Acoustic Surveys of Abundance and Distribution of the Japanese Sardine *Sardinops melanostictus* in the Spawning Grounds off Southern Kyushu, Japan

Ichiro Aoki*¹ and Tadashi Inagaki*¹

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Distribution patterns of the spawning population of the Japanese sardine *Sardinops melanostictus* off southern Kyushu were investigated by the acoustic method in relation to water temperature and the Kuroshio current in three successive winters from 1990 to 1992. Acoustic data were obtained by single-beam 50 kHz echo sounders interfaced to digital integrators. Sardine distribution varied during January–March as time advanced. It was closely associated with both water temperature and spawning activity. Maturing sardine stayed on the inshore side of the Kuroshio front while spawning sardine occurred in the higher temperature offshore waters further than the Kuroshio front that appear to have acted as a barrier to distribution previously. The fish abundance in the area of sardine concentration decreased markedly over the 3 years.

The Japanese sardine *Sardinops melanostictus* is one of the most important fish species in Japanese fisheries. Annual sardine catches in Japan reached their highest level of 4,490 thousand tons in 1988. However, the catches began to decrease in 1989, being 3,680 thousand tons in 1990, 3,010 thousand tons in 1991 and 2,300 thousand tons in 1992.

It has been known that during periods of high abundance, the spawning grounds of the Japanese sardine mainly occur in the area around southern Kyushu, southwestern Japan.^{1,2)} In 1980 the main spawning grounds were formed off southern Kyushu as in the 1930s when population levels were high. Then the distributions of sardine eggs and larvae began to extend offshore in the main stream area of the Kuroshio current in 1983, this tendency showing a yearly increase in the 1980s.³⁾ Japanese sardine inhabit the inshore side of the Kuroshio current.⁴⁾ They usually occur in a water temperature range of 10 to 17°C⁵⁾ or 10 to 20°C.⁶⁾ The extension of the distribution into the Kuroshio area where temperature >20°C appears to be a significant feature found only in the spawning season.

There has been limited information on the distribution of adult Japanese sardine in the spawning season. Kuroda⁷⁾ has reported on the occurrence of adult sardine collected by fishing in the Kuroshio area. However, detailed information on the abundance and distribution of pelagic fish

in time and space would be difficult to obtain by fishing alone. Acoustic techniques provide rapid and continuous measurements throughout the water column and more complete information on the distribution and behavior of pelagic schooling fishes. This study investigated horizontal distribution patterns of spawning sardine in relation to water temperature and the Kuroshio current off southern Kyushu in three successive winters from 1990 to 1992 using the acoustic method.

Materials and Methods

Acoustic data on the spawning population of sardine were obtained during four cruises conducted in the area off southern Kyushu (Table 1). Single-beam 50 kHz echo sounders were used: a Furuno FQ-50 mounted on the RV 'Tansei Maru' (470 t) and a Furuno FQ-71 on the RV 'Hakuho Maru' (3,987 t). Each echo sounder was interfaced to a digital integrator, logging system, and personal computer. Transducers were hull-mounted. The acoustic systems processed echoes and output the mean volume backscattering strength (*SV* in dB) in real time for nine 10 m depth strata from 10 to 100 m at horizontal integration intervals of 0.2 or 0.4 nautical miles (nm). Acoustic surveys consisted of grid surveys with wide areal coverage and repeated surveys along a transect. The surveys were conducted in the

*¹ Ocean Research Institute, University of Tokyo, Nakano, Tokyo 164, Japan (青木一郎, 稲垣 正: 東京大学海洋研究所).

Table 1. Dates of acoustic surveys, and settings and calibration parameters of acoustic equipment

Cruise	KT-90-3	KT-91-1	KH-91-2	KT-92-3
Date	MAR 3-9, 1990	JAN 20-23, 1991	Leg 1 FEB 14-22, 1991 Leg 2 FEB 26-MAR 1, 1991 Leg 3 MAR 9-14, 1991	FEB 25-MAR 3, 1992
Echo sounder	FQ 50	FQ 50	FQ 71	FQ 50
Source level (dB)	223.0	223.3	219.3	225.2
Pulse duration (ms)	1.2	1.2	1.2	1.2
Equivalent ideal beam factor (dB)	-19.6	-19.6	-14.5	-19.6
Absorption coefficient (dB)	12.0	12.0	14.3	12.0
Receiving sensitivity (dB)	-182.8	-182.4	-184.2	-182.8
Amplifier gain (dB)	49.2	49.2	46.8	49.2

KT and KH denote RV 'Tansei-Marū', respectively.

daytime and night-time at a ship speed of about 10 knots.

The acoustic calibration of the systems was performed in port at Tokyo before each cruise for KT-91-1 and KH-91-2 or after each cruise for KT-90-3 and KT-92-3. Source level and receiving sensitivity were measured by means of a hydrophone, and the gain of amplifiers of the systems was also measured. Parameter settings of the acoustic systems are shown in Table 1.

The absorption coefficient requires attention because it depends on oceanographic conditions such as water temperature and salinity. The acoustic surveys were made with the absorption coefficient set by anticipation on the values in Table 1. The actual absorption coefficients based on oceanographic conditions were calculated using CTD data in the cruise KH-91-2 and Francois and Garrison's equation⁹⁾ for two representative sites of the inshore and the Kuroshio regions: 13.75 dB/km for the inshore region and 12.75 dB/km for the Kuroshio region in the range of 0 to 100 m depth. The setting values of the absorption coefficient in this study differed by 1.74 dB/km at most from the calculated values. This difference corresponds to a bias of 0.174 dB (4%) at 50 m depth. There was a difference of 2.3 dB/km in the absorption coefficient between the two acoustic systems, which corresponds to 0.23 dB (5%) at 50 m depth. Because this is likely to be a minor source of error in the 10 to 50 m depth range for which acoustic data were analyzed, no correction was made for the absorption coefficient.

Fish traces above 50 m depth on echograms were identified by a gill net, fishing lines, and underwater TV. Sardine predominated considerably in fish collections, while other fish species

including mackerel, scads, and round herring occupied only a small portion of the collections. In addition, schooling sardine were observed consistently by the underwater TV. Therefore, fish traces above 50 m depth were assumed to be due to sardine shoals. Acoustic data analysis was restricted to the 10 to 50 m depth range, because (1) the vast majority of sardine were recorded above 50 m depth and (2) echo traces which were shaped differently from those of sardine shoals in the upper layer were observed sometimes below 50 m depth.

The scaled body length and body weight of the sardine collected were measured and used for calculations of target strength and biomass. Maturity data were also obtained from the samples, but they are described briefly in this paper. For further details on maturity, consult Aoki and Murayama⁹⁾ and Murayama *et al.*¹⁰⁾

Surface temperature data were collected along tracklines throughout the surveys with a continuous sea water temperature recorder. Temperature profiles were obtained from CTD casts. Sardine were distributed in the surface mixed layer, where temperature was similar to surface temperature.

The mean *SV* was converted to the mean fish density using the following equations (1) and (2).

$$n = 10^{0.1(SV - TS)} \quad (1)$$

$$TS = -68.2 + 20 \log FL \quad (2)$$

where *n* is the mean fish density in number (no. of fish/m³), *SV* the mean volume backscattering strength in dB, *TS* the target strength in dB, and *FL* the fork length in cm. The *TS*/length relationship at 50 kHz was derived from Miyano-hana *et al.*¹¹⁾ Mean target strengths were obtained for

Table 2. Body length and body weight of sardine sampled and target strength calculated according to Miyano-hana *et al.*¹¹⁾

Cruise	Sample size	Body length (cm, mean $\pm$ SD)	Body weight (g, mean $\pm$ SD)	Mean target strength (dB)
KT-90-3	71	19.5 $\pm$ 0.93	75.3 $\pm$ 11.7	-42.0
KT-91-1	65	19.7 $\pm$ 0.62	90.3 $\pm$ 8.1	-41.9
KH-91-2 Leg 1	200	19.2 $\pm$ 0.72	78.4 $\pm$ 9.3	-42.1
Leg 2	292	19.4 $\pm$ 0.72	85.2 $\pm$ 11.6	-42.1
Leg 3	229	19.7 $\pm$ 0.77	85.1 $\pm$ 12.2	-41.9
KT-92-3	8	19.4 $\pm$ 0.78	84.5 $\pm$ 8.9	-42.1

each of the cruises using equation (2), with mean fork lengths calculated from mean scaled body lengths (fork length = $0.970 \times$ body length + 1.44, $r = 0.926$, $n = 20$) (Table 2). Next, the mean fish density in weight per unit surface area (D , g/m²) was computed as follows.

$$D = n \times BW \times R \quad (3)$$

where BW is the mean body weight in g, and R the integration depth range, *i.e.* 40 m. Hereinafter D is referred to as the mean fish density.

Results

The mean SV for the 10 to 50 m depth range and the 5 nm distance interval was calculated and converted to the mean fish density. The distributions of mean fish densities in 1990, 1991, and 1992 are illustrated along tracklines with isotherms (Figs. 1–3). The Kuroshio current region approximately corresponded to surface temperature $>20^\circ\text{C}$. Each 5 nm-segment was classified by observing echograms: one where echo traces of small pelagic schooling fish occurred, and the other where only weak diffuse scattering layers due to plankton appeared. The mean SV in the former segment was converted to fish density, and for the latter segment fish density was defined as $D = 0$.

In 1991, it is evident that sardine distribution varied during January–March as time advanced. Sardine occurred mostly in the coastal region where temperature $<19^\circ\text{C}$ from late January to mid February (Fig. 2a, b). The pattern changed toward early March, when sardine were found offshore in the frontal and Kuroshio regions where temperature $>20^\circ\text{C}$ (Fig. 2c). Then, in mid-March most sardine were again concentrated in the coastal waters $<19^\circ\text{C}$, while a few shoals were found in the Kuroshio region (Fig. 2d). Comparing distribution patterns in the same period of early March among the 3 years, though fish densities were different, it is consistent that sardine

Fig. 1. Distribution of sardine densities off southern Kyushu during March 3–9, 1990.

Vertical bars show the mean densities of sardine (g/m²) for the 10–50 m depth range and 5 nm distance intervals. Thin solid lines: tracklines of the vessel; thin broken lines: surface isotherms in 1°C steps. For the area enclosed by bold broken lines sardine abundance was estimated in the 3 years 1990–1992.

shoals were generally aggregated in the inshore waters $<19^\circ\text{C}$ along the coast of southern Kyushu and occurred occasionally in the offshore Kuroshio region (Figs. 1, 2d, 3).

Figure 4 shows variations in SV and surface temperature along transects off Cape Hi-saki cross-

Fig. 2. Distribution of sardine densities off southern Kyushu during January–March, 1991.

Vertical bars show the mean densities of sardine (g/m^2) for the 10–50 m depth range and 5 nm distance intervals. Thin solid lines: tracklines of the vessel; thin broken lines: surface isotherms in 1°C steps. a: January 20–23; b: February 14–17 and 20; c: February 26–March 1; d: March 9–12. Locations of Cape Sata, Cape Hi-saki and Cape Toi are shown by A, B, and C, respectively in panel (a).

sing the Kuroshio front. The SV values were higher as a whole on the inshore side of the front than in the Kuroshio region beyond the front. It seems that the Kuroshio front acts as a barrier to the distribution of the sardine.

The results of the repeated surveys along the same transect crossing the Kuroshio front in 1991 indicated a change in sardine distribution (Fig. 5). From February 28 to March 1, the majority of sardine were concentrated in the Kuroshio waters $>20^\circ\text{C}$, while sardine distribution was confined to the inshore side of the 20°C isotherm for other periods. At that time, the sardine moved offshore in response to an offshore shift in the Kuroshio current. The situation is illustrated in Fig. 6 by the distribution of SV and the vertical section of temperature along the transect. Ovarian histologi-

cal examinations of the female sample collected at the same times showed that most of them had either translucent hydrated eggs, new postovulatory follicles, or migratory nucleus oocytes, being about to spawn or in the act of spawning. On the other hand, another sample caught at a location 25 nm distant from the coast on February 25 contained only females having ovaries at the developing stage. The sardine distribution was closely associated with both water temperature and spawning activity. Also, in March 1990, ovarian histology indicated that spawning activity was higher in the Kuroshio region than in the inshore region.¹²⁾ Only 2 females were caught inshore in March 1992, and they were at the yolk stage. In conclusion, maturing sardine stayed on the inshore side of the Kuroshio front while spawning sardine

Fig. 3. Distribution of sardine densities off southern Kyushu during February 25–March 3, 1992.

Vertical bars show the mean densities of sardine (g/m^2) for the 10–50 m depth range and 5 nm distance intervals. Thin solid lines: tracklines of the vessel; thin broken lines: surface isotherms in 1°C steps.

occurred in higher temperature offshore waters further than the Kuroshio front.

Fish abundance variations in time and space were further analyzed for the area east of Cape Sata from the fish density map shown in Fig. 2. The area was divided into 4 subareas by a south-eastward line from Cape Toi and 20 nm distant line from the coast. (1) NI: inshore and north of Cape Toi, (2) NO: offshore and north of Cape Toi, (3) SI: inshore and south of Cape Toi, and (4) SO: offshore and south of Cape Toi. Generally, surface temperature was below 20°C within the 20 nm distance from the coast and above 20°C beyond the 20 nm distance.

As the survey area was varied, relative abundance rather than absolute abundance was considered for comparison in time and space. Fish abundance (B) can be expressed as

$$B = (\overline{sv}/\sigma_{bs}) \times m \times R \times A$$

where $\overline{sv}$ is the mean volume backscattering coefficient ($10 \log \overline{sv} = \overline{SV}$) for the whole 5 nm-segment where sardine echo traces were observed, σ_{bs} the

Fig. 4. Variations in volume scattering strength (SV) and surface temperature (T) along a transect off Cape Hi-saki crossing the Kuroshio front.

SV is the mean for the 10–50 m depth range and 0.2 nm (a) or 0.4 nm (b) distance intervals. a: 1639–2217 hr, March 3, 1990; b: 0640–0935 hr, March 14, 1991. The location of Cape Hi-saki is indicated in Fig. 2a.

mean backscattering cross section ($10 \log \overline{\sigma_{bs}} = \overline{TS}$), m the number of 5 nm-segments where sardine echo traces were observed, R the integration depth range ($R=40$ m), A the hypothetical area represented by one 5 nm-segment. As R and A are constant, $(\overline{sv}/\sigma_{bs}) \times m$ is proportional to sardine abundance. Next, fish abundance index (BI) was defined as

$$BI = 10 \log ((\overline{sv}/\sigma_{bs}) \times m) \\ = \overline{SV} - \overline{TS} + 10 \log m$$

The abundance index in the inshore areas increased by about 2 orders of magnitude (18 dB) in mid-February compared with those in late January, and it was higher in the southern area than in the northern area (Fig. 7). At the beginning of March sardine in the SO subarea were 20 times (13 dB) as abundant as those the SI subarea. In mid-March the abundance index showed a tendency to increase in the northern areas in contrast to February. These variations in relative fish abundance in the 4 subareas probably reflected fish movements in the spawning season.

Fish abundance was estimated for the same area where sardine occurred most frequently and

Fig. 5. Change in fish densities along the same transect crossing the Kuroshio front during January–March, 1991.

The mean densities of sardine (g/m^2) for the 10–50 m depth range and 5 nm distance intervals are given. Isotherms in 1°C steps are also shown. Small circles denote no fish shoal. The location of Cape Hi-saki is indicated in Fig. 2a.

for the same period in the 3 years 1990–1992 (Table 3). The estimates were obtained by simply averaging fish densities within this area and by multiplying it by the area. The estimated spawning biomass in this area decreased annually, and in 1992 it reached only 6% of the level of 1990.

Discussion

Acoustic surveys in the spawning grounds off southern Kyushu in 1990–1992 indicated that the distribution of the spawning population of the Japanese sardine was closely associated with water temperature or the Kuroshio front, and that its

abundance decreased markedly over the 3 years. Especially, repeated surveys during January–March 1991 revealed that sardine were aggregated on the lower temperature inshore side of the Kuroshio front at the beginning and end of the spawning season, and that the majority of spawning sardine occurred in the Kuroshio region where temperature $>20^\circ\text{C}$ in the peak spawning period. The physiology of spawning seems to change the preference for temperature. Spawning sardine crossed the Kuroshio front, even though it appeared to have acted as a barrier to distribution till then. Around 1950, when stock levels were low, the Japanese sardine spawned inshore on the con-

Fig. 6. Distribution of volume scattering strength (SV) along the same transect as in Fig. 5 crossing the Kuroshio front February 28–March 1, 1991.

Averaged SV values for 10 m depth strata and 0.2 nm distance intervals are shown in a color scale of 12 steps in dB. Vertical section of temperature from CTD casts is superimposed.

Table 3. Fish abundance estimates with acoustics for the same period in the three years, 1990–1992

Cruise	Date	Distance of transects (nm)	Mean density $\pm$ 95% CI (g/m ²)	Fish abundance $\pm$ 95% CI (t)
KT-90-3	MAR 3-9, 1990	195	40.2 $\pm$ 11.9	319,000 $\pm$ 94,000
KH-91-3 Leg 3	MAR 9-12, 1991	140	5.98 $\pm$ 3.81	47,000 $\pm$ 30,000
KT-92-3	FEB 27-MAR 2, 1992	205	2.48 $\pm$ 1.15	20,000 $\pm$ 12,000

The Area in which fish abundances were calculated is shown in Fig. 1. Area = 7.94×10^3 km².

tinental shelf.¹³⁾ The Japanese sardine probably changed their spawning behavior in response to increased population size.

During the period of high abundance in the 1930s, the sardine catches recorded a peak in 1936. Later, sardine stock declined abruptly and the spawning grounds off southern Kyushu disappeared in 1941.¹⁾ Our survey in 1992 showed that a much smaller number of sardine shoals occurred inshore. The spawning grounds south of Kyushu disappeared as soon as in the 1930s after the peak abundance.

According to egg surveys by the Nansei National Research Institute of the Fishery Agency during February–March, sardine egg abundance off southern Kyushu decreased distinctly in 1991 against that in 1990 and declined to an extremely low level in 1992.^{14, 15)} The change in fish abundance esti-

mates in 1990–1992 in our study is consistent with the results of these egg surveys. On the other hand, many sardine eggs were observed off Shikoku and Kii Strait in 1992, as in 1990 and 1991.¹⁵⁾ Additionally, sardine catches from the waters east of Kyushu during February–March did not decrease in 1990–1992.^{*2} These facts indicate that the sardine no longer migrated to spawn so far as south of Kyushu in 1992. While the nearshore temperature off southern Kyushu in March was slightly higher in 1990 than in 1991 and 1992 (Figs. 1–3), it showed no certain tendency in February 1990–1992.^{*2} The observed decline of abundance of spawning sardine off southern Kyushu was probably related to the sharp decrease in population size reflected by the catches rather than to oceanographic conditions.

There are some assumptions and potential

*2 Annual Reports of Fishing and Oceanographic Conditions, Miyazaki Prefectural Fishery Experimental Station (1991, 1992, 1993). (in Japanese)

Fig. 7. Comparison of mean relative fish abundance (BI) in the 4 subarea east of Cape Sata, southern Kyushu during January–March, 1991.

95% confidence intervals are shown by vertical bars. Numerals below each column indicate (no. 5 nm-segment where shoals appeared)/(no. of 5 nm-segment surveyed). a: January 20–23; b: February 14–17 and 20; c: February 26–March 1; d: March 9–12. NI: inshore and northern subarea; NO: offshore and northern subarea; SI: inshore and southern subarea; SO: offshore and southern subarea.

sources of error in estimating fish abundance because of certain limitations in the current acoustic method.

The numerical estimates of sardine density were restricted to a depth range of 10–50 m. Echoes from the upper 10 m of water column were excluded from this analysis because of the near surface noise. Since few echo traces of pelagic fish shoals were found above a depth of 10 m, mean fish densities in the 10–50 m depth range were not extrapolated to near the surface. It is impossible to identify individual targets such as sardine directly. We estimated densities of sardine above a depth of 50 m to exclude fish other than sardine. The restriction to the 10–50 m depth range may be a source of underestimation. The following, on the other hand, may lead to overestimation: echoes from plankton in 5 nm-segments where fish shoals were observed were not excluded in calculating fish densities, and all of the fish traces above a depth of 50 m were assumed to be due to sardine shoals. To establish the reliability of acoustic estimation new procedures should be developed to identify species of individual targets and to separate the fish concerned from background biological noise due to plankton.

It has been generally accepted that it is preferable for target strengths to be measured *in situ*. Unfortunately, the acoustic systems used in this study were insufficient to carry out *in situ* measurement. The *in situ* measurement of target strengths is constrained by the condition that fish are dispersed enough to make resolution of single targets easy. It is generally difficult to obtain adequate numbers of target strength measurements for small pelagic fishes schooling cohesively such as sardine. The empirical relationship for the length-normalized target strength used in this study was based on the measurements of sardine, which were 11–24 cm in fork length, tethered in a tank, and on averaging values for tilt angles with a mean of 5° head-down and SD of 15°. The target strength varies with the tilt angle of the fish. Diurnal variations in the tilt angle are presumed. Japanese anchovy in the night-time have been observed to have tilt angles with a mean of about 10° head-up and SD of about 25°. There is no available data on sardine tilt angles while swimming. More observations of the behavior of individual fish in the sea are needed to understand variations in target strength. Also, it is important to use lower frequencies at which target strength is less influenced by tilt angle.

In this study, survey grids were not designed statistically to provide estimates of total spawner biomass off southern Kyushu. Fish abundance

estimates in the 3 years were limited to the certain area where sardine shoals were most concentrated. The estimates by simply averaged fish densities had large confidence intervals because of a small number of transects. We only occasionally surveyed the western area south of Kyushu, where fish shoals were also observed. As is evident in the surveys, fish abundance in the western area south of Kyushu was never negligible. Jolly and Hampton¹⁸⁾ have shown that valid estimates can be obtained by taking a stratified random sample of parallel transects. A cruise needs to be carried out with survey grids designed adequately for acoustic assessment of total sardine spawner biomass.

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References

- 1) Z. Nakai: Studies relevant to mechanisms underlying the fluctuation in the catch of the Japanese sardine, *Sardinops melanosticta* (Temminck & Schlegel). *Jap. J. Ichthyol.*, 9, 1-115 (1962).
- 2) K. Kuroda: Yearly changes of the main spawning grounds of the sardine, *Sardinops melanostictus* (T. et S.) in the waters along the Pacific coast of southern Japan. *Bull. Japan. Soc. Fish. Oceanogr.*, 52, 289-296 (1988).
- 3) F. Hanaoka and Y. Konoshi: Distributions of spawning grounds, eggs and larvae of sardine in the southwestern Japan, Report of Pelagic Fish Resources Investigations by the Fisheries Agency, Tokyo, 1988, pp. 59-71 (in Japanese).
- 4) K. Kondo, Y. Hori, and K. Hiramoto: Life pattern of the Japanese sardine, *Sardinops melanosticta* (Temminck et Schlegel), and its practical procedure of marine researches of the stock (2nd Edition), Japan Fisheries Resource Conservation Association, Tokyo, 1976, pp. 1-67.
- 5) K. Kondo: On the mode of distribution and migration of the Japanese sardine, *Sardinops melanostictus* (Temminck & Schlegel), at high level stock size. *Bull. Tokai Reg. Fish. Res. Lab.*, 124, 1-33 (1988).
- 6) K. Kuroda: Studies on the recruitment process focusing on the early life history of the Japanese sardine, *Sardinops melanostictus* (Schlegel). *Bull. Natl. Res. Inst. Fish. Sci.*, 3, 25-278 (1991).
- 7) K. Kuroda: Occurrence of the mature sardine, *Sardinops melanostictus*, around the Kuroshio Current in recent years. *Bull. Japan. Soc. Fish. Oceanogr.*, 51, 373-376 (1987).
- 8) E. E. Francois and G. R. Garrison: Sound absorption based on ocean measurements. Part 2: Boric acid contribution and equation for total absorption. *J. Acoust. Soc. Am.*, 72, 1879-1890 (1982).
- 9) I. Aoki and T. Murayama: Spawning pattern of the Japanese sardine *Sardinops melanostictus* off southern Kyushu and Shikoku, southwestern Japan. *Mar. Ecol. Prog. Ser.*, 97, 127-134 (1993).
- 10) T. Murayama, M. Shiraishi, and I. Aoki: Changes in ovarian development, GSI, egg diameter and plasma levels of sex steroid hormones in the wild female Japanese sardine (*Sardinops melanostictus*) during spawning period. *J. Fish. Biol.* (submitted).
- 11) Y. Miyanoana, K. Ishii, and M. Furusawa: Measurements and analyses of dorsal-aspect target strength of six species of fish at four frequencies *Rapp. P.-v. Reun. Cons. int. Explor. Mer*, 189, 317-324 (1990).
- 12) I. Aoki and T. Murayama: Distribution and maturation of the spawning sardine, *Sardinops melanostictus* in the waters off southern Kyushu of Japan. *Bull. Japan. Soc. Fish. Oceanogr.*, 55, 93-104 (1991).
- 13) Z. Nakai, S. Usami, S. Hattori, Y. Honjo, and S. Hayashi: Progress Report of the Cooperative Iwashi Resources Investigations, Tokai Reg. Fish. Res. Lab., Tokyo, 1955, pp. 1-84.
- 14) M. Ishida: Distributions of eggs and larvae of fishes in the area off southwestern Japan in the winter and spring of 1991. Annual Report of Eggs, Larvae and Plankton Surveys in Central Block, National Research Institute of Fishery Science, No. 12, 88-93 (1991) (in Japanese).
- 15) M. Ishida: Distributions of eggs and larvae of fishes in the area off southwestern Japan in the winter and spring of 1992. Annual Report of Eggs, Larvae and Plankton Surveys in Central Block, National Research Institute of Fishery Science, No. 12, 1-7 (1991) (in Japanese).
- 16) I. Aoki and T. Inagaki: Photographic observations on the behaviour of Japanese anchovy *Engraulis japonica* at night in the sea. *Mar. Ecol. Prog. Ser.*, 43, 213-221 (1988).
- 17) M. Furusawa: Study on echo sounding for estimating fisheries resources. *Bull. Nat. Res. Inst. Fish. Eng.*, 11, 173-249 (1990).
- 18) G. M. Jolly and I. Hampton: A stratified random transect design for acoustic surveys of fish stocks. *Can. J. Fish. Aquat. Sci.*, 47, 1282-1291 (1990).