J. Cons. int. Explor. Mer, 47: 104–111. 1990

Monthly estimates of fish numbers using a long-range sonar

D. E. Weston and H. W. Andrews

Weston, D. E., and Andrews, H. W. 1990. Monthly estimates of fish numbers using a long-range sonar. – J. Cons. int. Explor. Mer, 47: 104–111.

Sonar records are available for the Perranporth area for 1963 to 1968, showing many wriggling tracks due to shoals of fish. The numbers of shoals, assumed to be composed of sardines, have been estimated for a sector between 4 and 37 km from the array. There is a marked seasonal dependence, with the largest numbers usually appearing from May to October. The density of shoals reached in the summer is typically three per km along the sonar beam and also three per km^2, though the lower limit of shoal size is ill defined. This translates with certain assumptions into about 2×10^{-3} sardines per m^3 when dispersed, which compares well with other estimates. The pros and cons of long-range sonar for fish population surveys are contrasted with those of conventional echo-sounding surveys.

D. E. Weston and H. W. Andrews: Admiralty Research Establishment, Portland, Dorset DT5 2JS, England. D. E. Weston, present address: 77 Wyke Road, Weymouth, Dorset DT4 9QN, England. H. W. Andrews, present address: 9 Beechtree Close, Cattistock, Dorset, England.

Introduction

Surveys of fish populations are conventionally carried out by echo-sounding along relatively closely spaced tracks (Foote, 1989), and inevitably this is costly and time-consuming. So an obvious ploy is to consider changing from a short-range high-frequency vertically directed sonar to a long-range low-frequency horizontally directed sonar. The authors know of only two sets of experiments which might qualify in testing this idea.

The first set used the experimental correlation sonar laid on the seabed off Perranporth in southwest England, in the western part of the Bristol Channel, extending towards the Celtic Sea (Fig. 1). Operating frequency was 1 kHz until 1965 and 2 kHz after 1966. Typically, all the scatterers in a fixed narrow beam were displayed out to 40 nm (nautical miles)/74 km, and this provided a remarkable long-term behaviour record for fish such as sardine and sprat (e.g. Weston and Revie, 1971; Revie *et al.*, 1974; Weston, 1988). The second set employed the GLORIA sidescan sonar, towed by RRS "Discovery" and operating at 6.4 kHz. Rusby *et al.* (1973) surveyed the herring fishery in the Sea of the Hebrides with detection ranges up to 15 km.

The purpose here is to take a quantitative look at the first set, concentrating on the returns from the sardine or pilchard (*Sardina pilchardus*) in their daytime shoals. We present monthly data from 1963 to 1968, and in this respect point out that Weston and Andrews (1990) present monthly data on the timing of shoal appearance and disappearance for the same period and using the same records. The pilchard fishery in this neighbourhood is described by Hodgson and Richardson (1949), Bridger (1965), Culley (1971), and Cushing (1973). Our present estimates of pilchard abundance are compared with those from other methods, both quantitatively for the given area and qualitatively as regards methodology.

Of course it is the fish echoes which are of interest to a fisheries scientist, most of the sonar background being just a nuisance. But for other workers in underwater acoustics the situation is the reverse; it is the fish returns which are the nuisance, the echoes from shoals being described as "false targets". Thus this paper contributes both on fisheries and on the incidence of false targets.

The records

The measurement area is shown in Figure 1. The sonar receiving array was 18 m long and laid on the seabed at 50°22′N 05°12′W. Measurements were made in the narrow beam defined by its natural acoustic axis on bearing 348°, as illustrated, though it was possible to steer the beam electronically.

Up to 1965 the precise carrier frequency was 1.01 kHz, with various bottom-mounted projectors giving source levels up to +229 dB re 1μPa at 1 m, and with receiver beamwidth 4°. After 1965 the precise carrier frequency was 1.85 kHz with a new projector of source level +235 dB re 1μPa at 1 m, and receiver

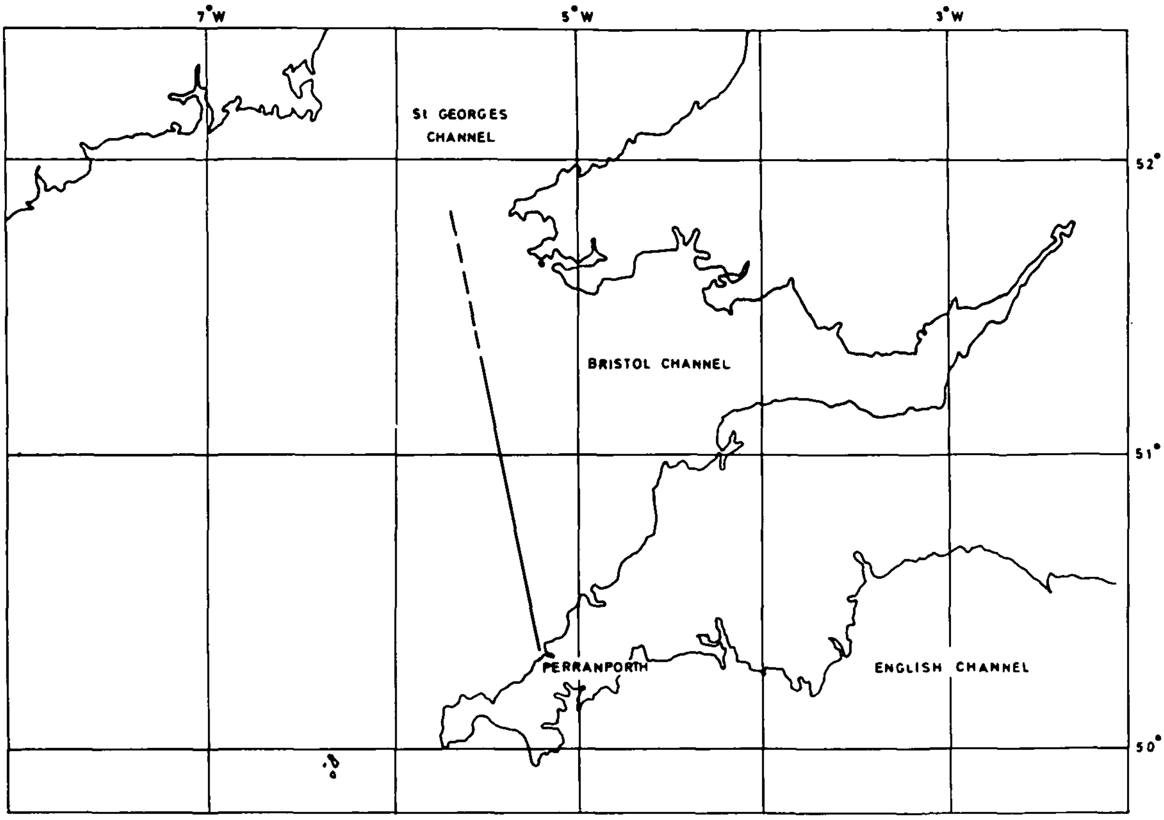

Figure 1. Trials area in the Bristol Channel. The usual sonar beam direction is shown, with width only 4° or 2°, at 1 and 2 kHz respectively.

beamwidth now 2°. Linear FM pulses of duration 4 sec and bandwidth 100 Hz were used for all the work reported here, with typical repetition period 100 sec, allowing for a nominal range of 40 nm or 74 km. The pulses were generated and the returning signals processed by various experimental correlators, originally CORA and later JANICE 2.

The main sonar output was presented as an intensity modulated range–time display on a large drum recorder using teledeltos paper and covering up to 24 h. Typically, 2 or 3 d of recording would be made each month, but our analyses are based on between one and 24 recordings for a given month. The 24 figure pertains to June 1964, as described by Revie *et al.* (1974). Another long period of continuous recording extended from 13 September to 18 October 1968. Most of our records are in the period 1963 to 1968.

These records are our stock-in-trade for the present study, and Figure 2 gives an example emphasizing the complicated and changing structure in the reverberation. In the daytime we see the wriggling tracks as the fish shoals are carried on the tide, and at night (thick line on the time axis) their replacement by the diffuse patterns of the dispersed fish. We can also see the returns at a fixed range due to areas of bottom roughness, and further patterning due to the modal interference which arises from the wave nature of the sound propagation. Figure 3 is on an expanded scale and indicates the nature of the problem of counting the shoals.

Three echo travel-time or range sectors were selected for counting: 5–10 sec (2–4 nm or 3.7–7.4 km), 15–25 sec (6–10 nm or 11.1–18.6 km) and 40–50 sec (16–20 nm or 29.7–37.1 km). These choices were intended to minimize masking by bottom roughness returns, and also minimize cases of inadequacy of signal-to-noise ratio in poor conditions. For example, the transmission loss to the longer ranges may be unacceptable due to high winds. Unfortunately it can then be very difficult, especially at 1 kHz, to know whether a blank record is due to lack of fish (enter reading zero) or to poor propagation (reject that record). A further complication is that shoals may break up in stormy conditions. All readings were taken at mid-day.

The counts were reduced to 2.5 sec travel time or 1 linear mile (1.853 km), averaged within each month, and plotted to form the top three sections of Figure 4. The 1967/1968 results for the sector centred on 8 nm/15 km have been averaged month-by-month and replotted, with a multiplier, in Figure 5. The other parts of

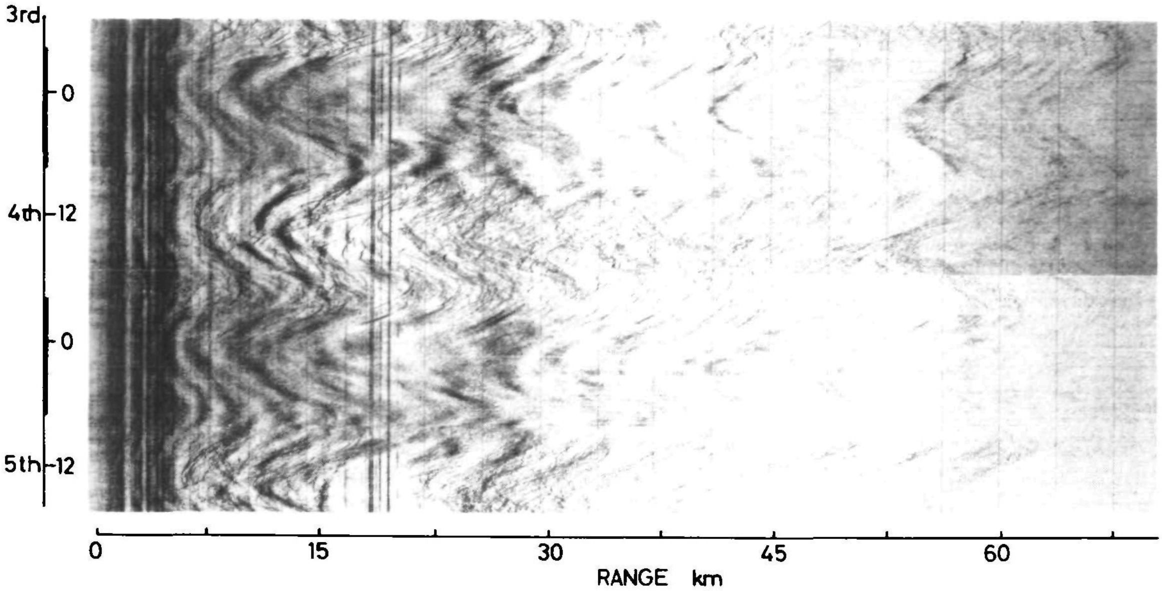

Figure 2. Example of echo-ranging display of 2 kHz reverberation, 3–5 September 1968.

Figures 4 and 5, with more information generally, are introduced later.

Discussion

(a) Shoal size distribution

The essentially arbitrary nature of the assigned shoal count number is stressed. Sometimes the display is clear, counting is easy and different observers will agree. For instance the Figure 2 sector round 18 nm/33 km (of course only for daylight hours) is moderate to good, as is the whole of Figure 3. But sometimes the display is confused, counting is difficult and our observers may differ by 10% or more, as in the Figure 2 sectors round 3 nm/6 km and 8 nm/15 km. And quite apart from observers the answer depends on all the details of the sonar, the display, the environment, the shoal size distributions, etc. These points are underlined in the two examples following.

We start the first example by describing the position as regards resolution in time or range. The 100-Hz bandwidth implies a resolution of 10 msec, but the correlator design for our 1-kHz carrier frequency degraded this to 20 msec. In our common 10-sec echo travel time sector there are therefore 500 resolution cells at 1 kHz. In comparison, the largest number of shoals (of sardines) counted is 48, seen on single days in both July and October 1963. The ratio of about 10 is reasonable, even though the larger shoals may spread through several cells. Suppose now that our shoals are uniform in size and that they increase in numbers, significantly beyond 48. Eventually it will not be possible to resolve them and the count will decrease rather than increase. In our experiences this effect is not serious for sardines; but it certainly can be for sprats – fortunately not the main subject of this paper. There is of course an analogy with saturation effects in other fish counting schemes.

In the second example we suppose that the background for detection of the larger shoals is set, not by noise, but by the scattering from smaller unresolved shoals. Under these conditions we cannot, using a sonar with automatic gain control, learn anything about the absolute magnitude of the returns. The appearance will depend only on the shape of the distribution of the shoal sizes, and not on the average shoal size.

These related examples show that the simple count is not only arbitrary but can be inadequate without some knowledge of sizes.

(b) Identification

The shoals of fish causing our main tracks have been identified as sardines in many experiments, by courtesy of our collaborators from the Fisheries Laboratory, Lowestoft, particularly in a major trial in June 1964 (Revie *et al.*, 1974). But occasional tracks due to other fish are liable to be mixed in, and in particular there are sometimes large numbers of sprats – although these tend to come in different parts of the area and have a different sonar appearance with many very close shoals. It is obviously impractical to check each shoal or even a selection of shoals every time the sonar is switched on. In general, identification must be lumped with sizing as one of the basic problems of any long-range sonar survey.

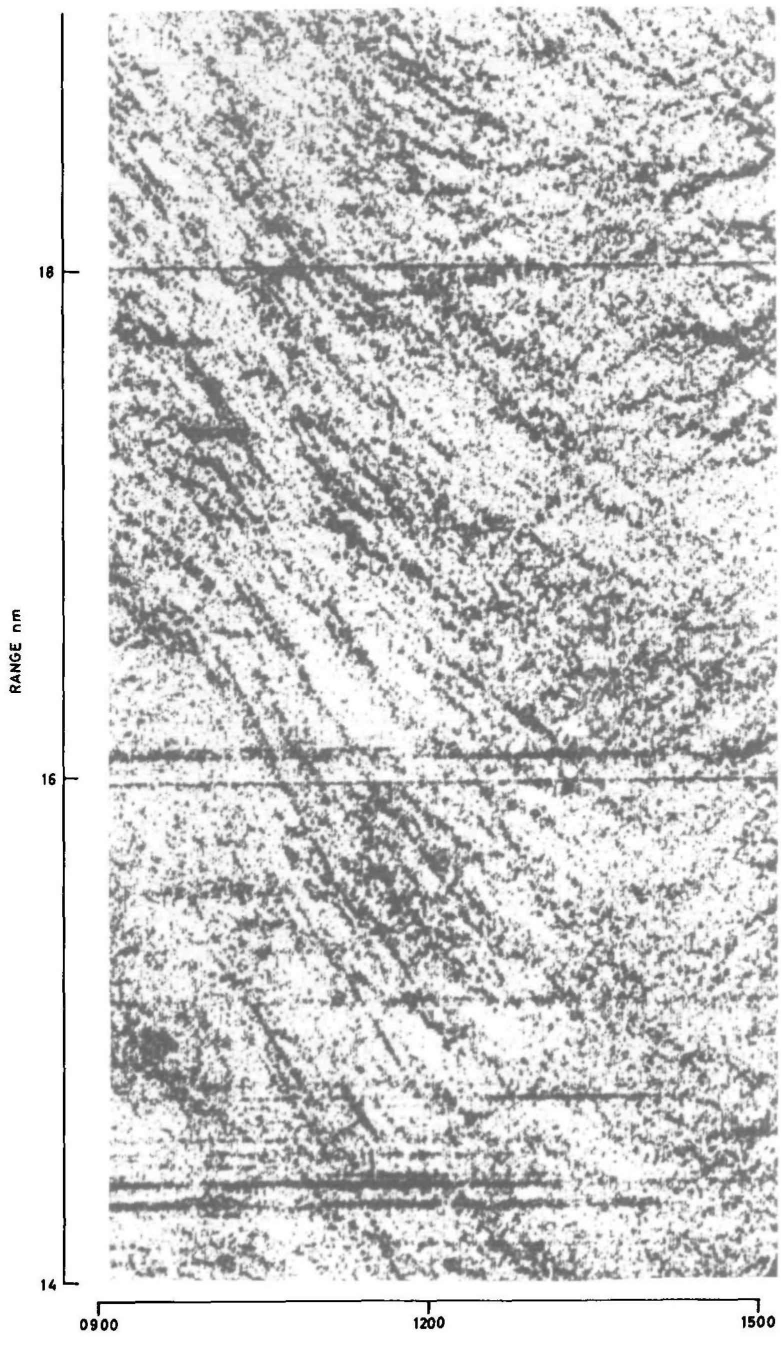

Figure 3. Enlarged scale for part of echo-ranging display, 10 May 1967 (1 nm = 1.853 km).

(c) Sonar frequency

It is difficult to distinguish real effects from apparent effects due to changes in the sonar operation, particularly the frequency change at the end of 1965. Occasional comparisons of interleaved 1 and 2 kHz transmissions were insufficient to resolve this. From Figure 4 we tentatively conclude that there is no great effect on numbers for the 8 nm sector, as discussed quantitatively in our later section on abundance. At 18 nm the 2-kHz numbers appear to be artificially higher because of the increased power and long-range performance of the 2-kHz system. At 3 nm the 2-kHz numbers seem to be the lower, but this is thought to be at least in part a real effect.

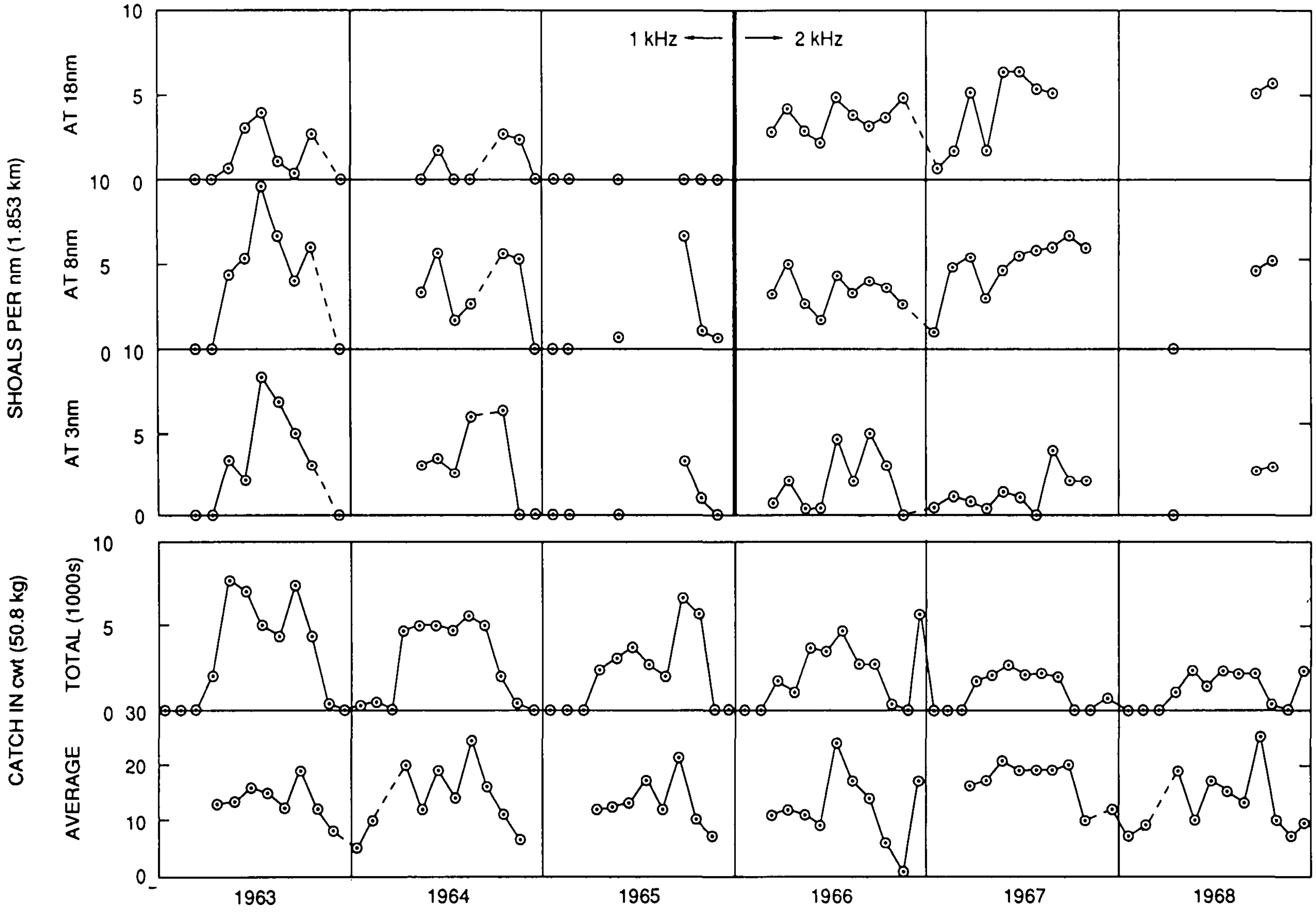

Figure 4. Monthly values of sonar shoal density and of pilchard catch, 1963 to 1968.

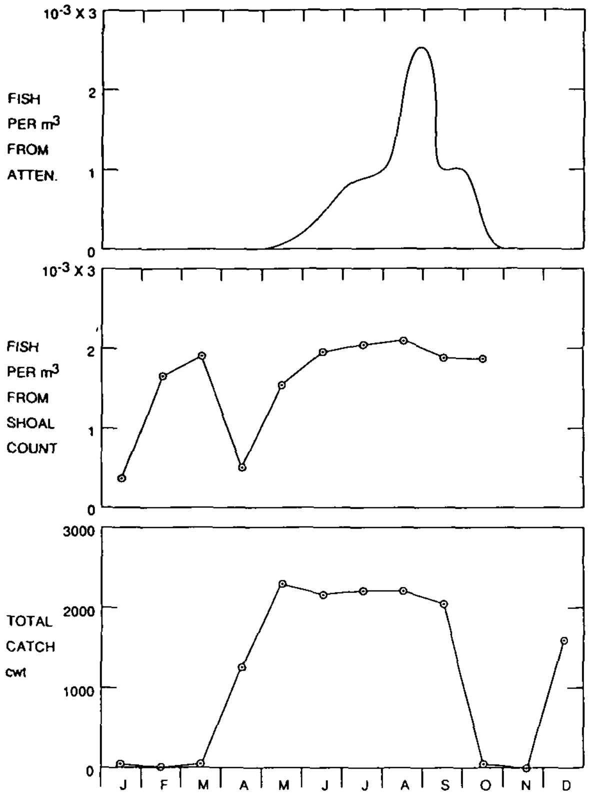

Figure 5. Seasonal estimates of fish density from attenuation, fish density from sonar shoal count, and recorded pilchard catch, all averaged for 1967 and 1968.

(d) Long-term trends

Naturally our remarks here reflect those in (c). Our results at 8 nm and 18 nm do show differences from year to year, but they are not thought to provide any good evidence for trends in the fish population.

At 3 nm there appears to be a general trend downwards in the numbers of sardine shoals, but this is confused by an increase over the years in the importance of the local bottom echoes. We point out that these fixed bottom echoes, at all ranges, come and go with a great spread of time scales. Even the major group of echoes near 10 nm/18 km (see Fig. 2) sometimes virtually disappears for days. Echoes are certainly associated with bottom roughness, and there could be changes due to sediment movement. But we know that a part of the return is associated with bottom-living creatures such as demersal fish – we have even used the sonar to watch a supposed rock pick itself up and swim off.

Revenons à nos sardines; we cannot be sure whether the trend at 3 nm is an artefact due to masking by the increasingly strong bottom echoes, whether indeed it is a real effect due to sardines avoiding areas with demersal fish, or whether it is an independent real effect.

Figure 4 also shows the total English catch of sardines in the southwest, the sum of monthly figures for the Eddystone and Mounts Bay region. Most of this catch would come from areas west and south of the Cornish peninsula, the latter right around the corner from our area and actually in the English Channel (Fig. 1). Many factors affect the catch, but we do see over the years a decreasing importance for this fishery, continuing a trend started earlier than our period of interest. The average catch per landing (averaged again for the two regions) does not show this trend. The catch data were kindly supplied by J. W. Horwood of the Lowestoft Fisheries Laboratory. Trends for this area have recently been reviewed by Southward and Boalch (1989).

(e) Range dependence

The number of shoals seen per linear mile might be expected to increase in proportion to the range, because area examined is proportional to range. Figure 4 does not show the effect. There may be real differences in area density, as discussed for the 3 nm sector in (d). There will certainly be a fall-off in our average sonar performance with range. One reason for this can be effects due to the presence of the fish themselves, such as the residual attenuation and shielding discussed by Ching and Weston (1971). And there may be complicated effects associated with shoal size distribution as discussed in (a). It is impressive how little the appearance of the tracks on our records does vary with range over quite a wide range interval. We consider, somewhat arbitrarily, that our most reliable results are for the 8 nm sector.

(f) Seasonal dependence

Figure 4 shows our fish indications most strongly from May to October. The 1-kHz 1963 and 1964 data show separate peaks, in June–July and in October. The 1-kHz 1966 and 1967 results show an additional peak in March–April, which is also evident in Figure 5. The total catch statistics generally support our May–October thesis, but sometimes with double peaking and sometimes with a new peak in December. Note that the sardine is a warm-water fish and that the Bristol Channel is the northern limit of its range; it is therefore quite reasonable to see it mainly in the summer.

(g) Linear shoal density

A typical summer figure is five shoals per linear mile or three per km. To go beyond this we have to start making assumptions, and this is reserved for the next section.

Quantitative abundance

(a) Long-range fish shoals

We concentrate now on our 8-nm results, and start at

1 kHz where the sonar beamwidth is 4°. We can convert the Figure 4 plots to an area density, e.g. our five shoals per linear nm become nine per square mile or three per square km.

To find the numbers of individual fish we need to know how many there are in a shoal. A typical shoal has previously been taken as having target strength +5 dB re 1 m^2, averaged over all directions, equivalent to acoustic scattering cross section 40 m^2. Dimensions are known to be in the order of tens of metres (Weston and Revie, 1971). It is also known that within a shoal the mean separation of the fish is of the same order as their length (Breder, 1959), the latter taken here as 23 cm. The simplest assumptions we can make are of perfect acoustic reflectivity at the surface of the shoal (implying that 40 m^2 is the horizontal projected area, say a cylinder 13 m across by 3 m deep), and of exact equality between separation and length. This leads to some 3×10^4 sardines per shoal. In fact the separation is usually greater than the length: Cushing (1973) quotes a factor 4.0 for sardines and Serebrov (1976) and Misund and Beltestad (1989) use 2.44 for similar fish. The necessary correction is large. But for such a spacing the partial discussion of shoal target strength in Weston (1967) shows that the surface reflectivity will be greatly reduced, and in order to obtain the quoted target strength we will need a bigger shoal. In the light of our ignorance we allow these factors to cancel and stay with 3×10^4 fish per shoal. The water depth at 8 nm is 46 m and it turns out that the results in Figure 4 must be multiplied by 3.4×10^{-4} to give the mean density of the dispersed fish per m^3. But we freely admit the considerable uncertainties in fish per shoal, as well as the relationship between typical shoal and average shoal counted.

Following our earlier discussion on the lack of any obvious effect of sonar frequency we adopt the same factor 3.4×10^{-4} at 2 kHz. We recognize that shoal reflectivity may be different, perhaps less at 2 than at 1 kHz due to the greater removal from the bladder resonance frequency and to the greater ratio of separation to wavelength, but believe that this is overcome by the improved sonar performance. We also note that the 2-kHz beamwidth is only 2°, so that the conversion from typical linear to typical area density gives five or six shoals per km^2, and that this must refer to shoals smaller on average (say 1.5×10^4 fish) than those seen at 1 kHz.

The middle plot in Figure 5 shows the resulting mean density each month for the average of 1967 and 1968, typically 2×10^{-3} m^{-3} in the summer.

(b) Dispersed fish at long range

We have not explained why we decided to work with the shoals present in the daytime rather than the patterns of dispersed fish visible on our records at night. We sometimes see individual shoals right out to the limits of our commonly chosen display at 40 nm/74 km, as shown in previously published records. In fact, on 3 June 1966 (with an increased repetition period), a shoal was seen at 50 nm/92 km. But when the fish disperse at night they should scatter *more* sound back to the sonar, and on the night of 2/3 June fish traces were seen at 55 nm/102 km – this with an imperfect matching of pulse type to the target extent.

Unfortunately if we wish to use this we have to make a quantitative measurement of the returned level which is not nearly as convenient as simply counting a shoal. We also need to know the propagation loss out to the, somewhat uncertain, depth of the scatterers. It is the variability of the propagation loss which finally destroys the concept.

(c) Attenuation

The dispersion of the fish at night can be used in a different way by measuring the increase in attenuation over some long range. The top curve in Figure 5 is based on the mean of a large number of 870-Hz and 1-kHz measurements in 1967–1968, along a 23-km line running west from our sonar position (Ching and Weston, 1971; see also Weston, 1972). It has its own uncertainties, including that due to the unknown fish depth. It is therefore very pleasing that magnitudes agree with those in our shoal deductions, and that significant effects again run from May to October. But there are considerable differences in shape, though these could be partly due to the differences in measurement track.

(d) Cushing estimate

Cushing (1957) netted the English Channel for pilchard eggs in June 1950 and knowing the number produced by a female pilchard he was able to work back to estimate the pilchard population. This came to 10^{10} adults or 8×10^5 tonnes in the Channel. A corresponding mean density is about 4×10^{-3} m^{-3}, and we adduce this as critical support for the results in both (a) and (c) above.

(e) Catch

The total annual catch from the Figure 4 data is typically 3×10^4 cwt, or about 1/500 of Cushing's total figure for the Channel in 1950. We do not learn anything new from this, merely that the annual catch is compatible with Cushing's result and that only a small fraction of the Channel area would need to be fished in order to produce it.

(f) Echo-sounding surveys

The object here is a brief discussion of methodology (cf. Foote, 1989) rather than the presentation of results for our area. Some echo-sounding surveys (e.g. Misund and Beltestad, 1989) have looked at shoals, with the advantage over our long-range work that size and even fish type can be monitored. But conventional echo-sounding surveys look at individual fish, either by counting echoes or by echo integration. This method does have its own quantitative problems, e.g. what proportion of fish are frightened away by the ship, but these are nowhere near as great as for long-range sonar.

The echo-sounding and the long-range sonar work may be regarded as extremes. Both are quite expensive. The echo-sounding slowly builds up an area picture of reasonable accuracy. The long-range sonar can almost immediately give a synoptic picture over a large patch of sea, but with more limited accuracy. It too can if necessary cover an area. In our case this merely involves transmission and reception on different bearings. Of course the ideal solution is a combination of long-range sonar and echo-sounding surveys. And there is further interesting equipment, such as the high-resolution sector-scanning sonar.

Conclusions

The long-range sonar display provides a marvellous synoptic record for the study of fish behaviour, a marvellous record for showing how the relative abundance changes with time, and a record which is limited in providing absolute results on abundance. Nevertheless, our estimates happen to agree quite well with those from other approaches.

The largest numbers of sardine shoals are seen between March and October, typically three per linear km or about three per square km. Assuming 3×10^4 fish per shoal we deduce a mean summer density of about 2×10^{-3} sardines per m^3.

Similar but more difficult studies could be carried out using the same stock of records. This would be worthwhile for the bottom features with bottom-living fish, and also for the sprat population.

Acknowledgements

It is a pleasure to acknowledge the cooperation of Admiralty colleagues J. Revie and staff then at Perranporth, P. A. Ching, P. D. Hocking, etc. We have also had the benefit of our long-term collaboration with members of the Lowestoft Fisheries Laboratory, including D. H. Cushing, F. R. Harden Jones, R. B. Mitson, and J. W. Horwood.

References

Breder, C. M. 1959. Studies on social groupings in fishes. Am. Mus. Nat. History Bull., 117: 393–482.

Bridger, J. P. 1965. The Cornish pilchard and its fishery. Laboratory leaflet (new series) No. 9, Fisheries Laboratory, Lowestoft.

Ching, P. A., and Weston, D. E. 1971. Wideband studies of shallow-water acoustic attenuation due to fish. J. Sound Vib., 18: 499–510.

Culley, M. 1971. The pilchard, biology and exploitation. Pergamon, Oxford, 241 pp.

Cushing, D. H. 1957. The number of pilchards in the channel. Fishery Investigations Ser. II, 21(5): 27 pp.

Cushing, D. H. 1973. The detection of fish. Pergamon, Oxford, 200 pp.

Foote, K. G. 1989. Fisheries acoustics: diagnosis and prognosis. Proc. Inst. of Acoustics 11, Pt. 3: 1–10.

Hodgson, W. C., and Richardson, I. D. 1949. The experiments on the Cornish pilchard fishery in 1947–48. Fishery Investigations Ser. II, 17(2): 21 pp.

Misund, O. A., and Beltestad, A. K. 1989. School sizing of small pelagic species off Mozambique by density estimation and acoustic dimensioning. Proc. Inst. of Acoustics 11, Pt. 3: 260–266.

Revie, J., Wearden G., Hocking, P. D., and Weston, D. E. 1974. A twenty-three day twenty-mile echo record of fish behaviour. J. Cons. int. Explor. Mer, 36: 82–86.

Rusby, J. S. M., Somers, M. L., Revie, J., McCartney, B. S., and Stubbs, A. R. 1973. An experimental survey of a herring fishery by long-range sonar. Marine Biology, 22: 271–292.

Serebrov, L. I. 1976. Relations between school density and size of fish. J. Ichthyol., 16: 135–140.

Southward, A. J., and Boalch, G. T. 1989. Aspects of long term changes in the ecosystem of the Western English Channel in relation to fish populations. *In* Proc. Int. Symp. Long Term Changes Mar. Fish Pop. (Vigo 1986). Ed. by T. Wyatt and M. G. Larraneta.

Weston, D. E. 1967. Sound propagation in the presence of bladder fish. *In* Underwater acoustics, Vol. 2, pp. 55–88. Ed. by V. M. Albers. Plenum, NY. 416 pp.

Weston, D. E. 1972. Fisheries significance of the acoustic attenuation due to fish. J. Cons. int. Explor. Mer, 34: 306–308.

Weston, D. E. 1988. The RWB Stephens lecture: sonar ichthyology. Proc. Inst. of Acoustics 10, Pt. 2, Book 1: 57–74.

Weston, D. E., and Andrews, H. W. 1990. Seasonal sonar observations of the diurnal shoaling times of fish. J. Acoust. Soc. Am., 87: 673–680.

Weston, D. E., and Revie, J. 1971. Fish echoes on a long-range sonar display. J. Sound Vib., 17: 105–122.