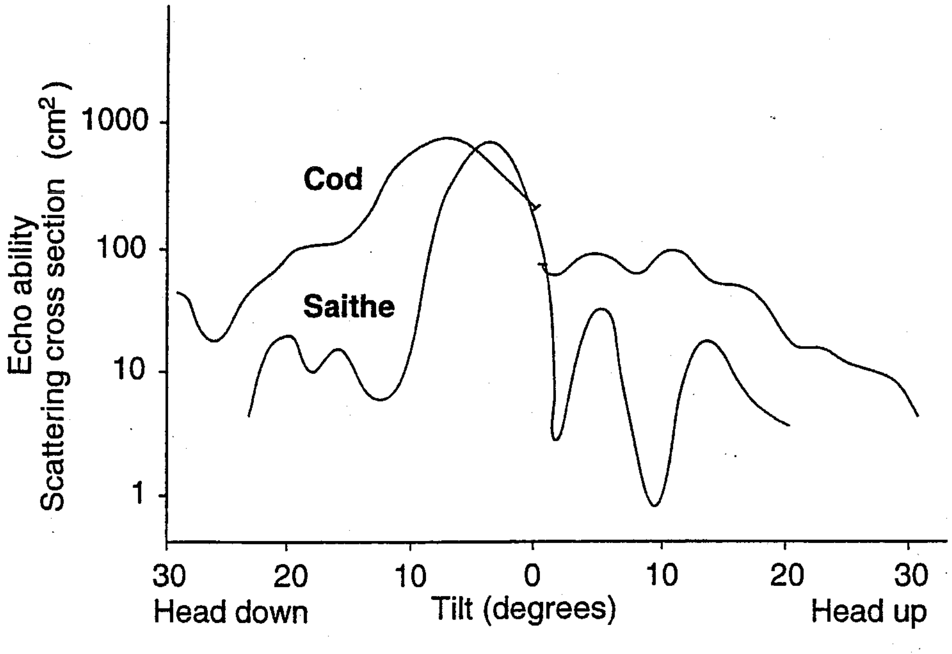

Fig. 6 Dorsal aspect reflectivity pattern of a cod (46 cm) and saithe (46 cm) at 38 kHz. (Redrawn from Midttun and Hoff 1962).

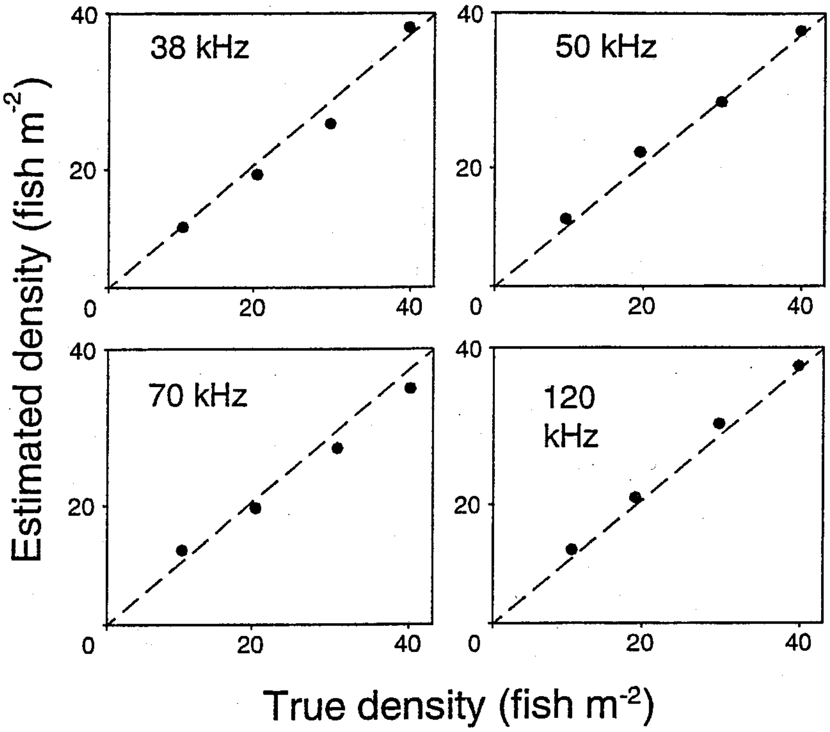

Fig. 7 Comparison of estimated and true densities of caged fish at four frequencies (Source: Foote 1983).

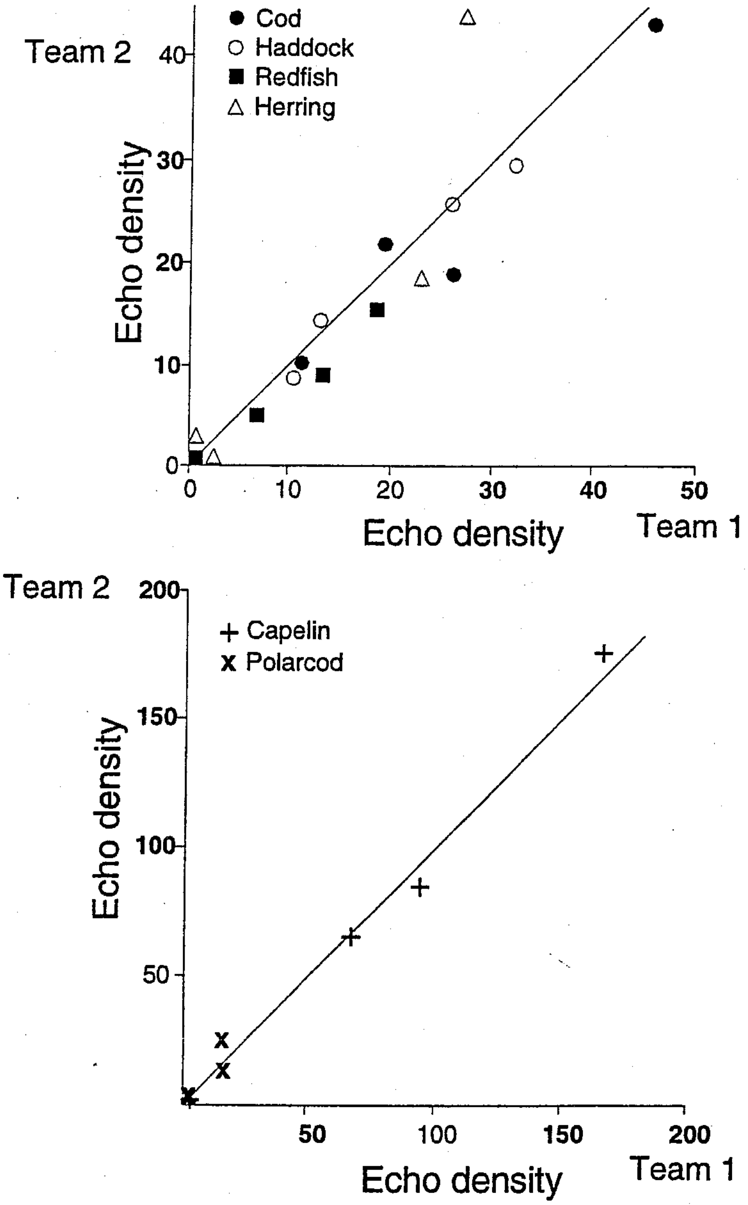

Fig. 9 Mean values of echo density (sa) in four areas as allocated to species by two teams of observers. (Redrawn from Korsbrekke and Misund 1993).

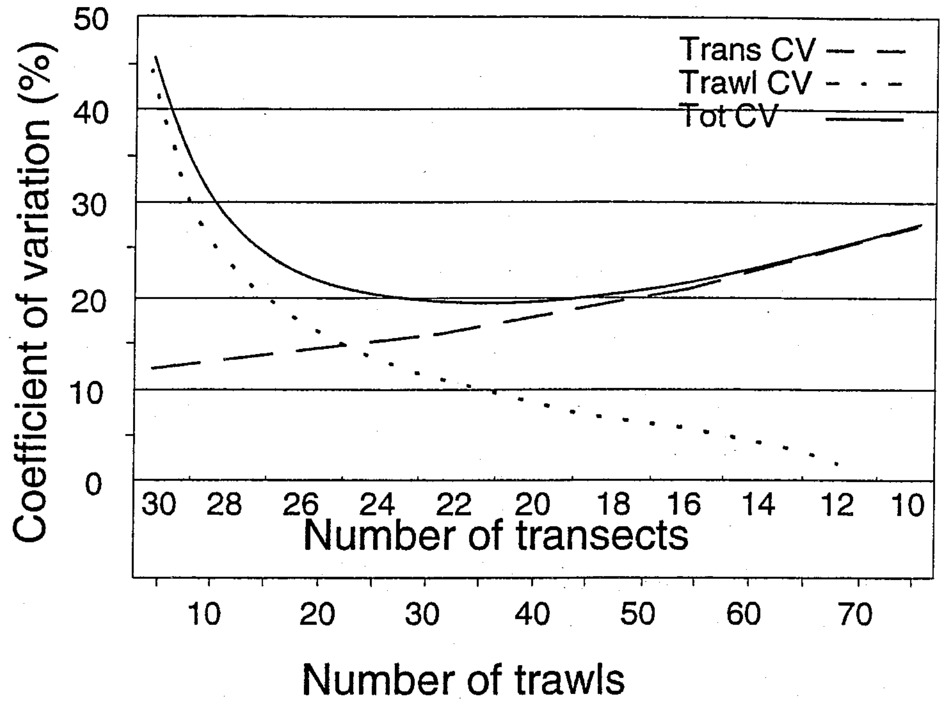

Fig. 10 Coefficient of variation for differing proportions of trawls (dotted) and transects (dashed) and combined (solid) assuming in dependence of identification and age data errors. Arrows mark 1 % change in CV. (From Simmonds 1995).

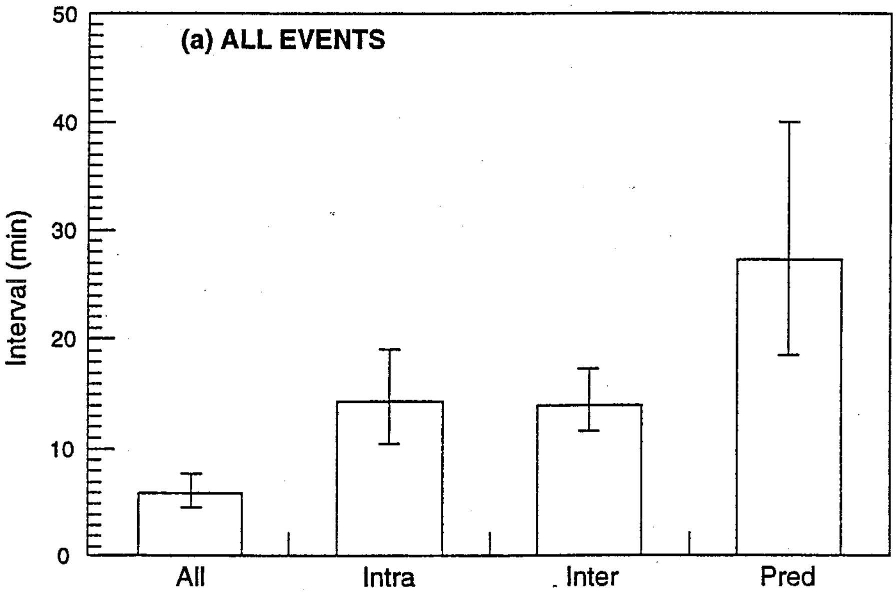

Fig. 11 Mean frequencies intervals (columns) and 95 % confidence limits (bars) for behavioural events scored for 14 tracked herring schools. All) all events, Intra) intra school events, Inter) inter school events, Pred) predator events. (From Pitcher et al. 1996).

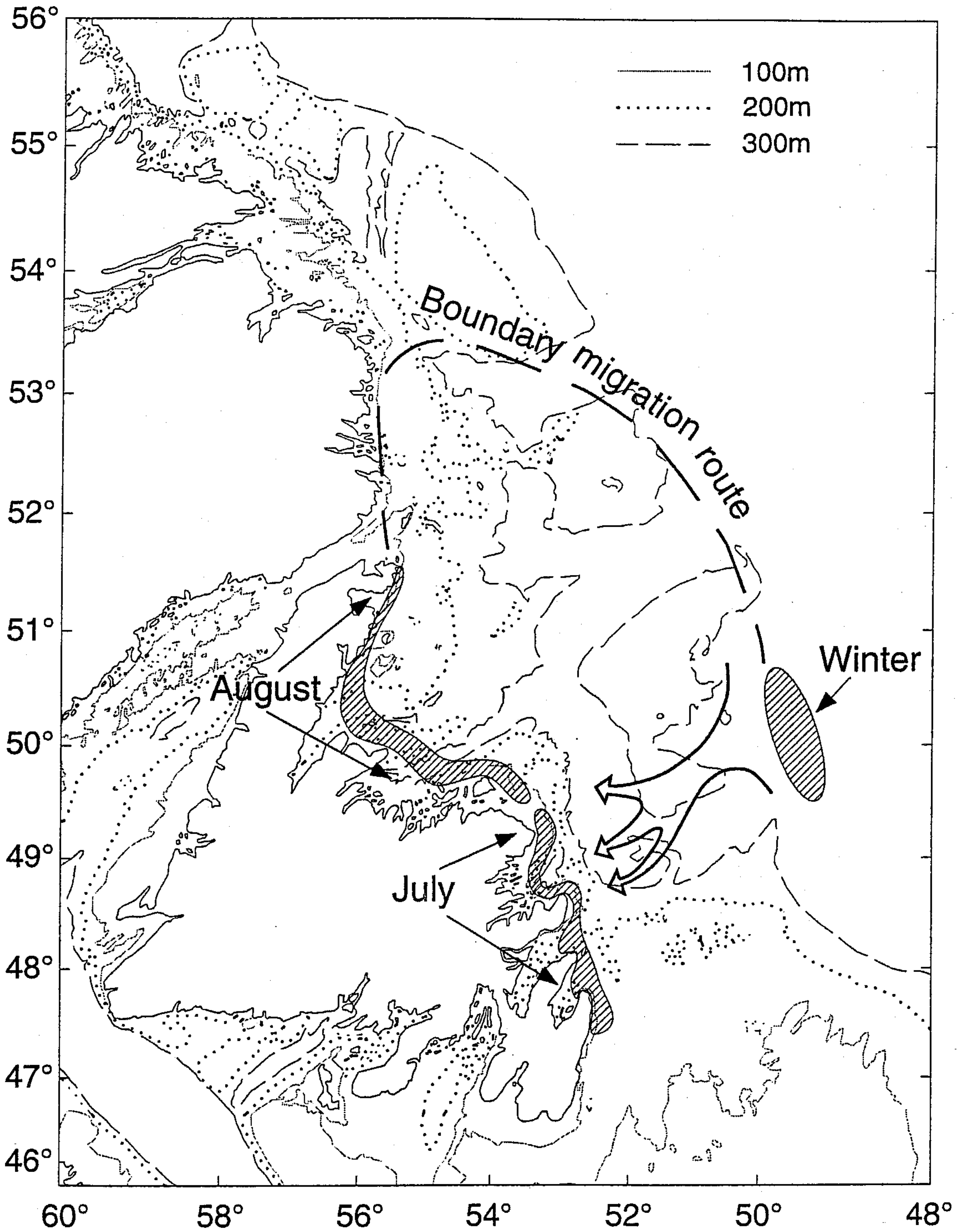

Fig 12 Migration patterns of cod observed with echo sounders in 1990, 1991 and 1992. Hatched areas show tag returns from taggings along the route. (From Rose 1993).

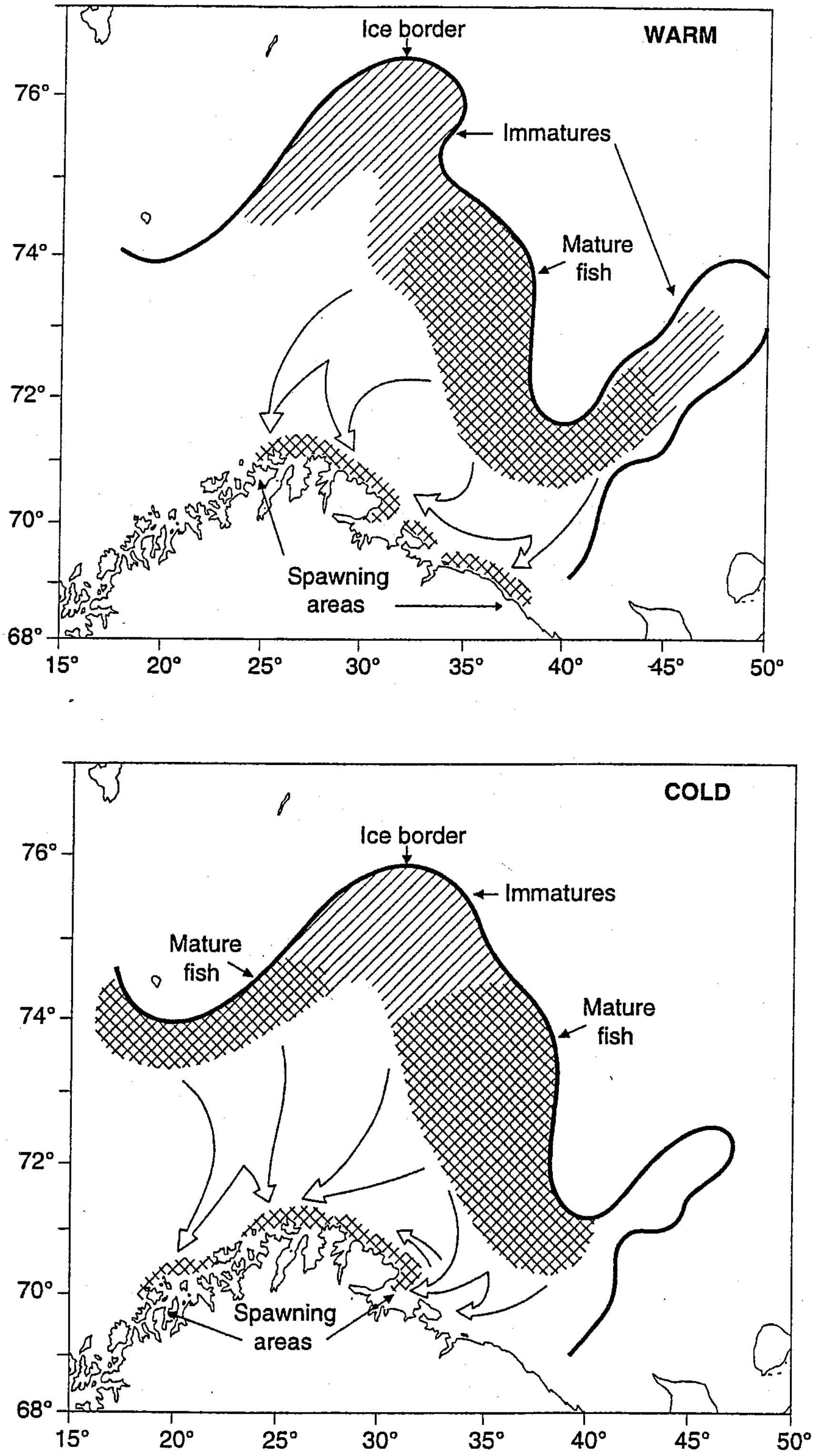

Fig. 13 Barents Sea capelin. Winter concentrations, spawning routes and spawning areas in warm (upper) and cold (lower) years. (From Ozhigin and Luka 1985).

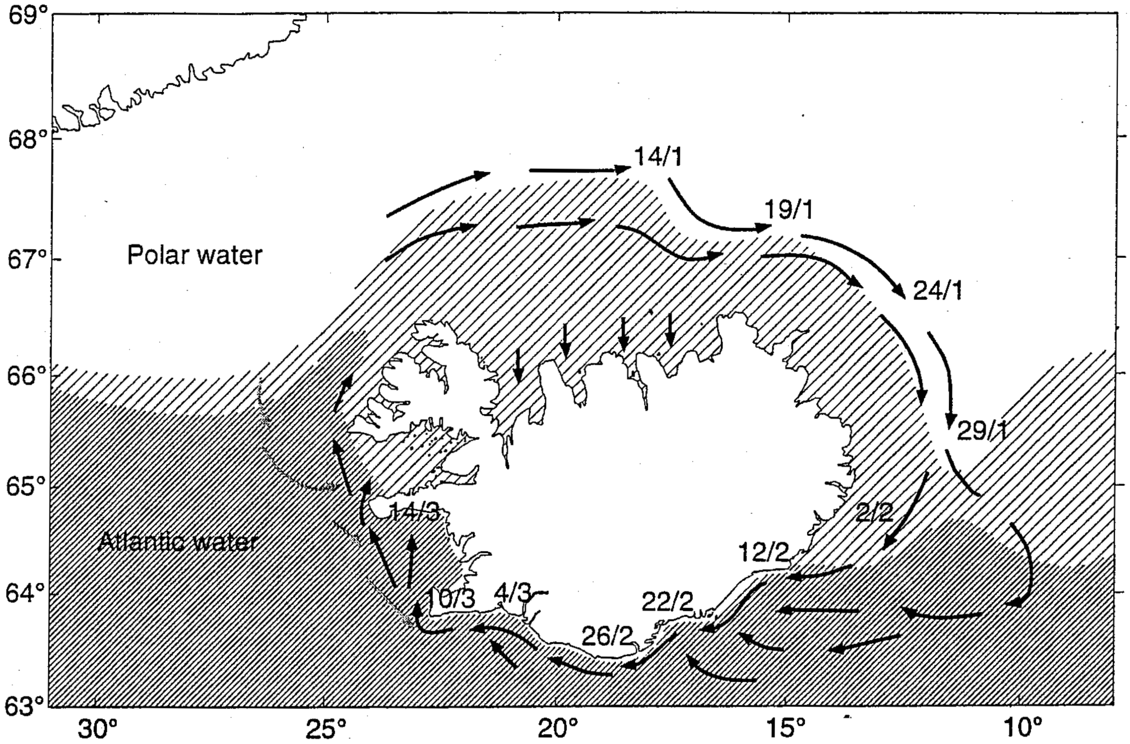

Fig. 14 Spawning routes of Icelandic capelin. Dates indicate the front of the concentrations in 1973. (From Vilhjálmsson 1994).