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Three-dimensional structure and avoidance behaviour of anchovy and common sardine schools in central southern Chile

F. Gerlotto, J. Castillo, A. Saavedra, M. A. Barbieri,
M. Espejo, and P. Cotel

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We studied the avoidance behaviour and three-dimensional (3-D) structure of anchovy (*Engraulis ringens*) and common sardine (*Strangomera bentincki*) schools mixed in high concentrations in a coastal area of central southern Chile. Observations were carried out during an acoustic survey in January 2002 by means of a vertical echosounder and a multi-beam sonar. The sonar harvested around 900 series of 3-D school images, and 3000 2-D school images were collected with the echosounder. The results showed that all fish aggregations presented the same internal structure, but different global morphologies, from single small schools (with length three times the height) on the edges of the distribution to large dense layers (length more than seven times the height) in its centre. Observation of avoidance in the vertical and horizontal planes indicated that limited vertical diving occurred close to the ship (fish dive from the surface to the 5–10-m depth layer below the vessel), while no horizontal avoidance was observed.

Keywords: 3-D acoustics, fish avoidance, fish behaviour, pelagic fish, school structure.

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F. Gerlotto and P. Cotel: IRD, CRHMT, BP 171, 34203 Sète Cedex, France. J. Castillo, A. Saavedra, M. A. Barbieri, and M. Espejo: IFOP, Blanco 839, Valparaiso, Chile. Correspondence to F. Gerlotto: tel: +33 4 99 57 32 00; fax: +33 4 99 57 32 95; e-mail: gerlotto@ird.fr.

Introduction

Schools are the most important structure in the life of many pelagic fish populations, for several reasons. First, such structures are vital for these species: a sardine cannot survive alone. Second, because fishers and predators take advantage of schooling to catch them (e.g. pelagic trawls and purse-seines). A large number of exploited pelagic stocks are monitored by acoustic methods, especially by echo-integration. Such methods present great advantages for studying these populations (see MacLennan and Simmonds, 1992; Fréon and Misund, 1999; Rivoirard *et al.*, 2000; and others), but there are drawbacks, among which is the avoidance of survey vessels by schools of small pelagic fish. Previous studies have shown that fish schools present highly variable avoidance patterns, depending on factors such as vessel noise (Goncharov *et al.*, 1989; Soria *et al.*, 1996, 2003; Fernandes *et al.*, 2000), trawl noise (Ona and Godø, 1990), taxonomy and physiological status (Misund, 1993; Engås *et al.*, 1995), and fish learning (Pyanov, 1993; Soria *et al.*, 1993). When it exists, avoidance induces a bias that must be evaluated in abundance estimates (Misund and Coetzee, 2000). Moreover, there is no real agreement about the magnitude of this avoidance effect; the literature presents cases where strong avoidance is recorded (Olsen *et al.*, 1983) and others where no avoidance can be detected (Fernandes *et al.*, 2000).

Avoidance is a complex behavioural process that can have different consequences (Fréon *et al.*, 1992, 1993). It may be horizontal or vertical and can change or even destroy the structure of aggregations. The significance of avoidance also depends on the level of aggregation: fish in schools are more reactive than scattered fish.

All these considerations point to a need to measure the collective characteristics of fish aggregations as well as their reaction to survey vessels. Measuring avoidance during acoustic surveys is impossible if the information is restricted to data from vertical echosounders. There is a need for additional data, such as data from a silent platform (e.g. rafts or buoys; Vabö *et al.*, 2002) or autonomous underwater vehicles (Fernandes *et al.*, 2000). Another way to measure the impact of a ship is to observe fish distribution at long horizontal distances from the vessel using a multi-beam sonar (Misund, 1990), which we applied in this study.

This paper considers the 3-D characteristics of fish schools in the central southern region of Chile and possible avoidance patterns from several points of view: the magnitude, the direction (vertical vs. horizontal), and distance of school avoidance. We took advantage of the dominant pelagic species in the region (limited by the latitudes 34°S and 40°S): anchovies (*Engraulis ringens*) and common sardines (*Strangomera bentincki*). These species show differences in their general distributions relative to environmental conditions but during the austral summer they share a common area in the central region of Chile. This area of concentration is limited to shallow coastal waters (<50-m depth, <30 nmi from the coastline). Sardine and anchovy schools cannot be differentiated acoustically, so they are not considered separately in our work.

Material and methods

Data come from a survey performed by day in January 2002, at an average speed of 8 knots aboard the Chilean RV "Abate Molina" (43.6-m scientific trawler). The survey comprised parallel transects perpendicular to the coastline, separated by 10 nmi. Forty pelagic trawl hauls at 3.5 knots were carried out using an Engel pelagic trawl (97 m in length and 14 m in height) with otter boards Suberkrub. Two acoustic devices were deployed: a 38-kHz split-beam echosounder SIMRAD EK500 and a 455-kHz multi-beam sonar type SeaBat 6012, Reson. The specifications and settings of the two devices are summarized in Table 1. Vertical echosoundings (VES) were recorded throughout the day and during fishing operations and stored under ECHOVIEW format. The results were expressed in NASC (Nautical Area Scattering Coefficient: MacLennan *et al.*, 2002) values for 0.5 nmi elementary distance sampling units (EDSU; MacLennan *et al.*, 2002). We saved the echograms and acoustic information in digital files for post-processing. We extracted the following information from these values: maps of fish abundance distribution (in NASC and in tonnes), echogram structures, vertical distribution of fish density, and school characteristics (in density and shape).

Table 1. Settings of the two acoustic devices used during the survey.

Device settings	Echosounder	Sonar
Type	SIMRAD EK500	Reson SeaBat
Frequency	38 kHz	455 kHz
Beam characteristic	ES38B (split-beam)	60 beams
Individual beam angle	7.1°	(1.5° * 22°)
Pulse length	1 ms	0.06 ms
Pulse rate	1 s^{-1}	3.5 s^{-1}
Transmission power	2 kW	–
TVG	20 log R	20 log R
Range	Variable	50 or 100 m

Multi-beam sonar (MBS) data were only recorded when schools were detected in order to avoid the storage of irrelevant data. The sonar transducers, set on the starboard side of the vessel at 4-m depth (same depth as the EK500 transducer), ensonified the vertical plane perpendicular to the vessel's route, which was delineated by the surface and the vertical line below the vessel. Sonar data were collected following Gerlotto *et al.* (1999) methods. The range was usually set at 100 m.

We used several processing methods for analysing the data. VES data were processed using ECHOVIEW. Fish schools were individualized using ECHOVIEW procedures and a NASC value was calculated for each of them. The main school parameters were measured (school length, height, area, bottom depth, school depth). MBS data were processed using SBI Viewer software. Two methods were used: first, all the data recorded were explored using SBI Viewer, and basic measurements on each school were done by eye on the SBI Viewer images. This set of measurements produced a 2-D database from which we extracted school length (horizontal dimension parallel to transects), width, height, minimum distance to the vessel, minimum distance to the surface, and bottom depth. Corrections were made for length and distance to the vessel. To correct the length values from beam shape effect, we applied Johannesson and Losse's (1977) method:

$$\mathrm{Lcorr} = [\mathrm{L} - (2\tan(\alpha/2))]$$

where Lcorr is the corrected length, L the measured length, α the beam angle (in our case, $\alpha = 22°$). This correction presents a drawback when schools are smaller than 2 tan(α/2), and, thus, the length can become negative. Such schools were discarded. A measurement bias exists for the second variable (distance to the vessel): we defined distance to the vessel as the smallest horizontal distance between the vertical line below the vessel and the school's border. Therefore, all the schools below the transducer are also counted (i.e. including those split by this vertical plane). This artificially increases the number of schools observed at 0 m from the vessel by a factor related to school width. In order to remove this bias, a total of 58 schools under the vessel with a width smaller than the mean school width (which was 11 m) were removed.

Second, for the schools that could be extracted individually using the software, more detailed information was obtained; particularly the school mean density, actual volume and surface, internal structure (roughness, number, and dimension of holes), etc. This produced the 3-D database from which we calculated morphological (length, width, height, surface, volume, and roughness (S/V) of the school), geographical (distance to the vessel, bottom, and surface), and structural (school density, number, surface, and volume of holes inside the school) characteristics. Holes are defined as empty cells inside the school. Each cell is a cube representing the smallest volume unit defined by SBI Viewer. This elementary volume varies according to the distance from the transducer. All the morphological, geographical, and hole dimensions are in metres and densities are expressed in relative unit on a 256-step scale.

In order to evaluate school horizontal avoidance, two calculations were made using the MBS data. First, we evaluated the distribution of schools according to distance from the vessel. Soria *et al.* (1996) define the "null hypothesis" (i.e. no lateral avoidance) as an even distribution of schools at any distance from the vessel. Any other distribution results from a reaction to the vessel by an accumulation of schools at given distances. Second, we investigated the relationship between length and width of the schools. Using the same equipment, Gerlotto and Paramo (2003) and Soria *et al.* (2003) showed that when schools avoid they alter their shape, the length (i.e. dimension parallel to the vessel route) becoming longer than the width (dimension perpendicular to the route). Soria *et al.* (2003) showed that this anisotropy is the result of an avoidance reaction. Measuring this parameter is useful in evaluating any avoidance effect. We note that schools are selected in a different way in the two bases: the 2-D base cannot take into consideration most of the "layer shape" schools, which do not present a regular shape on the screen and would be overestimated. On the contrary, schools present inside the noisy area can readily be discriminated by eye. The layers can be extracted by the 3-D base software and give accurate results from their actual shape, but noisy schools are not extracted. This difference is responsible for important differences in the values between the two bases for the same dimension measured on the school.

Results

Spatial distribution

The two acoustic devices were not operated simultaneously at all times. As a result, the areas surveyed are not equivalent: the echosounder and the sonar recorded 2904 and 1453 schools, respectively, along the 2757 nmi covered. Among the schools observed using sonar, 520 could be measured in 2-D, while for 416 schools we could extract data for 3-D analysis. With the exception of vertical avoidance measurements, the remaining schools were not included because of contamination from background noise, or because of incomplete data records.

Sardine and anchovy stocks are mixed and concentrated in sectors close to the coast in several types of aggregations from small schools to dense layers. Within this area, the fish distribution obeys a general pattern directly linked with distance to the coast. Following an east to west transect perpendicular to the coast, one first records a series of small scattered schools, then bigger and clustered schools, and finally a dense shallow layer in the centre of the distribution. Once this region has been crossed, the pattern is symmetrical: dense and aggregated schools, then small scattered schools (Figure 1). The mean depth of schools varies with type: schools are distributed throughout the water column at different distances from the surface, while layers are closer to the surface (fish in layers were visible from the vessel at the surface of the sea).

We define two distinct structures, the "school" structure and the "layer" structure, based on the relationship between length and height in the MBS database, which can be separated into two modes (Figure 2). These two groups clearly define schools as structures with length less than three times the height, and layers with length superior to ten times the height. The length:height ratio value = 7 was used to separate the two groups.

All the morphological dimensions (height, length, width) of schools and layers are significantly different, as are the distances of the structures to the surface and to the ship (Table 2). In contrast, internal structure and density are not significantly different between schools and layers (Table 2). In order to compare the number and dimensions of holes for schools and layers, the surface and number/volume of holes were standardized relative to the surface and volume of the aggregation.

Horizontal avoidance

Our results show a very stable number of schools at any distance from the vessel (Figure 3). For statistical comparisons between the null hypothesis and the observed distribution, we did not consider classes farther than 40 m, which means a lower number of schools; at distances farther than the average bottom depth, schools are often within a noisy area and cannot be extracted safely, which artificially results in an underestimate of the number of schools. In order to test the difference between the theoretical (even number of schools at any distance from the vessel) and observed distributions, we performed a chi-square test. The results (chi-square = 14.518; d.f. = 13; $p < 0.339$) show that they are not significantly different (Figure 3). In this area, and regarding the survey conditions, fish schools do not avoid the research vessel laterally.

Relations between length and width of schools

In the 2-D data the pattern of increased length relative to distance is not apparent in our observations (Table 3). School length and width are not significantly different (n = 427; t = −1.271, d.f. = 426, p = 0.205). This similarity between length and width also appears in the 3-D database (n = 415; t = 1.12; d.f. = 414; p = 0.026),

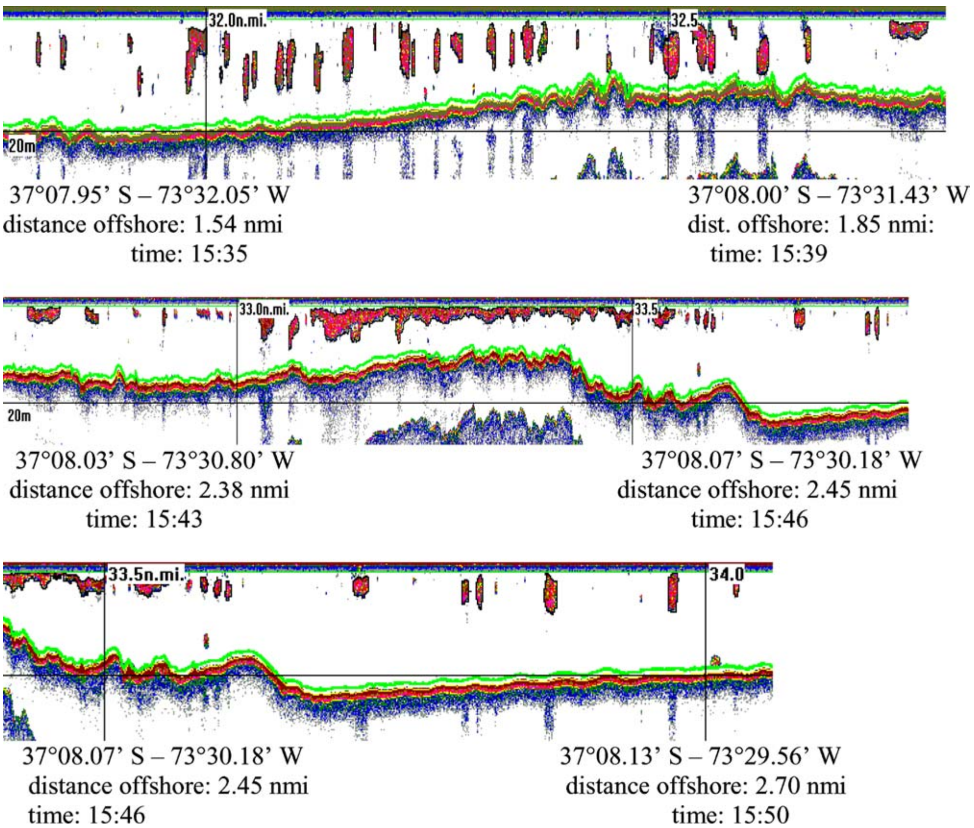

Figure 1. Part of the echogram from a transect showing the distribution of fish across a local area of concentration, from 37°07.95′W to 37°08.13′W. The succession of scattered small schools, clustered large schools, and layers can be observed (recording from the VES).

although the dimensions are more than twice the length and width of the 2-D base. The important value of the standard deviation in both cases shows that the dimensions are highly variable, with the same magnitude in the two databases.

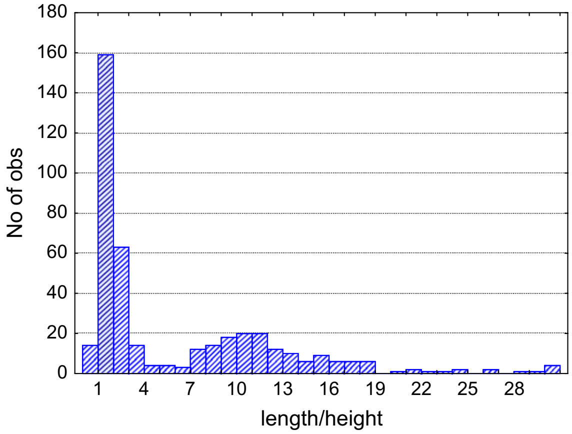

Figure 2. Frequency histogram of the length:height ratio for schools and layers observed with the MBS in the 3-D database.

Vertical avoidance

VES data

Frequency histograms of the NASC values per layer and number of schools per layer were calculated. Depths are given relative to the transducer location, which is 4 m below the sea surface.

There is a strong decrease in frequency in the upper layers, which is apparent from 4 to 6 m (no data can be obtained in the 0–4-m "blind zone" for acoustical reasons) (Figures 4, 5). In addition to this decrease at the surface, schools seem evenly distributed in the layers from 7 to 9 m; their frequency then decreases slowly from 10 to 12 m, and strongly at depths over 12 m (Figure 5). No evidence of vertical avoidance can be extracted from this set of data. But it is important to note that if there is any vertical avoidance the histograms show clearly that it cannot appear at more than 6 m: if we can say that the lower abundance of fish at less than 6 m below the vessel may be due to vertical avoidance, no behavioural pattern could explain why avoidance would only begin at distances above 12 m, and not closer to the vessel. Therefore, any analysis of vertical avoidance could be restricted to the layer 0–6 m below the surface.

Table 2. Mean values of the main characteristics of schools and layers calculated using the 3-D base. Schools are defined as aggregations with ratio length:height < 7; layers with length: height ≥ 7. Data on holes are standardized relative to the surface (for the surface of holes) or volume (for the number and volume of holes) of the structure.

	Mean school	Mean layer	t-value	d.f.	p
Number	261	154			
Distance to the ship	29.29	37.77	−4.563	413	<0.001
Ratio depth:distance to the surface	9.8	11.9	−2.484	413	0.013
Length	20.9	36.4	−9.554	413	<0.001
Width	20.1	36.2	−11.509	413	<0.001
Height	11.6	2.9	16.172	413	<0.001
Volume	605	253	4.698	413	<0.001
Surface	2 816	1 312	4.483	413	<0.001
Roughness	5.7	6.4	−3.526	413	<0.001
No. holes m^{-3}	1.27	1.00	1.385	413	0.167
Surf. H m^{-2}	0.09	0.15	−1.011	413	0.312
Vol. H m^{-3}	0.032	0.031	0.394	413	0.693
Density	52.7	54.2	−0.493	413	0.622

MBS data

Calculation of the correlation coefficient between the depth of a school and its distance to the vessel extracted from the 2-D data does not show any significant effect of distance to the vessel at this depth ($n = 415$; $r = 0.025$; $p = 0.567$). This indicates that no diving reaction of the whole school occurs even at small distances. Nevertheless, we observed an "empty volume" around the transducer on the raw data traces. To test whether any "partial avoidance" occurred, we selected schools observed at no more than 5-m depth, and which were also present below the vessel. From this new set of 153 schools (out of 1453), the upper depth limit of each individual aggregation was measured at 0, 5, 10, and 15 m from the vessel. The results detailed in Figure 6, particularly mean depth and the standard errors for each distance, show that part of the school clearly dives below the ship, and practically no fish are present at less than 5 m from the transducer in any direction (the blind zone for MBS is less than 1 m) immediately below the vessel and up to 5 m away. Beyond this point, there is no evidence of diving.

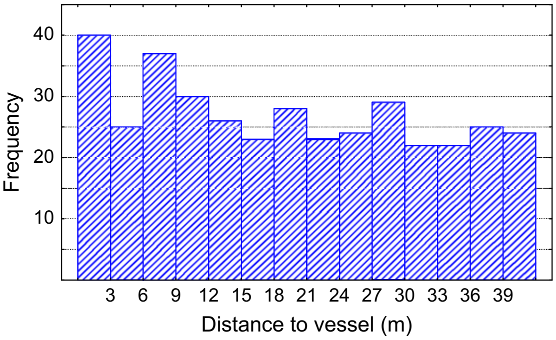

Figure 3. Frequency histogram of the number of schools in relation to distance from the vessel measured using the 2-D data.

Table 3. Statistical characteristics of the main morphological and geographic parameters of the schools measured in the 3-D and 2-D bases; Dist./V = smallest distance of the school to the vessel. All dimensions in metres. Length is corrected from the beam effect.

	Mean 3-D	Mean 2-D	s.d. 3-D	s.d. 2-D
Length	27.03	11.60	19.40	9.89
Width	26.20	11.46	16.07	6.25
Height	8.37	7.57	6.72	4.03
Dist./V	32.58	20.06	18.90	17.58

Discussion

There was no horizontal avoidance of schools during this survey. Horizontal avoidance has been extensively documented in many studies (e.g. Soria *et al.*, 1996; Fréon and Misund, 1999; Brehmer *et al.*, 2004; Vabö *et al.*, 2002). Avoidance differs substantially among settings and species, and ranges from a strong avoidance reaction (Olsen *et al.*, 1983) to no reaction at all (Misund, 1993; Fernandes *et al.*, 2000; this work). An important factor causing avoidance is vessel noise (Olsen *et al.*, 1983; Mitson, 1995; Fernandes *et al.*, 2000), but the reaction may differ among species. So far, there is not enough information with which to determine the factors that might explain the lack of horizontal avoidance reaction observed during this survey. In any case, it is extremely difficult to draw a universal model of fish avoidance.

There is much less information in the literature on the vertical avoidance of fish, especially in the "subsurface

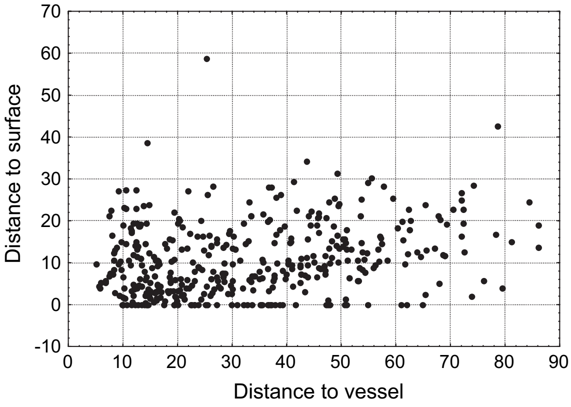

Figure 4. Relationship between school depth (distance to the surface) and distance to the vessel (distances in metres; measured on the 2-D database).

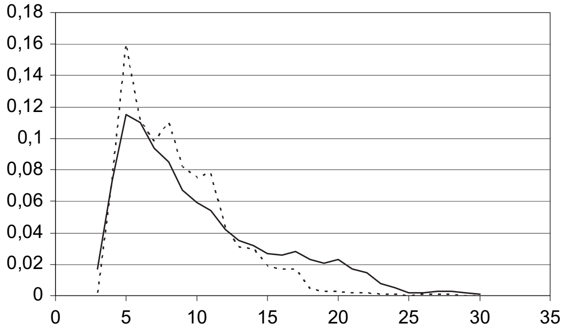

Figure 5. Distribution of mean NASC (solid line) and number of schools (broken line) for each depth layer below the VES transducer. X-axis = depth in metres; Y-axis = frequency in % (measured on all the VES survey data).

blind area" (i.e. the first 10 m), where limited acoustic information is available (Gerlotto and Fréon, 1992; Vabö *et al.*, 2002). Using the MBS, we can obtain some information on the way fish occupy this near-surface layer, and evaluate whether the distribution of fish below the vessel is the result of vertical avoidance.

Our observations indicate that the vertical distribution of biomass and schools shows a clear, albeit limited, vertical avoidance from the surface during our survey up to a distance of approximately 5−10 m. The apparent contradiction between (i) no visible vertical avoidance when observing the whole schools and (ii) a demonstrated vertical avoidance when observing the NASC values and the horizontal cross-sections, shows that avoidance is restricted to a very limited area below the vessel. For a given school, only the part entering in close proximity to the vessel will dive. This very limited diving behaviour is consistent with observations made by Gerlotto and Fréon (1992) on tropical Clupeids in Venezuela. However, we consider that in this case we are dealing with "physical protection" diving rather than avoidance per se. Fish have to leave the volume that will be occupied by the ship, which is certainly not the same behaviour as long-range "anti-predator" avoidance.

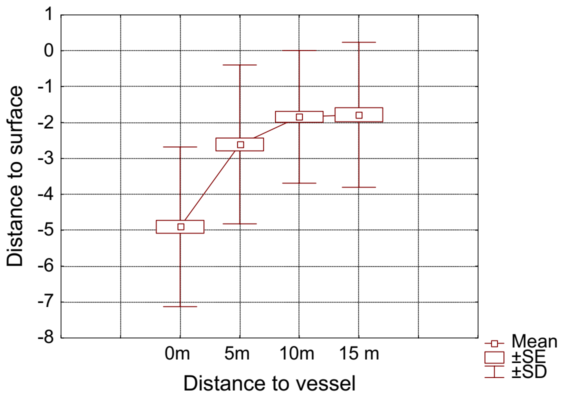

Figure 6. Box-plot presenting the mean (square), standard error (box), and standard deviation (whiskers) for the distance between the upper part of a school and the surface at 0, 5, 10, and 15 m off the side of the vessel.

As schools do not present avoidance reactions to the vessel, we can assume that the dimensions and structures we measured represent the natural school characteristics. We observed two main categories of aggregations: schools, with diameter less than three times the height, and "layers", with a diameter much longer than the height (over 10). These two structures do not present any significant difference in density or internal structure (holes), but are different in their overall dimensions and position in the water column: layers were observed in close proximity to the surface (fish could even be seen from the deck), while schools were deeper. The overall horizontal dimension value may be biased by the relatively small sonar observation range: large layers (more than 100 m in diameter) are not thoroughly sampled. This may explain why the layers are much shorter in the 3-D base than in the vertical echograms. However, this may be due to a bias in the echograms which makes it difficult to define the real dimensions of aggregations using a vertical echosounder, and several distinct aggregations may be seen as a single one.

Schools are almost four times thicker than the layers. In our database, height is the discriminating factor between schools and layers. From these observations, it appears that fish aggregations are structurally similar (internal characteristics), but their shapes may be determined by external factors, producing schools or layers. Two main potential factors might be suspected: the overall abundance of fish in the area and/or the bottom depth, but their contribution remains unclear.

Conclusions

Generally, we can conclude that in the central zone of Chile, sardine and anchovy do not avoid survey vessels, despite a limited vertical diving of the fish and schools below the hull, with a range that should be around 5 m. Such behaviour is highly favourable to acoustic assessment: fish which are normally located in the "acoustic blind volume" close to the sea surface become observable by the VES when diving. If correct, this implies that there is no bias due to avoidance (horizontal or vertical) or presence in inaccessible sectors, in the sardine and anchovy acoustic abundance estimates in central southern Chile. The only possible effect of this diving behaviour of fish that might affect TS values is if the fish are in motion when the ship passes over them. Some TS analyses could document this point. However, the occurrence of avoidance should be evaluated within a range of environmental and exploitation conditions and no general behaviour should yet be assumed. Therefore, the only safe way to evaluate the possible effects of fish avoidance on acoustic abundance estimates consists in measuring it as part of any survey.

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