Practical target strength of free-swimming chub mackerel Scomber japonicus

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Practical target strength of free-swimming chub mackerel *Scomber japonicus*

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Abstract

Chub mackerel *Scomber japonicus* is a migratory fish widely distributed around Japan, and is an important fishery resource. However, target strength (*TS*) measurements of chub mackerel are limited, and the relationship between *TS* and fork length has not been fully clarified, despite its importance for the estimation of chub mackerel abundance. In this study, the *TS*–fork length (*FL*) relationship in chub mackerel was evaluated under realistic conditions. TS_{mean} and TS_{max} tended to increase with fork length at both 38 and 120 kHz, and *TS* histograms were bimodal for most individuals. In the TS_{mean}–*FL* relationship, when the coefficient *a* was fixed at 20 (the standard for fish with swim bladders), TS_{cm} (standardized by the square of the fork length) was −67.9 dB ($r^2 = 0.70$) at 38 kHz and −69.2 dB ($r^2 = 0.45$) at 120 kHz. Additionally, the swimming angle had a peak of around 0° with a mean of −1.23°, and the mean swimming speed was 0.16 *FL*/s with a standard deviation of 0.07 *FL*/s. *TS* reached a maximum between −20° and 0° and then decreased drastically as the swimming angle increased or decreased. Our results have practical implications for the management of chub mackerel.

Keywords Chub mackerel · Target strength · Free-swimming · Swimming behavior · Quantitative echo sounder

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Introduction

The chub mackerel *Scomber japonicus* is a migratory fish widely distributed around Japan and an important fishery resource in Japan (Okada 2020). This species has been designated as a target for determination of total allowable catch (TAC) in Japan (Yatsu et al. 2019), and thus stock assessment and management have been conducted for the Pacific stock and the Tsushima Warm Current stock (Kurota et al. 2019). Chub mackerel is a small pelagic and mass-caught fish, and its abundance fluctuates substantially (Goto 2020). Fishing pressure is high for the species, and stock declines are likely to occur due to inadequate management, especially during periods of declining recruitment (Kawai et al. 2002; Yatsu and Kaeriyama 2005). In addition, since the distribution of chub mackerel depends on its abundance and environmental factors (Goto et al. 2020; Sassa and Tsukamoto 2010), it is important to clarify the characteristics of its distribution according to abundance levels (Kurota et al. 2019). For these reasons, detailed information on changes in abundance and fishing grounds of chub mackerel is essential for effective stock management.

Cohort analyses (e.g., virtual population analysis [VPA]) are the main approach for the assessment of chub mackerel in Japan (Nakayama and Hiramatsu 2010; Ichinokawa et al. 2017). In VPA, the spawning stock biomass and recruitment number are calculated based on the age-specific fishing mortality coefficient (Ichinokawa and Okamura 2014). Since the estimation recruitment accuracy using VPA increases with the number of years of data accumulation, it is difficult to grasp the abundance of age-stock at an early life stage (Shimura et al. 2009; Muko and Kurota 2018). In addition, the VPA assumes that the catch is proportional to abundance, and the estimation accuracy may be low for fish species with large fluctuations in abundance (Furusawa 1991). Thus, to estimate the abundance of chub mackerel more accurately, VPA needs to be corrected using recent resource indices (Ichinokawa and Okamura 2014). Therefore, there is a need for a method that enables the rapid and accurate estimation of the present abundance level and distribution.

Recently, acoustic monitoring methods that enable the quantitative visualization of fishery resources have attracted attention (Miyashita 2019; Munoz et al. 2020; Zhu et al. 2021a, b). Among these, a quantitative echo sounder (hereafter, echo sounder) can be applied to a wide area in a short time and can be used to estimate the abundance quickly and quantitatively, independent of the fishery catch (Abe et al. 1999; Zhu et al. 2021a, b). The volume backscatter strength (*SV*, dB) or area backscatter strength (*SA*, dB) obtained from the echo sounder is obtained and the biological density is calculated using the target strength (*TS*, dB), indicating the strength per target organism, to estimate the abundance (Amakasu et al 2003; Hirose et al. 2005; Tong et al. 2022). Therefore, the *TS* of target organisms is very important for accurate abundance estimation (Tong et al. 2022). However, the relationship between *TS* and fork length in chub mackerel has not been fully clarified owing to limited *TS* data (Miyanohana et al. 1990; Mukai et al. 1994; Miyanohana 1994). Thus, it is important to collect more *TS* data and obtain a *TS*-fork length equation with high accuracy for the chub mackerel stock assessment.

Since *TS* depends on the swimming posture of fish, measurements should be obtained under natural conditions (in situ method) (Sawada 2002). However, it is difficult to accurately determine the species and target fish length in the natural environment (Simmonds and MacLennan 2005). Therefore, measurements are frequently obtained in a controlled environment (i.e., ex situ method). The suspension and cage methods are common ex situ methods; however, these approaches restrict swimming behavior, and it is difficult to obtain practical *TS* values close to those in natural conditions (Mukai et al. 1994). To obtain robust and accurate *TS* data, it is important to evaluate target fish swimming freely in a physically controlled environment.

Therefore, the objective of this study was to accurately estimate the *TS*–fork length relationship by measuring the *TS* of free-swimming chub mackerel in a large indoor aquarium with a stable physical environment.

Materials and methods

TS measurement

Eighteen individuals (fork length [*FL*]: 17.4–34.0 cm) caught by angling along the coast of Hakodate, Hokkaido, during March 2021, August 2021, and December 2022, were used as experimental fish (Table 1). The caught fish were immediately transported to the Hakodate Research Center for Fisheries and Oceans (hereafter referred to as the Research Center). After acclimation, they were fed and reared in a 2500-L vinyl aquarium (D × H: 2 × 0.8 m).

Two types of *TS* measurements were conducted in a large indoor aquarium (W × L × H: 5 × 10 × 6 m) at the Research Center using two types of nets. Between March 8, 2021, and April 7, 2021, we used a circular net (D × H: 3 × 6 m), which was placed in the center of the large aquarium (Fig. 1a). Between August 23 and August 27, 2021, and December 1 and December 13, 2022, we used a nylon partition net. The nylon partition net was installed from the water surface to the bottom of the aquarium, dividing the long side of the aquarium into two equal parts, and one half of the aquarium

Table 1 Experiment date and *TS* of each experimental individual

Date	Net Type	Fork length (*FL*, cm)	TS_{mean} (dB)		TS_{max} (dB)	
			38 kHz	120 kHz	38 kHz	120 kHz
8 March 2021 ~ 7 April 2021	Circular net	17.4	−43.9	−43.4	−36.1	−33.9
		24.1	−40.6	−47.3	−35.9	−33.8
		24.3	−39.1	−40.4	−34.6	−32.2
		28.0	−39.4	−40.9	−33.4	−31.1
23 August 2021 ~ 27 August 2021	Partition net	20.3	−39.9	−43.4	−34.4	−31.6
		22.0	−38.8	−41.5	−35.2	−31.6
		25.6	−37.2	−39.4	−32.5	−30.1
		34.0	−35.6	−39.9	−30.0	−30.0
1 December 2022 ~ 13 December 2022	Partition net	17.8	−42.8	−42.2	−37.8	−34.8
		17.9	−43.0	−46.0	−38.0	−35.0
		19.3	−41.9	−42.6	−36.4	−33.3
		19.4	−42.3	−46.7	−37.6	−34.8
		19.5	−44.9	−44.8	−37.4	−34.8
		21.5	−43.7	−41.5	−36.5	−32.3
		22.3	−42.5	−42.6	−36.7	−32.5
		22.4	−41.6	−41.1	−35.4	−32.3
		24.2	−40.6	−39.2	−35.9	−32.3
		27.4	−39.5	−37.7	−32.5	−30.0

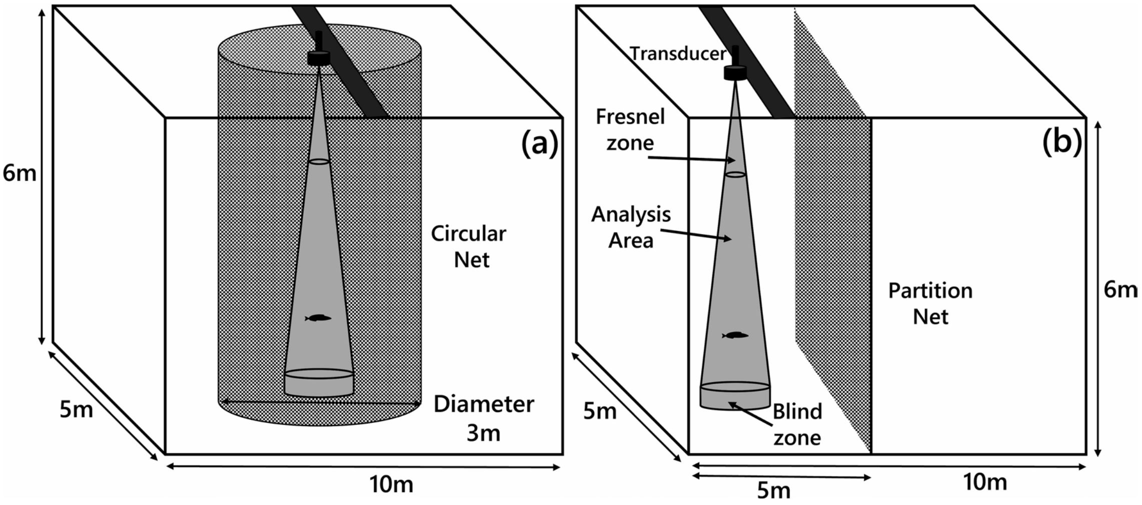


Fig. 1 Experimental design. **a** Experiment with the circular net. **b** Experiment with the partition net

was used as the experimental area (Fig. 1b). For *TS* measurements, one individual was placed into the aquarium at a time.

In all experiments, a split-beam echo sounder (KSE-300, Sonic; frequencies: 38 and 120 kHz) capable of obtaining three-dimensional locations of fish was used (Table 2), and acoustic data were recorded for at least 12 h. During the experiment, the transducers of the echo sounder were fixed to a movable bridge, and the transducer surface was positioned at about 40 cm below the water surface in the center of the experimental area. The positions of the transducer were fine-tuned so that the net did not interfere with the beam of the echo sounder. Before the start of each experiment, a tungsten carbide metal standard sphere (φ38.1 mm), which is a standard reflector with a known *TS*, was used to calibrate the echo sounder. Since air bubbles adhering to the gills of experimental fish can cause large measurement errors (Sawada 2002), efforts were made to prevent the fish

Table 2 Specification of quantitative echo sounder KSE-300 during *TS* measurements

Transducer	T-178	T-182
Frequency (kHz)	38	120
−3 dB beam width (degrees)	8.4	8.2
Transducer type	Split beam	
Pulse length (ms)	0.3	
Ping interval (s)	0.2	

from encountering air during transport to the experimental aquarium. Furthermore, since water temperature influences the swimming behavior of fish (Wardle 1980), it must be controlled for *TS* measurements. The appropriate water temperature for chub mackerel varies depending on the season, with ranges of 14.1–16.4 °C from January to April and 17.7–21.7 °C from May to December (Okunishi et al. 2020). Therefore, the water temperature in the experimental aquarium was kept at 14 ± 1 °C during the March experiment and 18 ± 1 °C during the August and December experiment to prevent a decrease in the swimming ability of chub mackerel.

Analysis of acoustic data

TS values were determined by the algorithm for *TS* detection using the echo sounder and output as a CSV file (Sawada 2002). Since echoes from garbage in the water can be misidentified as echoes of chub mackerel, unwanted echoes were excluded based on the signal-to-noise ratio (SNR). The background noise during the measurements in this study was approximately −80 dB or less, and a SNR of 20 dB or more is sufficient to accurately estimate *TS* (Sawada 2002); therefore, the lower threshold of *TS* was set to −60 dB. In addition, due to the performance of the echo sounder, accurate *TS* values cannot be obtained near the transducer and near the bottom (Kawauchi et al. 2019); accordingly, these data need to be excluded from the analysis. For the data near the transducers, the boundary of the far-field (*Rend*, m) (Medwin and Clay 1988), where sound pressure is stable and *TS* can be measured with high accuracy, and the diameter of the first Fresnel zone (z, m) (Yilmaz 1987), where the full length of the experimental fish must fit, were used as standards. Data shallower than that standard depth were excluded (Table 3). Next, data obtained up to 0.24 m from the bottom, corresponding

Table 3 Upper analytical depth based on the acoustic far-field boundary (*Rend*, m) and the diameter of the first Fresnel zone (z, m)

Fork length (L, cm)	*Rend* (m)		Measurable L under *Rend* (cm)		z (m)	Final upper threshold (m)	
	38 kHz	120 kHz	38 kHz	120 kHz	120 kHz	38 kHz	120 kHz
17.4	1.55	0.62	35.0	12.5	1.21	1.55	1.21
17.8					1.27		1.27
17.9					1.28		1.28
19.3					1.49		1.49
19.4					1.51		1.51
19.5					1.52		1.52
20.3					1.65		1.65
21.5					1.85		1.85
22.0					1.94		1.94
22.3					1.99		1.99
22.4					2.01		2.01
24.1					2.32		2.32
24.2					2.34		2.34
24.3					2.36		2.36
25.6					2.62		2.62
27.4					3.00		3.00
28.0					3.14		3.14
34.0					4.62		4.62

to the acoustic blind zone, were excluded (Mitson 1983; Simmonds et al. 1992).

Using the *TS* data for chub mackerel extracted by the above procedure, the mean *TS* (TS_{mean}) and maximum *TS* (TS_{max}) values were obtained for each experimental condition. The equation for the *TS–FL* relationship was estimated by the least-squares method. In general, the *TS–FL* relationship is expressed by the following equation.

$$TS = a10log_{10}FL + b \quad (1)$$

where *a* and *b* are coefficients and *FL* is the fork length (cm). It has been theoretically (Furusawa and Miyanohana 1988) and experimentally (Miyanohana et al. 1990) proven that the *TS* of fish with swim bladders, such as chub mackerel, is proportional to the square of the fork length. In this case, *a* is fixed at 20 and *b* is TS_{cm} standardized by the square of the fork length, which is expressed by the following equation.

$$TS = 20log_{10}FL + TS_{cm} \quad (2)$$

At the time that *TS* data were recorded, changes in three-dimensional coordinate information as the fish swam were also measured for each ping. Using this coordinate information, it is possible to estimate the swimming speed and absolute swimming angle using the echo tracing method (Henderson et al. 2008; Furusawa and Amakasu 2010). The swimming angle obtained in this study is the angle of elevation/degradation in the direction the fish is moving, which is different from the exact posture angle. However, since the direction of the fish's body changes in accordance with the direction the fish is moving, it is possible to use the swimming angle as an indicator of the posture change. For this reason, the relationship between *TS* and swimming behavior of chub mackerel was examined from these swimming data. In this study, only tracking data for which echoes were taken for more than five pings in a row and for cases of straight swimming (i.e., low tortuosity: $Tor \leq 1.2$) (Henderson et al. 2008) were used.

The *TS*, swimming angle, and swimming speed were calculated in R ver. 4.1.0. Additionally, the parameters of *TS–FL* relationships were estimated using nonlinear least square methods by the *nls* function in R. Since tracking data were more obtained at 120 kHz than at 38 kHz, the swimming angle and swimming speed were verified by pooling data for all individuals at 120 kHz.

Results

For each individual, 13–9713 pings were obtained at 38 kHz, and 24–9577 pings were obtained at 120 kHz. Over 100 pings at both frequencies were obtained for more than 83% of individuals. The *TS* histograms were bimodal for most individuals (Figs. 2 and 3). In addition, TS_{mean} values calculated from the measured data ranged from −44.9 to −35.6 dB at 38 kHz and from −47.3 to −37.7 dB at 120 kHz, while TS_{max} values ranged from −38.0 to −30.0 dB at 38 kHz and from −35.0 to −30.0 dB at 120 kHz (Table 1). At both frequencies, TS_{mean} and TS_{max} tended to increase with fork length. Furthermore, TS_{mean} was stronger at 38 kHz than at 120 kHz in most individuals. At TS_{max}, the pattern inverted, and values were stronger at 120 kHz than at 38 kHz.

The relationships between fork length and TS_{mean}, and between fork length and TS_{max} at both frequencies were obtained as shown in Fig. 4. In the relationship between fork length and TS_{mean}, when the coefficients were not fixed, *a* and *b* were 27.4 and −77.9 dB ($r^2 = 0.75$) at 38 kHz, respectively, and 23.3 and −73.7 dB ($r^2 = 0.46$) at 120 kHz, respectively. When the coefficient *a* was fixed at 20, TS_{cm} was −67.9 dB ($r^2 = 0.70$) at 38 kHz and −69.2 dB ($r^2 = 0.45$) at 120 kHz. In the relationship between fork length and TS_{max}, when the coefficients were not fixed, *a* and *b* were 24.9 and −68.9 dB ($r^2 = 0.96$) at 38 kHz and 20.1 and −59.6 dB ($r^2 = 0.96$) at 120 kHz, respectively. When the coefficient *a* was fixed at 20, TS_{cm} was −62.3 dB ($r^2 = 0.97$) at 38 kHz and −59.5 dB ($r^2 = 0.96$) at 120 kHz.

The swimming angle estimated in this study had a peak of around 0°, with a mean of −1.23° and a standard deviation of 11.50° (Fig. 5a). The mean swimming speed was 0.16 *FL*/s with a standard deviation of 0.07 *FL*/s (Fig. 5b). In addition, the relationship between the swimming angle and TS_{cm}, which was calculated using measured TS and FL, is shown in Fig. 6. In all individuals, TS_{cm} reached a maximum between −20° and 0°, and then decreased drastically as the swimming angle increased or decreased.

Discussion

Swimming behavior

Although the swimming angle is different from the posture angle, it is an indicator of postural changes that affect *TS* (Kawauchi et al. 2019). Here, we compared the swimming angle and swimming speed with those previously estimated for chub mackerel. Nauen et al. (2002) evaluated the swimming angle and posture of chub mackerel in an aquarium using a video camera, revealing that the fish tended to turn their bodies downward by approximately 3° relative to the direction of travel. Similar results were obtained by Gibb et al. (1999), who found that chub mackerel tended to swim with a downward tilt at all swimming speeds. In addition, Ito et al. (2015) tracked echoes of chub mackerel schools in the field using a broadband quantitative echo sounder with 80–120 kHz frequency on a research vessel, resulting a peak of slight smaller value than 0° for the swimming angle.

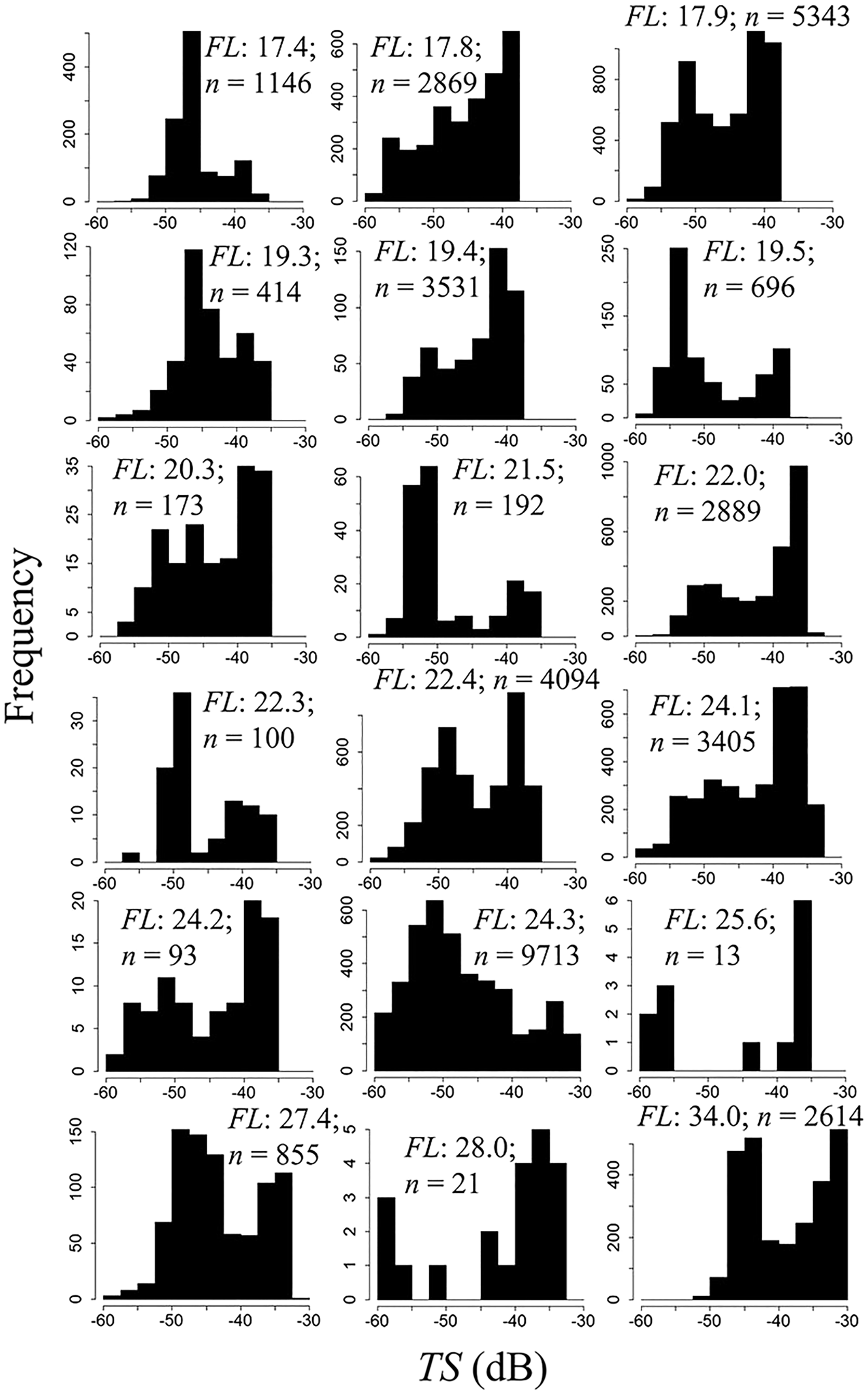


Fig. 2 *TS* histograms at 38 kHz. *FL* indicates the fork length of all individuals, and *n* indicates the number of *TS* detected by the echo sounder

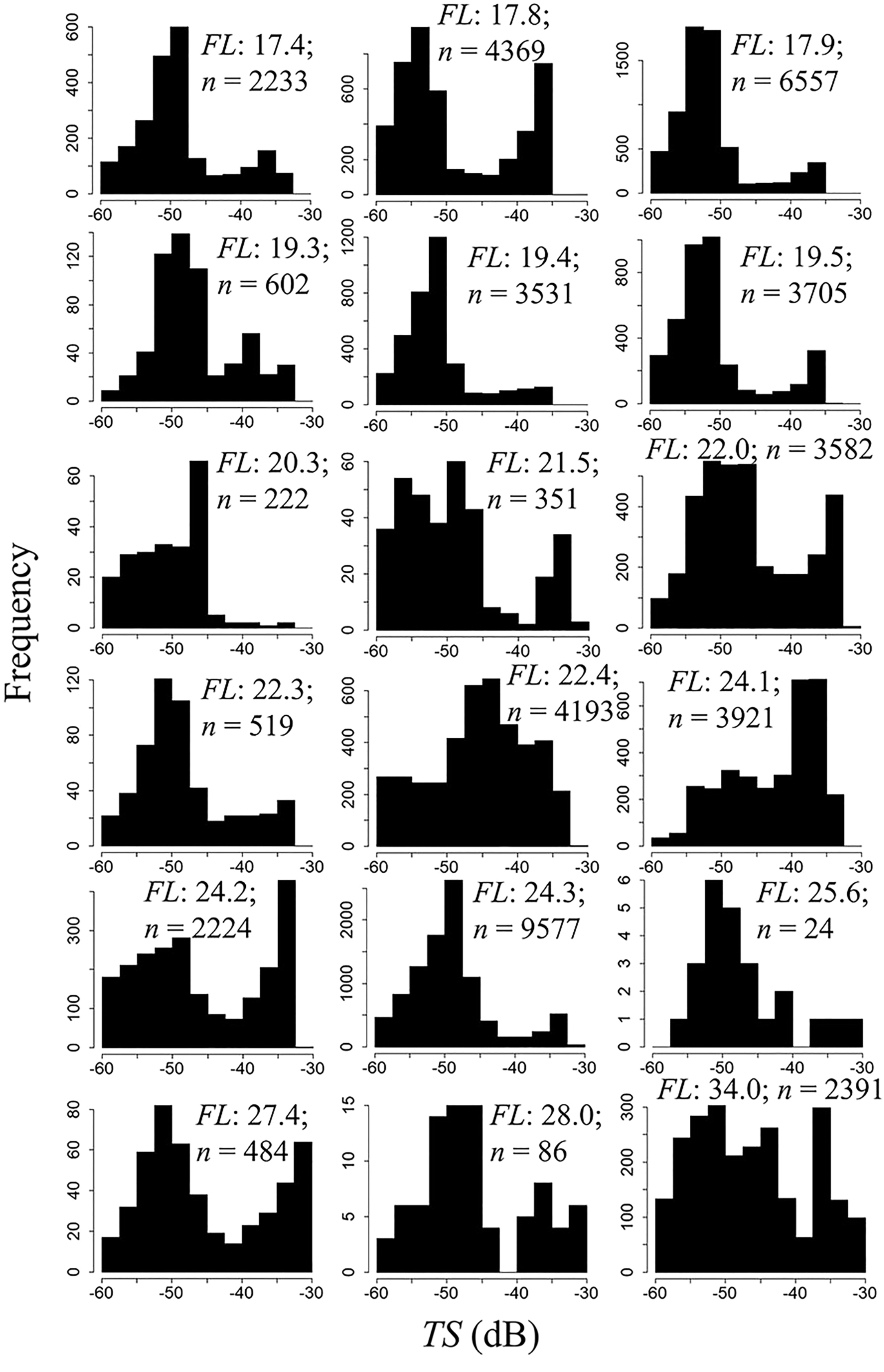


Fig. 3 *TS* histograms at 120 kHz. *FL* indicates the fork length of all individuals, and *n* indicates the number of *TS* detected by the echo sounder

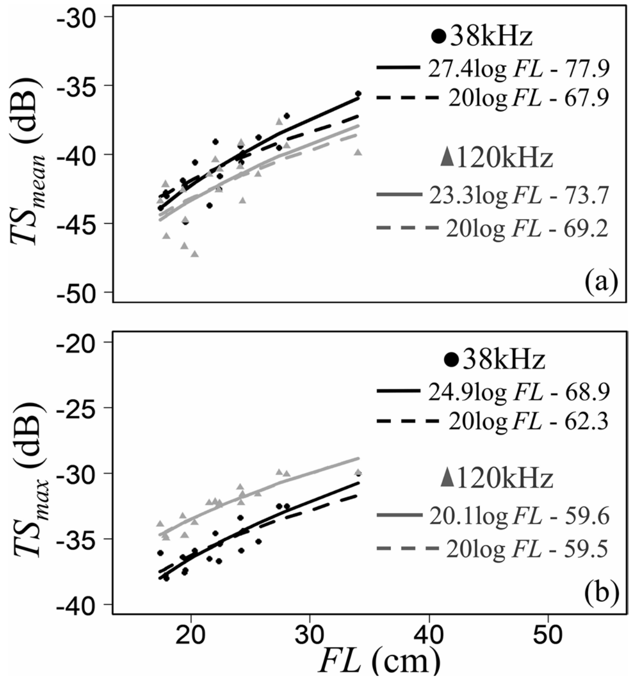


Fig. 4 Relationship between fork length (*FL*) and estimated TS_{mean} (**a**), and between fork length (*FL*) and estimated TS_{max}, (**b**) of chub mackerel in this study

Therefore, it seems that chub mackerels often swim horizontally or downward with a slight body tilt. In the present study, the estimated swimming angle had a peak of around 0° with a mean of −1.23°, indicating that the results of this study are consistent with those of previous studies on swimming behavior.

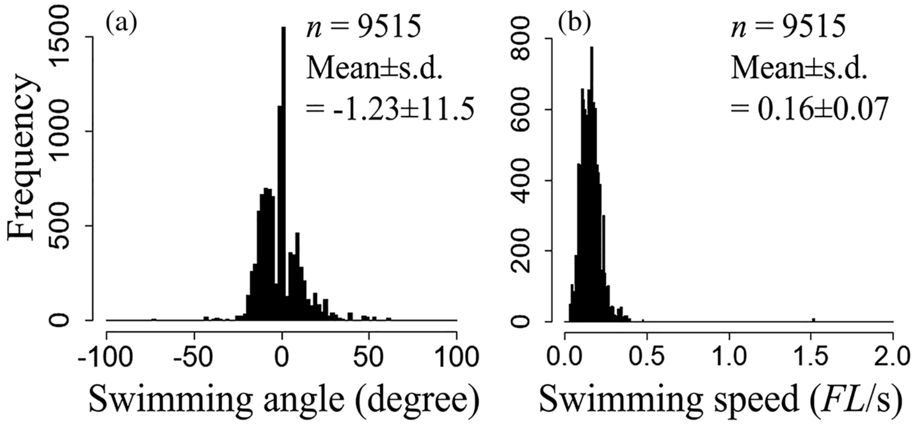
Additionally, in a previous study of the swimming speed of chub mackerel in the natural environment, as determined using a video camera in an underwater bulb, the average swimming speed of chub mackerel was 1.73 *L*/s (Hasegawa and Kobayashi 1989). However, the mean swimming speed in this study was 0.16 *FL*/s, which was slower than that reported by Hasegawa et al. (1989). This difference in swimming speed is thought to be caused by the difference in swimming between solitary animals and groups. In a study of rose bitterling *Rhodeus ocellatus ocellatus*, the swimming speed of the group increased as the number of individuals increased (Kanehiro et al. 1985). Therefore, our results could be interpreted to obtain a part of the main behavior.

As described above, the swimming angles obtained in this study were roughly similar to those measured in previous studies, suggesting that the behaviors observed in this study were not abnormal. However, the swimming speed of the chub mackerel in this study may not fully reflect the swimming behavior of chub mackerel in the wild. Therefore, it is important to improve the accuracy of estimation by measuring the *TS* of multiple individuals for fish species that swim in schools. In the future, by increasing the sample size, it will be possible to conduct measurements in swimming conditions similar to those in actual sea areas, leading to more accurate and practical *TS* estimation.

Relationship between the swimming angle and TS_{cm}

The TS_{cm} values in this study tended to be larger when fish were swimming slightly downward, with swimming angles ranging from −20° to 0°. This may be due to the increase in the projected area of the swim bladder in the dorsal direction during downward movement and the synchronous enhancement of acoustic reflection. In most fish with a swim bladder, the swim bladder is tilted upward relative to the fish body (Amakasu et al. 2010), and the dorsal cross-sectional area of the swim bladder is maximized when the fish head is tilted downward (Tanigami et al. 2006). Since the strongest acoustic reflector in the fish body is considered to be due to the swim bladder (Foote 1980), the *TS* tends to increase as the cross-sectional area of the swim bladder increases. Therefore, in this study, the peak TS_{cm} was observed when the chub mackerel swam slightly downward, which may reflect

Fig. 5 Histogram of **a** swimming angle and **b** swimming speed at 120 kHz; *n* indicates the number of swimming tracks



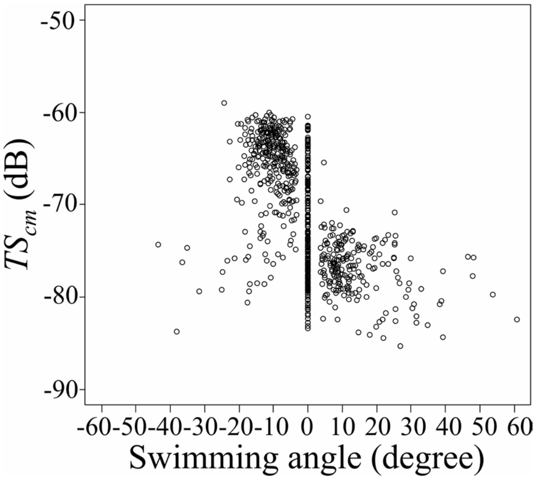


Fig. 6 Relationship between the swimming angle and TS_{cm} for experimental individuals at 120 kHz. Black circles indicate measured values

the upward orientation of the swim bladder in relation to the body axis.

Measured *TS*

In this study, chub mackerel showed a length-dependent trend in which *TS* increased with increasing fork length at both frequencies. In general, the *TS* of fish with a swim bladder is proportional to the square of the fork length. The slope *a* of the TS_{mean}–*FL* relationship estimated in this study was 27.4 at 38 kHz and 23.3 at 120 kHz, which is close to 20. Additionally, the slope *a* of the TS_{max}–*FL* equation was close to 20 at both frequencies. In general, when *a* was fixed at 20, the TS_{cm} of maximums *TS* (Max TS_{cm}) in the dorsal direction of fish with a swim bladder did not reflect the effect of posture angle, and Max TS_{cm} calculated from a quantitative echo sounder was almost −59 to −61 dB, regardless of the frequency (Miyanohana 1994). In this study, the estimated Max TS_{cm} values were −62.3 dB at 38 kHz and −59.5 dB at 120 kHz, which are close to the theoretical values. Therefore, the *TS* values measured in this study were considered reasonable.

In addition, the *TS* histograms of chub mackerel showed a bimodal distribution at both frequencies. Similar bimodal distributions have been obtained for related species and other taxa which have a similar type of swim bladder shape, including the Atlantic mackerel *Scomber scombrus* measured by in. situ methods (Palermini et al. 2021) and the free-swimming Japanese jack mackerel *Trachurus japonicus* (Kawauchi et al. 2019). This distribution may be explained by the high directionality of *TS* with respect to posture angle (Miyanohana et al. 1990) and the sharp decrease in *TS* values with an increasing or decreasing posture angle from the peak of the main lobe. With a wide range of swimming posture data, it is highly likely that *TS* histograms will be bimodal.

Furthermore, for many length classes, TS_{mean} was larger at 38 kHz than at 120 kHz; however, this pattern was reversed at TS_{max}, with greater variation in *TS* at higher frequencies. Similar results were obtained by Mukai et al. (1993). This is thought to be because directionality becomes stronger at high frequencies (Matsukura et al. 2013), and even small changes in posture angle cause large fluctuations in *TS* values. Additionally, in bladder fish, *TS* fluctuates significantly with posture when the standardized body length L/λ (i.e., the body length L standardized by wavelength λ) is large (Furusawa et al. 1989). In the case of chub mackerel in the length range covered in this study, L/λ was smaller at 38 kHz than at 120 kHz, and thus *TS* could be measured more stably at 38 kHz. These results suggest that low frequencies are suitable for future analyses of the abundance of adult chub mackerel, as estimates are less affected by the posture angle.

Equations relating TS_{mean} to FL

We compared the newly estimated TS_{mean}–*FL* equations with those for the chub mackerel and related species reported in the literature (Table 4, Fig. 7). The TS_{cm} of chub mackerel (20.0–30.0 cm) estimated using in situ methods by Kuznetsov et al. (2021) were approximately 4 dB weaker than those of the present study at both frequencies. One of the reasons for this difference is that *TS* measurements obtained by in situ methods may include other fish species, since the target fish cannot be confirmed (Sawada 2002). The uncertainty in species identification might affect the accuracy of the *TS*, resulting the lower TS_{cm} in the previous studies.

On the other hand, the theoretically estimated TS_{cm} at 38 kHz was −66.0 dB for adult chub mackerel (16.0–28.0 cm), slightly different from 1.9 dB in the present study but 3.2 dB higher than that at 120 kHz in the present study (Park et al. 2022). Similar results for adult chub mackerel (26.2–38.3 cm) were found by Lee et al. (2005), where differences were small at low frequencies and became larger at high frequencies. This large difference at 120 kHz is thought to be due to a difference in the assumed mean of posture angles, and the change in *TS* with respect to the change in posture angle is larger at higher frequencies. The posture angle in the previous studies was assuming a normal distribution with a mean of −5° and a standard deviation of 15°; however, the mean swimming angle in this study was −1.23° with a standard deviation of 11.5°. Since the chub mackerel tended to turn their bodies downward by approximately 3° relative to the direction of travel (Nauen and Lauder 2002), assuming this 3° relative to the swimming angle in this study, the mean posture angle is −4.23°, which is 0.77° more parallel to the previous study. Because the directivity of *TS* with respect to posture angle becomes

Table 4 Coefficients of TS_{mean}–fork length (FL), TS_{mean}–body length (L) and TS_{mean}–total length (TL) estimates by previous studies for chub mackerel and their related species plotted in Fig. 7

Reference	Method	Species	Size range (cm)	Frequency (kHz)	TS_{cm}
This study	Free-swimming	*Scomber Japonicus*	FL: 17.4–34.0	38	−67.9
				120	−69.2
Kuznetsov et al	In situ		L: 20.0–30.0	38	−72.8
				120	−73.6
Park et al	Ex situ		FL: 15.4–26.2	38	−66.0
				120	−66.0
Lee et al	Ex situ		L: 26.2–38.3	50	−67.2
				120	−66.9
Tong et al	Ex situ		L: 12.0–22.2	38	−73.3
				120	−74.2
Gutierrez et al	In situ	*Scomber scombrus*	L: 26.0–30.0	38	−70.9
				120	−70.8
Scoulding et al	In situ		TL: Ave. 33.3	38	−90.1
				120	−86.7
Palermino et al	In situ		L: 31.6–40.6	38	−71.6
				120	−74.8
Kawauchi et al	Free-swimming	*Trachurus japonicus*	FL: 12.5–27.5	38	−66.7
				120	−69.5

stronger at high frequencies, it is possible that this slight difference is more significant at 120 kHz than at 38 kHz, and that the TS_{cm} at 120 kHz in this study was estimated lower.

Additionally, the TS_{cm} of chub mackerel (12.04–22.17 cm) estimated by the Kirchhoff-ray mode (KRM) model, which uses average posture angle N (−3°, 4°), was −73.27 dB at 38 kHz and −74.18 dB at 120 kHz, which were 3.2–5.3 dB weaker than the estimates in the present study (Tong et al. 2022). This can be explained by the difference between the parameters used in the theoretical model and those relevant to natural conditions. For example, theoretical values were used for the probability density distribution of posture angle and the ratio g between the fish body and seawater (different acoustic impedances), which are important parameters for model calculations (Matsukura et al. 2013). For theoretical values, g is assumed to be uniform within the fish body; however, there are multiple boundaries even within the fish body. Since the g is affected by the posture angle, it is quite difficult to predict the movement of fish bodies under natural conditions and to account for these changes in the calculation of TS. Therefore, it is considered that the assumed parameters in the theoretical cannot reflect all the conditions of the fish in the natural environment and that this may have led to a low TS_{cm} estimate. We believe that the results of this study are more realistic than those of previous studies because they account for the swimming characteristics of chub mackerel.

Finally, the equation for the TS–FL relationship in this study was compared with those for closely related species and other small-pelagic fish (Table 4, Fig. 7). First, we compared our TS values with those of the Atlantic mackerel, which is closely related to chub mackerel. Many estimates obtained by in situ methods were significantly lower than those in the present study, even for the same length class (Palermino et al. 2021; Gutierrez and MacLennan 1998; Scoulding et al. 2017). The low TS in the Atlantic mackerel can be explained by its lack of a swim bladder. The difference in TS due to the influence of the swim bladder has been verified using a theoretical scattering model; even for fish of the same shape, the TS of bladder-less fish was more than 10 dB lower than that of fish with a swim bladder (Sawada 2002). On the other hand, the TS_{cm} of Japanese jack mackerel, which has a similar shaped physoclistous swim bladder to that of chub mackerel, was estimated using the same method as in this study, yielding similar results (i.e., −66.7 dB at 38 kHz and −69.5 dB at 120 kHz) (Kawauchi et al. 2019). In the future, we expect the method used in this study to be useful for obtaining accurate TS values for other fish species under natural conditions.

Future prospects

In this study, we collected free-swimming chub mackerel TS data over a wide length range, enabling us to derive highly accurate TS data (i.e., close to values in natural conditions) and to derive a highly accurate TS–fork length relationship. However, our analysis did not fully account for the posture angle and swimming speed of school swimmers. For fish species that swim in schools in the wild, it is necessary to obtain measurements in schooling conditions.

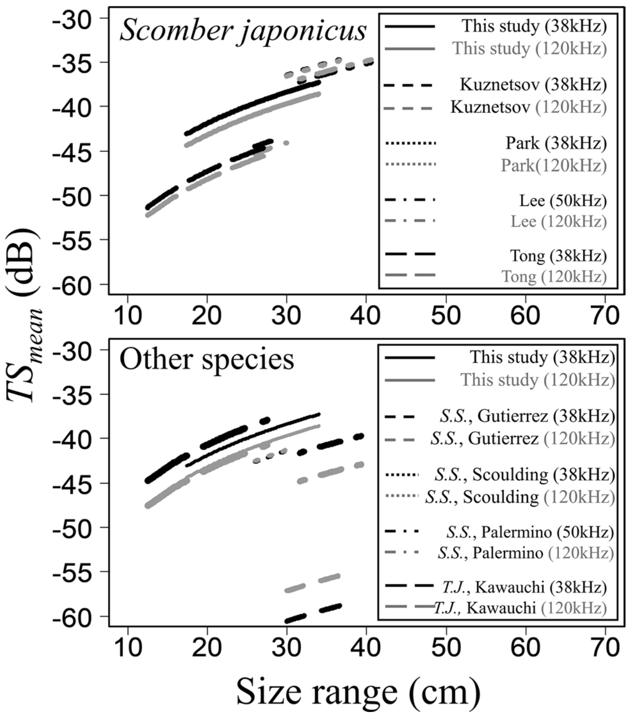


Fig. 7 Estimated *TS*–length relationship of chub mackerel and other species from the literature and this study. *S. S.* is an abbreviation for Atlantic mackerel and *T. J.* is an abbreviation for Japanese jack mackerel. Kuznetsov et al. (38 kHz: 20log*L*-72.8; 120 kHz: 20log*L*-73.6), Park et al. (38 kHz: 20log*FL*-66.0; 120 kHz: 20log*FL*-66.0), Lee et al. (50 kHz: 20log*L*-67.2; 120 kHz: 20log*L*-66.9), Tong et al. (38 kHz: 20log*L*-73.3; 120 kHz: 20log*L*-74.2), Gutierrez et al. (38 kHz: 20log*L*-70.9; 120 kHz: 20log*L*-70.8), Scoulding et al. (38 kHz: 20log*TL*-90.1; 120 kHz: 20log*TL*-86.7), Palermino et al. (38 kHz: 20log*L*-71.6; 120 kHz: 20log*L*-74.8), Kawauchi et al. (38 kHz: 20log*FL*-66.7; 120 kHz: 20log*FL*-69.5)

Therefore, further studies are needed to improve the accuracy of the *TS*–fork length relationship, such as analyses of *TS* in schools.

The frequencies used in this study are carried by many research vessels, and we expect the *TS*–fork length relationship obtained in this study to be used for high-precision estimation of the abundance of chub mackerel in the future. Additionally, the TS_{mean} at 38 kHz was slightly higher than that at 120 kHz for the same fork length, indicating frequency-dependent characteristics of chub mackerel. Since such differences in reflection intensity among frequencies differ among species (Kang et al. 2002; Sato et al. 2015), we believe that these frequency characteristics can be used for species identification in the sea. In the future, our approach can be applied to measure *TS* in more fish species and to clarify practical *TS* and frequency characteristics. Our results are expected to provide a basis for the estimation of the abundance of fish species in different areas with a high degree of accuracy.

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