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Seasonal hydro-acoustical observations of small pelagic fish behaviour in Bahía Magdalena, Mexico

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Abstract — Bahía Magdalena, located on the southwest coast of Baja California Sur, Mexico (24°20'N, 111°30'W), is an important area for fishing of small pelagic fish. The Pacific sardine (*Sardinops caeruleus*) comprises more than 75 % of the total catch in the bay. Hydro-acoustic surveys were carried out in this bay using a single-beam echo sounder, Simrad EY-200 (200 kHz), during three oceanographic surveys (March, July and December 1996). Results demonstrate that in July more than 75 % of the positive observations (those echograms with more than 100 echoes in the volume sampled) and most of the echo counts were recorded in the 5–10-m-deep layer. During March and December, positive echograms in the upper stratum were below 50 % and most of the echo counts were detected in the lower layer (10–20 m). These results were related to the availability of Pacific sardine to the commercial fleet, specifically to the capture-per-unit-effort. Results support the hypothesis that sardines migrate during late summer and autumn and that a new recruitment occurs during the winter within the bay. © 2000 Ifremer/Cnrs/Inra/Ird/Cemagref/Éditions scientifiques et médicales Elsevier SAS

Hydro-acoustics / seasonal migration / Pacific sardine / *Sardinops caeruleus* / Bahía Magdalena / Pacific Ocean

Résumé — Les observations hydro-acoustiques et saisonnières sur le comportement des poissons pelagiques de petites tailles dans la baie de Madgalena. La baie de Madgalena, située au sud-ouest de la partie sud de la Basse Californie, au Mexique (24°20'N, 111°30'W), est une région très importante en ce qui concerne la pêche des poissons pélagiques de petites tailles. Dans cette baie, la sardine du Pacifique (*Sardinops caeruleus*) représente plus de 75 % des prises. Trois campagnes hydro-acoustiques ont été effectuées dans cette baie au moyen d'une échosonde Simrad EY-200 (kHz) en mars, juillet et décembre 1996. Les résultats montrent qu'en juillet, plus de 75 % des observations positives (celles ayant plus de 100 échos dans le volume étudié) ainsi que la plupart des échos furent enregistrés dans la couche comprise entre 5 et 10 m de profondeur. En mars et décembre, les échogrammes positifs dans cette couche furent inférieurs à 50 % et la plupart des comptages (échos) furent enregistrés dans la couche inférieure, de 10 à 20 m. Ces résultats furent reliés à la disponibilité de la sardine du Pacifique et celle de la flotte commerciale, et en particulier à la capture par unité d'effort. Ces résultats confirment l'hypothèse de la migration des sardines à la fin de l'été et de l'automne ainsi que celle de leur retour dans la baie pendant l'hiver. © 2000 Ifremer/Cnrs/Inra/Ird/Cemagref/Éditions scientifiques et médicales Elsevier SAS

Hydro-acoustique / migration saisonnière / sardine du Pacifique / *Sardinops caeruleus* / baie de Magdalena / océan Pacifique

1. INTRODUCTION

The area extending along the Pacific coast of the United States and northern Mexico is one of the major coastal upwelling ecosystems of the world. In these regions, small pelagic fish such as sardine and anchovy exist in considerable biomass. Starting in the early 1900s, the harvesting and processing of the California

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sardine (*Sardinops caeruleus*) became a major industry. On the west coast of Baja California, Mexico, at least two populations of sardines have maintained a sustained fishery. These are based in the northern port of Ensenada (30°N), and in the south of Baja California, in Bahía Magdalena (24° N) [9]. In Bahía Magdalena, there are two canneries with fishmeal plants and the fleet size has been relatively constant over the years, five to seven boats with capacities between 60 and 120 metric tons. Fish-catch monitoring in Magdalena shows that small pelagic species are captured throughout the year. More than 75 % of the total catch is Pacific sardine (*S. caeruleus*). However, Pacific mackerel (*Scomber japonicus*), herring thread (*Opisthonema libertate*), and anchovy (*Cetengraulis mysticetus*) are also captured. The Pacific sardine population is composed of seven age groups, the most common in the catches being age groups 1, 2 and 3 (< 16 cm) [7, 8]. The fishing activity in the bay is well documented [8, 9]. These investigations claim that during the early part of the year a reproductive stock of *S. caeruleus* inhabits the bay. Later in the year, the oldest sardines (largest size-classes) apparently migrate outside the bay, although the small age-classes remain within the bay throughout the year. However, investigations on changes in fish distribution and abundance through the seasons are virtually nonexistent. Hydro-acoustic monitoring is a valuable tool to estimate population size and schooling behaviour [17]. We surveyed the main opening of the bay (about 4 km wide) to study the small pelagic fish behaviour using hydro-acoustics and fishery data. In particular we wanted to explain how the small pelagic fish species are distributed inside and outside the bay, how the abundance and fish length distribution changes between seasons and what the relationship is between fish school distribution and the environmental conditions.

2. MATERIALS AND METHODS

Three oceanographic surveys were carried out in the main mouth of Bahía Magdalena, Mexico (24°20'N, 111°30'W) (*figure 1*) during March, July and December 1996, on board the R/V 'El Puma' (50 m long). An 18-km-long transect was defined in each survey to cover three zones, each about 6 km long: inside the bay, with a maximum depth of 30 m; at the bay's mouth, with depths between 30 and 50 m; and the open sea, outside the bay with an average depth of 100 m. We established three sampling stations located at the ends and the middle of the transect. Recording of the water column using hydro-acoustics was carried out starting from the open-sea area, heading inside the bay, returning to the middle station, and finishing at the open-sea station again about 4 h later. We repeated this circuit about eight times during each cruise. Using this procedure, we had echograms (i.e. a sector between stations) on the neritic part of the bay, the mouth area and in the open sea.

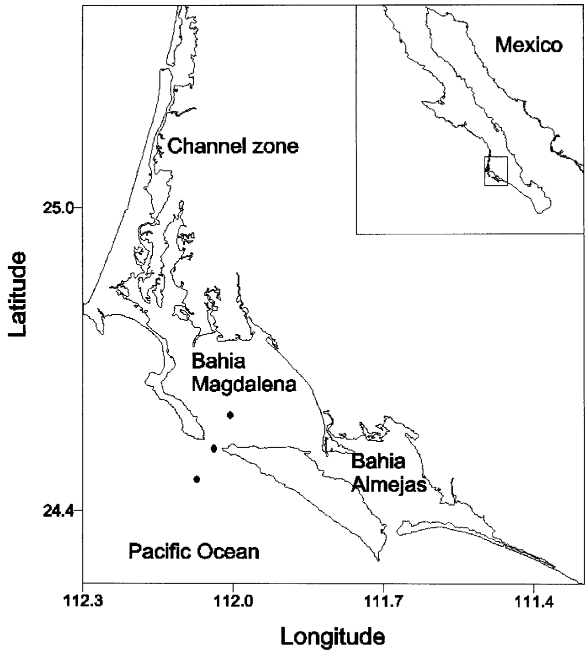

Figure 1. Map of the area of study indicating the sampling stations.

The ship speed along the oceanographic transect was on average 9 knots. At each station, temperature and salinity along the water column were recorded using an Inter-Ocean SO4 CTD. An Isaacs-Kid midwater net (4-m-wide mouth) was used between stations where acoustic information showed the presence of strong echoes. Sea surface temperature and salinity (4 m deep) were recorded continuously with a thermosalinometer fitted to the ship's hull. Observations started on 19 March at 14:30 hours and finished on 21 March at 12:00 hours. In July, observations started on the 9th at 14:00 hours and finished on the 11th at 11:00 hours. In December, observations started on the 6th at 19:00 hours and finished on the 11th at 11:00 hours.

2.1. Hydro-acoustic system

Hydro-acoustic data were collected using a Simrad EY-200 single-beam echo sounder, 200 kHz, with a nominal beam width of 7 degrees. The transducer depth was 4 m and the echo analysis started 1 m from the transducer, i.e. 5 m below the surface. The unit was calibrated with a 13.7-mm copper sphere (–45 dB). Pulse duration was set at 0.3 ms and because we performed echo counting, a 40 LogR TVG function was set [17]. Ping rate was 1.7 pings per second and the minimum threshold noise level was 400 mV. For analysis, we used the hydro-acoustic data acquisition system (HADAS, version 4.01) developed by Lindem and Houari [14]. This is an echo-counting method that transforms the received echo distribution into area densities and hence abundance estimates. The system is based on a combination of hardware and computer software that together provide the capability to digitise and store hydro-acoustic data. To calculate target strength, HADAS uses a modification of the Craig and Forbes [4] algorithm to remove the beam pattern effect.

For analysis, the target strength range was set from –45 to –37 dB. Love [16] published an algorithm to estimate the size of the fish using the target strength data. He collected hydro-acoustic data on many species using several echo sounders operating from 15 to 1 000 kHz. According to his equation: TS = 19.1 log L + 0.9 log λ – 23.9 dB, where TS = target strength, L = total length of the fish (m), and λ = length wave (m), the target strength analysed in this study for a 200-kHz transducer, mean fish body lengths between 10 and 26 cm long. Moreover, this equation showed a good consistency with data obtained using our equipment on anchovies (*Engraulis mordax*) 8–14 cm long as determined by Isaacs-Kid catches on the west coast of Baja California [20].

2.2. Fishery data

Catch and fishing effort data from San Carlos harbour in Bahía Magdalena were obtained from the cannery's business records every 2 months. Information includes species, landing (metric tons) and number of trips. For more detailed methodology concerning the registered landing of small pelagic fish in Bahía Magdalena, see Félix-Urage [8] and Félix-Uraga et al. [9]

3. RESULTS

3.1. Environmental conditions

A temperature–salinity (TS) diagram indicates significantly different environmental conditions at each month (*figure 2*). During March, well-mixed water with low salinity (34.2–34.4), low temperatures (14 and 18 °C), and a weak and shallow thermocline (0–10 m deep) was the result of the California current or local upwelling (*figures 3* and *4*). During July, the initial influences of the North Equatorial current were clear, with increased salinity (34.23–35.0), temperatures (16–21 °C) and a strengthening of the thermocline (about 15 m) (*figures 3* and *4*). During December, salinity and temperatures were highest (34.6–34.9 and 21–23 °C) and the thermocline was deepest (about 30 m in the oceanic area). On average, the zone around the opening bay had significantly lower values of temperature than the littoral and oceanic zones (two-way ANOVA, $P < 0.05$). This could be the result of strong tidal currents favouring mixing in this region. However, no significant difference was found in diurnal values of temperature and salinity (two-way ANOVA, $P > 0.05$).

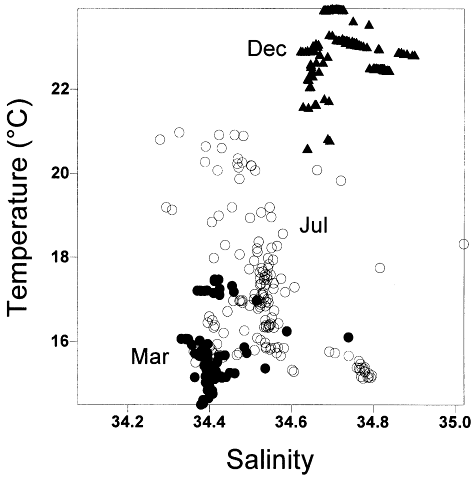

Figure 2. Temperature salinity relation of an 18-km-long transect during March (closed circles), July (open circles) and December (triangles) 1996 in Bahía Magdalena.

3.2. Hydro-acoustic records

All results are presented with data gathered during the night, between 19:00 and 05:00 hours, when fish are most dispersed. This is important because the echo-counting analysis is based on the size distribution of single fish echoes [17]. To evaluate fish distribution and behaviour the water column was split into two layers, 5–10 and 10–20 m in depth.

3.3. Overall descriptive behaviour from the echograms

Figure 5 shows the sardine's typical schooling behaviour observed in the echograms each month, summarised from the 226 echograms obtained. During March, most of the echoes were observed inside the bay close to the bottom (*figure 5a, b*). In July, abundance increased in the upper layer (5–10 m) and the echoes were more dispersed, covering inside the bay and the mouth region (*figure 5c, d*). During this month, a bloom of red crab *Pleuroncodes planipes* (Crustacea: Galatheidae) was observed in deeper waters outside the bay. During December most of the echoes were observed close to the bottom, inside the bay and in dense, discrete schools (*figure 5e, f*).

3.4. Positive echograms

For analysis we defined the criteria of positive echograms as those with more than 100 echoes in the volume sampled. *Table I* shows results of positive echograms for regions and depth during the three seasons. During March, the 10–20-m-deep layer had most of the positive observations, except outside the bay where none of the echograms analysed in this stratum were positive. During July, the three regions had high positive observations in both strata. During

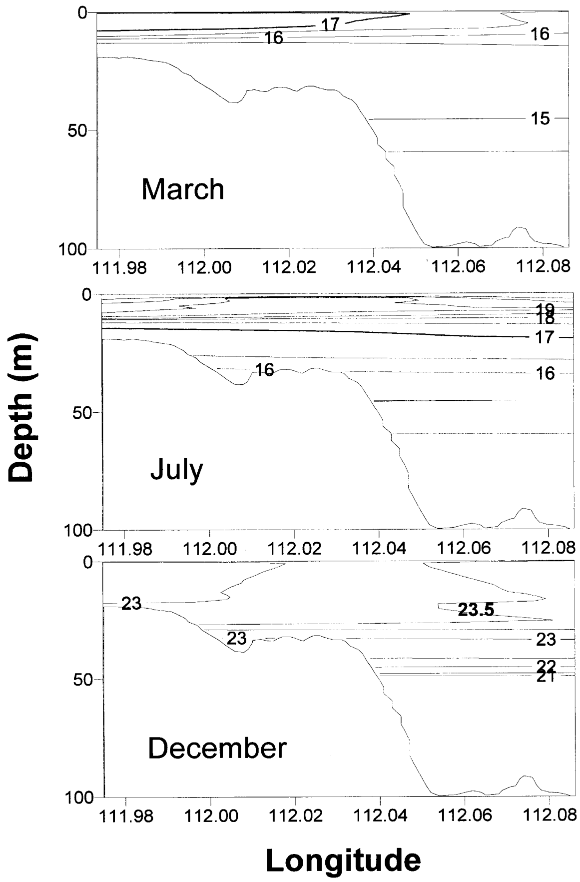

Figure 3. Vertical temperature distribution along the oceanographic transects in Bahía Magdalena.

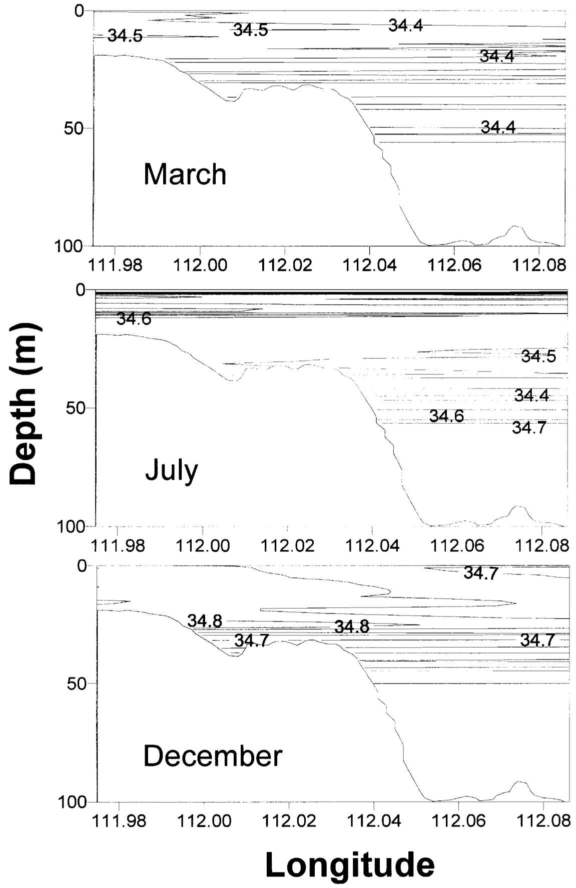

Figure 4. Vertical salinity distribution along the oceanographic transects in Bahía Magdalena.

Table I. Numbers of positive echograms, those with more than 100 echoes, observed in two depth layers during March, July and Decembre 1996 and the three regions in Bahia Magdalena. The number of echograms analysed is shown in parenthesis.

Months	Inside the bay		Mouth of the bay		Outside the bay	
	5–10 m	10–20 m	5–10 m	10–20 m	5–10 m	10–20 m
March	1 (8)	6 (8)	0 (13)	13 (13)	5 (18)	0 (18)
July	9 (13)	10 (13)	11 (12)	12 (12)	9 (12)	8 (12)
December	1 (12)	9 (12)	2 (11)	6 (11)	0 (14)	0 (14)

Table II. Mean number of individual echoes (transformed to natural logarithm) in two depth layers during March, July and December 1996 and three regions in Bahía Magdalena. The number of echograms analysed is shown in parenthesis.

Months	Inside the bay		Mouth of the bay		Outside the bay	
	5–10 m	10–20 m	5–10 m	10–20 m	5–10 m	10–20 m
March	0.8 (8)	4.3 (8)	1.0 (13)	3.6 (13)	0.7 (18)	1.3 (18)
July	3.1 (13)	2.3 (13)	3.4 (12)	2.5 (12)	2.9 (12)	2.3 (12)
December	1.1 (12)	4.8 (12)	1.7 (11)	4.0 (11)	1.2 (14)	1.5 (14)

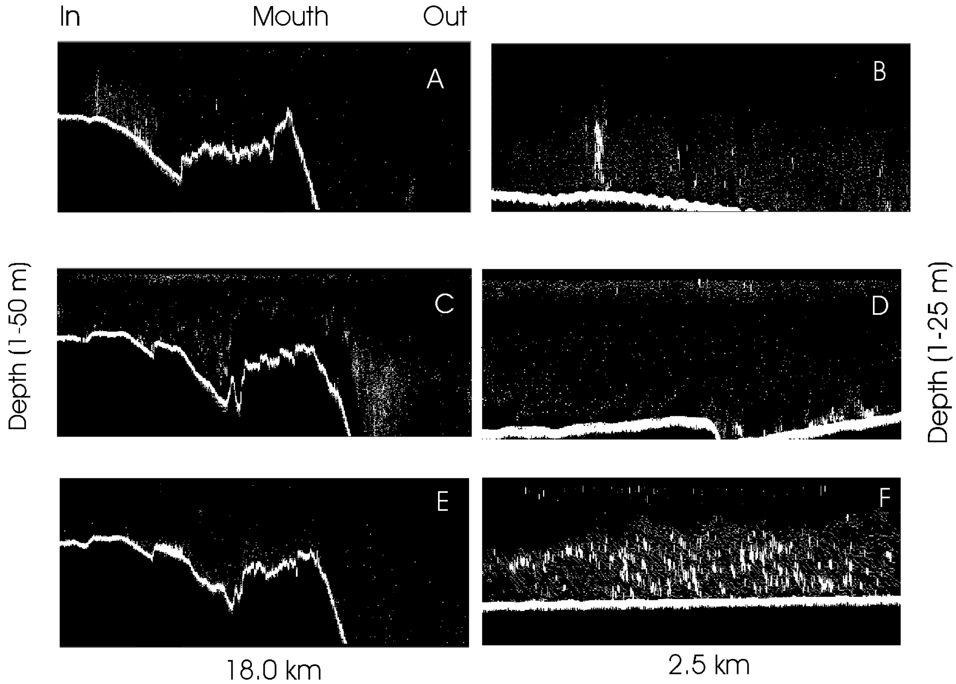

Figure 5. An example of echograms obtained during the three cruises. The white continuous layer is the bottom. (A) The whole transect in March; (B) a zoomed view of the previous echogram showing the shallower part of the transect; (C) the whole transect in July; (D) a zoomed view of the previous echogram presenting an area between the shallower part of the transect and the mouth; (E) the whole transect in December; (F) a zoomed view of an echogram obtained inside the bay during December, not shown in E.

December, most of the echoes were recorded inside the bay and in the mouth within the 10–20-m-deep stratum.

3.5. Echo counting within seasons

Since a 40 LogR TVG function was used we were not able to estimate fish density. However, echo counting was used to describe the distribution of echoes. To do this we counted the number of echoes for each echogram, within the range –45 to –37 dB, and converting to natural logarithm to normalise the data set.

In March, inside the bay and in the mouth region, the mean number of echoes counted in the deeper layer was significantly higher than in the upper layer (ANOVA, $F = 29.5$, $P < 0.001$; $F = 17.0$, $P = 0.001$). Outside the bay, there were no significant differences ($F = 1.10$, $P > 0.05$). A comparison between regions and integrating both strata showed that the mean number of echoes in the mouth and inside the bay were significantly higher than outside the bay (F = 12.30, $P < 0.001$) (*table II*).

During July, the mean number of echoes in both layers in the three regions was not significantly different ($F = 2.68$, $P > 0.05$; $F = 2.45$, $P > 0.05$; $F = 0.150$, $P > 0.05$). Moreover, there were no differences between regions ($F = 1.69$, $P > 0.05$) (*table II*).

In December, inside the bay and in the mouth, most of the echoes came from the lower layer ($F = 15.6$, $P < 0.001$; $F = 25.3$, $P < 0.001$). In the ocean, there were no significant differences ($F = 1.10$, $P > 0.05$; $F = 0.95$, $P > 0.05$). A comparison between regions integrating both strata showed that the mean number of echoes in the mouth and inside the bay is significantly higher than outside the bay ($F = 9.86$, $P < 0.001$) (*table II*).

3.6. Echo counting between seasons

Comparisons were made by pooling echo counting from the three regions and comparing between depths. In the lower layer the mean number of echoes increased from March to December (March 2.29, number of echograms in the analysis $n = 39$; July 2.43, $n = 37$; December 3.43, $n = 37$) ($F = 3.50$, $P < 0.05$). In the upper layer the maximum was observed in July (March 1.2, $n = 39$; July 3.2, $n = 37$; December 1.37, $n = 37$) ($F = 30.79$, $P < 0.001$).

3.7. Target strength histogram distribution

To calculate TS distribution and in order to avoid bias with multiple echoes [3], we used echograms where single echoes were evident. In some echograms with dense concentrations (such as those observed in December), TS was obtained in the periphery of the

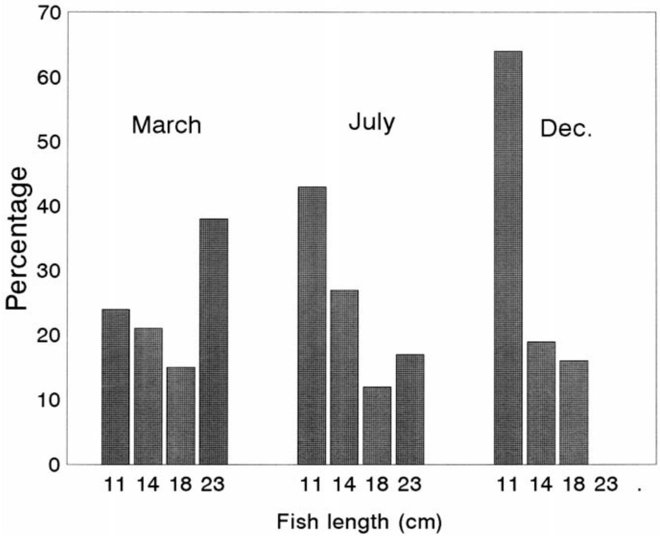

Figure 6. Relative frequency of abundance for fish length calculated using the relation acoustic intensity–fish length proposed by Love [16].

schools. In each survey, size echo-distribution was particularly different (*figure 6*). In March and July, the range of TS analysed showed a similar distribution of fish sizes ranging from 14 to 23 cm. In July the distribution of TS changed to smaller organisms, but there were still large organisms in the sampling. In December, most of the echoes came from small organisms (11.5–15.5 cm accounted about 81 %) indicating recruitment at this size range inside the bay. During this month the larger fish (> 23 cm long) disappeared from the size distribution.

3.8. Small pelagic fishery in Bahía Magdalena

Commercial catches during 1996 comprised mainly three species: the Pacific sardine, *Sardinops caeruleus* accounting 73 % of the total catch, Pacific mackerel, *Scomber japonicus* (8 %), and herring thread, *Opisthonema libertate* (7 %). The commercial fishery also reported catch as a mix of Pacific sardine and mackerel, which together represented about 12 % of the total annual catch. From commercial catches it would appear that the Pacific sardine shows two peaks of abundance, from March to June and October to November. Although these peaks have more or less the same year-to-year, inter-annual differences occur. In general, when the Pacific sardine catches decrease, the mackerel catch increases.

Fishery data are presented for March–April, June–July and November–December (*table III*). During March and April 123 trips were registered capturing a total of 9.11×10^3 tons (74 % of the total being Pacific sardine). During June and July the number of trips and total captures were reduced to 33 and 43 %, respectively (~ 94 % of the total was Pacific sardine). However, capture-per-unit-effort (CPUE) for sardine increased 8 % and CPUE for other species was reduced 78 %. During November and December sardine capture was reduced to 45 % from that captured in the spring and the total catch reduced to 35 % (71 % of the total was Pacific sardine). CPUE of sardine was reduced to 16 % and CPUE for other species increased 94 %.

Commercial fishery uses the same mesh size net throughout the year. Therefore, differences in size–frequency distribution can indicate different size distributions of the population. Commercial catches give only the size–frequency distribution of the recruited population (> 10 cm). Two size–frequency groups were caught during 1996. The first peak of abundance including organisms from 16 to 20.5 cm in total length from January to September and the second peak composed of relatively small organisms 11.5–16 cm from October to December.

4. DISCUSSION

From this study, there are three main observations derived from hydro-acoustics differentiated among seasons: number of positive echograms, vertical distribution of echo counting and target strength distribution. However, the use of a single beam to detect size–frequency distribution should be analysed carefully. Using this technique it is possible to estimate single target strength referenced as a probability distribution; therefore, the size of the animals can be estimated only in a relatively wide range of sizes. In addition these are estimations of dorsal TS, and TS is known to change as a function of fish orientation.

Table III. Small pelagic fish landings (metrix tonx × 1 000) recorded in Bahía Magdalena during 1996. Results are for Pacific sardine *Sardinops caeruleus*. Pacific mackerel *Scomber japonicus*, herring thread *Opisthonema libertate* and the anchovy *Cetengraulis mysticetus* are included in the group ‘other’.

Months	Pacific sardine	Other species	Total catch	Percentage of Pacific sardine	Number of trips	CPUE Pacific sardine	CPUE others
March–April	6.74	2.36	9.10	74.0	123	54.8	7.2
January–July	4.88	0.32	5.20	93.8	83	58.8	1.6
November–December	3.72	1.10	4.82	77.1	81	45.9	13.5

CPUE, capture-per-unit-effort in metric tons per trip.

Moreover, this method does not completely allow knowledge of the fish size inside the schools.

4.1. Positive echograms, echo counting and fish capture

We were not successful in catching fish using the Isaacs-Kid mid-water net. However, several sources confirmed that what we observed from the echo sounder in the three cruises was Pacific sardine: first, data provided by the local fishery; second, radio information of catches obtained from the fishing boats on the same days that we were in the bay. Additionally, for the summer cruise, other sources were the observations made by Gallo-Reynoso [10] and our own direct observations on groups of sardines swimming near the surface. All these gave us the confidence to conclude that the high number of positive echograms and the high number of echoes observed in the upper layer during July were Pacific sardine schools. It is likely that the way that fish behave at this period of the year (i.e. swimming close to the surface) may contribute to the high CPUE reported for this species, specifically due to the increase in availability of Pacific sardine to the fleet. First, the high number of positive transects means that the resource is distributed over a wide area and may be easily found by fishermen. Second, the fact that the sardine is found in the upper layers may be translated as a manageable situation where fish are easily captured, since observations during the night of the surface schools are important to fishermen for catching sardines.

Fishery data show decreasing captures towards winter (*table III*). However, our hydro-acoustic data show an increase in density in the lower layer during December by small-sized fish. Explanation of such a discrepancy may lie in fish schooling behaviour. During December, our data show a reduced encounter rate with the schools (low positive echograms), but those encountered were high in density and swimming in the lower stratum. This means that fish were found in discrete, high-density isolated schools. For the fishery this behaviour could also increase the search time for schools. Moreover, contrarily to what is observed in July, schools have to be caught in deeper waters.

4.2. Seasonal vertical migration and schooling behaviour

Results suggest that in addition to the circadian up and down movements [20], the Pacific sardine undertake seasonal vertical migrations. This behaviour may be related to physical factors such as water temperature, daily amount of light, spawning behaviour, and/or seasonal migration of the preferred food [11]. The observations during July cannot be associated with reproductive mating schools because the peak of abundance of egg and larvae of this sardine species usually occur from January to March [21]. However, a strong thermocline was recorded in July; this stratification could keep most zooplankton biomass above or around the thermocline [22]. Since the adult population fed actively in and around the productive shallow waters of Bahía Magdalena [9], this may explain the sardine school observed near the surface during this month. In support of this hypothesis, Inagake and Hirano [13] found that Japanese sardines (*Sardinops melanostica*) moved to shallower layers when the seasonal thermocline became sharp resulting in the schools becoming thinner vertically but occupying a wider space horizontally. Holliday and Larsen [12] studying the anchovy schools of southern California, found a correlation between mean depth of the schools and the seasonal thermocline, arguing that water density microstructure may lead to an aggregation of some part of the fish food supply in thin layers.

Schooling behaviour during December may be related to fish size. It has been reported that some fish species form large schools as juveniles but increasingly smaller schools as they grow [5]. During this month schools were large, dense and composed of the smallest fish sizes recorded in this study. However, there are other observations where large fish tend to be found in large shoals compared with smaller fish [2]. Schooling behaviour is quite dynamic and may be the result of many factors other than physical variables. It may change owing to feeding patterns [19], presence of predators [6] and ultimately may reflect the individual fish decision to stay or leave the group [18].

4.3. Fish size distribution

Significant differences in the target strength distribution suggest that different populations were found throughout the year. Data from the local fishery and the hydro-acoustic data suggest that during January to March a reproductive stock composed of individuals larger than 16 cm long remains inside the bay. Magdalena is an important hatching area where egg and larvae abundance peaks from February to March [21]. After completion of the reproductive activity, the oldest and biggest sardines probably migrate outside the bay during late summer and fall. This hypothesis has been proposed in the past [23]. However, we are the first to provide direct observations independent of fishery catches. In the past, migrations of sardine stocks have been deduced indirectly from horizontal distribution range and centres of abundance [9, 15]. During December small individuals appear in the bay as indicated by both fishery and acoustic survey data. This may indicate a new recruitment due to the immigration of a southern subpopulation, presumably composed of younger animals [1, 8].

Further observation with a higher frequency sampling could provide more forceful information to verify the observations made in this study. However, because most of the bay has a depth of more than 10 m, a hydro-acoustical monitoring of all the bay cannot be carried out by the near-field effect of the echo sounder in shallower waters. This is an important shortcoming because some sardine schools have been seen in these shallower areas.

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