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Size and Age Composition of Southern Bluefin Tuna (*Thunnus maccoyii*) in the Central Indian Ocean Inferred from Fisheries and Otolith Data

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Jen-Chieh Shiao, Shui-Kai Chang, Yu-Ting Lin, and Wann-Nian Tzeng (2008) Size and age composition of southern bluefin tuna (*Thunnus maccoyii*) in the central Indian Ocean inferred from fisheries and otolith data. *Zoological Studies* **47**(2): 158-171. Estimating the age of the commercial catch of southern bluefin tuna (SBT, *Thunnus maccoyii*) is essential to the age-based stock assessment process and an understanding of the population dynamics of the species. This information is, however, very incomplete for the central Indian Ocean (CIO), where only the Taiwanese fleet catches SBT, and will be influential in providing an overall picture of the recently suspected weak recruitment that emerged from several fishery indicators in the SBT's nursing and feeding grounds. Based on commercial logbook data of Taiwanese longliners with the size of each SBT attached, this report provides age composition information from 2002-2005 with annual mean ages of 4.3-5.0 yr, through length-to-age conversions by cohort slicing procedures. The commercial length distributions have been verified by those obtained from 10 trips of scientific observations, and the age compositions were compared with those estimated from directly aging 473 otolith samples collected by those observers. About 90% of the total SBT catch was < 8 yr old, the presumed youngest age at first sexual maturity. Thus, SBT caught in the CIO may consist mostly of sexually immature individuals and showed no geographical trends. Four yr of age and size composition data indicated a stable migrating SBT stock in the CIO, compared with the weak recruitment of young fish to the southern Australian nursing grounds and New Zealand feeding grounds during the same period. http://zoolstud.sinica.edu.tw/Journals/47.2/158.pdf

Key words: Southern bluefin tuna, *Thunnus maccoyii*, Size composition, Otoliths, Length-weight equation.

The southern bluefin tuna (SBT) *Thunnus maccoyii* Castelnau is widely distributed in southern hemisphere waters between 30° and 50°S but rarely found in the eastern Pacific. The only known spawning ground is in the Indian Ocean, southeast of Java, Indonesia (Jenkins and Davis 1990, Caton 1991). Otolith microchemical and mitochondrial DNA analyses failed to detect genetic or spatial heterogeneity within the species (Proctor et al. 1995, Grewe et al. 1997). Therefore, the SBT is managed as a single stock.

SBT have been fished since the early 1950s mainly by Japan and Australia. The total catch rapidly increased during the 1950s and peaked at about 80,000 metric tons in the 1960s. The fleets of Taiwan, Korea, Indonesia, and New Zealand began fishing SBT as a seasonal target or bycatch in the 1970s, and the catch by these countries has gradually increased. Continuous warnings from scientists that the stock was being fully exploited resulted in the introduction of a quota management system in the mid-1980s by the 3 major fishing countries (Japan, Australia, and New Zealand). The quota system was expanded and applied to other fishing countries, i.e., Korea and Taiwan, under management by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT, established in 1994). Due to persisting concerns about the stock's status, the overall catch limit was set at 14,930 metric tons (Hayes 1997, Lee 1998)

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and later reduced further to 11,810 metric tons for 2007-2009 (Anonymous 2006).

Although the highly migratory SBT is found throughout the southern oceans except the eastern Pacific, the distribution of the catch and fishing effort across these regions varies greatly both temporally and spatially, with large areas with little or no effort, particularly in more-recent years (Gunn et al. 2003). The Australian surface fishery targets recruiting young in the Great Australian Bight (GAB), the Japanese longline fishery targets subadult individuals in the southern oceans (around 35°-45°S), and the New Zealand-Japanese chartered longline fishery targets subadult and adult fish in New Zealand coastal waters (Gunn et al. 2003) (Fig. 1). A simple calculation based on the size data from the CCSBT Secretariat (pers. comm. with Mr. Robert Kennedy, the Database Manager of CCSBT), the average SBT size is around 100 cm for the Australian fishery, 130-140 cm for the Japanese fishery, and 140-170 cm for the New Zealand fishery (Fig. 2). The Korean fishing grounds roughly overlap the Japanese fishing grounds in the Indian Ocean (Gunn et al. 2003).

Taiwanese longliners catch mostly young SBT at a size differing from other fishing fleets (around 120 cm, Fig. 2), specifically in the Indian Ocean

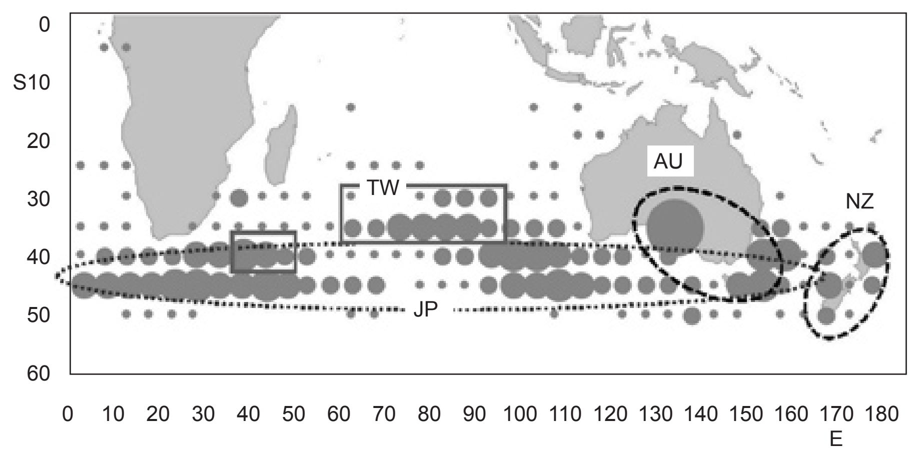

Fig. 1. Geographic distribution of southern bluefin tuna (SBT) caught by members of the CCSBT during 2000-2005. Key areas are surrounded by dark dashed circles for the Australian and New Zealand fleets, light dashed circles for the Japanese fleet, and solid rectangles for the Taiwanese fleet. The key area of the Korean catch is not shown as it basically overlaps the Japanese one. (Data source: CCSBT Secretariat 2007; some data points in the tropical regions still require further investigation.)

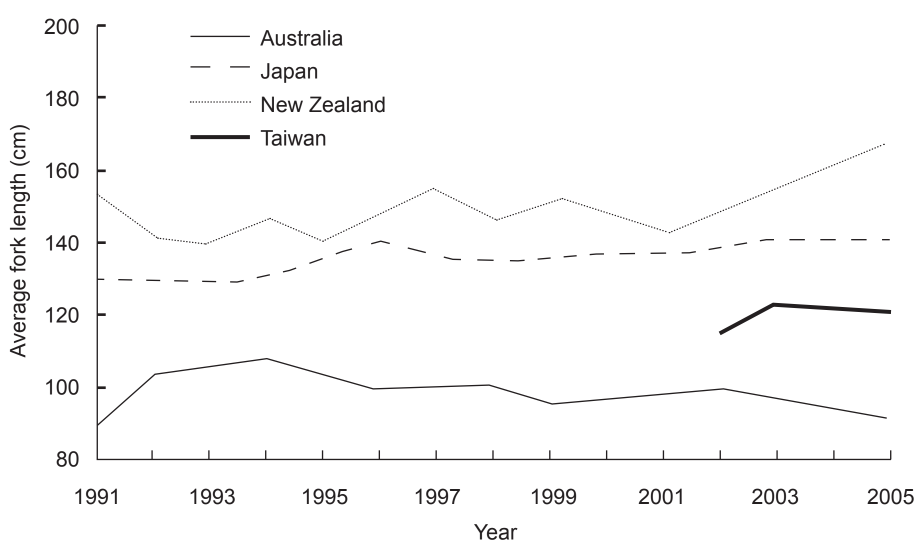

Fig. 2. Annual average size (fork length in cm) of southern bluefin tuna (SBT) caught by members of the CCSBT. The size of the Korean catch is not shown as it was in a similar range with the Japanese catch. The size of the Taiwanese catch is shown only for years after 2002 due to complete size data only being available for those years.

between 20° and 45°S and 20° and 110°E which is north of the Japanese fishing grounds. There are 2 major fishing grounds and seasons: one in the central Indian Ocean (CIO) during May to Oct., and the other in waters off the Republic of South Africa (RSA) during Nov. to the following Feb. (Fig. 3). Annually, around 95% of the overall Indian Ocean SBT catch is taken in the 1st fishing ground, and this percentage has increased in recent years. In addition, ranges of SBT sizes of the 2 components are similar (Fig. 4). Therefore, they were combined together in this study and referred to ad hoc as the CIO for convenience. The Taiwanese fishery also catches SBT in the Atlantic and Pacific Oceans but the proportion is small at around 0.5%-10% of the total number (unpublished data).

Determining the age composition of the SBT catch is a basic requirement for age-based stock assessment models; originally Virtual Population Analysis and now statistical catch-age models are used (Murphy and Majkowski 1981, Kolody and Polacheck 2001). In this regard, the age structure in each fishing ground is very important for understanding the population dynamics. The estimated growth equation for the SBT exhibits a slow growth rate after an age of 10 yr (Polacheck et al. 2004), and the maximal age of SBT was shown to be greater than 40 yr (Kalish et al. 1996). This phenomenon introduces unexpected risks and biases to the length-to-age conversion during the adult stage (> 10 yr) due to the high variability in length with age. Consequently, Thorogood (1987) developed direct aging techniques by reading otolith annuli for SBT aged 2-9 yr; this approach was further modified and validated for fish up to approximately 30 yr old (Kalish et al. 1996, Clear et al. 2000). Otolith microstructure is also used to determine the age of larval and juvenile SBT (Jenkins and Davis 1990, Itoh and Tsuji 1996). Scales have also been used for age estimation, but are not reliable for fish larger than 130 cm (> 7 yr old) (Yukinawa 1970). Therefore direct aging using otoliths has been used to estimate the age of thousands of SBT collected from Australian and Japanese catches by reading sectioned otoliths (Farley et al. 2007). The results indicated that the Australian surface fishery in the GAB is dominated by 2-4 yr olds and the Japanese catches in the southern oceans are comprised of 2-to > 30-yr-old fish (Farley et al. 2007). However, information on the size and age structure of SBT across the CIO is very sparse and incomplete. The most recent work on the age composition of the Taiwanese catch in the CIO was done by Farley et al. (2007) based on logbook data from only 29 vessels in the central region and 3 off RSA, but no otoliths were collected for direct age estimation.

Weak recruitment of young SBT has recently occurred in the nursing grounds of the GAB and in the feeding grounds of New Zealand coastal waters (Hobsbawn et al. 2005, Kendrick et al. 2005). The reasons for these variations are still contradictory and ambiguous. Furthermore, whether weak recruitment also occurred in other feeding grounds such as the CIO is unclear because of a lack of supporting fishery or scientific information. The Indian Ocean, especially the middle to lower latitudes is predominantly exploited by Taiwanese longliners, and their logbook fishery data may provide useful information to address these questions. Tuna catch data (logbook data) from the Taiwanese longline fishery in the Indian Ocean have been collected by the Taiwan fisheries management authority since 1967. Regular logbook data include geographical and temporal information on the number and weight of SBT catches. The logbooks also include length measurements of the 1st 30 fish, regardless of

Table 1. Onboard observer data collected from Taiwanese southern bluefin tuna (SBT) longline vessels during 2002-2005

	Trips	SBT catch[a]	Length samples	Length-weight samples[b]	Otoliths
2002	1	498	338	338	0
2003	2[c]	222	174	174	102
2004	3	1292	1290	1281	316
2005	4	3189	2217	2215	77

[a]SBT that had been bitten by whales or sharks and were discarded are not included. [b]Number of useful samples (totally 4008) with both length and weight measured for the study. Originally 4019 samples were collected but 11 outliers were excluded in this study. [c]The 2 trips in 2003 only conducted short observation periods on the SBT fishing ground

species, that are retained in a set; however, lengths of SBT subsequently caught are not recorded. Since 2002, due to strengthened regulations, SBT fishing vessels have been required to record the weight and length of each SBT caught in new SBT logbooks.

For the purpose of collecting more-detailed fishery information and biological samples for both the target and bycatch species, a pilot observer program was launched on Taiwanese longline vessels in the Indian Ocean in 2001. The program was extended to cover all of the 3 oceans thereafter. There were 1, 2, 3, and 4 observation trips on SBT vessels in the Indian Ocean during

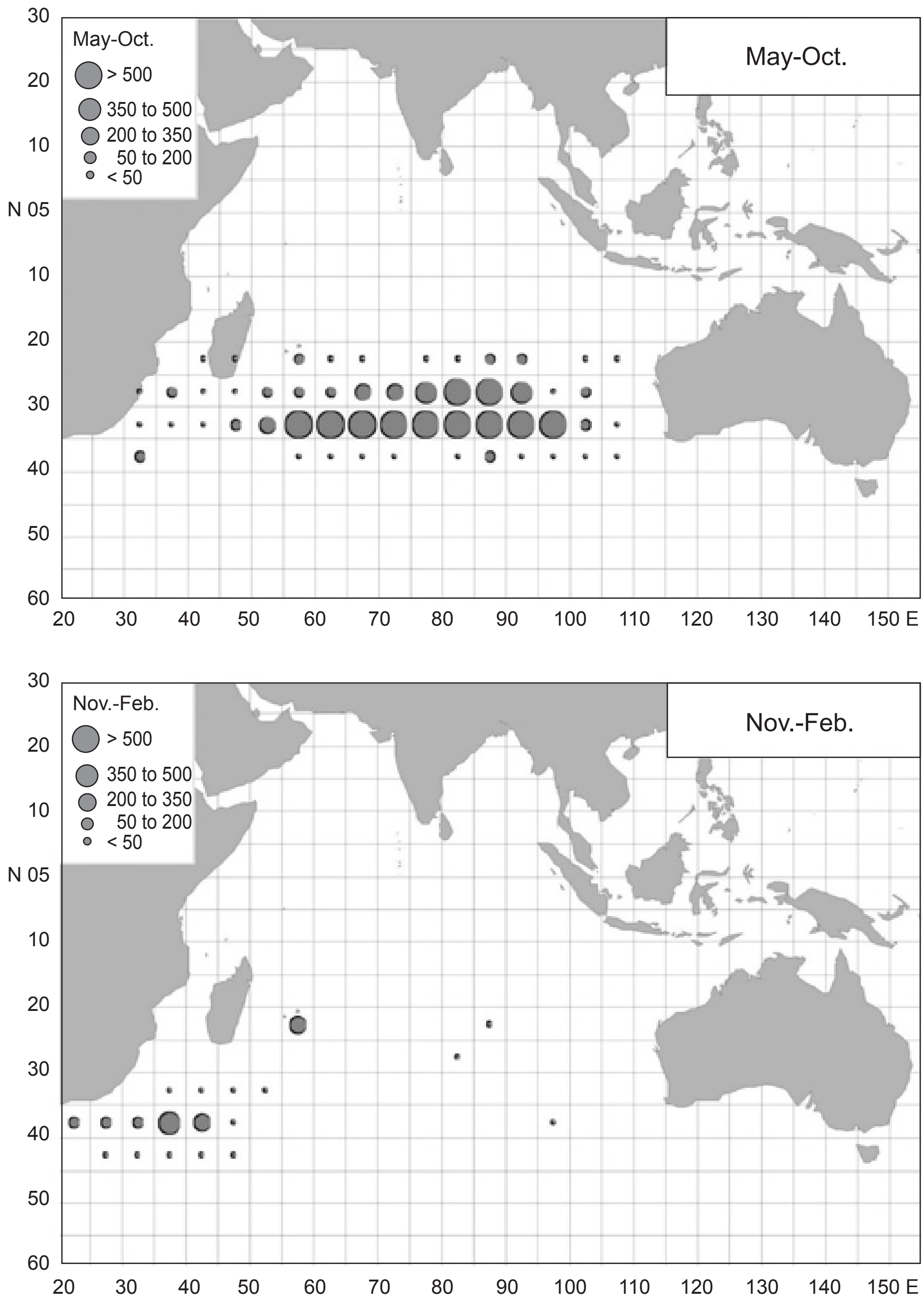

Fig. 3. Catch distribution of southern bluefin tuna (SBT) caught by Taiwanese longliners during 2002-2005 in 2 major fishing seasons (May to Oct. and Nov. to Feb.).

2002-2005, respectively, which totally collected 4019 pairs of length-weight data (Table 1).

A more-comprehensive understanding of the SBT population in the CIO is provided in this study through examining 4 yr (2002-2005) of commercial size data and resultant catch-at-age data from the Taiwanese longline fishery. The increasing knowledge of SBT size and age compositions derived from Taiwanese catches will help improve scientific advice for managing and conserving this species.

MATERIALS AND METHODS

Fisheries data and study area

Logbooks were obtained from Taiwanese longline vessels operating in the Indian Ocean in 2002-2005, and include data on individual SBT weight and length, and the total catch. Because the monthly size data were spatially scattered and unevenly distributed, they were aggregated and only annual data are presented here. Data were expressed as the mean ± standard deviation (SD, n = number of fish). Fork length was logarithmically (base 10) transformed to meet the assumptions of a normal distribution and equal variance for the parametric statistical analysis. Therefore, statistical differences in mean fork lengths among years were analyzed by one-way analysis of variance (ANOVA) followed by Tukey's pairwise multiple comparison tests to identify differences among groups. Significance was set at $\alpha \leq 0.05$. Sample size is often the primary influence on whether or not results are statistically significant. The R^2 values given in the standard ANOVA output were therefore used to evaluate the effect size. Values of R^2 of 0.01 are regarded as a small effect size, of 0.09 as a medium effect size, and of 0.25 as a large effect size, with of > 0.25 as a very large effect size (Cohen 1988).

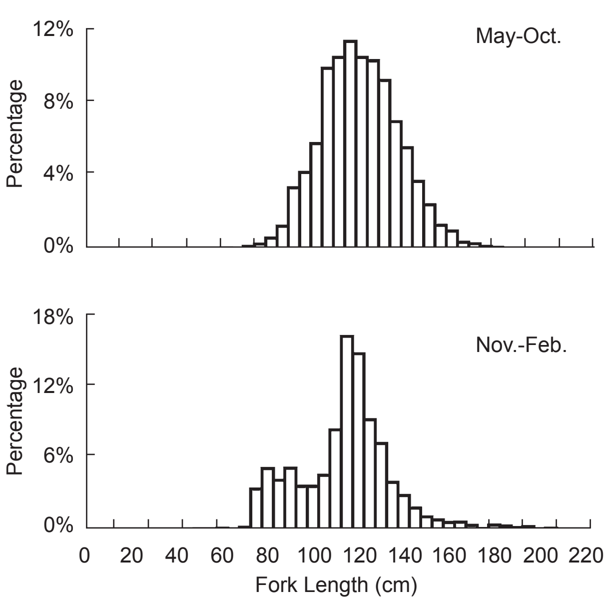

Fig. 4. Length distribution of southern bluefin tuna (SBT) caught by Taiwanese longliners in the 2 major fishing seasons (May to Oct. and Nov. to Feb.) of 2002-2005.

Observer data

Scientific observers were deployed on Taiwanese SBT longline vessels in 2002-2005 in the Indian Ocean (1-4 trips per year; Table 1). Since about 95% of the SBT caught by Taiwanese from the Indian Ocean comes from the central region of this ocean, all observer deployments and data collected during this period were from this region, and none came from waters off the RSA.

Observers measured and recorded the processed weight (gilled and gutted, to the nearest 1 kg) and fork length (from the tip of upper jaw to the tail fork, to the nearest 1 cm) of most of the SBT catch. In total, 5201 SBT were caught during the trips in 2002-2005, with 4019 fish (about 77% of the total) measured for individual length and weight data. However, only 4008 sets of length-weight data were used (11 outliers were excluded from the development of length-weight equation). The equation was developed by nonlinear least-squares estimation procedures that used the Levenberg-Marquardt algorithm. The length-weight equation was used to convert the logbook individual weight to lengths. The reported weights in the logbook system are usually viewed with greater confidence than lengths due to fishers' usual practice of weighing every fish of high commercial value onboard. A comparison was then made between the reported and converted

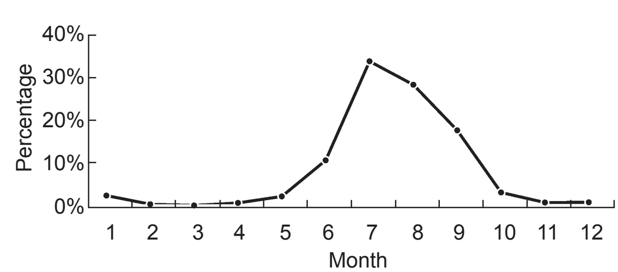

Fig. 5. Monthly catch percentages of the overall southern bluefin tuna (SBT) catch during 2002-2005.

lengths to determine the accuracy of the logbook length data.

Each scientific observer was requested to collect otoliths from every SBT caught until the goal of 100 pairs of otoliths was reached. In 2004, observers were requested to collect more otoliths, and 316 pairs were sampled by 3 observers. The otoliths were collected between June and Aug. each year. The otoliths were extracted from a core taken from the posterior cranial material by a hole-saw (35 mm in diameter) attached to a battery-powered drill to minimize damage to the fish body. The core was obtained by drilling from either side of the cranium (Clear et al. 2000). The points of entry for the hole-saw were the basioccipital plates. The disconnected core was cleaned of tissues, and the otoliths were extracted. The otoliths were cleaned immediately after extraction. After air-

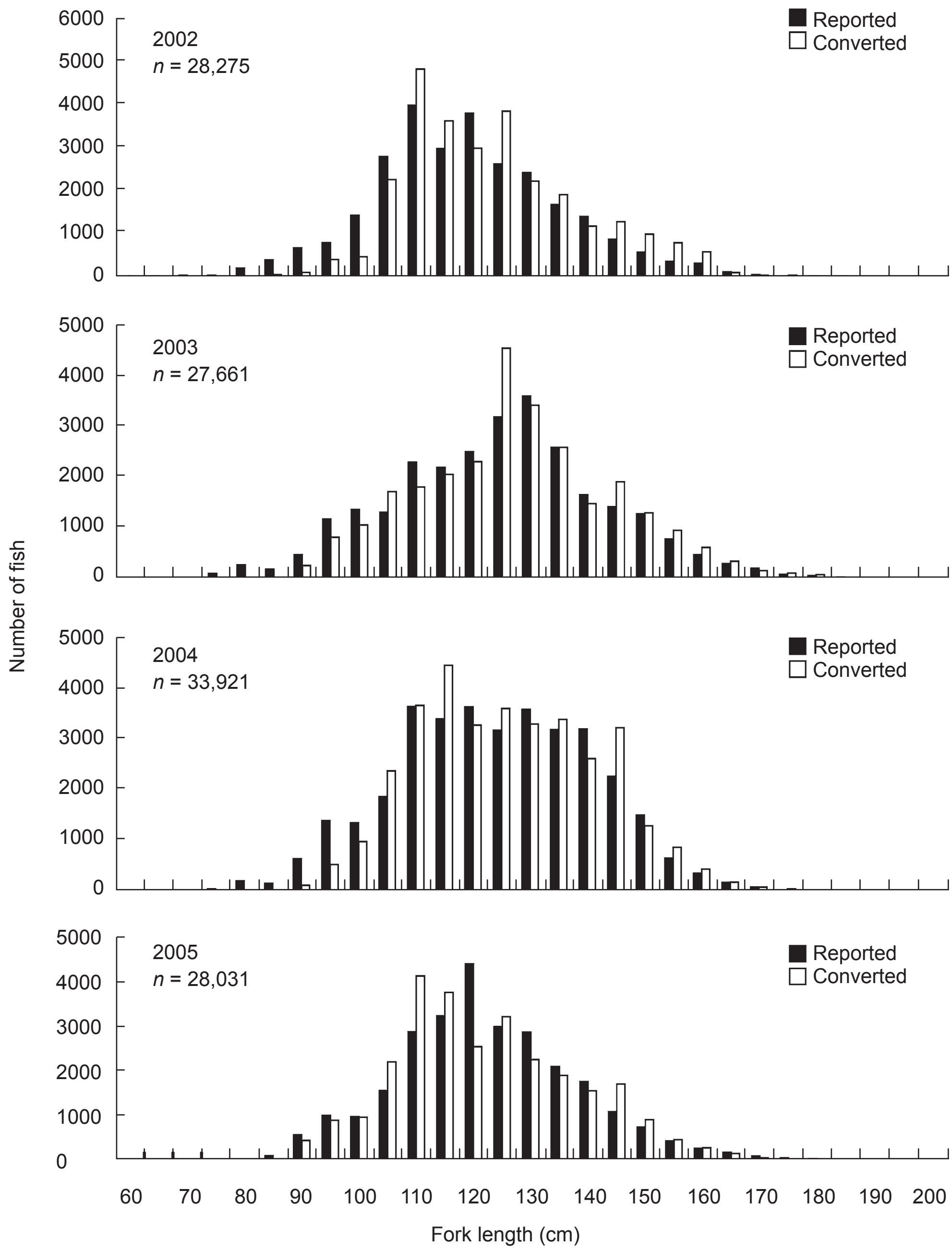

Fig. 6. Comparison of southern bluefin tuna (SBT) fork length frequencies reported in logbooks and converted from fish weights in logbooks via the length-weight equation developed in this study, 2002-2005.

drying, they were stored in plastic vials.

Otoliths were not collected in the 1st year of deployment of the scientific observers on SBT vessels in 2002 (Table 1). Otoliths were collected from 102 (30°-32°S and 67°-89°E), 316 (only 294 of which were analyzed, 29°-32°S and 65°-90°E), and 77 SBT (30°-32°S and 70°-80°E) in 2003, 2004, and 2005, respectively.

Age estimation

The length data in the logbooks were converted to age using cohort slicing and the annual cut point lengths (Anonymous 2001). Fish in each length class were assigned an age class by month. The cut point is the minimum length at each age and is computed from the SBT growth curve (Anonymous 2001). The SBT growth rates after 2000 were similar, so we did not create a monthly list of cut points for each subsequent year.

To estimate the age of the SBT sampled, otoliths were embedded in epofix resin and the core was identified under a stereomicroscope using transmitted light. A marking pen was then used to draw a line across the core of the otolith on the resin. This allowed the core to easily be located during sectioning. A transverse section approximately 400 μm thick was cut from the resin block with a slow-speed saw (Isomet, Buehler, USA) fitted with a diamond-edged blade. The thin section was repeatedly ground on both sides or on either side with the sandpaper on a grinder-polisher machine (Buehler Metaserv 2000, USA) until the annuli were clearly visible under the stereomicroscope. Then the otoliths were finally polished with a microcloth and 0.05 μm alumina paste to remove scratches and smooth the surface. The prepared otolith thin section was approximately 300 μm thick. An image of the otolith section was taken with a compound microscope equipped with a digital camera using transmitted light. Two experienced readers independently read the otoliths from the computerized image using standardized techniques (Anonymous 2002). After reading, the 2 age estimates were compared, and questionable samples were reexamined and discussed until agreement was achieved between the 2 readers. SBT otoliths for this study were collected between June and Aug. corresponding to the season that otolith annuli form (Clear et al. 2000). SBT spawn predominantly from Nov. to Feb. (Farley and Davis 1998). Therefore, reading otolith annuli may have overestimated the real age by approximately

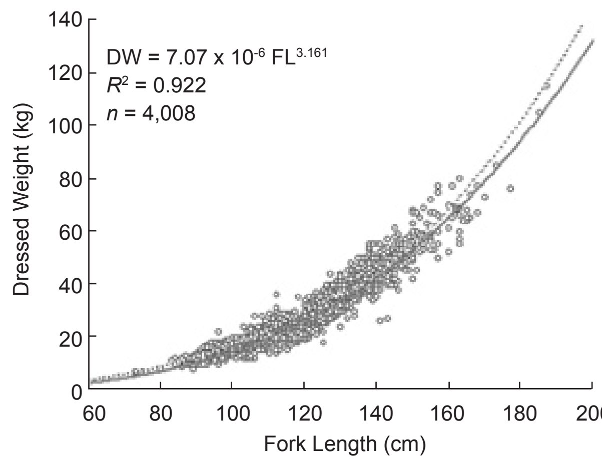

Fig. 7. Length-weight equation (solid line) for southern bluefin tuna (SBT) based on observer data (circles) of the Taiwanese fleet in 2002-2005. The equation currently agreed to be used by the CCSBT which is applicable to the study area (for fish < 130 cm: DW = 0.0000313088 x $FL^{2.9058}$ /1.15; for fish > 130 cm: DW = 0.000002942 x $FL^{3.3438}$) is also shown by the dashed line. DW, dressed weight; FL, fork length.

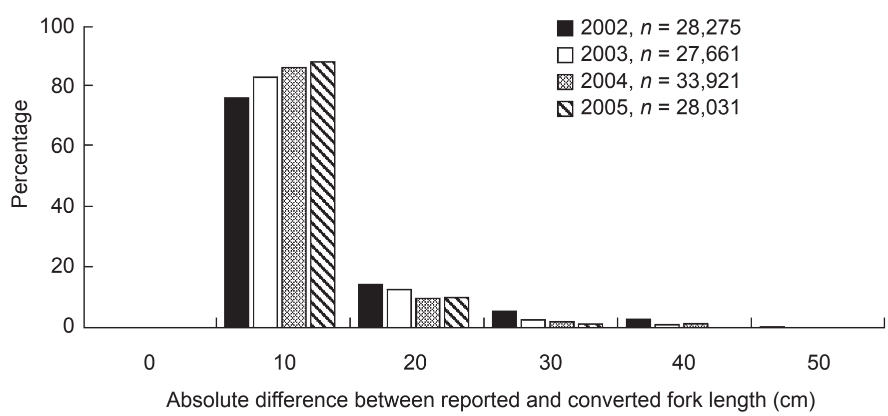

Fig. 8. Frequency distribution of the absolute differences between reported and converted fork lengths of southern bluefin tuna (SBT) in 2002-2005.

0.5-1 yr. This potential error was not corrected as each fish was not assigned to its correct cohort.

SBT caught by Taiwanese longliners were predominantly small fish, and thus were insufficient to construct a reliable growth curve. Therefore, the estimated age data by otolith direct aging were not used to generate an age-length key.

RESULTS

SBT catches

The Taiwanese longline fleet caught SBT mainly in the area of 25° - 35°S and 45°-110°E of the Indian Ocean (Fig. 1) during the austral winter (late May to Oct.), and June to Sept. was the main fishing season (Fig. 5). More than 95% of the total Taiwanese SBT catch in the Indian Ocean was made in this region and time period by 50-90 vessels (mostly as incidental catches). After the season, some of the fleet moved southwestwards to the region off the RSA (Fig. 3). About 4% of the total SBT catch in the Indian Ocean was made in this region during the austral summer (Nov. to the following Feb.) by 4-9 vessels. Very little of the SBT catch came from Mar. and Apr.; only about 1% of the total catch came from the area of 30°- 40°S

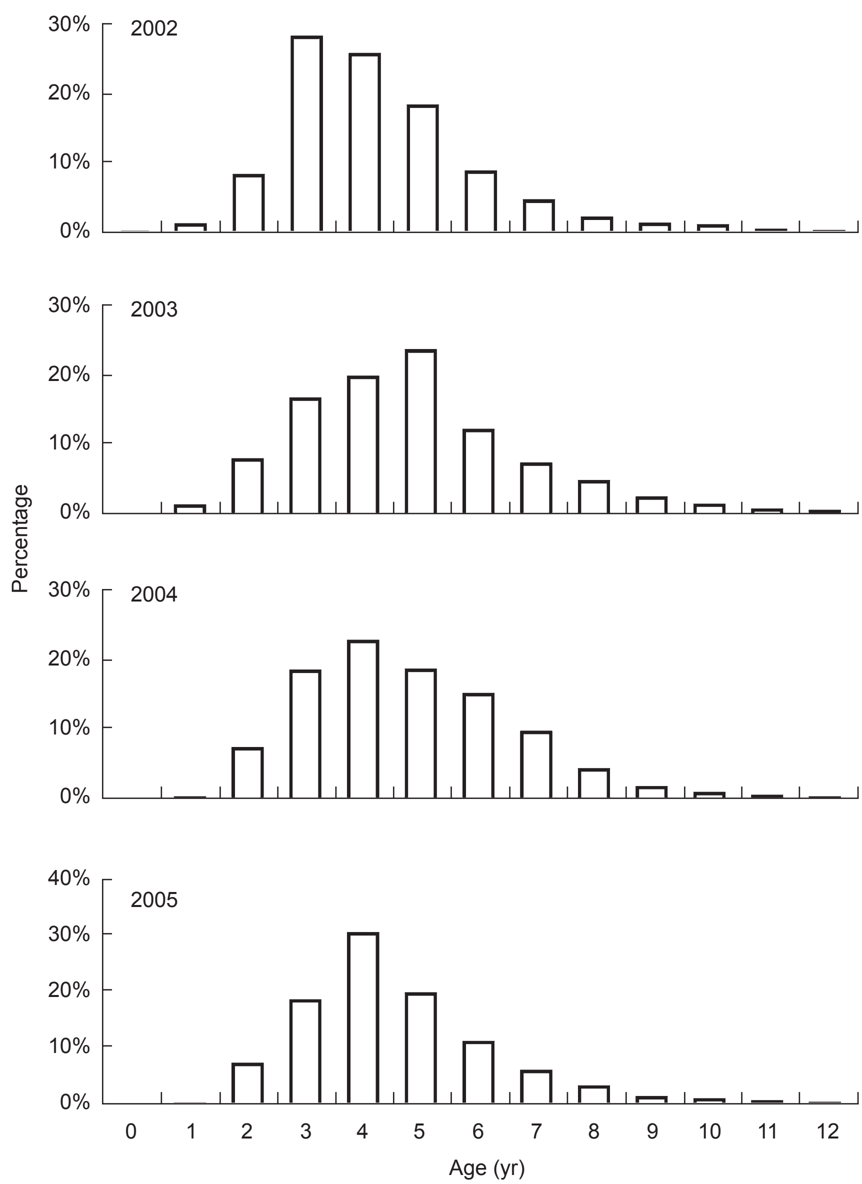

Fig. 9. Age composition of southern bluefin tuna (SBT) caught by Taiwanese longliners in 2002 (*n* = 28,275), 2003 (*n* = 27,661), 2004 (*n* = 33,921), and 2005 (*n* = 28,031). SBT aged 15-21 yr old (0.2%-0.6% each year) are not shown in the figure for clarity.

and 85°-105°E.

Size composition of SBT

Both SBT catch sizes in the central region of the Indian Ocean and in the waters off the RSA were in the range of 80-160 cm (Fig. 4). They did not notably differ: the average size was 118 ± 19 cm for the central region and 109 ± 20 cm off the RSA, and both peaked at around 120 cm.

Based on the fishery logbook data from 2002 to 2005, SBT fork lengths were approximately normally distributed with mean lengths of 117.4 ± 17.3, 123.1 ± 18.8, 122.3 ± 17.3, and 121.1 ± 16.7 cm for the 4 yr, respectively (Fig. 6, Table 2). Fish of 80-190 cm comprised approximately 99% of the total catch. The dressed weights of the total catch in 2002-2005 were skewed towards small sizes, with respective mean weights of 29.1 ± 12.5, 32.1 ± 14.2, 30.8 ± 12.6, and 28.2 ± 12.5 kg. Fish of 20-90 kg comprised approximately 99% of the total catch. The mean fork lengths and dressed weights of the total catch significantly differed among years (F = 584.6, $d.f.$ = 117,887 for lengths

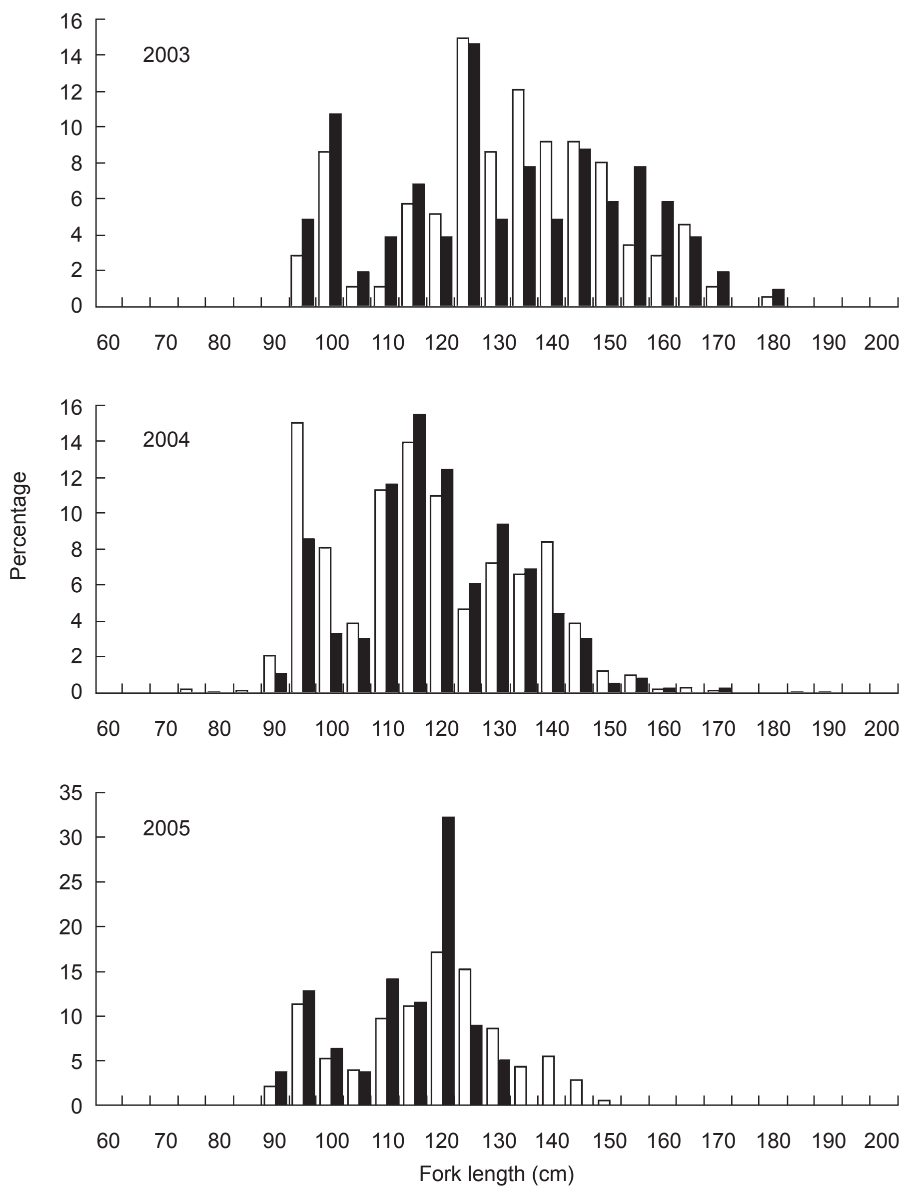

Fig. 10. Fork length frequency distribution of southern bluefin tuna (SBT) sampled for otoliths (solid columns) and that of total measured individuals (open columns) by observers. In 2003-2005, fork lengths of 174, 1281, and 2215 SBT were measured, respectively. Among them, 102, 316, and 77 SBT were sampled for otoliths in 2003-2005, respectively.

and $F = 544.1$, $d.f. = 117{,}887$ for weights, both $p < 0.001$), with the largest mean lengths and weights occurring in 2003 and the smallest mean length in 2002 and smallest mean weight in 2005 (Tukey's pairwise multiple comparison, $p < 0.05$) (Table 2). The R^2 values of the strength of the association for both dressed weight and fork length were similar and small at 0.014 and 0.015, respectively.

Length-weight equation

The SBT length-weight equation ($n = 4008$, $R^2 = 0.92$) is given in figure 7. The equation, developed by Japan and currently agreed to be used by the CCSBT, is also shown in figure 7 (pers. comm. with the CCSBT Secretariat, 2007). By comparison, for fish > 150 cm, the Japanese equation implies heavier fish in the same length category. This might have resulted from that Japanese equation was estimated based on larger-sized fish which were the main target of their fishery.

The equation developed in this study was used to convert the processed weight of each SBT recorded on the fishers' logbooks to a length. The mean absolute differences between the logbook-reported fork lengths and converted fork lengths were 7.9, 6.1, 5.6, and 5.3 cm for 2002 to 2005, respectively. The constructed length-weight equation was based on data between 80 and 170 cm and may have less predictive power at extremely small and large lengths. Approximately 80%-90% of the absolute differences between the reported and converted fork lengths were ≤ 10 cm (Fig. 8), especially between the lengths of 100 and 150 cm, and the differences gradually declined with year. However, the mean reported and converted fork lengths significantly differed for each year's data (paired *t*-test, $p < 0.001$).

The converted annual length frequency was similar to the length frequency data from the logbooks, except in the small size range; logbook data indicated a greater abundance of 80-100 cm fish than the converted data (Fig. 6). Nevertheless, the similarity in patterns of both sets of length data indicates that the logbook size data are suitable for studying the SBT size composition in the CIO.

Table 2. Annual mean (± standard deviation) fork length, dressed weight, and age for the yr 2002-2005. Length and weight data are from logbooks, and age data are estimated from cohort slicing using the fork length data. Different superscript letters indicate statistically significant differences of the mean value among years. Small R^2 values of 0.01 indicate that the statistical differences were due to the large sample sizes

Year	Sample size	Fork length (cm)	Dressed weight (kg)	Age (yr)
2002	28,275	117.4 ± 17.3^{d}	29.1 ± 12.5^{c}	4.3 ± 2.0^{c}
2003	27,661	123.1 ± 18.8^{a}	32.1 ± 14.2^{a}	5.0 ± 2.3^{a}
2004	33,921	122.3 ± 17.3^{b}	30.8 ± 12.6^{b}	4.8 ± 1.9^{a}
2005	28,031	121.1 ± 16.7^{c}	28.2 ± 12.5^{d}	4.7 ± 2.1^{b}

Age composition

Age compositions estimated from cohort slicing for the annual catches were similar among the 4 yr examined (Fig. 9) and were skewed to younger ages with mean ages of 4.3 ± 2.0, 5.0 ± 2.3, 4.8 ± 1.9, and 4.7 ± 2.1 yr in 2002-2005, respectively (Table 2). Differences in mean ages among the years were small but statistically significant ($F = 541.2$, $d.f. = 117{,}869$, $p < 0.001$). The mean ages in 2003 and 2004 were significantly older than in 2002 and 2005, while the mean age in 2005 was significantly older than that in 2002 (Tukey's pairwise multiple comparison, $p < 0.05$) (Table 2). The R^2 value of the strength of association for age was small at 0.012. In 2002-2005, young SBT < 5 yr old comprised 40%-60% of the total annual catches; SBT of 5-7 yr old comprised about 40%, and SBT > 7 yr old comprised < 10%.

The mean fork lengths of SBT with otoliths sampled were 129.2 ± 21.6 (range, 92-177) cm in 2003, 117.1 ± 14.6 (range, 87-170) cm in 2004, and 111.1 ± 11.3 (range, 88-131) cm in 2005 (Fig. 10). In 2003 and 2004, the length frequency distributions of the SBT sampled for otoliths were very consistent with the total measured SBT by the observers. However, SBT > 130 cm were not sampled for otoliths in 2005 (Fig. 10).

The otolith-based age estimate of SBT ranged from 2 to 15 yr, with a mean age of 5.4 ± 3.1 yr in 2003; ages ranged 2-21 yr with a mean of 5.9 ± 2.2 yr in 2004, and they ranged 2-6 yr with a mean of 3.9 ± 0.7 yr in 2005 (Fig. 11). The younger ages in 2005 were very likely due to a sampling bias since otoliths of SBT > 130 cm were not collected by the observers.

Since the sampling of otoliths was not based on the size composition of the total catches, these age compositions obtained from otoliths might not closely represent the real age composition of the total catch of the Taiwanese longline fishery. Nevertheless, they still show that a high percentage of the catch is below the age of 1st maturity, and the composition patterns (Fig. 11) were generally coincident with those of the total catches (Fig. 9).

DISCUSSION

Information on population dynamics, such as age and size composition, is critical for effective resource management and fishery practices. The catch-at-size (age) data indicate that Taiwanese longliners predominantly catch young SBT in the CIO with occasional adults. SBT caught by Taiwanese longliners differ from those of the Australian surface fishery that target 1-4-yr-old recruits, from the Japanese longliners that predominantly target subadults in the feeding grounds of the southern ocean and New Zealand coasts, and from Indonesian longliners that catch spawners in the tropical ocean as a bycatch.

As noted above, there are 2 fishing grounds with different fishing seasons in the Indian Ocean for Taiwanese longliners. However, catch sizes of the 2 components did not broadly differ, either in the same size range or the peak at similar lengths (Fig. 4). It was also noted that < 5% of Taiwanese SBT catches in the Indian Ocean were from the component off the RSA. Although the fishing ground off the RSA overlaps with the Japanese one (Fig. 1), the fishing seasons differ: Nov. to Feb. for the Taiwanese and Apr. to Aug. for the Japanese (Farley et al. 2007). Furthermore, their sizes also differed: about 110 cm for the Taiwanese and about 140 cm for the Japanese (Figs. 2, 4). These observations suggest that it would be appropriate to combine the component off the RSA with that in the CIO. Recent discussions among CCSBT members on the Taiwanese size data have also drawn a similar conclusion that the 2 components' data should be combined (e-mail communications between members of the CCSBT and its Secretariat during Feb. 6-28, 2006).

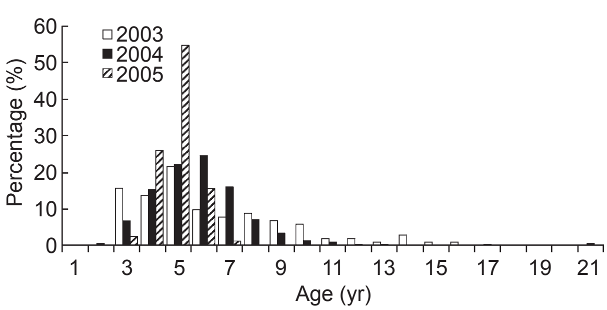

Fig. 11. Age frequency distributions of southern bluefin tuna (SBT) sampled for otoliths in 2003 (*n* = 102), 2004 (*n* = 316), and 2005 (*n* = 77).

Much research evidence indicates that the SBT may reach 1st maturity at 8 yr old, but it may be as late as 11-12 yr old (Farley and Davis 1998, Davis et al. 2001). Therefore, at least 90% of the SBT caught by Taiwanese longliners in the CIO were fish under the size at 1st maturity as judged from their small size. The mean weights and fork lengths stratified by 5° grids of latitude and longitude showed that the SBT caught in the CIO were predominantly fish of 20-50 kg dressed weight or approximately 100-150 cm in fork length (Figs. 2, 3). A typical geographical variation in the mean size of the catch is shown in figure 12. There were no trends in the size of SBT caught by latitude or longitude, except for relatively larger fish being caught in the southeastern Indian Ocean (35°-40°S, 90°-105°E), where the mean size increased from 150 to 180 cm (Fig. 12). SBT in this size range are considered to be larger than the size at 1st maturity, but the volume of the catch is small. High catches of more than 200 fish per year occurred around 25°-35°S and 50°-100°E, and catches of fewer than 50 fish per year occurred north of 25°S and south of 35°S (Fig. 3).

Majkowski and Hampton (1983) found that age classes of SBT derived from an age-length relationship were unreliable after an age of 14 yr. This high uncertainty was due to a reduced growth rate at older ages combined with variability in the length at age that results in the length having little predictive power. Most of the Taiwanese SBT catches were younger than 14 yr based on cohort slicing. Therefore, estimating the SBT age structure from an age-length key based cohort slicing would be relatively less biased and might be acceptable for Taiwanese catches although the length-at-age for these individuals were still variable.

The precision and accuracy of age estimates from counts of otolith annuli depend on the experience and training of the age readers as well as on sample preparation. The CCSBT held a Direct Age Estimation Workshop in 2002 to develop a common standard for estimating SBT age by reading otolith annuli (Anonymous 2002). A follow-up international SBT otolith exchange program was initiated among CCSBT members in 2003, and the results indicated that there were no systematic discrepancies among the ages determined by readers from Australia, New Zealand, Japan, and Taiwan. The mean difference among the readers was small, approximately 1 and 2-3 yr for SBT younger and older than 10 yr, respectively.

The estimated age composition of SBT in this study generally agreed with the results of a previous study (Farley et al. 2007) that most SBT caught in the CIO are fish under the size at 1st maturity. Based on the 4 successive years of commercial fishing data, only around 10% of the SBT caught in the CIO were adults (> 8 yr old). According to direct aging data, around 7% (2003), 15% (2004), and 0% (2005) of SBT sampled for otoliths in the CIO were adults (> 8 yr old). However, the lack of adult SBT in 2005 was due to a sampling bias by the observers (Fig. 10). The absence of < 1-yr-old fish in the catches across the CIO is consistent with the present understanding of the SBT's migratory history. After completing larval and juvenile stages in the tropical oceans, most if not all young SBT move southward along the Australian continental shelf and arrive southwest of Australia at around 1 yr old. SBT aged 2-15 yr, but mostly < 8 yr, are caught across the CIO. The size compositions stratified by 5° grids of latitude and longitude in the CIO showed large variations but no evident geographical patterns, except that larger fish are found in the southeastern Indian Ocean. This indicates a highly mixed feeding population of SBT younger than 15 yr old in the CIO.

Direct and indirect data, i.e., tagging and fishery-dependent data, strongly suggest that the SBT is a highly migratory species. From Nov. to Mar., SBT younger than 4 yr old are predominantly caught on both sides of the Indian Ocean: in the GAB by Australian and off southeastern Africa by Taiwanese longliners (Farley et al. 2007). Archival tagging studies showed that a large proportion of 3-4-yr-old SBT tagged in the GAB during the summer undertake seasonal cyclic migrations into the Indian Ocean (Gunn and Block 2001). The high catch of 3-5-yr-old SBT across the CIO might be outmigrants from the GAB or southern Africa. This notion is supported by the frequent appearance in Taiwanese longline catches of tagged SBT, which had been released by Australian researchers in the GAB (e.g., Clear et al. 2000). SBT aged > 5 yr old are seldom found along coasts and usually appear in the central and southern Indian Ocean (Olson 1980). SBT older than 15 yr are seldom found in the CIO and frequently appear in the southern ocean and along New Zealand coasts. These collective observations indicate age- or size-based habitat disparities or preferences among the life stages of SBT and support the hypothesis that the SBT occupies different feeding areas during different stages of its growth (Shingu 1978).

Kendrick et al. (2005) recently reported a clear and continuous decline in the 1999-2001 cohorts in the New Zealand fishery after a long-term survey of size and age compositions from 2001 to 2005. Evidence of the growth of all year classes was apparent during the same period, but there was no evidence of recruitment of smaller fish (1999-2001 cohorts) to the New Zealand fishery. Discarding small fish was not possible in

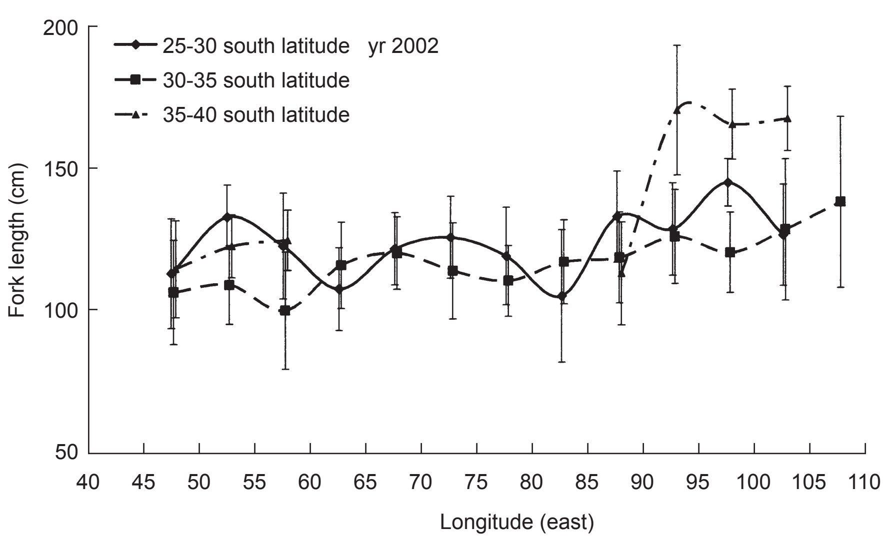

Fig. 12. Mean fork length of southern bluefin tuna (SBT) stratified by 5° grids of latitude and longitude across the central Indian Ocean. Only data from 2002 are shown.

the New Zealand-Japan charters because of 100% coverage of the fishery by scientific observers. The weak recruitment has garnered great concern by scientists and fishery managers. Overfishing of young recruits (1-4 yr old) in the GAB was considered to be one of the reasons for the weak recruitment to the New Zealand fishery although other possibilities exist. A coincident change in the size and age composition was also noted in purse seine catches in Australian waters. The Australian surface fishery prefers to target 3- and 4-yr-old SBT, but the catch shifted to 2- and 3-yr-old in the 2003-2004 and 2004-2005 fishing seasons (Hobsbawn et al. 2005). This dramatic change suggested weak 2000 and 2001 cohorts, although the Australian industry ascribed the reduced size of the catch composition to various reasons including the mixing of 2- and 3-yr-old fish, reduced search times, and weather constraints (Hobsbawn et al. 2005).

The evidence of weak 2000 and 2001 cohorts also seemed to be recorded in the Taiwanese commercial data. The 1999 cohort (aged 3 yr in 2002) accounted for approximately 28% of the total catch, but the 2000 and 2001 cohorts (aged 3 yr in 2003 and 2004) accounted for only 17% and 19% of the total catch, respectively (Fig. 9). Nevertheless, Taiwanese commercial data did not indicate a continual weak recruitment of smaller SBT in the CIO as observed in the New Zealand fishery. This difference indicated that constant fishing pressure on the nursery grounds of southern Australia might be having a greater negative influence on the eastward recruitment to the New Zealand fishery than on westward recruitment to the feeding grounds in the CIO. The weak recruitment of young SBT to the New Zealand fishery might be exacerbated by the preferable migration of young SBT in the GAB to the Indian Ocean rather than to the Pacific Ocean based on a long-term conventional and archival tagging program (T. Polacheck 2005, pers. comm.).

This study provides new insights into the characteristics of the SBT stock in the CIO. Although in the statistical tests, the annual means of fork length, dressed weight, and age significantly differed, this inference is probably due to the effect of large sample sizes because the effect sizes were small. Based on the large sample sizes, the small differences between annual sample sizes may be trivial and not biologically significant. Consequently, compared with the higher variation of the stocks in the GAB and in New Zealand coastal waters, the age and size composition of SBT in the CIO is less susceptible to natural variations in recruitment or the catch of young recruits in the GAB, which was likely because the scale of the SBT fishing grounds and the life stage of SBT targeted in the CIO are different.

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