Age, Growth and Reproductive Cycle of the Jack Mackerel Trachurus japonicus in the Southwestern Sea of Japan

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Age, Growth and Reproductive Cycle of the Jack Mackerel *Trachurus japonicus* in the Southwestern Sea of Japan

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Abstract

The growth and reproductive cycle of the jack mackerel (*Trachurus japonicus*) that were caught in the southwestern Sea of Japan during 2016-2017 were examined based on otolith annuli and gonad histology. Translucent and opaque zones on transverse sections on otoliths were identified and opaque rings were counted. The von Bertalanffy growth curve was expressed as follows: $FL_t = 445\{1 - \exp(-0.149\,(t + 1.74))\}$ $(0.250 < t < 7.67)$, where FL_t is the fork length (mm) at age t. The estimated body length at age t in the growth model was smaller than that of jack mackerel in the East China Sea. The spawning period was evaluated from May to September based on the monthly changes in the gonadosomatic index and histological observations. The spawning period starts later than in the East China Sea, but the minimum size at first maturity was similar to that of the jack mackerel in the East China Sea. The information generated in this research can contribute to the sustainable management of the species in the Sea of Japan.

Discipline: Fisheries
Additional key words: maturity size, otolith, ovary histology, spawning period

Introduction

Jack mackerel (*Trachurus japonicus*) are distributed in the continental shelf waters derived from the Tsushima Warm and Kuroshio Currents. The main fishing grounds of the Japanese fisheries are the East China Sea (ECS) and the southwestern Sea of Japan (SWSJ). The total jack mackerel catch from the ECS and SWSJ was 300,000-400,000 tons in the early 1960s but decreased to 170,000 tons in the late 1960s (Hotta & Mako 1970). Currently, the annual catch of Japanese fishery is around 100,000 tons in these areas (Yoda et al. 2021). Jack mackerel is one of the most important target species for purse seiners.

The oceanographic conditions of the Sea of Japan changed from colder to warmer regimes between 1988 and 1989 (Katoh et al. 2006). For example, the winter sea surface temperature has increased by 1.6°C-2.4°C over the last century (Takatsuki et al. 2007, Yamano 2011). Climate variability alters fish composition and regional fishery production in the Sea of Japan (Ho et al. 2020).

The effects of seawater temperature on fish growth and maturity have been studied in several species (e.g., Wada et al. 1995, Watanabe & Yatsu 2004). Previous studies on the growth and maturation of jack mackerel in the Sea of Japan have been reported from the northern part of the sea (Nishida & Hasegawa 1994). To assess the jack mackerel stock in the Sea of Japan, it is important to determine the biological characteristics of jack mackerel in the SWSJ. In the current study, we determined the age and examined the annual reproductive cycle of the jack mackerel collected from the SWSJ.

Materials and methods

1. Sample collection

All specimens were collected from the catch of purse seine fisheries between April 2016 and May 2017 in Sakaiminato, Tottori Prefecture, Japan (Fig. 1). The fork length (FL) and body weight (BW) of 4,177 fish were measured to the nearest 1 mm and 0.1 g, respectively (Fig. 2). Otoliths were collected from 755 fish for subsequent growth analysis. The ovary weight (OW) of jack mackerel was measured to the nearest 0.1 g after sex determination. Small portions of ovaries from 526 females that were larger than the minimum size for maturation (identified in a preliminary study to be 170 mm FL), were excised and preserved in 10% buffered formalin solution. The gonadosomatic index (GSI; $GSI = OW \times 100 / BW$) was

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calculated for each sample.

For the reference index of the oceanic condition, the monthly mean water temperature at 50 m depth layer in the sampling area shallower than 200m depth (Fig. 1, shaded area) was calculated based on the re-analyzed daily data with a spatial resolution of 0.1° regarding latitude and longitude from the Fisheries Research and Education Agency - Regional Ocean Modeling System II (FRA-ROMSII) dataset (https://fra-roms.fra.go.jp/fra-roms/), an ocean forecasting system based on FRA-ROMS (Kuroda et al. 2017) that has an improved model performance for the Sea of Japan.

2. Otolith measurement and growth analysis

The sagittal otoliths were extracted and kept dry. Next, they were oven-dried at 150°C for 15 min using a dryer (DO-300A; AS ONE, Osaka, Japan), embedded in epoxy resin (Epoxicure; Buehler, Esslingen, Germany), and sectioned transversely through the core using a micro cutter (MC-201, Maruto, Tokyo, Japan). Following this, the sectioned otoliths were mounted on a glass slide with epoxy resin and polished with waterproof sandpaper (#400-#1,200) and alumina polishing powder (0.3 µm) to be approximately 0.3 mm thick. The otolith section was observed using a microscope (AZ100, Nikon Corporation, Tokyo, Japan) under transmitted light (Fig. 3). The number of opaque zones (N) was counted and the distances between the core and the inside margins of the Nth opaque zone (r_N) and between the core and the outer margin (R) were measured at 100× magnification using an otolith measurement system consisting of a light microscope equipped with charge-coupled device (CCD) camera controlled using a personal computer (ODRMS, RATOC, Tokyo, Japan).

Each otolith was examined three times, with at least 1-month interval between examinations. Only otoliths with countable rings and two or more consistencies in the examination were used for the growth analysis. The index of the average percentage error (IAPE) was calculated to measure the precision of the count as follows (Beamish & Fournier, 1981):

$$\mathrm{IAPE} = 100 \times \left({}^{1}\!/_{\mathrm{A}}\right) \sum \left[\left({}^{1}\!/_{\mathrm{T}}\right) \sum \left(\left|\mathrm{X_{ij}} - \mathrm{X_j}\right| / \mathrm{X_j}\right)\right]$$

where A is the number of fish counted, T is the number of times each otolith was counted, X_{ij} is the opaque zone count from the i^{th} reading of the j^{th} fish, and X_j is the average number of opaque zones of the j^{th} fish.

The marginal increment (MI) rate was examined to define the period of opaque zone formation. MI was defined using R, r_N, and r_{N-1}, $MI = (R-r_N) / (r_N-r_{N-1})$.

The von Bertalanffy growth equation was fitted to the FL-at-age data using the least-squares method (von Bertalanffy 1938). The von Bertalanffy growth parameters were estimated using the Microsoft Excel solver. The growth equation used was $FL_t = L_\infty[1-\exp\{-K(t-t_0)\}]$, where FL_t is the FL (mm) at age t (year), L_∞ is the asymptotic FL, K is the growth coefficient, and t_0 is the hypothetical age at $FL = 0$. In this estimation, the age of each fish was assigned at 1-month (=1/12 year) intervals. April was assumed to be the month when age increased each year because most of the young jack mackerel caught in the SWJS were hatched in April (Takahashi et. al. 2022). Individuals with a wide translucent zone on the otolith edge and with relatively high MI value that were collected from April to June, were categorized into ages based on the number of opaque zones + 1 year because their new opaque zones were not yet formed.

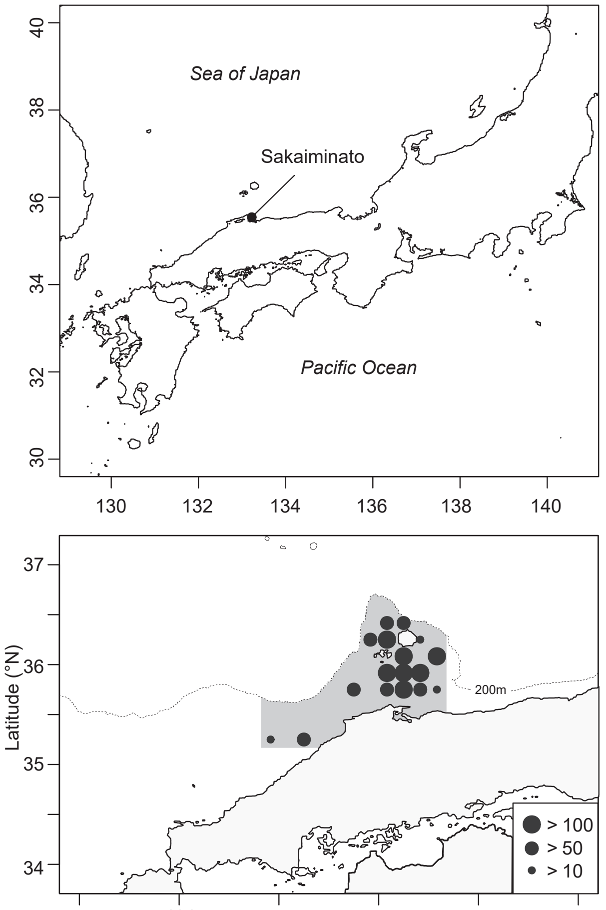

Fig. 1. Location of the specimens caught in the southwestern Sea of Japan
The circle size indicates the number of fish caught at each site in this study. The shaded area indicates the locations from where water temperature data was collected.

A previous study found no significant differences in the growth equations between sexes (Yoda et al. 2014). Males and females were therefore pooled to estimate growth parameters in the present study.

3. Histological observations

For histological analysis, the preserved ovaries were dehydrated and embedded in Technovit resin (Kulzer, Wehrheim, Germany). The sectioned gonads (2-3 µm thick) were stained with 1% toluidine blue solution and observed under an optical microscope (OPTIPHOT-2, Nikon Corporation, Tokyo, Japan). According to the histological characteristics, each ovary was classified into one of six maturity phases based on the most advanced oocytes found in the ovary (Yoneda et al. 2002). These maturity phases were: the immature phase (Im), in which the perinucleolus and yolk vesicle stage were the most advanced; the developing phase (D), in which vitellogenic oocytes in the primary to tertiary yolk stages were the most advanced; the mature phase (M),

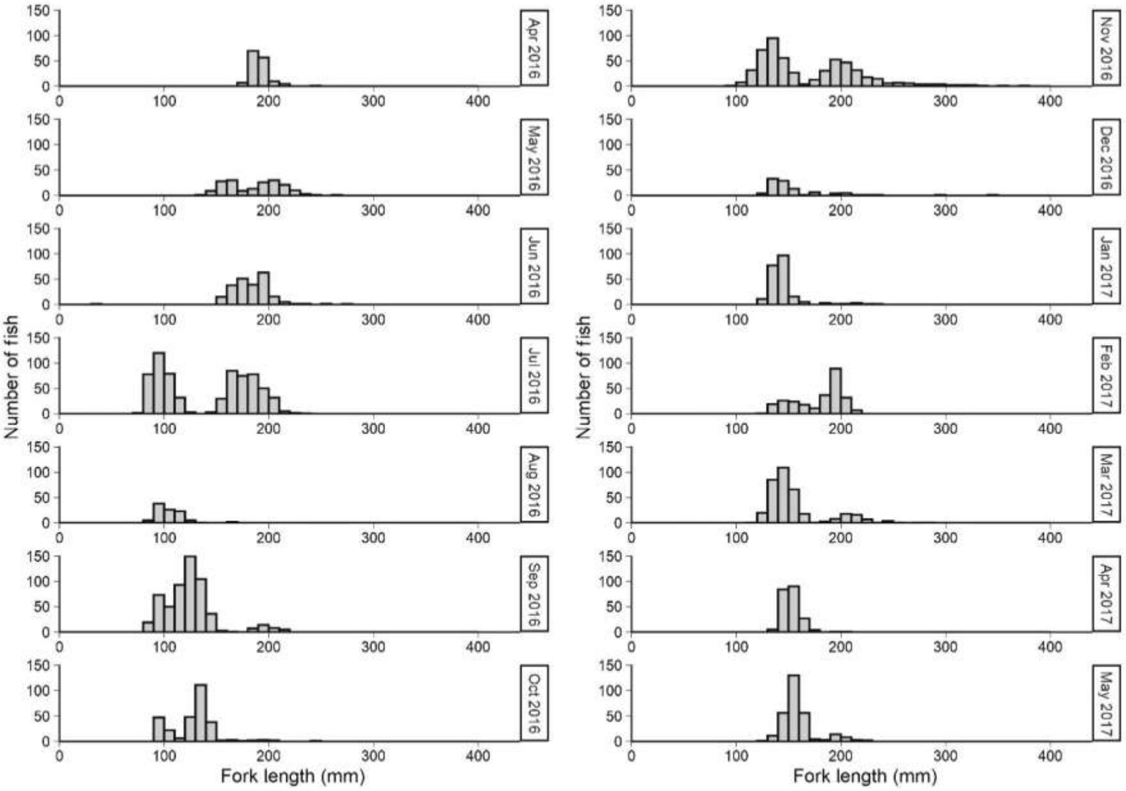

Fig. 2. Monthly fork length histograms of *Trachurus japonicus* caught in the southwestern Sea of Japan

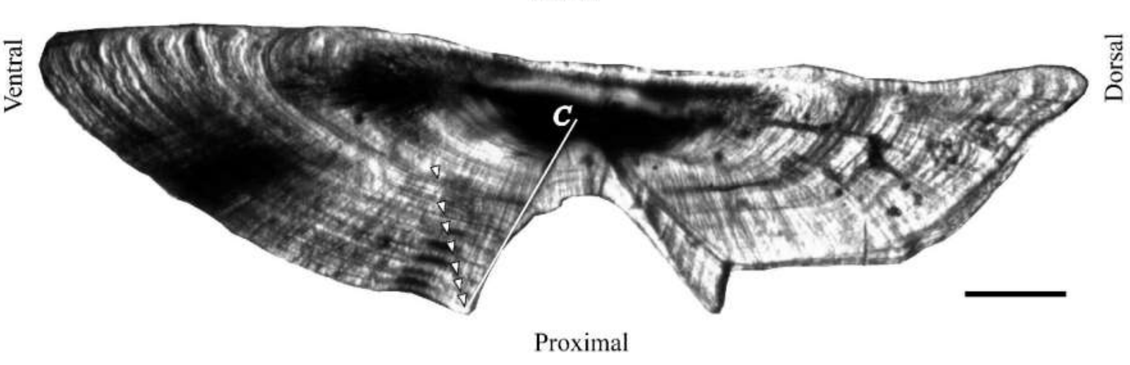

Fig. 3. Section of an otolith from *Trachurus japonicus* with seven ring marks

C: core; white line: measurement line used to calculate marginal increment (MI); white arrows: ring marks. Scale bar (right) indicates 500 µm.

oocytes at the migratory nucleus or mature stages were the most advanced; the spawning phase (Spa), in which yolked oocytes and postovulatory follicles were present; the spent phase (Spe), in which all yolked oocytes were in the early atretic stage; and the resting phase (R), in which late atretic stage oocytes and non-yolked oocytes were present.

4. Sexual maturity

Size at maturity estimation was based on the histological observation of 302 females collected from May to September (spawning season). Sexually mature specimens were defined as females with ovaries in the developing, mature, or spawning phase. To estimate FL at 50% maturity (FL_{50}), a logistic function was fitted using a generalized linear model (GLM), assuming binomial error using the statistical software R ver. 4.0.3 (R Core Team 2020). The logistic equation was as follows:

$$P_{FL} = \frac{1}{1 + e^{-a(FL-FL_{50})}}$$

where P_{FL} is the estimated proportion of mature specimens at a given FL, FL_{50} is the length at 50% maturity.

Results

1. Length-frequency distribution

The monthly length-frequency distributions of the specimens are shown in Figure 2. FL ranged from 35 to 371 mm, and the smallest fish were collected in June. FL less than 200 mm was recorded in a majority of the collected specimens (approximately 90%). The smallest sized group that was in the 70 mm-130 mm range FL appeared in July 2016, and this group gradually grew in size throughout the month. The modal size of the group reached 150 mm in May 2017.

2. Marginal increments

All specimens were consistent in at least two of the three readings. A total of 755 specimens were examined, and in 362 otoliths (47.9%), no distinct ring marks were observed; these were considered as 0 ring otoliths. The IAPE of 393 specimens (excluding the 0 ring otoliths) was 4.38%. There is no clear criterion for an acceptable APE; however, it is generally less than 5% (Morison et al. 1981). The IAPE value in our study was relatively lower than that in other studies, indicating that the accuracy of age determination was satisfactory (Campana 2001). In addition, MI decreased from May to June (Fig. 4), suggesting that the opaque zone formation was completed during this period.

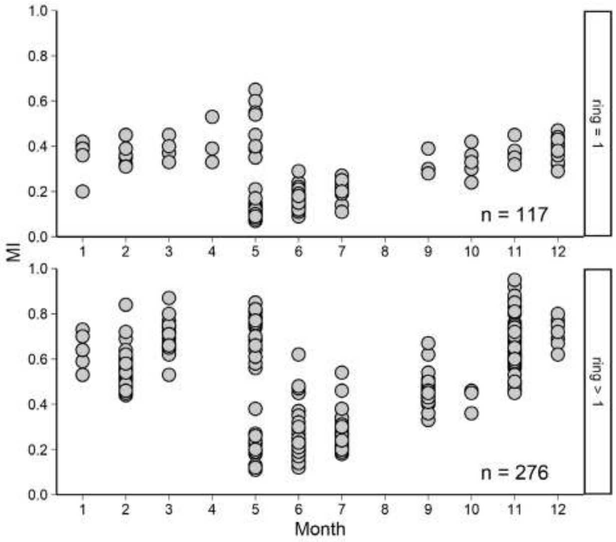

Fig. 4. Monthly change in the marginal increment (MI) rate of jack mackerel by ring group
Above: 1 ring group; Below: 2-6 rings group. Circles indicate individual specimens.

3. Age and growth

The estimated maximum age was 7 years. The estimated growth model based on the FL and age (t) data (Fig. 5) was as follows:

$$FL_t = 445\{1-\exp(-0.149(t + 1.74))\} \quad (0.25 < t < 7.67)$$

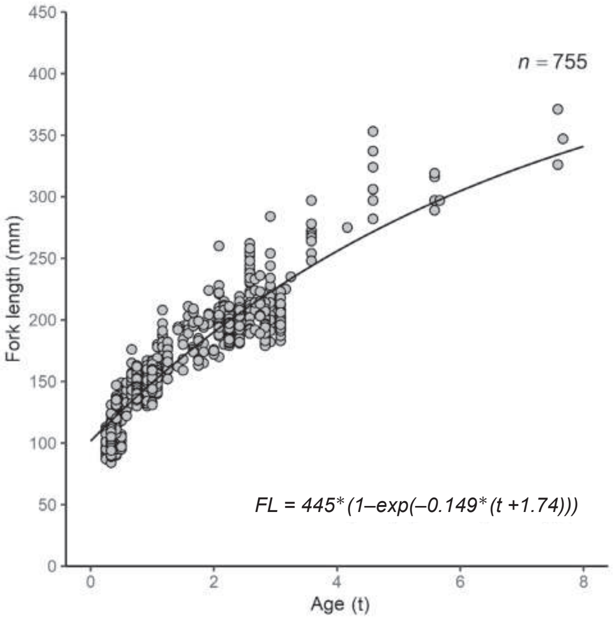

Fig. 5. Relationship between fork length (mm) and age in *Trachurus japonicus*
Von Bertalanffy growth curves were fitted to the growth data.

4. Sexual maturity

For the specimens collected in July, the minimum size of the fish that had mature-stage oocytes was 170 mm FL. The FL_{50} was estimated as 189 mm, but the size range of mature specimens overlapped considerably with that of immature specimens (Fig. 6).

Based on histological observations, immature females were observed from November to July (Fig. 7). Females with developing ovaries were observed from March to September, excluding August and November. Females with ovaries in the mature and spawning phases appeared from May to September, but not in August. Females with spent ovaries were collected from April to July, October, and November, and those with resting ovaries were collected from May to December, except for August and October.

Female jack mackerel with a high GSI value (GSI > 3.0) appeared from May to September, except that the samples were not collected in August. The maximum value of the GSI was 9.07 in May (Fig. 8). After September, the GSI decreased and remained low between October and April.

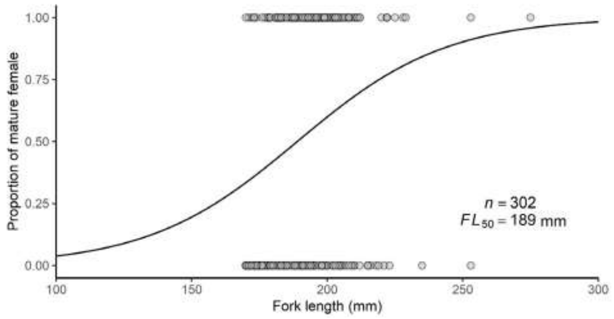

Fig. 6. Relationship between fork length and maturation of female *Trachurus japonicus* based on the spawning season (May to September)
The curve is based on a logistic equation for the proportion of maturity against fork length.

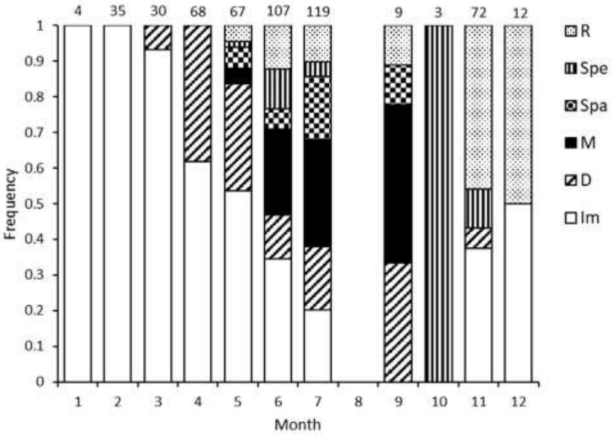

Fig. 7. Monthly change (2016-2017) in the frequency of various maturity phases in the ovaries of *Trachurus japonicus*
Only specimens larger than the minimum required size at sexual maturity (170 mm) were used for this analysis. Im, immature phase; D, developing phase; M, mature phase; R, resting phase; Spa, spawning phase; Spe, spent phase. Numbers above the bars indicate sample sizes.

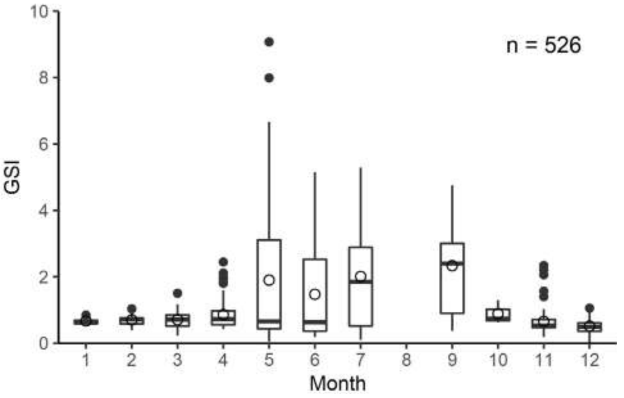

Fig. 8. Box-plot of the gonadosomatic index (GSI) for female *Trachurus japonicus* for each month
Lower and upper box boundaries represent 25th and 75th percentiles, respectively, and line inside box represents median. The upper whisker is located at the smaller value of the maximum value and is 1.5 times the interquartile range from upper quartile. The lower whisker is located at the larger value of the minimum value and is 1.5 times the interquartile range from lower quartile. The filled circles define data reaching past 1.5 times in the interquartile range and the open circles indicate mean value.

Discussion

We distinguished seven annuli in the otoliths, and the annulus formation season was from May to June, which corresponded to the active spawning period for the jack mackerel in the waters of the SWSJ. Table 1 shows the comparison of the estimated size at age between jack mackerels in the present study area and in other waters. The growth rate of jack mackerel estimated in this study was relatively close to that of Niigata Prefecture (Nishida & Hasegawa 1994) and southern Joban-Boso area (Taga & Yamashita 2018) for individuals aged under 3 years. However, the growth rate was considerably lower than that estimated in previous studies in Oita Prefecture (Katayama et al. 2019) and the ECS (Yoda et al. 2014) (Table 1). Compared to Miyagi Prefecture, the growth rate was lower except for that of 1-year-old individuals. The growth of marine fish varies with density, environmental factors such as water temperature, and their combined effects (Moyle & Cech 2002). Ochiai et al. (1983) reported that the optimal temperature for growth of 0-year-old fish is ascertained to be between 18°C and 26°C in captivity. In the present study, the monthly mean water temperature at 50 m in the sampling area is lower than 18°C between January and June (Fig. 9). The relatively low temperature may cause the slow growth of jack mackerel caught in the present study area.

Several studies on jack mackerel growth in the Pacific coastal waters have reported maximum ages as 19 (Taga & Yamashita 2018) and 17 years (Katayama et al. 2019), which showed that they were much older than the specimens of the present study. Few specimens in the present study were over 3 years of age, and most were between 0- and 1-year old. Taga and Yamashita (2018) reported that the age of jack mackerel caught in the Pacific coastal waters by purse seine and bottom trawl were mostly under 3 years. Our specimens were also collected by purse seine fisheries, which tend to catch younger fish. However, growth varies in response to internal (e.g., density dependence) and external factors (e.g., environmental variables such as temperature and size-selective fishing pressure) (Burton et al. 2019). The inconsistency in maximum fishing age among different areas is possibly due to the differences in these factors or fishing gear. Therefore, there is a need to examine specimens collected by methods other than purse seine fishing.

Our findings showed that the jack mackerel in the SWSJ spawned during May to September, which suggests that their spawning season starts later than that in the ECS, which starts in February (Yoda et al. 2014). In many temperate fish species, maturation normally occurs within a species-specific ambient temperature range (Clark et al. 2005, Lam 1983). In captivity, jack mackerel did not mature under 19°C at the age of 1 year (Ochiai et al. 1983). Nishida (2006) suggested comprehensively that mean water temperature of jack mackerel spawning around Japan ranged from 19°C to 21°C. The mean water temperatures in the sampling area at 50 m were the lowest during February and March and increased from May and exceeded 20°C during August and November (Fig. 9). The delay in the start of the maturation season was possibly due to the low ambient temperatures in the SWSJ. On the other hand, 3- to 4-year-old fish had atretic oocytes over 18°C in captivity (Ochiai et al. 1980), which suggested that the older fish stopped spawning in high

Table 1. Estimates of fork length by age for jack mackerel in the waters in the vicinity of Japan

Sampling area	Estimated FL (mm) at age (years)							References
	1	2	3	4	5	6	7	
Southwestern Sea of Japan (SWJS)	149	190	225	256	282	305	324	Present study
Niigata	148	206	249	282				Nishida & Hasegawa (1994)
Southern Joban-Boso	160	202	231	251	264	274	280	Taga & Yamashita (2018)
Miyagi	143	219	259	281	292	298	301	Katayama et al. (2019)
Oita	168	253	297	319	330	336	339	
East China Sea (ECS)	179	233	272	303	326	345		Yoda et al. (2014)

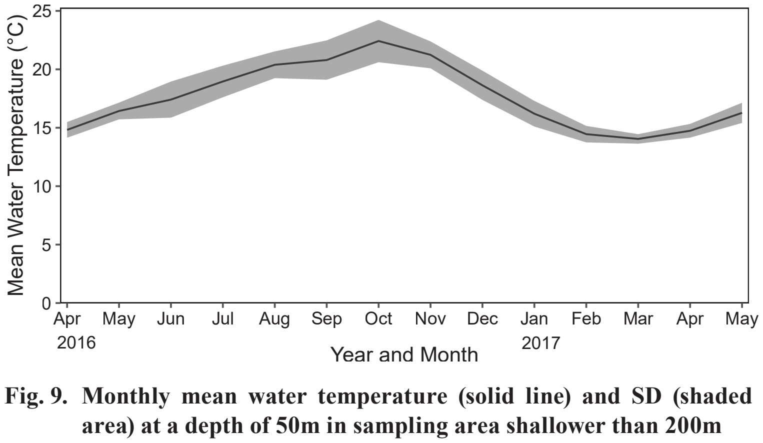

Fig. 9. Monthly mean water temperature (solid line) and SD (shaded area) at a depth of 50m in sampling area shallower than 200m
The value for each month is monthly averages of daily temperatures.

temperatures. In October, the mean water temperature at 50 m depth was over 21°C in the study area, which coincided with reproductive cessation.

A previous study reported the minimum size at maturity for female jack mackerel as 171 mm, presumed to be of 1-year-old fish in the ECS (Yoda et al. 2014). The minimum size at maturity for females in the present study was comparable to that of females in the ECS. However, the growth rate was slower than that of females in the ECS. Many 1-year old females of SWJS will not reach the minimum size required at maturity in the spawning season. Therefore, it is anticipated that the spawning population in the SWJS will mainly be females older than 2 years. Nishida (2006) reported that the maturation of jack mackerel depends on body size rather than age, which is consistent with our results. However, the minimum size of mature females that underwent otolith and histological analysis was 172 mm FL for 2-year-old fish with ovaries in the developing phase. The relationship between body size and maturity overlapped in this wide size range. Some females larger than the minimum required size at maturity stopped spawning during the spawning season. Therefore, future studies need to examine whether the maturation threshold depends on age or size.

In conclusion, our results demonstrate that jack mackerel in the SWSJ have a slower growth rate than those in the ECS reported in other studies. Furthermore, they spawn mainly when older than 2-years of age. In addition, the spawning season in the SWSJ is May-September, which is later than that in the ECS. Jack mackerel spawning grounds are distributed in the coastal waters around western Japan and the shelf-break region of the ECS. Therefore, the extended spawning season and widely distributed spawning grounds may help sustain the population under environmental fluctuations. Biological information on growth and reproduction in this study can contribute to the sustainable management of this species in the Sea of Japan.

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