NOTES

THICKNESS AND DEPTH DISTRIBUTIONS OF SOME EPIPELAGIC FISH SCHOOLS OFF SOUTHERN CALIFORNIA

Many schooling fish species such as northern anchovy, *Engraulis mordax;* jack mackerel, *Trachurus symmetricus*; and Pacific mackerel, *Scomber japonicus*, are adept at avoidance of surface vessels, even those moving at relatively high speeds. Evasion behavior has complicated measurement of the vertical extent, thickness, and distribution in depth of such fish schools using standard echo sounding techniques. In addition, hull-mounted echo sounders are usually 3 to 4 m below the surface, are blanked for the duration of the transmitted pulses and are relatively ineffective for another 5 to 10 m due to high surface and volume reverberations immediately following the pulse transmission. The combination of evasion behavior and transducer mounting and operation often results in poor sampling of the upper 10 to 20 m of the water column by hull-mounted echo sounders.

Commercial fishermen routinely use air spotters to guide them to school groups (Squire 1972). Fishermen often set their gear visually in water so rich with plankton that visibility is severely restricted. An awareness of these practices and of the implication that many of the fish landed commercially are caught at relatively shallow depths emphasizes the need for a good tool for studying shallow schools. Determination of fish size from swim bladder resonance data requires accurate measurement of the depth and thickness of schools, including those in the upper 20 m (Holliday 1977).

When operating an echo sounder in shallow water, multiple "bottom" echo traces often appear. The second "bottom" in these traces is an image of the sea surface as reflected by the sea floor. With appropriate attention to signal processing it is possible to make measurements on subsurface targets detected via sound which has been reflected from the seabed. Under these conditions, a school of fish near the surface will appear just above the second "bottom." The procedure used to obtain the data presented in this paper is a variation on this observation.

Materials and Methods

Measurements of the mean depth and thickness of schools or aggregations of marine organisms were made at three locations in the California Current near the southern California coast. Each location was occupied during a different season, the first in December 1976, the second in May 1977, and the last during September 1977. The December and May work was done near Santa Catalina Island and the September data were taken about 15 mi southwest of Oceanside, Calif. In December, only 17 schools were studied, because the location of the ship at that time did not coincide with the presence of a large school group. All measurements were made during daylight hours. The schools studied were previously detected on the 30 kHz sonar in its normal side-looking mode. In May, 121 schools were studied and in September measurements were made on 221 targets.

Our bottom bounce system was implemented using the sonar aboard the NOAA ship *David Starr Jordan*. The procedure involved a 30 kHz sonar, steerable in the vertical and horizontal planes, with a capability for depression to 90°, i.e., vertical as in the standard echo sounding mode. Over a flat bottom, the sonar was normally operated at a depression angle of 80° to 85°, depending on water depth. The horizontal steering was to either port or starboard, that is, normal to the ship's track. This allowed sampling of a path whose width varied with water depth on the selected side of the ship and parallel to the ship's track (Figure 1). As an example, for a flat bottom, a depression angle of 80° and a water depth of 500 m, a path was studied with an inner edge which intersected the surface 70 m from the ship's track, and an outer edge which extended to 275 m. These limits were derived from the sonar's 12° beam width, defined as the -6 dB point on the two way (transmit and receive) beam pattern.

The data reported in this note were acquired using 1 ms CW pulse waveforms. It was determined that reliable measurements could be made in water depths up to 500 m with bottom slopes of up to 1.4° using a source level of 216 db//1 μPa at 1 m. Bottom characteristics were thought to be

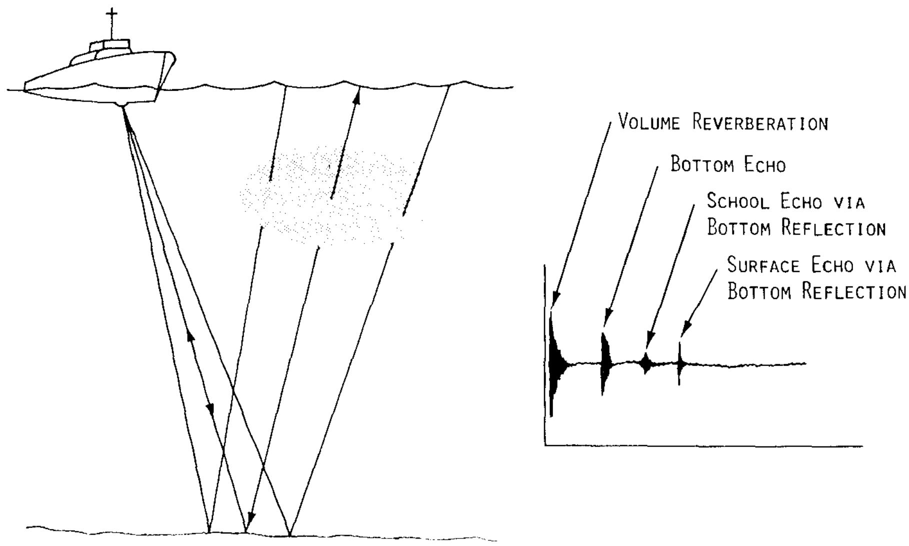

FIGURE 1.—Illustration of bottom bounce technique geometry and typical time-amplitude graph of sonar echo.

either mud or mud and sand in the operating areas (Revelle and Shepard 1939:247), but no bottom samples were taken. Relative to that over a flat bottom, performance appeared to be slightly improved in areas with a gentle slope, presumably because of a change in bottom composition or roughness. Schools were easily detected when surface waves were <3-5 ft, but acoustic measurements became more difficult when the wind increased in strength and whitecaps were formed. This was partly due to uncertainties in the precise location of the surface reflection which is used as a reference in determining target depth. The surface reflection was substantially more diffuse when moderate numbers of whitecaps were visible. This effect may have been due to increased surface scattering and absorption by small air bubbles entrained by wave action near the surface. Although we made no direct measurements of school target strengths, our best estimates range between −5 dB and +10 dB for side aspect target strengths of the schools studied. These estimates are based on earlier measurements made for schools similar in size and suspected composition (Larsen[1]). Ventral aspect target strengths are possibly 3-6 dB less (Love 1977) based on measurements for individuals rather than schools.

[1]Larsen, H. 1974. Distributions of target strengths and horizontal dimensions for aggregations and schools of marine organisms. Tracor Doc. No. T74-SD-1054-U, 66 p.

Results and Discussion

Examination of the bottom bounce data for the depth distribution of schools (Figure 2) revealed an apparent preference of the schools for depths near the seasonal thermocline. The accumulation of the number of observations per depth interval, when normalized to achieve a display with a unit area under the curve, is one means of estimating the probability density function (p.d.f.) for a quantity such as school mean depth (Feller 1971:36). The most probable value (depth, thickness) of a random variable is defined as the value of the quantity at the largest peak in its p.d.f. (Papoulis 1965:140). Though the thermocline was less well defined in May than in December and September, the most probable depth at which a school was found in each survey generally coincided with the maximum thermal gradient (Table 1; Figure 2a, f, k). In order to quantify the apparent relation of fish school distribution and the thermal profile, the mean depth of each school was determined. The data were sorted into 10 m depth intervals. Because of the sonar's beam shape, the volume searched by the bottom bounce procedure varied for a given school depth interval as the bottom depth changed. For a bottom depth of 300 m, about 40% more water was searched for schools at 5 m depth than for schools at 150 m. The number of schools observed during each survey in a particular depth interval (Figure 2a, f, k) was normalized

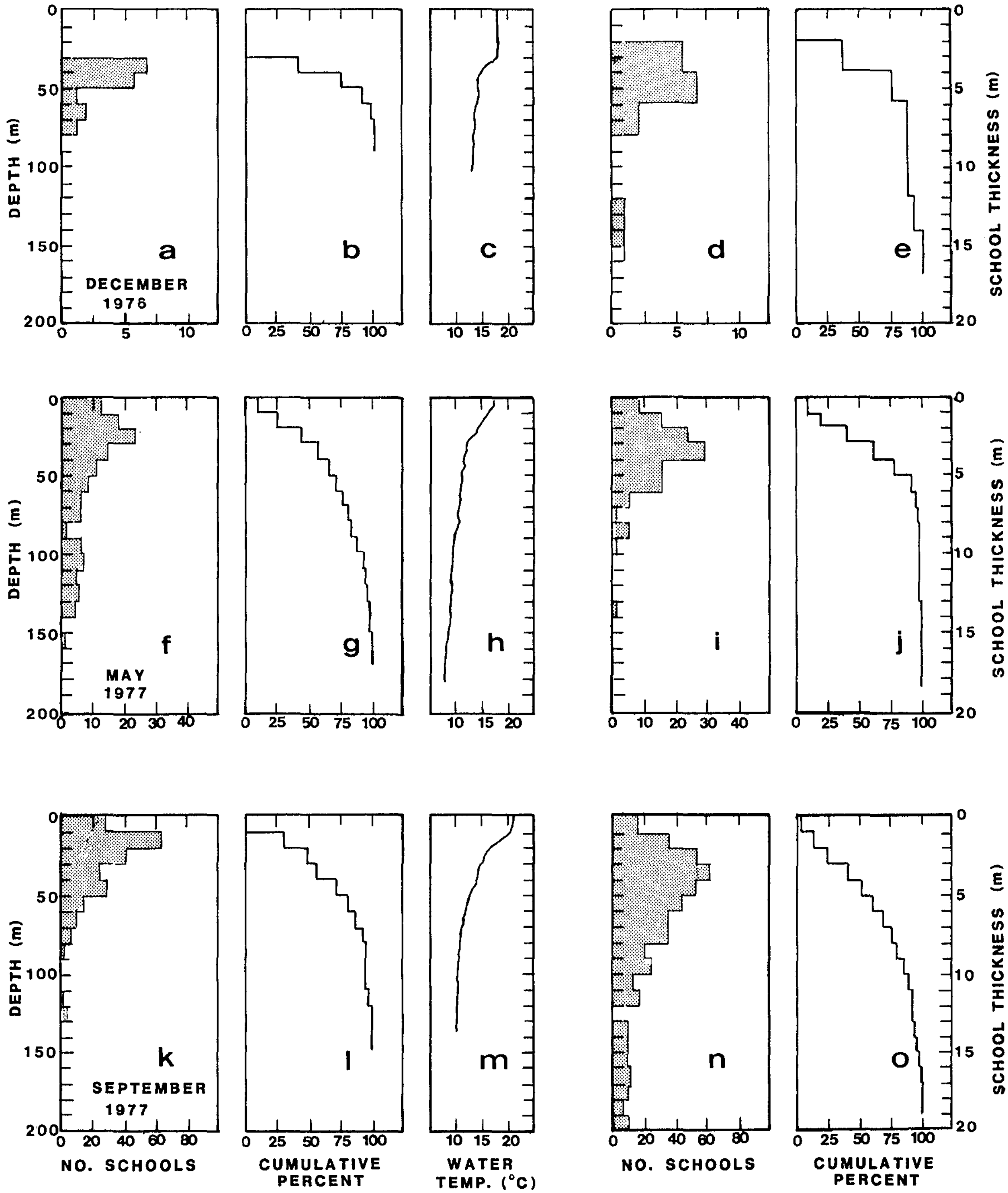

FIGURE 2.—Bottom bounce data and temperature profiles for the December (a-e), May (f-j), and September (k-o) surveys. The distribution of schools mean depth (a, f, k), the cumulative distribution of mean school depths (b, g, l), and the thermal profile (c, h, m) are given versus depth with the scale on the left. The distribution of school thickness (d, i, n) and the cumulative distribution function for thickness (e, j, o) are associated with the scale on the right.

TABLE 1.—Characteristics of depth and thickness of pelagic fish schools studied during three seasons.

Measure	Dec. 1976	May 1977	Sept. 1977
Total number of schools	17	121	221
Mean depth, m	45	47	22
Most probable depth, m	35	23	12
Median depth, m	37	35	20
Maximum depth, m	70	158	122
Mean thickness, m	4.8	4.1	6.0
Most probable thickness, m	4	4	4
Median thickness, m	3.8	3.4	4.5
Maximum thickness, m	15	14	19
Depth of maximum thermal gradient, m	35	22	12

to a common volume before the correlations were calculated. The average temperature gradient was calculated for each depth interval. Correlation coefficients of −0.97 ($N = 9$, 17 schools), −0.95 ($N = 17$, 121 schools), and −0.91 ($N = 13$, 221 schools) were computed between the thermal gradients and the school depth distribution for December, May, and September, respectively. The measurements of temperature gradient, and to some degree the fish distributions, are derived from continuous measures and tend to be serially correlated. Without a measure of the degree of this correlation confidence limits cannot be expressed for the correlation coefficients indicated. Hence, these correlation coefficients are provided as descriptors of this specific data set rather than for predictive purposes. For these locations, times, school groups, and the 10 m vertical resolution, a linear equation based on the thermal gradient described the school vertical distribution with <6% unexplained variation in December, 10% in May, and 17% in September.

We suggest that the observed correlation in all three measurement sets is evidence of a causative factor rather than chance. In December, the most probable school location was at a depth whose temperature was 16°-17° C. Temperatures at the corresponding depths in May and in September were 14°-15° C and 18°-20° C. Within this range of temperatures (16°-20° C) we did not find any seasonal pattern indicating a preference for a particular water temperature. We think the correlation of the thermal gradient with school mean depth and the relatively thin character of the schools is more likely evidence of a thermally associated thin layering of some part of the fishes' food supply rather than a direct result of the temperature profile.

An analysis of the thickness measurements indicates a tendency toward thin schools in each survey (Figure 2d, i, n). To the extent that the data base collected is characteristic of the entire school group, the most probable thickness of a school selected randomly from the three groups studied was consistently near 4 m. In May, one-half of the schools were thinner than 3.4 m. As will be discussed later, the schools in May exhibited sound-scattering characteristics consistent with a dominant population of anchovy larvae. The school horizontal dimensions did not differ substantially from those measured previously for adult fish in other seasons (Hewitt et al. 1976; Larsen see footnote 1; Holliday[2]).

Over one-third of the fish schools observed were at depths <20 m. More than 11% of the schools were above 10 m. An echo sounder operated in the conventional manner would have properly represented the distribution of fish school depths only in December, when the thermocline was relatively deep. A direct comparison of the bottom bounce procedure and conventional sounding was conducted in September when an 18 kHz hull-mounted sounder was used simultaneously with the bottom bounce instrumentation. The bottom bounce data distribution (Figure 2) is seen to differ in both shape and sample size from the comparable conventional sounder data (Figure 3). The differences in shape are principally due to undersampling of the top 20 m of the water column by the conventional system. The large difference in numbers of schools observed simultaneously by the two methods is due to a combination of the factors mentioned in the introduction plus the smaller sampling volume of the conventional system at shallow depths.

Broadband acoustic signatures of the targets within the school group were obtained either during the bottom bounce measurements or within a few hours of the bottom bounce data acquisition. The broadband signatures of the targets varied, but were largely consistent with several sizes of northern anchovy. The acoustic signatures, supporting biological data, and ancillary environmental data are detailed elsewhere (Holliday see footnote 2). The acoustic resonances observed during December were consistent with adult anchovy (0.2 to 0.7 ml swim bladder volume) and a small percentage of unknown targets not containing gas-filled swim bladders. In May, the schools were dominated by acoustic scattering consistent with 25-30 mm anchovy larvae and a few juvenile an-

[2]Holliday, D. V. 1978. MORDAX II/III/IV. Tracor Doc. No. T-78-SD-002/3/4/-U, San Diego, Calif., 2260 p.

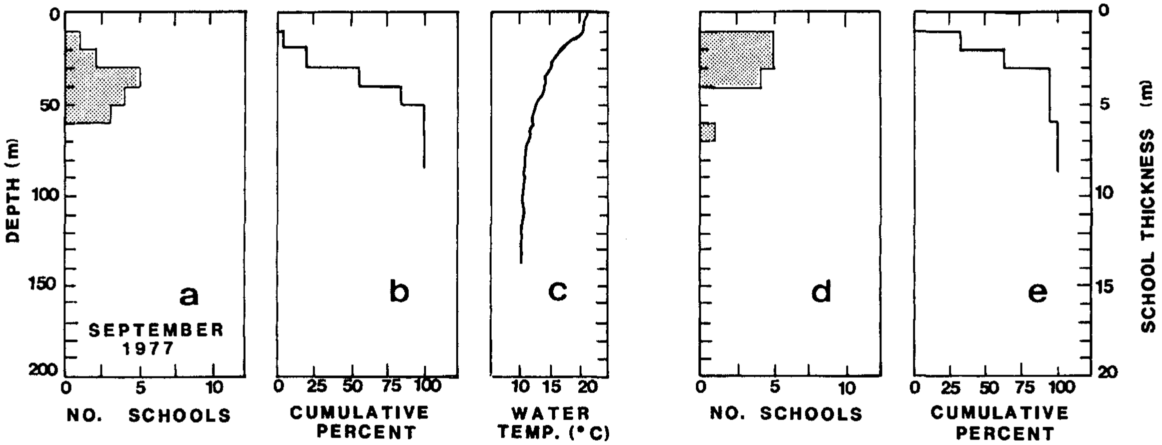

FIGURE 3.—Data measured with a conventional echo sounder operating at 18 kHz. The fish school depth distribution (a), cumulative distribution (b), and thermal profile (c) are associated with the scale on the left. The distribution of school thickness (d) and cumulative distribution (e) are associated with the scale on the right.

chovy, 60-90 mm long. The September broadband acoustic work revealed sound-scattering characteristic of a mix of juvenile and adult anchovy with a minor component of jack mackerel. These observations are consistent with known abundances of pelagic fish in the area (Squire 1972). In December and September, the presence of anchovy, jack mackerel, and squid was confirmed by trawl results from depths near the seasonal thermocline. The trawls were conducted during the night following each of the acoustic measurement periods. The trawl results from May were largely negative with respect to adult schooling fish. Qualitatively, increased water clarity in the area off the north end of Santa Catalina Island during May may have permitted greater trawl avoidance than was the case closer to shore at the December and September stations.

Only one of many possible variations of the bottom bounce technique has been discussed. Before attempting an adaptation of the procedure to a particular problem, one should consider, as a minimum, the impact of the following. One of the first parameters at a designer's disposal in acoustics is the frequency to be used. The reflectivity of the target, the bottom, and the surface are all dependent on frequency as is the absorption of the sound in the water column. Ambient noise, ship's self-noise, and reverberation levels are also strongly frequency dependent. Pulse length, pulse type, and a variety of signal processing techniques are also at the designer's disposal and must be determined.

Some important parameters are not available to the designer for selection. These include bottom characteristics (scattering, absorption, and penetration), bottom slope, and surface conditions such as roughness and the presence of entrained bubbles. These characteristics of the intended operating area must be considered as well as maximum and minimum water depths before designing a bottom bounce system for a particular application. While it is readily apparent that there will be a maximum effective operating depth for any given system design in a particular physical environment, it is also important to realize that shallow reflection angles at the bottom and surface may limit shallow water operation. Another important shallow water limitation is the persistence of bottom reverberation for ranges at which one desires to make measurements on schools.

Conclusions

The thickness and vertical distributions of shallow schools of many fish cannot be accurately measured by conventional echo sounding techniques. Consequently, a new approach which makes use of the bottom bounce acoustic propagation path has been developed and used for measurements on northern anchovy schools off southern California. These measurements, at three locations in three different seasons, revealed that the schools occupied a depth zone only a few meters thick. Good agreement was found between occurrences of the mean depths of the schools and the seasonal thermocline, where it is hypothesized that thermal stratification, and associated water density microstructure may lead to an aggregation of some part of the fishes' food supply in thin layers.

Acknowledgments

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THE EFFECT OF BODY SIZE ON THE STANDARD METABOLIC RATE OF SKIPJACK TUNA, *KATSUWONUS PELAMIS*

The standard metabolic rate (SMR) of fish is the energy requirement of a postabsorptive animal completely at rest (Beamish and Mookherjii 1964; Fry 1971; Brett 1972). It approximates the energy demand of all metabolic processes except swimming and digestion. The SMR (and its relation to fish size) is an important input parameter for energetics, growth, and population models (Kitchell et al. 1974; Kitchell et al. 1977). The SMR may also be used to predict optimal fish cruising speed (Weihs 1973, 1977). I undertook this study to provide SMR measurements for skipjack tuna, *Katsuwonus pelamis*. These measurements may be incorporated into models such as those described in Sharp and Francis (1976), Kitchell et al. (1978), and Sharp and Vlymen (1978).

The SMR is generally determined by extrapolation of a metabolic rate versus swimming activity curve back to a zero activity level (Beamish 1964; Brett 1965; Muir et al. 1965). However, because it is difficult simultaneously to measure metabolic rate and activity level of large, highly active, pelagic species such as skipjack tuna, SMR was measured directly.

Methods and Materials

Skipjack tuna, purchased from local fishermen, were maintained at the Kewalo Research Facility of the National Marine Fisheries Service (described in Nakamura 1972). Fish were kept in outdoor tanks from 2 days to several weeks before use. Food was presented to all fish daily; however, a fish was not fed for at least 20 h prior to its use in an experiment. This allowed sufficient time for an animal to clear its stomach and intestine and for its blood glucose level to return to prefeeding levels (Magnuson 1969).

To reduce struggling and minimize injury during handling, each fish was injected with the neuromuscular blocking agent gallamine triethiodide (approximately 1 mg kg^{-1}). The animal was then placed in a Plexiglas[1] flow-through box respirometer, similar to that described in Stevens (1972). The spinal cord was cut immediately behind the skull to stop all overt muscular activity

[1]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.