Migration patterns of young Pacific bluefin tuna (*Thunnus orientalis*) determined with archival tags

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Abstract—We investigated the migration and behavior of young Pacific bluefin tuna (*Thunnus orientalis*) using archival tags that measure environmental variables, record them in memory, and estimate daily geographical locations using measured light levels. Swimming depth, ambient water temperature, and feeding are described in a companion paper. Errors of the tag location estimates that could be checked were –0.54° ±0.75° (mean ±SD) in longitude and –0.12° ±3.06° in latitude. Latitude, estimated automatically by the tag, was problematic, but latitude, estimated by comparing recorded sea-surface temperatures with a map of sea-surface temperature, was satisfactory. We concluded that the archival tag is a reliable tool for estimating location on a scale of about one degree, which is sufficient for a bluefin tuna migration study. After release, tagged fish showed a normal swimming behavioral pattern within one day and normal feeding frequency within one month. In addition, fish with an archival tag maintained weight-at-length similar to that of wild fish; however, their growth rate was less than that of wild fish. Of 166 fish released in the East China Sea with implanted archival tags, 30 were recovered, including one that migrated across the Pacific Ocean. Migration of young Pacific bluefin tuna appears to consist of two phases: a residency phase comprising more than 80% of all days, and a traveling phase. An individual young Pacific bluefin tuna was observed to cover 7600 km in one traveling phase that lasted more than two months (part of this phase was a trans-Pacific migration completed within two months). Many features of behavior in the traveling phase were similar to those in the residency phase; however the temperature difference between viscera and ambient temperature was larger, feeding was slightly more frequent, and dives to deeper water were more frequent.

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Pacific bluefin tuna (*Thunnus orientalis*), a highly migratory species, is mainly distributed in the temperate zone of the northern Pacific Ocean (Yamanaka, 1982; Bayliff, 1994) in contrast to *T. thynnus,* which inhabits the Atlantic Ocean (Collette, 1999).

Current knowledge on the migration of Pacific bluefin tuna is summarized in the following studies: Aikawa (1949); Bell (1963a); Okachi (1963); Orange and Fink (1963); Nakamura (1965); Clemens and Flittner (1969); Shingu et al. (1974); Yorita (1976); Bayliff (1980); Yamanaka (1982); Yonemori (1989); and Bayliff et al. (1991). The majority of bluefin tuna spawn in the northwest Pacific Ocean in an area from the Philippines past Taiwan to Okinawa from April to June, and small numbers spawn off southern Honshu in the Pacific Ocean in July and in the Sea of Japan in August (Yabe et al., 1966; Ueyanagi, 1969; Okiyama, 1974; Yonemori, 1989; Kitagawa et al., 1995). Carried by the Kuroshio Current, juveniles arrive near the coast of Japan, move northward during summer and early autumn, and then most turn around and move back southward during late autumn and winter along the Japanese coast. During the first few years of their lives, the majority of young fish repeat a similar north–south seasonal migration. However a small fraction, increasing each year, moves away from the Japanese coast and often reaches the eastern side of the Pacific Ocean, off the United States and Mexico. These fish stay in the eastern Pacific Ocean for 1–3 years. Some time later, as mature fish, they gather in the northwest Pacific Ocean to spawn and then disperse after the spawning season.

This information on Pacific bluefin tuna movements has been accumulated through analyses of fishery catch data and tag-recapture data. Fishery catch data are based on different individuals from limited areas where, and particular seasons when, fishing took place. Conventional tagging data provide migration information regarding only two points: release and recapture. Acoustic tracking, another method used for investigating behavior and migration of individuals, can collect detailed information on fish movements and behavior on a time scale of seconds, but the duration of the tracking period of each individual has usually been less than several days in studies of Pacific bluefin tuna (Marcinek et al., 2001; Hisada et al.[1]) as well as in other studies of *Thunnus* species (e.g. Carey and Olson, 1982; Holland et al., 1990; Cayré, 1991; Cayré and Marsac, 1993; Block

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[1] Hisada, K., H. Kono, and T. Nagai. 1984. Behavior of young bluefin tuna during migration. *In* Progress report of the marine ranching project 4, p. 1–7. Nat. Res. Inst. Far Seas Fish. Pelagic Fish Resource Division, 5-7-1 Shimizu-Orido, Shizuoka, Shizuoka, 424-8633, Japan. [In Japanese, the title was translated by authors.]

et al., 1997). These methods have not yielded detailed information regarding migration, behavior, and their relation to environmental factors for Pacific bluefin tuna over a long period.

An archival tag is an electronic device that measures environmental variables and records data in its memory. When attached to an animal, it allows direct examination of the relationship between an animal's behavior and physiological condition, or the ambient environment. One type of "archival" tag merely stores data; however, another type not only stores data but also provides daily geographical locations of the fish by processing the measured environmental data. This type of archival tag was anticipated since the 1980s as a tool that could collect detailed information on individual fish behavior (Hunter et al., 1986; Anonymous, 1994). Metcalfe and Arnold (1997) estimated the geographical locations and tracks of plaice, a demersal species, by comparing tidal depth variations with the time series depth data recorded by archival tags attached to the fish. However, this method is not suitable for pelagic fish, which change swimming depth freely. A type of archival tag that can estimate geographical locations based on change of light levels during a day—a method more suitable for pelagic species—has been commercially available since the early 1990s. So far, archival tags of this type have been used in several tagging projects (Arnold and Dewar, 2001). The results published in a few reports on southern bluefin tuna (*T. maccoyii*) (Gunn and Block, 2001), and Atlantic bluefin tuna (*T. thynnus*) (Block et al., 2001), show the remarkable value of archival tag data.

As archival tags have come into wide use, results of several experiments conducted to evaluate the reliability of its geolocation estimates have been published (Welch and Eveson, 1999; Musyl et al., 2001; Gunn et al.[2]). However, several points remain to be tested: tag reliability when a number of tags are deployed for long duration, reliability of sensors for variables other than light, and the effects of attaching the tag to fish.

After two preliminary experiments with tags in 1994, the first with tags placed at a known outdoor location on land and in air, and the second with tags attached to young Pacific bluefin tuna held in pens, we applied archival tags to wild young Pacific bluefin tuna to investigate their behavior and migration. In the present study we report the characteristics of migration for this species based on data on daily geographical location, as well as the reliability of archival tag data and the effect of attachment of the tag to fish. Analyses for swimming depth, ambient water temperature, and feeding frequency of the species are undertaken in other papers (Kitagawa et al., 2000; Itoh et al., 2003).

Materials and methods

Outline of the archival tag used in this study

The archival tag used in this study (Northwest Marine Technology, Inc. Shaw Island, WA) had a cylindrical stainless-steel body (16 mm in diameter and 100 mm long, and weighing 52 g) that was implanted in the animal. A flexible sensor stalk 2.2 mm in diameter and 150 mm long extended from the tag through the skin of the animal into the water. The end of the stalk housed an external temperature sensor and a light capture region. Light was led from the capture region by optical fiber to a photodiode sensor in the body of the tag, which also housed sensors for pressure, internal temperature, and light. Response times for the temperature sensor were three seconds for the external sensor and 20 seconds for the internal sensor, and temperature resolution was 0.2°C for both sensors. Resolution of the pressure sensor record was 1 m at shallow depths up to 126 m, then changed to 3 m from that depth to the scale limit of 510 m. Clock drift was less than 30 seconds per year. The tag had a data measurement interval of 128 seconds, a 256-kByte data memory, and an operating life exceeding seven years. Data were downloaded from recovered tags by using a personal computer and a fiber-optic connector.

Two types of data files were created within the tag memory. One data file stored daily records containing date, estimated times of sunrise and sunset, water temperatures at 0 m plus two other selectable depths (we selected 60 m and 120 m), and other information required for, or produced in, the course of location estimates for each day. This file is referred as the "summary file" in the "Results" section, and it stored data for all days after the memory was last cleared. The times of sunrise and sunset were estimated within the tag from sea-surface light intensities, which were inferred from measured depth and measured light intensity at depth and a water opacity factor determined from the measured data each Universal Time (UT) day. The time of midday was determined as the midpoint between sunrise and sunset times, and longitude was calculated from the difference between the midday time and 1200h UT, at a rate of 15 degrees longitude per hour, corrected for astronomical effects. Latitude was estimated from the duration of daylight (Hill, 1994).

The second data file contained unprocessed time series data records taken at 128-second intervals. The tag could record at any integer multiple of its 128-second measurement interval and a multiple of one was chosen. Each record consisted of external temperature, internal temperature, pressure, and light intensity, and corresponded to a known time. This is referred to as the "detail file" in the "Results" section. It could hold about 54,000 records, or about 80 days of steady recording at the high data rate chosen—a small fraction of the tag's overall lifetime. The time-series memory was divided into two sections, and the size allocations for the two sections were determined by the user. The first section filled first and did not change thereafter. The second section filled next, but once full, it was continually overwritten by new data. Thus the first section always contained the earliest data retrieved from a tag; the

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[2] Gunn, J., T. Polacheck, T. Davis, M. Sherlock and A. Betlehem. 1994. The development and use of archival tags for studying the migration, behavior and physiology of southern bluefin tuna with an assessment of the potential for transfer of the technology to groundfish research. Proc. ICES mini-symposium on migration, St. Johns, Newfoundland. ICES C.M. Mini:2.1, 23 p. International Council for the Exploration of the Sea, Palægade 2-4, DK-1261 Copenhagen K, Denmark.

second always contained the latest data. We divided the file into two 40-day sections for releases in 1995 and 1996, and into 20- and 60-day sections for releases in 1997.

Reliability and calibration of archival tags in air

To examine the reliability of location estimates made by archival tags, 117 archival tags were left outdoors (34°59′N; 138°59′E) where they were not affected by artificial light during July–September 1996 (55 days, five tags), May–August 1997 (86 days, 14 tags), and October 1997 (five days, 100 tags). Two of the tags were used in two of the experiments.

Calibration tests of internal and external temperature sensors were conducted for all tags before being implanted in fish that were released, and the sensors were recalibrated for nine tags after they were recovered. Temperature calibration was done by immersing tags into a series of water tanks that were set to temperatures ranging from 5.0° to 30.0°C by 5°C intervals. Calibration tests of pressure sensors were also conducted for all tags before release and on 27 tags after being recovered. Tags were placed in a pressure chamber with a resolution of 0.1 bar and examined up to 20 bar. The tags were left at least five minutes at each temperature or pressure to obtain at least two measurements at the 128-second recording interval.

Experiment with pen-held fish

Archival tags were attached to three pen-held young Pacific bluefin tuna of 93–97 cm fork length (FL) at Kasasa in Kagoshima Prefecture (31°25′N; 130°11′E) in November 1994. The fish had been reared in a net pen (40 m × 25 m with 12 m depth) for more than two years and were acclimated to the environment at the time of the experiment. Archival tags were inserted into the abdominal cavities of two of the three fish by the following method. A fish caught by hook and line was put into a styrofoam box, and its eyes were covered with a black polyethylene bag. The belly of the fish was cut with a scalpel about 4 cm anterior to the anus, 3–4 mL of antibiotic (artificial penicillin, Doil, Tanabe Seiyaku Co., Ltd., Osaka, Japan) was injected into abdominal cavity of the fish, and an archival tag was inserted there with the stalk extending through the incision. A stitch was made in the middle of the incision with an absorbable suture (Coated Vicryl, type J583G, Ethicon Inc., Cornelia, GA), and the fish was released back into the pen. All tools and tags were disinfected with 100% ethanol. No anesthetic was used because with their eyes covered, the fish remained quiet during the surgery. This simplified procedure (from making the incision to releasing the fish) could be completed in less than 90 seconds, thus minimizing total stress on the animal and, in later experiments on wild fish, providing the best chance for the animal to rejoin its original school. In this pen study, the third fish was tagged externally instead of internally, the tag being connected by a thin wire rope to a small metal arrowhead inserted in a muscle near the second dorsal fin base.

During the pen-held fish experiment, none of the fish were observed to die as a result of tagging. The tag that had been attached externally came loose from the fish and was retrieved from the bottom of the pen four days after tagging. One tagged fish escaped when the pen was broken. The remaining tag was recovered 453 days later when the fish was caught from the pen as part of a commercial catch.

Experiments with wild fish

Tag and release experiments on wild young Pacific bluefin tuna were conducted near Tsushima, at the northeastern end of the East China Sea, by using chartered commercial trolling vessels, every November and December from 1995 to 1997. A total of 166 fish, ranging from 43 to 78 cm FL (age 0 or 1), were internally tagged as described above and released immediately. Two dart-type conventional tags were also attached to the second dorsal-fin base of each fish in the 1997 experiment as visual markers in an attempt to improve the recovery rate.

Thirty archival tags (18.1%) were recovered. The durations at sea were 50 days or less for 13 fish, 96–211 days for 13 fish, and 359–375 days for three fish, all recaptured around Japan. One additional fish was recaptured off the west coast of Mexico, on the east side of the Pacific Ocean, at 610 days after release. Data could not be downloaded from one archival tag released in 1995 and recovered 30 days after release; all other tags returned data.

Results

Reliability of location estimates

The tag recovered from a fish penned in a known location for 453 days yielded a record of positions automatically estimated during that time. Figure 1 plots the errors in those estimates and the date when each was made. This tag provided the only position sequence of long duration obtained from a captive fish. Unfortunately it was discovered later, after the experiment was completed and after this particular tag was no longer available for further testing, that the light sensitivity of this tag, as well as that of the tag that yielded data for four days in the captive fish experiment, was at least a factor of ten lower than that of other tags. This discrepancy in light sensitivity could be seen in the daily noon-light intensity data in the summary file, both during the in-water experiment (when compared with typical values for tags in wild fish) and when tested in air (compared with other tags of the group tested in air). On dark days there was an unusual pattern of early sunset times and late sunrise times that the tag manufacturer interpreted as being associated with the low light sensitivity. Thus, although the general trends of error size with season can be expected to be representative, the absolute size of the errors was likely inflated in this, the only long-term record obtained from a captive fish.

Longitude error showed no change with season, but latitude error increased dramatically near the equinoxes as expected because day length does not vary significantly with latitude at that time, and therefore carries little in-

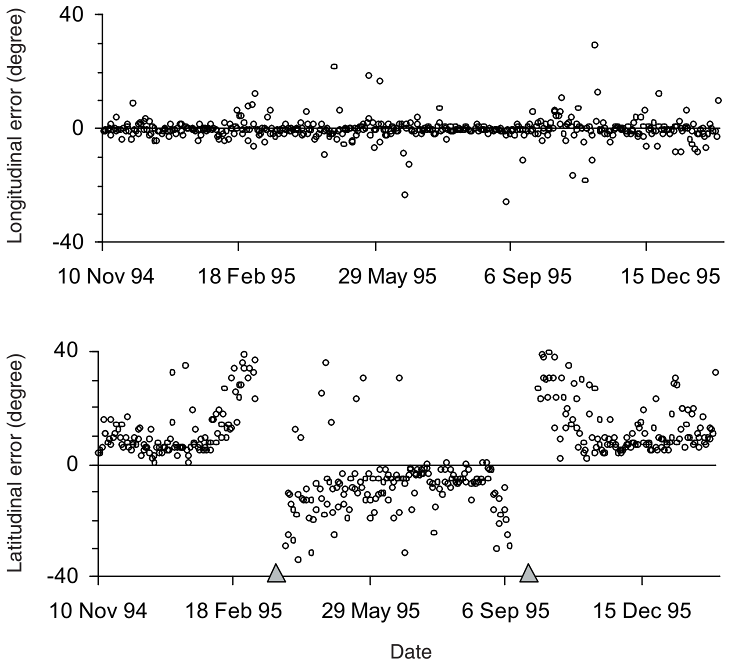


Figure 1

Seasonal change of errors in location estimate. Upper and lower panels show longitudinal and latitudinal errors, respectively. Triangles show equinoxes. Data are from an archival tag implanted in a fish held in a pen for 453 days.

formation about latitude. The tag did not provide a latitude estimate for 18 days around and at the vernal (autumn) equinox and had large errors for one month before (or after) as well as 10 days after (or before) that period, respectively. The same pattern was observed in the test with archival tags that were left in air. In addition, the latitude estimates were biased toward south in summer and toward north in winter, that is, toward erroneously short day lengths.

Occasional large deviations were observed in both latitude and longitude estimates. These were easily identified as outliers in our analyses of data obtained from wild fish by comparing them with estimated locations for adjacent days. When evaluating the accuracy of location estimates for practical use in analyses of wild fish movements, we excluded longitude or latitude estimates that differed more than 10° from the real location and the latitude estimates not provided by the tag near the equinoxes. These accounted for 2.8% of longitude estimates and 8.9% of latitude estimates obtained in the tests in air, as well as 4.8% of longitude data and 47.5% of latitude data obtained in the tests of pen-held fish.

Figure 2 shows the position estimates and error bars corresponding to one standard deviation for 117 tags tested in air—most of them for a 5-day period, five for 82 days, and twelve others for various intermediate durations. The aggregate of all observations in air yields an error estimate (mean ±standard deviation) of –0.54° ±0.75° for longitude, and –0.12° ±3.06° for latitude.

When individual tags tested in air were examined separately, 96% of tags (112/117) showed average position errors within a range of ±1.5° in longitude. Among these 112 tags with small longitude errors, 95 had been manufactured within the last half year and had an average and standard deviation of position error equal to –0.50° ±0.19°, and the other 17 tags were more than one year old and had an average position error of –0.51 ±0.75°. The average is not significantly different (ANOVA F=0.01, P>0.05) and the younger tags had a smaller standard deviation (F=412, P<0.01). No significant difference of accuracy was observed among the 17 older tags that could be related to their history, i.e. among four tags kept in air without release and 13 tags released with fish and recovered (F=1.01 for average and F=2.81 for standard deviation, both P>0.05).

For the two tags attached to fish in pens, one tag measured only five positions with a resulting error estimate of –2.38 ±0.39 for longitude, and –1.82° ±1.58° for latitude. The other measured 432 positions, with a resulting error estimate of –0.53° ±2.46° for longitude and 1.26° ±5.33° for latitude. This is the data series presented earlier in Figure 1. The large standard deviation in longitude error—much larger than that obtained in other tests—initially raised questions regarding the effect of water on the positioning techniques. However as mentioned earlier, the low light sensitivity of both tags used in captive fish was identified as the likely cause of these large errors.

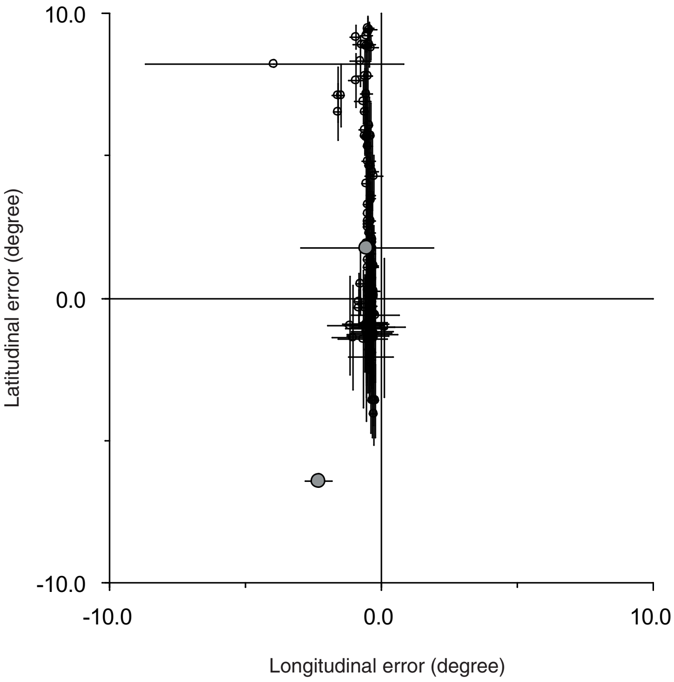


Figure 2

Average errors of location estimates from each archival tag in the benchmark tests. Smaller circles are the average errors of the tags tested in air and the larger circles are the average errors for archival tags implanted in pen-held fish. Bar shows a standard deviation.

A more useful measure of in-water accuracy was provided by comparison between actual recapture locations of 18 tags and the locations that those tags estimated one or two days prior to capture (thus avoiding the disturbed light data on the final day). Average differences of the 18 tags were –0.1 ±0.8° (range: –2.0 ±1.7°) in longitude and –1.6 ±1.8° (range: –5.7 ±0.6°) in latitude.

Because the tag's latitude estimate based on day length was found to have limited reliability, we estimated latitude using sea-surface temperature (SST) as recorded in the summary file for each day. The temperature reference field used was the SST map published by Japan Fisheries Information Service Center, which gave average SST weekly for the western Pacific Ocean (west of 160°E), and every 10 days for the eastern Pacific Ocean (east of 160°E). The longitude value determined automatically by the tag was used to choose a longitude on the SST map. Along that longitude line a point was sought where the map SST matched the SST value recorded by the tag. If multiple points were found to satisfy this criterion, the point that gave the most plausible movement was selected, based on fish locations on several adjacent days. If a location still could not be determined, it was interpolated as a midpoint between the adjacent two days' locations.

One example of location re-estimation is shown in Figure 3. After consulting with the SST maps, we used 1.4% of the locations estimated automatically from 29 recaptured tags, and 79.7% of latitudes were changed by +0.3 (±2.8°) on average with the SST method. The remaining 18.9% of days did not provide any reasonable location estimates for various reasons, including anomalous longitudinal estimates, no match points of SST along the estimated longitudinal line, or the existence of a wide latitudinal area showing the same SST.

Reliability of temperature and pressure sensors

One hundred tags calibrated within half a year of manufacture showed average errors of 0.1 ±0.1°C for both internal and external temperature sensors. Nine tags recovered from fish and tested more than one year after manufacture showed average errors of 0.0 ±0.1°C for both sensors. It thus appears that no deterioration of the temperature sensors occurred because of release-recapture or the passage of time.

No large error in pressure sensors was observed during calibration of tags before release. However, 20 of 27 tags recovered from tagged and released fish were found on recalibration to record substantially lower than actual pressure. One example is shown in Figure 4. No further deterioration of pressure sensors was observed when these tags were kept in air for an additional half year. There was no way to know exactly when the sensor deterioration had occurred during the time the fish were in water. However, the frequency of records showing swimming at 0 m depth was remarkably higher in the second part of

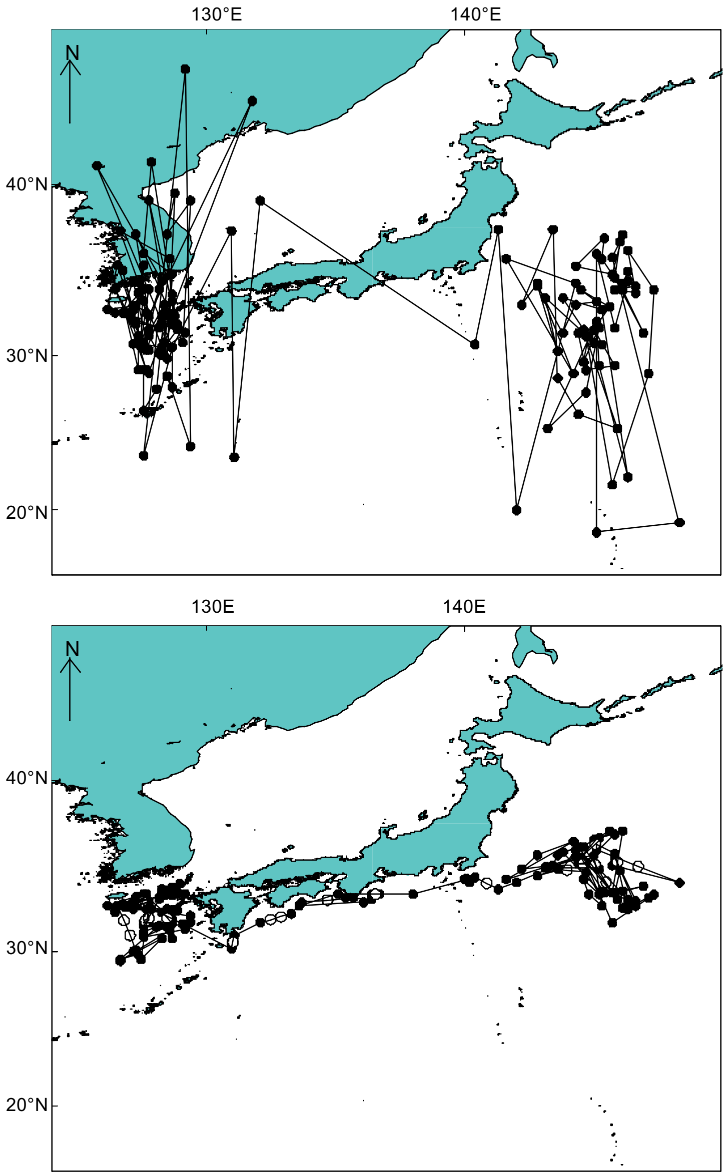


Figure 3

Locations estimated by an archival tag with a young Pacific bluefin tuna before (upper panel) and after (lower panel) replacement of the original latitudinal estimate based on day length by one using sea-surface temperature. Locations out of the range of the figure and those for which latitude was not estimated were not drawn in the upper panel. Estimated locations for all days are shown in the lower panel. Open circles in the lower panel are interpolated locations.

the detailed file (i.e. just before recapture) when compared to the first part of the detailed file (i.e. just after release). The tag manufacturer analyzed this deterioration in the pressure sensors, and expected the sensor characteristics to remain constant after an initial change (if one occurred), and agreed that the early and late pressure data should be treated separately. We assumed that the deterioration occurred sometime during the middle period of the time the fish was free, when no record was being kept in the detail file. Recorded depths in the second part of the detail file for eight tags with relatively large deterioration detected were corrected by using two regression lines joined at around 30 m in real depth for each tag (Fig. 4).

Effect of the archival tag on fish

The effect of both the implantation process and the presence of the implanted tag in the fish was investigated by macroscopic observation of recovered fish. Further information was obtained by comparing the weight at length

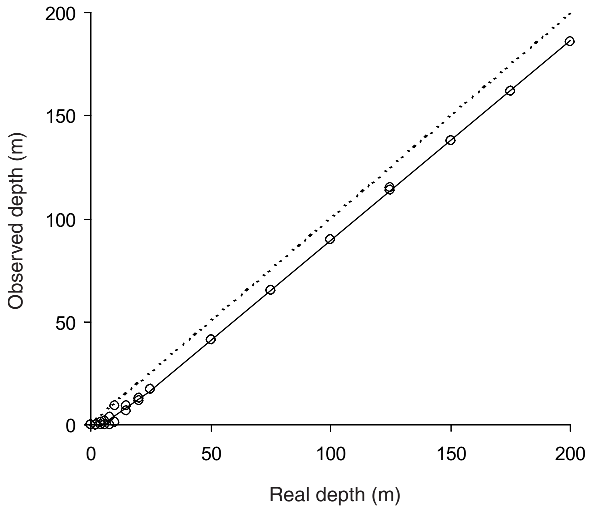


Figure 4

An example of observed deterioration in a pressure sensor of an archival tag in a postdeployment recalibration. The horizontal axis shows the test pressure, vertical axis is pressure recorded by the tag. Dots are observed data. The solid line bent at 25 m of real depth is formed from two regression lines, one fitted to data below and one to data above 25 m depth. This approximation to the deteriorated sensor characteristic was used to correct pressure data for this tag. Pressure values are converted to depth in meters. A broken line is that of observed depth equal to real depth.

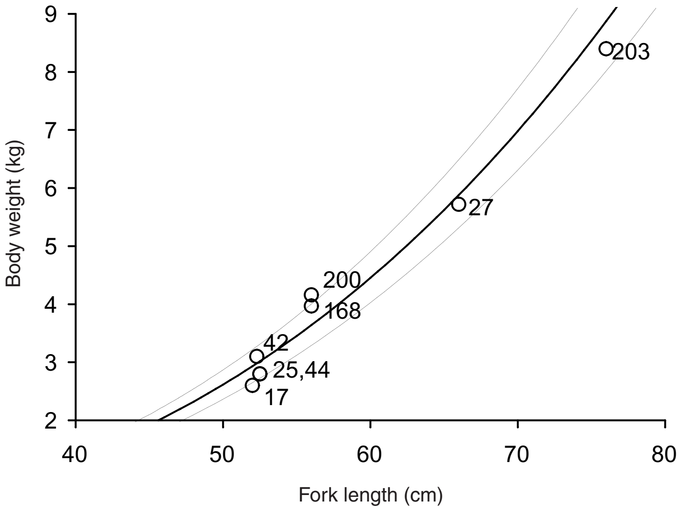


Figure 5

Comparison of weight at length of young Pacific bluefin tuna between recaptured fish tagged with archival tags and wild (untagged) fish. Numerals show days at liberty. An average (thick solid line) and upper and lower 95% confidence limits (thin solid lines) are derived from 11,777 wild fish from 40 to 80 cm in fork length caught in 1995 and 1996 around Japan. Equations for average is $W=2.844\times10^{5}\times L^{2.918}$, upper 95% limit is $W=3.028\times10^{5}\times L^{2.930}$, and lower 95% limit is $W=2.745\times10^{5}\times L^{2.906}$, where L = fork length in cm and W = body weight in kg.

and the monthly average growth rates of tagged fish with wild fish, and also by evidence of feeding to be found in the records returned in the tags.

The bodies of two fish among 30 recoveries were available for observation. One fish recaptured 27 days after release still had a scar on its skin but no trace of the tag insertion surgery was found in its belly muscle. Another fish recaptured 200 days after release had no trace of surgery either on its skin or in its belly muscle. Surface skin around tag stalks was ulcerated in both fish. The stalks were immobilized in the belly muscle. The cylindrical bodies of both tags were covered with membrane and located between the stomach and the pyloric caeca. No infection or necrosis was observed in the visceral organs around tag bodies or in the muscle around tag stalks.

Body weights of all recaptured fish that were measured (n=8, 17–203 days after release) were within the range of those of wild fish of the same fork length (Fig. 5). An average growth rate of recaptured fish was 1.4 ±0.5 cm per month (n=6, three fish recaptured at short durations of liberty that showed no or negative growth were excluded). A subgroup of four fish recaptured after more than 5 months from release, i.e. fish at liberty during the summer when growth might be expected to be faster, had an average growth rate of 1.3 ±0.6 cm—similar to that from all durations.

The average number of daily feeding events, which were found by specific changes of visceral temperature (Itoh et al., 2003), increased linearly from no feeding on the day of release up to a steady rate beginning about 30 days after release. Thus, it appeared that fish did not feed normally during this initial period (Fig. 6).

Horizontal movement

Estimated tracks of all fish that traveled out of the East China Sea along with one fish that remained in the East China Sea are shown in Figure 7 and Figure 8. All of these fish were released off Tsushima in November or December and remained in the East China Sea at least 90 days. After that, four fish entered the Sea of Japan and moved northward from April to July (Fig. 7, A–D). Two of them moved southward in November one year after release (Fig. 7, C and D), and one of the two fish returned to the region off Tsushima where the fish were released (Fig. 7C). One fish remained and was recaptured within the East China Sea in November, one year after release, although it had moved to the east coast of the Korea Peninsula for a period in August and September (Fig. 7E). Ten fish remained within the East China Sea for more than five months and were recaptured from May to June, five to seven months after release (Fig. 7F).

Two fish moved to the Pacific Ocean (Fig. 7G and Fig. 8). One of these fish entered the Pacific Ocean on 7 March 1996, and then traveled eastward straight from a position off the south coast of Kyushu (31°N, 131°E) to one off the east coast of Choshi (36°N, 142°E), then stayed for a while

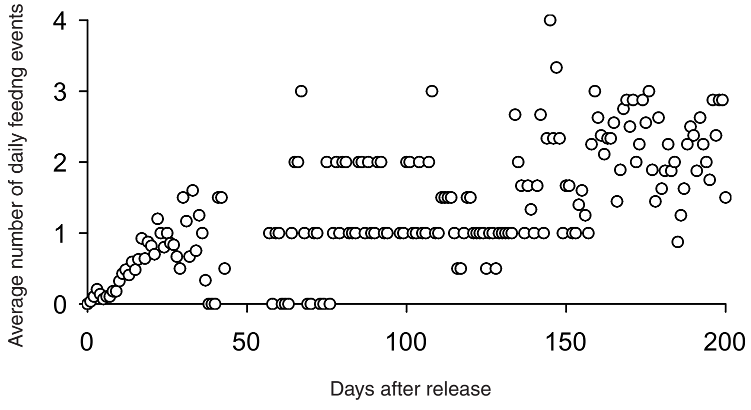


Figure 6

The average number of daily feeding events plotted against days after release.

in an area of 32–37°N, 143–147°E (Fig. 7G). This fish was recaptured by purse seine on 7 June 1996.

The other fish traveled from the western Pacific Ocean to the eastern Pacific Ocean as follows (Fig. 8). It was released off Tsushima on 29 November 1996 at 55 cm FL and remained for a period within the East China Sea. It moved to the Pacific Ocean on 1 May 1997 and then traveled eastward straight from a position off the south coast of Kyushu to one off the east coast of Choshi then stayed for a while in an area of 34–39°N, 143–150°E. It moved northeastward from 30 July to 18 August 1997, then stayed in the area 40–44°N, 152–163°E. It began the trans-Pacific migration on 11 November 1997 at 41°N, 163°E, and traveled straight to northern California, U.S.A. (36°N, 127°W) arriving on 15 January 1998.

After arriving in the eastern Pacific Ocean, this fish initially stayed in an area of 33–40°N, 122–128°W, then moved southward from 25 February to 3 March, then again stayed in an area of 25–29°N, 116–119°W. It started moving northward on 9 May and reached 40°N, 127°W on 25 May, but without staying there moved again southward and reached an area of 25–29°N, 116–120°W on 12 June, close to the place from which it had departed. The fish was recaptured by a recreational fishing vessel on 1 August 1998, 610 days after release, off Baja California, Mexico (31°48′N, 117°18′W), at 87.6 cm FL

The track of this fish consisted of apparently separable segments, five traveling periods and six resident ones. All of the fish that moved out of the East China Sea showed the same type of pattern, staying resident in an area for a relatively long period and then traveling continuously for at least several days in a stable direction.

The terms “traveling phase” and “residency phase” are used in the following description. If a fish moved continuously for more than three days in a stable direction covering more than 700 km in total distance, it was considered to be in a traveling phase—at all other times in a residency phase. A few movements for short periods or short distances (or both) were also observed during periods of a residency phase: a fish resident off the east coast of Hokkaido (40–44°N, 152–163°E) shifted eastward gradually within the area during a period of two months (Fig. 8). Another fish resident in the northern area of the East China Sea moved rapidly to the southern area of the East China Sea at the end of December and came back rapidly to the northern area in early May (Fig. 9). Individual movements were completed within a few days and the total distances moved were far shorter (380 and 310 km, respectively) than those seen in traveling phases.

A total of 12 traveling phases were identified in records of six fish (Table 1). The direction of travel stayed constant within each phase, except in one case where a fish completely turned around in the middle of traveling (in the eastern Pacific Ocean in May and June 1998). Daily distances moved during those traveling phases were calculated. To reduce the influence of scatter in the estimated locations, three-day running averages of latitude and longitude were used for calculation. Excluding the one trans-Pacific migration phase of exceptional length, 7636 km (66 days), the total distance per traveling phase ranged from about 730 to 3406 km (average: 1430 km). The duration of a traveling phase was four to 35 days (average: 17 days) and the distance traveled ranged from 59 to 182 km (average: 104 km). Six residency phases which occurred between two clearly identified traveling phases lasted from 40 to 125 days (average: 81 days). In total, 83% of days were in a residency phase and 17% of days were in a traveling phase. If residency phases for which the beginning or end could not be defined because of fish release or recapture were also included, the average duration of residency phases increased to 110 days, and the proportion days belonging to each phase became 87% in residency and 13% in traveling phases.

Comparison of fish behavior and ambient water temperature between traveling and residency phases

Several points regarding fish behavior, described in detail in Itoh et al. (2003), were compared between all days in a traveling phase and ten days in the residency phase that for four fish immediately preceded the traveling phase. In the case of one fish (no. 241) where data for preceding

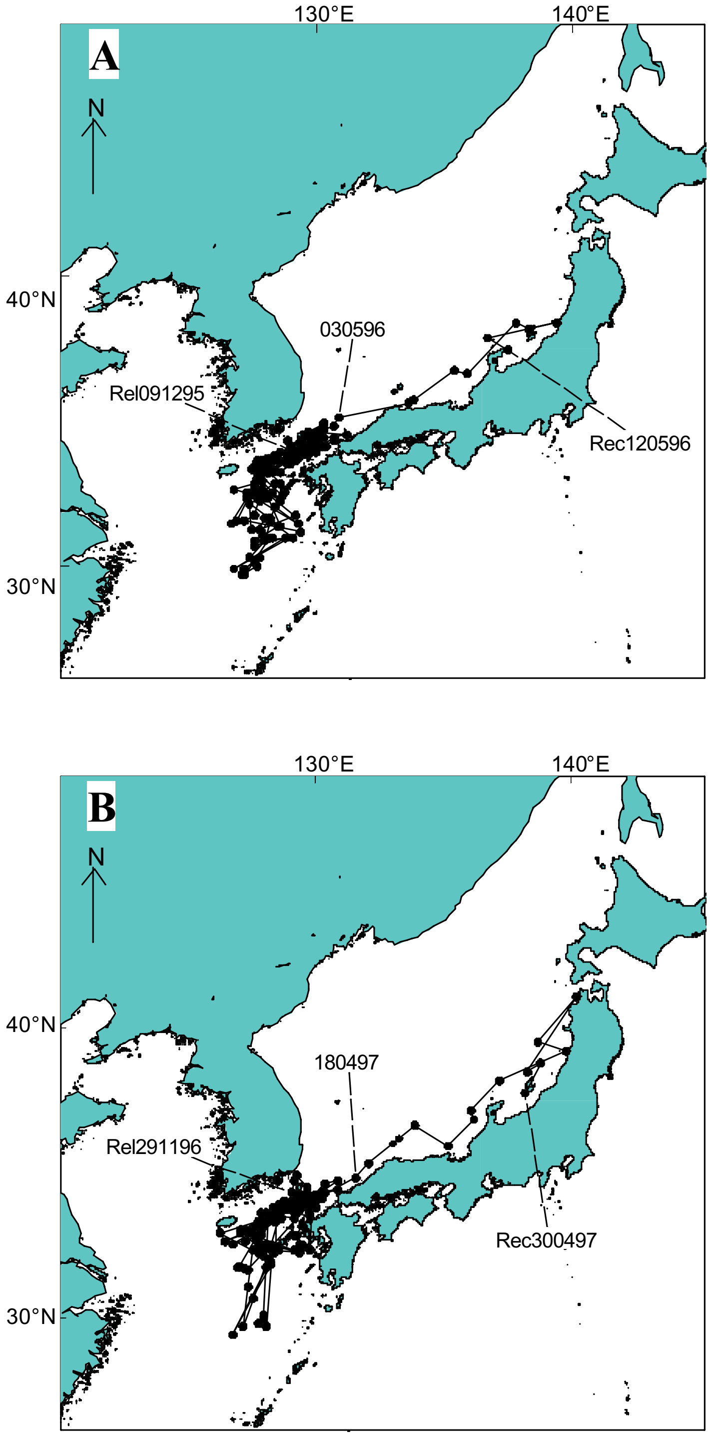


Figure 7

Tracks of young Pacific bluefin tuna estimated by archival tags. “Rel” and “Rec” mean release and recapture, respectively. Numerals are dates in ddmmyy. Each panel shows the track of one fish with an archival tag.

days were not available, ten days from the residency phase immediately following were used instead. Because errors in determining geographical positions introduced scatter in the sequence of estimated positions, the onset (or end) of a traveling phase was not always easy to define. In response to this situation, three days of the residency phase nearest

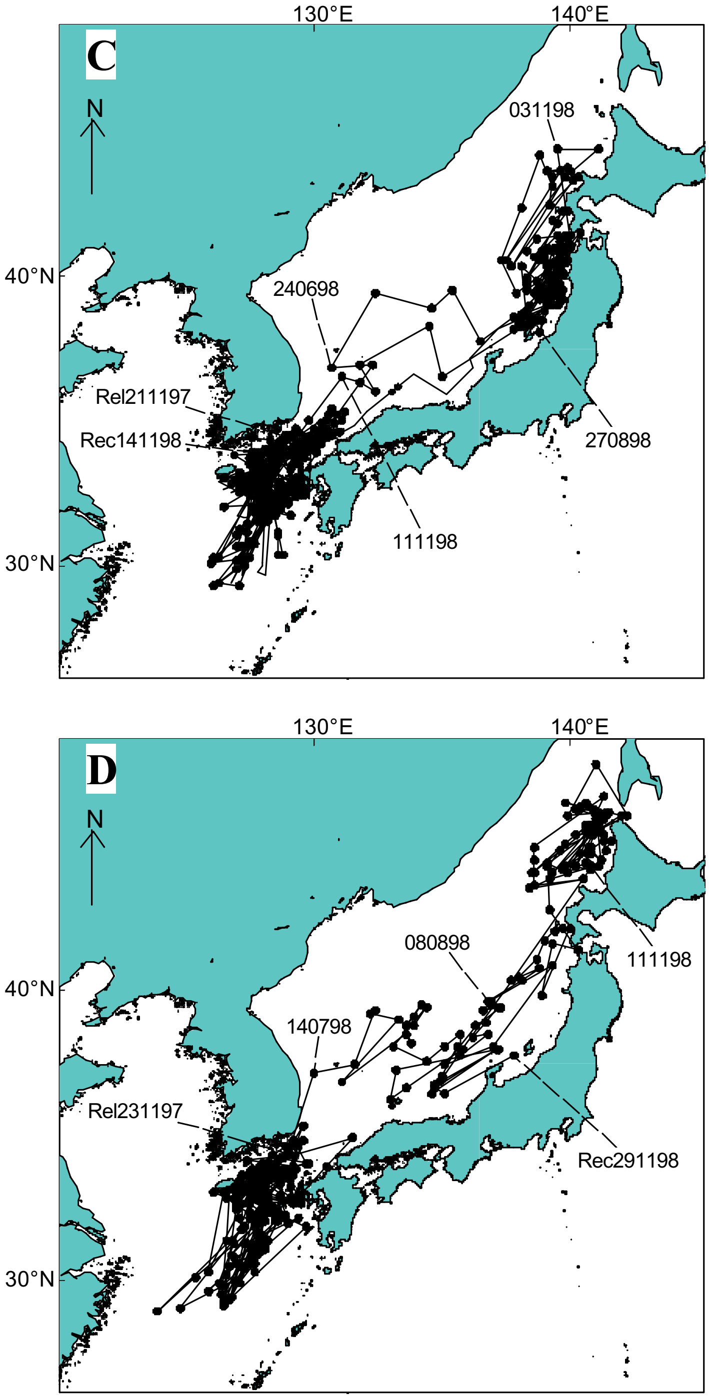
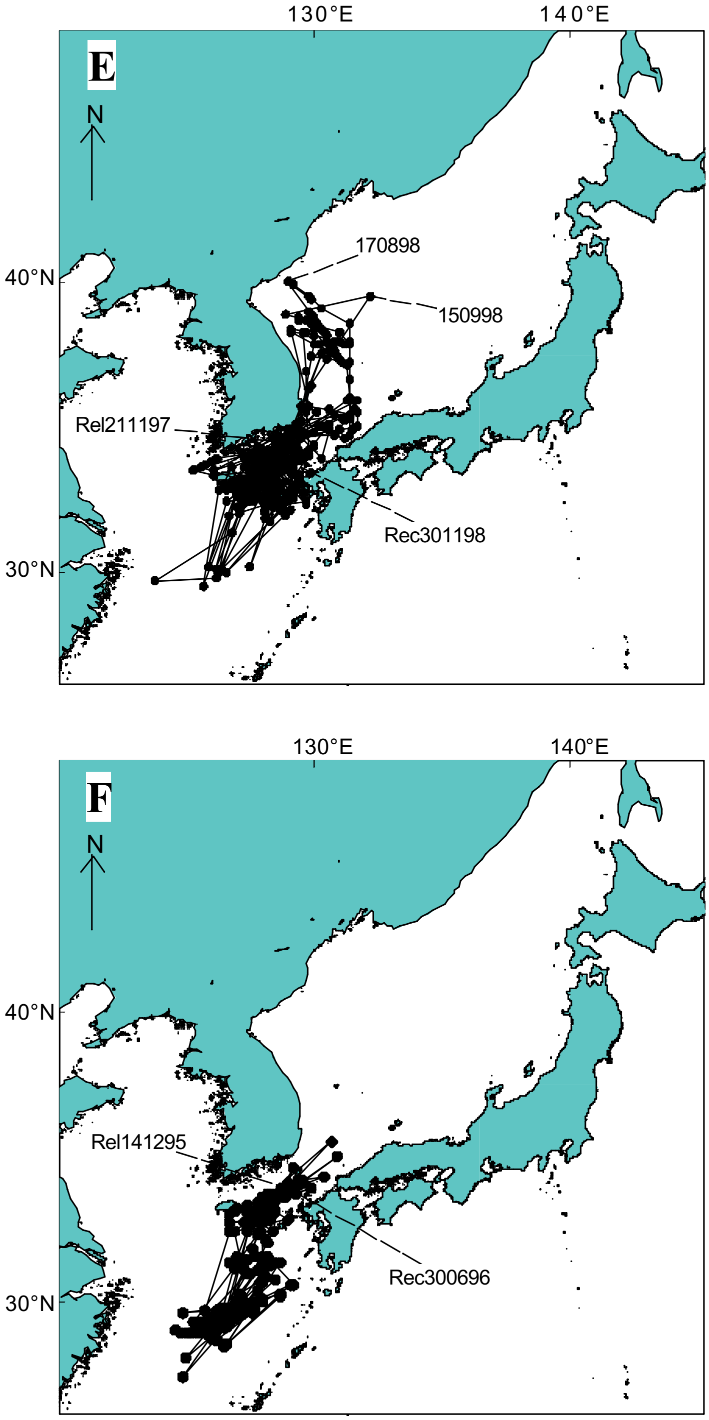


Figure 7 (continued)

to the traveling phase were not included, that is to say, ten days between the fourth and thirteenth days preceding (or following) the onset (or end) of a traveling phase were used.

Among 12 features investigated, three differed between the two phases (Table 2). The temperature difference between fish viscera and ambient water (thermal excess) was more than 1.0°C higher during the traveling phase for four out of five fish. In the one remaining fish (no. 241), data used for analysis were those from days at the end of the traveling phase. The larger thermal excess during a traveling phase was observed at both daytime and nighttime (Fig. 10). The second significant feature was that all fish dived to water deeper than 150 m more frequently during the traveling phase. Except for one fish (no. 241), which spent a long time in water deeper than 150 m, almost all



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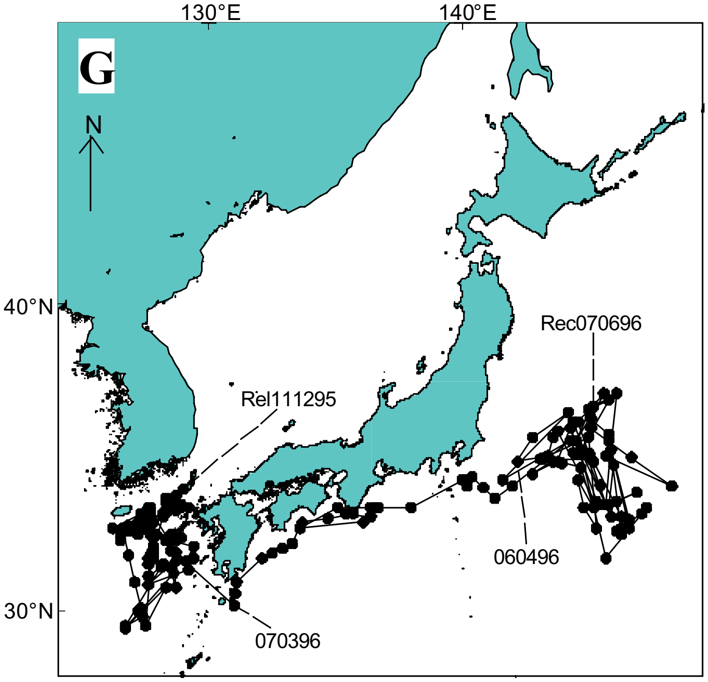
records of excursions below 150 m were due to spikes of deep diving of short duration, less than 10 minutes. Finally the frequency of daily feeding events, detected by a change of visceral temperature, was slightly higher during a traveling phase (1.6 ±0.6) than a residency phase (1.1 ±0.4).

Records of surface temperature from the summary file were examined to answer three questions regarding the relation of water temperature to traveling. The first question was whether any water temperature change, an increase in spring and summer or a decrease in winter, was observed several days prior to the onset of the traveling phase. Such a temperature change was observed in 10 out of 12 cases (Table 3, Fig. 11). In those 10 cases, the water temperature increased in spring and summer to 19–26°C (average of 22°C), and decreased in winter to 15–17°C (16°C).



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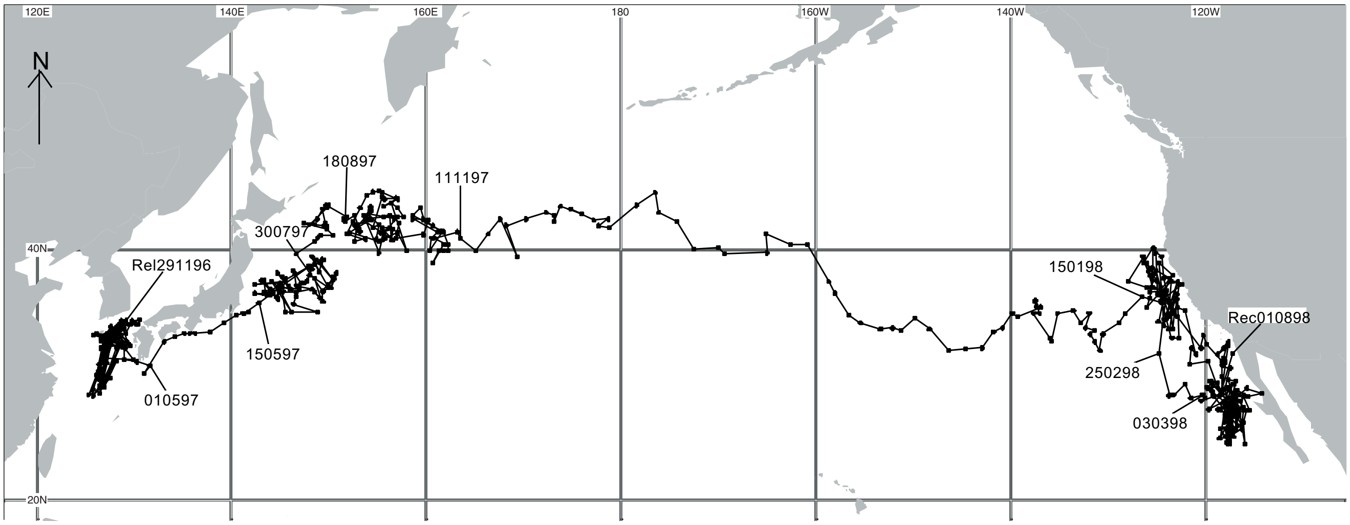

Figure 8

Track of a young Pacific bluefin tuna that traversed the Pacific Ocean, estimated with an archival tag. "Rel" and "Rec" mean release and recapture, respectively. Numerals are dates in ddmmyy.

The second question is whether the water temperature at the onset or end of traveling was within the temperature range of 14–20°C, considered to be in the temperature range preferred by young Pacific bluefin tuna (Itoh et al., 2003). If the act of traveling was simply a reaction to the water temperature, fish would be expected to travel from water with a temperature out of that range to one within that range. However that was observed in only two of 12 cases (Table 3).

The third question was whether the temperature at the end of traveling was a temperature that the fish encountered for the first time since the onset of traveling. We found, however, that there was no specific trend in water temperatures during traveling phases (Fig. 11). Six of 12 temperatures at the ends of traveling phases were not the first one that the fish had experienced during the phase (Table 3).

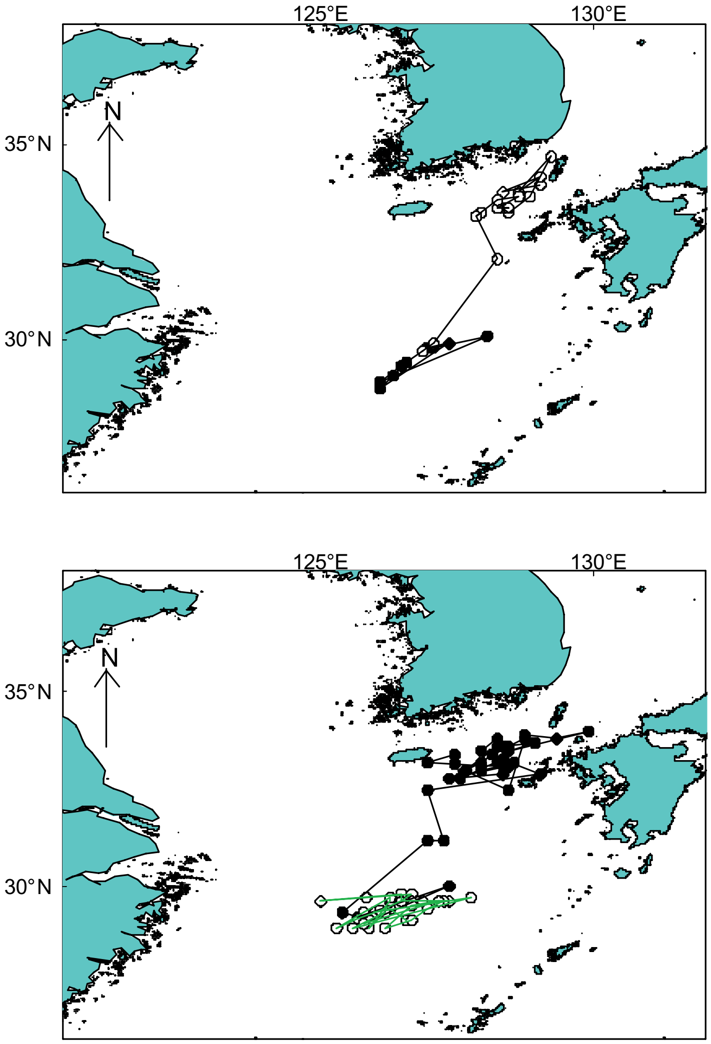

Figure 9

Rapid movements of a fish with an archival tag in the residency phase in the East China Sea. The fish moved rapidly south (upper panel; open circles are in December 1995 and solid circles are in January 1996) and north (lower panel; open circles are in April 1996 and solid circles are in May 1996).

Discussion

Reliability of archival tag data

The reliability of archival tag data for geolocation estimates based on measured light intensity has been examined by implanting the tags in pen-held fish or attaching the tags to a stationary subsurface mooring (Welch and Eveson, 1999; Musyl et al., 2001; Gunn et al.[2]). About one degree of reliability for both longitude and latitude were the results. Our study included further tests: for a large number of tags; for sensors other than light sensors; for reliability of tags over time; for tags manufactured by Northwest Marine Technology that were applied to wild young bluefin tuna and not fully examined in previous studies; and finally for the effect of tag attachment on Pacific bluefin tuna.

The benchmark test in this study showed that longitude estimated by archival tags had an error (mean ±standard deviation) of –0.54° ±0.75°, which differed by only –0.1° ±0.8° from a comparison of in-water tag position results with actual recapture locations. In the on-land benchmark test, the mean error did not change with tag age, although the standard deviation slightly increased. Ninety-six percent of all tags tested were considered to have sufficient reliability in longitudinal estimation. We concluded, therefore, that the archival tag is a reliable tool to estimate longitude on a scale of about one degree.

Latitudes estimated automatically from day length carried larger errors than estimations of longitude, and the accuracy of estimation changed with season as well as with the latitude itself (Hill, 1994; Hill and Braun, 2001). Smith and Goodman (1986) recommended estimating latitude by

Table 1

Information on traveling phases of young bluefin tuna as recorded by archival tags. Daily travel distances were estimated from a three-day running average of latitude and longitude.

ID of fish and number (e.g. M1) of traveling phase	Area	Onset of traveling phase		End of traveling phase		Duration of traveling phase (days)	Total distance traveled (km)	Daily distance traveled (km/day)
		Date	Location	Date	Location			
241 M1	western Pacific	1 May 1997	31N 132E	15 May 1997	36N 143E	15	1,341	89.4
241 M2	western Pacific	30 Jul 1997	40N 147E	18 Aug 1997	42N 152E	20	1,161	58.1
241 M3[1]	central Pacific	11 Nov 1997	41N 163E	15 Jan 1998	36N 127W	66	7,636	115.7
241 M4	eastern Pacific	25 Feb 1998	32N 126W	3 Mar 1998	29N 121W	7	1,043	148.9
241 M5[2]	eastern Pacific	9 May 1998	29N 119W	12 Jun 1998	27N 120W	35	3,406	97.3
209 M1	western Pacific	7 Mar 1996	30N 131E	6 Apr 1996	35N 142E	31	1,860	60.0
164 M1[2]	Sea of Japan	4 May 1996	36N 134E	12 May 1996	38N 138E	9	770	85.6
319 M1[2]	Sea of Japan	18 Apr 1997	35N 132E	30 Apr 1997	38N 138E	13	1,346	103.5
688 M1	Sea of Japan	23 Jun 1998	37N 132E	30 Jun 1998	39N 138E	8	877	109.7
688 M2[2]	Sea of Japan	3 Nov 1998	44N 140E	14 Nov 1998	34N 128E	12	1,611	134.2
760 M1	Sea of Japan	13 Jul 1998	35N 129E	8 Aug 1998	40N 137E	27	1,590	58.9
760 M2[2]	Sea of Japan	11 Nov 1998	44N 141E	14 Nov 1998	38N 136E	4	727	181.7
Average						16.5[3]	1430[3]	103.6

[1] Trans-Pacific migration.

[2] Detail file during the traveling phase exists and was used for analyses in Table 2.

[3] The trans-Pacific migration, which was too long in time and distance, was not included in the calculation.

comparing measured water temperatures at three depths to the water temperature maps at each depth. However, it is quite difficult to obtain water temperature maps for the whole range of times and areas where tuna migrate other than those for SST. Therefore we decided for the latitudinal estimation to rely on the SST maps and on longitude estimated by the tags. One difficulty with the SST method for latitude is that water of the observed surface temperature might occur at two different latitudes, thus not implying a single unique position. However because the latitude of about 80% of all days could be uniquely determined from SST, we considered the adjustment method taken here to be acceptable for the purpose of the present study. Although it was not possible to check the accuracy of the latitudinal estimation independently, judging from the accuracy of the longitude values we used to locate the appropriate North-South stripe on the SST maps and from the rapidity of temperature variations found along those stripes, which in most cases tightly constrained our estimates, we expected the accuracy of latitudinal estimation to be around one degree, which would be sufficient for a study of Pacific bluefin tuna migration.

Some deterioration was observed in pressure sensors. The need for recalibration of sensors after recovery should be emphasized.

Effect of the tag on fish

Fish in this study were much smaller than those in other archival tag studies of southern bluefin tuna and Atlantic bluefin tuna (Block et al., 2001; Gunn and Block, 2001). The tagging success achieved confirms that the type of archival tag we used can be applied to fish at least down to 43 cm FL. No fish died because of the attachment of the tag during the experiment on pen-held fish. The recovery rate (18.1%) for fish tagged with archival tags was similar to the rate (19.1%) for those in the conventional tagging experiment conducted in the 1980s off Nagasaki Prefecture, including Tsushima, for the same size fish of the species (Bayliff et al., 1991). This comparison should be made cautiously for the following reasons. The unusual appearance of an archival tag body would attract the attention of the finder who gutted the fish and might lead to a higher reporting rate. Increased fishing effort for young Pacific bluefin tuna in the northern part of the East China Sea in the 1990s compared to that in the 1980s might lead to a higher recapture rate. The inconspicuous stalk of an archival tag which was the only externally detectable sign of its existence might lead to a low discovery rate. Indeed, because many recoveries of archival tags were made by consumers while gutting the fish, archival tags implanted in the body of the fish must have been overlooked by fishermen and by sellers at fish markets. However, judging not only by the similar but also high recovery rates, it seems that damage and stress of handling at implantation and that due to the archival tags being carried by the fish did not have much more effect on fish survival than did the conventional tags.

Macroscopic observations of two wild fish recovered with archival tags showed that the surgical injuries that occurred during archival tag implantations healed after one month

Table 2

Comparison of various averaged environmental, physiological, and behavioral values between a traveling phase and a residency phase for young Pacific bluefin tuna.

		ID of fish					Average of difference
Subject	Phase	164	241	319	688	760	
Number of days	Traveling	9	2	13	12	4	
	Residency	10	10	10	10	10	
Swimming depth (m)	Traveling	8.7	22.7	12.0	22.8	7.5	
	Residency	14.0	15.0	45.3	10.2	17.4	
	Difference	–5.3	7.7	–33.3	12.5	–9.9	–5.6
Ambient water temperature (°C)	Traveling	12.9	17.4	12.8	19.8	16.3	
	Residency	17.2	17.9	15.6	18.7	15.3	
	Difference	–4.3	0.5	2.8	1.1	0.9	–1.1
Temperature of viscera (°C)	Traveling	17.8	21.1	17.5	25.9	22.7	
	Residency	20.7	21.8	19.1	23.2	20.8	
	Difference	–2.9	–0.7	–1.6	2.7	1.9	–0.1
Temperature difference between ambient water and fish viscera (°C)	Traveling	4.9	3.7	4.7	6.1	6.4	
	Residency	3.6	3.9	3.6	4.5	5.5	
	Difference	1.4	–0.2	1.2	1.6	1.0	1.0
The number of depth records deeper than 150 m per day	Traveling	5.4	36.0	1.6	3.7	4.3	
	Residency	1.3	13.7	0.0	0.3	0.2	
	Difference	4.1	22.3	1.6	3.4	4.1	7.1
The number of feeding events per day	Traveling	2.6	1.0	1.6	1.7	1.3	
	Residency	1.7	0.6	1.2	0.9	1.3	
	Difference	0.9	0.4	0.4	0.8	0.1	0.5
Percentage of days when a rapid ascent at dawn was observed	Traveling	11%	100%	8%	67%	0%	
	Residency	70%	70%	50%	40%	0%	
	Difference	–59%	30%	–42%	27%	0%	–9%
Percentage of days when a rapid descent at dusk was observed	Traveling	11%	50%	8%	27%	50%	
	Residency	80%	100%	50%	10%	40%	
	Difference	–69%	50%	–42%	17%	10%	–27%
Percentage of days when swimming depth was significantly deeper during daytime than at nighttime	Traveling	89%	100%	50%	75%	25%	
	Residency	80%	70%	90%	80%	100%	
	Difference	9%	30%	–40%	–5%	–75%	–16%
Percentage of days when ambient water temperature was significantly lower during daytime than at nighttime	Traveling	56%	100%	58%	67%	50%	
	Residency	70%	100%	30%	60%	70%	
	Difference	–14%	0%	28%	7%	–20%	0%
Percentage of days when temperature of fish viscera was significantly higher during daytime than at nighttime	Traveling	89%	0%	92%	75%	100%	
	Residency	80%	20%	100%	90%	100%	
	Difference	9%	20%	–8%	–15%	0%	–7%
Accumulated swimming depth change per day (m)	Traveling	5097	6031	6224	7884	4576	
	Residency	5639	4533	6123	5266	6386	
	Difference	–542	1498	101	2618	–1810	373

and there was no scar after a half year. No damage to visceral organs was observed for the two fish. The finding is consistent with that for southern bluefin tuna (Gunn et al.[2]).

Fish tagged with archival tags usually showed similar behavioral patterns, such as diurnal change of swimming depth and vertical excursions at dawn and dusk (Itoh et al.,

Table 3

Water temperature changes associated with the traveling phase of Pacific bluefin tuna.

Test 1: Circles mark the occurrence of a sea-surface temperature change before the onset of a traveling phase (increasing in spring-summer, decreasing in autumn-winter). T-change (temperature change) shows the maximum (in spring–summer) and minimum (in autumn-winter) water temperature (in the temperature change before traveling.

Test 2: Comparison of temperatures at the onset and end of traveling to a temperature range of 14–20°C, which is thought to be a preferred temperature range for young Pacific bluefin tuna. Temperature values within the range of 14–20°C are underlined.

Test 3: Circles mark cases where the temperature at the end of the traveling was a temperature that the fish encountered for the first time since the onset of the traveling Pacific.

			Test 1		Test 2		
Season	ID of fish	Traveling phase number	T-change		T-onset	T-end	Test 3
Spring	209	M1	○	20	20.7	17.0	—
	164	M1	○	19	14.7	12.4	○
	319	M1	—	16	15.6	13.0	—
	241	M1	○	23	21.7	19.1	○
Summer	241	M2	○	23	21.9	17.4	○
	241	M5	○	20	18.2	19.3	—
	688	M1	○	21	19.5	20.7	—
	760	M1	○	26	24.0	23.6	—
Autumn–winter	241	M3	○	15	14.7	14.3	—
	241	M4	—	13	16.0	17.4	○
	688	M2	○	17	19.9	22.3	○
	760	M2	○	15	14.5	20.1	○

2003) from the second day after release, and their feeding frequency reached a constant level one month after release. Also, the fish maintained weight-at-length similar to that of wild fish. The average growth rate of fish tagged with archival tags observed in our study (1.3 cm/month) was less than the growth rate of wild fish observed between ages one and two in previous studies (1.7–3.3 cm/month, Aikawa and Kato, 1938; Yokota et al., 1961; Yukinawa and Yabuta, 1967; Bayliff et al., 1991; Bayliff, 1993; Foreman, 1996), except for the result of Bell (1963b) (1.3 cm/month). Because similar growth rates were observed for fish recaptured more than a half year after release that spent the summer at large, it appears that the lesser growth rate in the present study is not due to the fact that some fish spent only winter at liberty, when the growth rate is less than that in summer (Yukinawa and Yabuta, 1967; Bayliff, 1993). Judging from these facts, we suggest that the effect of archival tags on fish behavior and physiology seems to be minor, although there is a possibility that carrying an archival tag caused a reduction in growth rate of the fish.

Horizontal movement

Archival tags revealed the movement pattern of young Pacific bluefin tuna individuals, which could be divided into the two clearly-separable phases of traveling and residency. These two phases were observed for all individuals that moved out from the East China Sea.

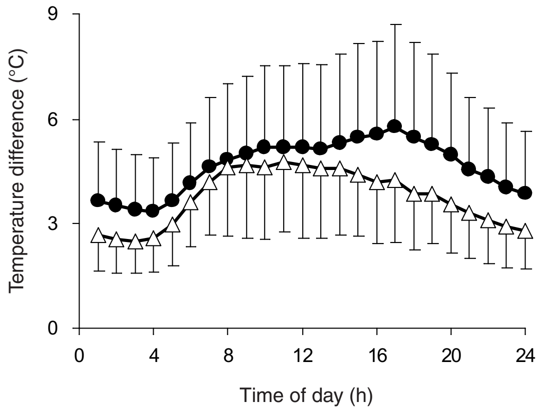

Figure 10

Hourly averages of temperature difference between ambient water and fish viscera in both traveling (circle) and residency phase (triangle) of young Pacific bluefin tuna with archival tags. Data from five individuals are all combined. Bar indicates the standard deviation.

The residency phase is considered a normal condition for young bluefin tuna, comprising 83–87% of their time. Fish with archival tags tended to stay in the areas of the East

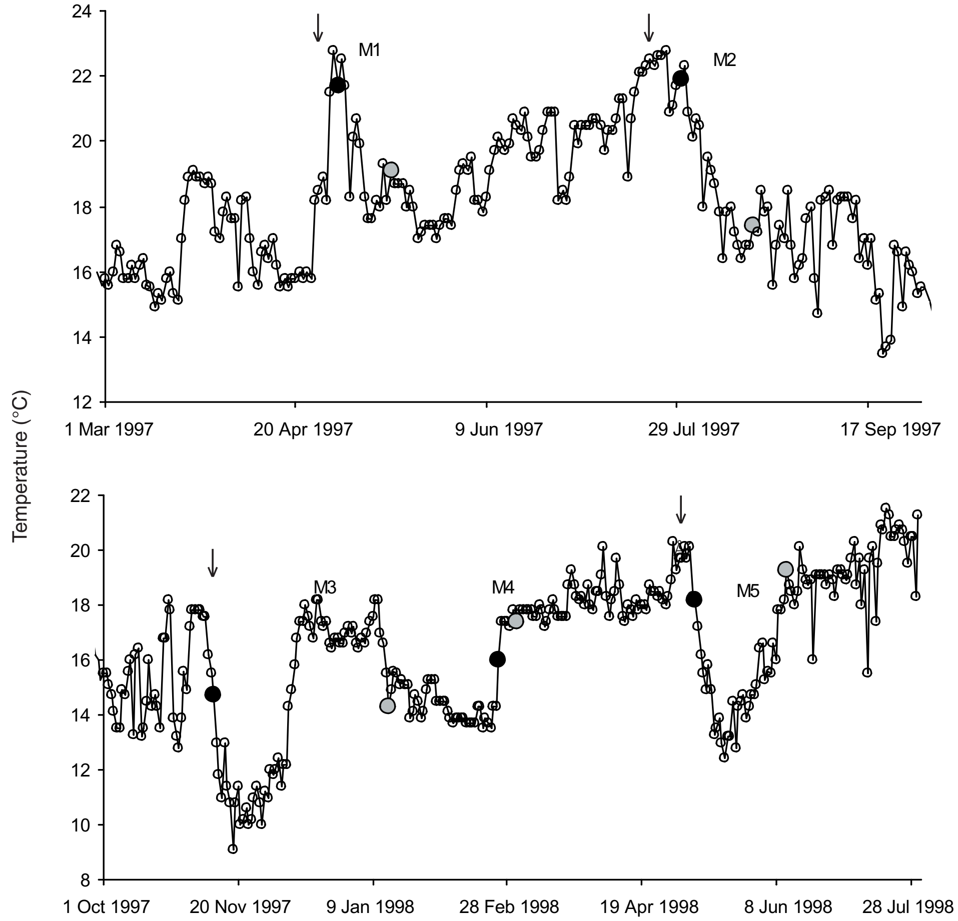

Figure 11

Changes in ambient water temperature recorded by an archival tag in a young Pacific bluefin tuna. Data are for the fish that traversed the Pacific Ocean. The symbols from M1 to M5 designate from the first to fifth traveling phase of the fish. Each dot is an ambient water temperature at 0 m depth recorded in the summary file of the archival tag each day. Large black and brighter circles are temperatures at the onset and end of traveling, respectively. Arrows indicate the observed ambient water temperature changes several days before the onset of the travel phase.

China Sea, off the east coast of Choshi, off the east coast of Hokkaido in the western Pacific Ocean, off Southern California and Baja California, off northern California in the eastern Pacific Ocean, and off the west coast between Akita and Hokkaido in the northern Sea of Japan. The first four areas correspond to the major known fishing grounds of young Pacific bluefin tuna.

The last two areas do not correspond to previously known fishing areas for young Pacific bluefin tuna. In the eastern Pacific, young bluefin tuna are usually caught in an area from 23 to 34°N, off California to Baja California, from May to October by purse seine (Calkins, 1982). Catch records in the northern area around 40°N were scarce, and all of them were for catches from summer to autumn (Radovich, 1961; Bayliff, 1994). It was not expected that young Pacific bluefin tuna were to be found around 40°N in winter, but the archival tag records showed fish staying in an area of 33–40°N, off northern California, from winter to spring. In the northern Sea of Japan, young Pacific bluefin tuna are usually caught by set nets in coastal areas, and are not caught in the offshore area. The archival tag records again showed fish staying in this area in summer and moving southward without being captured. These cases clearly indicate the ability and advantage of archival tags to provide information on fish distribution and migration when and where fishing has not been conducted.

An archival tag demonstrated that an individual young Pacific bluefin tuna was able to travel more than 7000 km without pause and to travel for more than two months. The daily moving distance during the traveling phase ranged from 59 to 182 km, and averaged 104 km. Assuming a constant swimming speed, the daily average swimming speed was estimated as a range from 1.3 to 4.1 knots (average of 2.3 knots).

These horizontal swimming speeds (1–4 knots) are comparable to those of larger young Pacific bluefin tuna and same-size fish of other *Thunnus* species, namely yellowfin tuna (*T. albacares*), bigeye tuna (*T. obesus*), and albacore (*T. alalunga*), determined from acoustic tracking experiments (Laurs et al., 1977; Carey and Olson, 1982; Holland et al., 1990; Block et al., 1997; Marcinek et al., 2001). Sustainable swimming speeds based on oxygen demand and supply for yellowfin tuna and skipjack tuna (*Katsuwonus pelamis*) of 1.5–2 kg in body weight were estimated to be 2–4 times FL per second (Brill, 1996; Korsmeyer et al., 1996), corresponding to 2.3–4.7 knots for fish of 60 cm FL. Applying to young bluefin tuna the same rule (2 –4 times FL) used by those workers as a summary of their data, the expected range of sustainable swimming speeds that do not accumulate an oxygen debt would cover the range of estimated average swimming speeds during traveling phases. Of course, the swimming speed of young Pacific bluefin tuna based on a constant moving speed between two successive daily locations obviously carries some errors. First, a fish might not maintain a constant swimming speed all day long. For example, the daytime swimming speed of albacore observed in an acoustic tracking experiment was reported to be 1.3–2.1 times as great as that at night (Laurs et al., 1977). Second, the influence of water current which should be taken into consideration (Brill, 1996) was completely ignored. Third, assuming straight-line travel between two daily positions would lead to underestimation of actual daily distances traveled, even though the direction during traveling phases could be approximated as a straight line. Even if these errors had been large and the true swimming speed had been twice as large as that which was estimated, these estimated average swimming speeds were still within the range of sustainable speeds.

Although the horizontal movement clearly differed, many features regarding vertical movement were the same for both residency and traveling phases. One parameter that did differ was that of temperature, where the difference between water and fish viscera was 1.0°C larger during the traveling phase than during the residency phase. Feeding causes an increase of visceral temperature in tuna (Carey et al., 1984; Gunn et al., 2001; Itoh et al., 2003). However, the slightly more frequent feeding in traveling phases was not enough to explain the large thermal excess. In addition, the larger temperature difference was observed not only at daytime when the visceral temperature was usually higher because of more frequent feeding, but also at night when the visceral temperature was usually lower (Itoh et al., 2003). The visceral temperature seemed to be raised by high muscle temperature during traveling phases. If this is indeed the case, this would lead to an increase in the delivery rate of oxygen to muscle, which would make the fish less tired and more able to travel (Stevens and Carey, 1981; Brill, 1996). The distinct traveling phase might be one of the tactics adopted by young Pacific bluefin tuna to use energy most efficiently for long distance travel.

During the traveling phase, the frequency of feeding increased slightly and the fish dived to water deeper than 150 m depth more frequently. The fish would feed and seek food at least as aggressively as in the residency phase.

Ambient water temperature is one of the most important environmental factors for young Pacific bluefin tuna (Sund et al., 1981; Koido and Mizuno, 1989; Ogawa and Ishida, 1989; Itoh et al., 2003). The onset of most traveling phases were preceded by specific water temperature changes that reached the upper or lower limit of the preferable water temperature of 14–20°C for young Pacific bluefin tuna (Itoh et al., 2003). Changes in ambient water temperature appears to be a possible trigger for a fish to move. Because no remarkable change in frequency of feeding was observed within several days before or after traveling began, the possibility that shortage of prey is a trigger for migration does not seem to be plausible.

If the impulse to travel in young Pacific bluefin tuna is regulated only by the search for the preferred water temperature range and the aim of traveling is to reach the preferred water temperature range, the ambient temperature would be expected to be out of the preferred range at the onset of travel and within that range at the end. However this did not occur in the fish studied. In addition, half of the observed traveling phases were continued after the fish encountered along the way the same temperature that was present at the end of traveling. According to these results, it appears that the preferred water temperature is neither the sole regulator of traveling in young Pacific bluefin tuna nor is it the sole aim of traveling.

Data from tagged fish released around Japan in the 1980s revealed that some fish released from Nagasaki prefecture migrated to the Sea of Japan and others to the Pacific Ocean (Bayliff et al., 1991). Archival tag data showed that fish released in the same season and same area migrated in various patterns involving different onset times and different destinations when traveling from the East China Sea. In addition, some fish continued to remain in the East China Sea. The migration scenario seems not to be fixed or limited for age 0–1 fish distributed around the East China Sea. A detailed examination of fish behaviors relating to the water temperature has suggested that although young Pacific bluefin tuna prefer a specific temperature range, they can still tolerate temperatures outside of this range (Itoh et al., 2003). This temperature tolerance would contribute to the diversity of migration scenarios for the species.

The trans-Pacific migration

The trans-Pacific migration of Pacific bluefin tuna was originally validated by tagging tuna both from the western Pacific Ocean to the eastern Pacific Ocean and from the eastern Pacific Ocean to the western Pacific Ocean (Orange and Fink, 1963; Clemens and Flittner, 1969). The duration required for trans-Pacific migration was estimated as 215 days from the shortest interval between the release of fish from one side of the Ocean to the recovery of fish on the other side (Bayliff et al., 1991). The present study obtained a full record of daily locations during a trans-Pacific migration of one fish. The fish took two months to traverse the whole Pacific Ocean, which was much shorter than expected from previous records. The starting time for trans-Pacific migration was estimated by Yamanaka (1982) as May–

August based on fishery information and as autumn and winter by Bayliff et al. (1991) based on tagging data. The fish observed in our study started its trans-Pacific migration in late autumn. Although data concerning distribution of young Pacific bluefin tuna in the central Pacific Ocean is limited, a record of young Pacific bluefin tuna catch (age 1–3, age 1 mainly) in the area of 35–45°N, 150°E–140°W from April to November has been reported (Saito et al.[3]). Moreover, two tagged fish were recaptured in the central Pacific Ocean at 38°N, 172°E in June and 39°N, 162°W in June, respectively (Bayliff et al., 1991). Although the seasons differ, the path of the fish tagged with an archival tag passed near these locations. The limited data available at present suggest that the trans-Pacific migration route lies in this area. Together with data which would be obtained from future recovery of additional fish tagged with archival tags, we expect that the overall features of trans-Pacific migration to be revealed in the near future.

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Literature cited

Aikawa, H.
1949. Fisheries population ecology. Sangyo Tosho Co. Ltd., Tokyo, 545 p. [In Japanese.]

Aikawa, H., and M. Kato.
1938. Age determination of fish. I. Bull. Japan. Soc. Sci. Fish. 7:79–88. [In Japanese.]

Anonymous.
1994. Archival tags 1994: present and future. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-SEFSC-357, 42 p.

Arnold, G., and H. Dewar.
2001. Electronic tags in marine fisheries research: a 30-year perspective. *In* Electronic tagging and tracking in marine fisheries (J. R. Sibert and J. L. Nielsen, eds.), p. 7–64. Kluwer Academic Publisher, Netherlands.

Bayliff, W. H.
1980. Synopsis of biological data on the northern bluefin tuna, *Thunnus thynnus* (Linnaeus, 1758), in the Pacific Ocean. Spec. Rep. IATTC 2:261–293.
1993. Growth and age composition of northern bluefin tuna, *Thunnus thynnus*, caught in the eastern Pacific Ocean, as estimated from length-frequency data, with comments on trans-pacific migrations. Bull. IATTC, 20:503–540.
1994. A review of the biology and fisheries for northern bluefin tuna, *Thunnus thynnus*, in the Pacific Ocean. FAO Fish. Tech. Pap. 336/2:244–295.

Bayliff, W. H., Y. Ishizuka, and R. B. Deriso.
1991. Growth, movement, and attrition of northern bluefin tuna, *Thunnus thynnus*, in the Pacific Ocean, as determined by tagging. Bull. IATTC 20:1–94.

Bell, R. R.
1963a. Synopsis of biological data on California bluefin tuna *Thunnus saliens* Jordan and Everman 1962. FAO Fish. Rep. 6(2):380–421.
1963b. Preliminary age determination of bluefin tuna, *Thunnus thynnus*. Calif. Fish. Game 49:307.

Block, B. A., H. Dewar, S. B. Blackwell, T. D. Williams, E. D. Prince, C. J. Farwell, A. Boustany, S. L. H. Teo, A. Seitz, A. Walli, and D. Fudge.
2001. Migratory movements, depth preferences, and thermal biology of Atlantic bluefin tuna. Science 293:1310–1314.

Block, B. A., J. E. Keen, B. Castillo, H. Dewar, E. V. Freund, D. J. Marcinek, R. W. Brill, and C. Farwell.
1997. Environmental preferences of yellowfin tuna (*Thunnus albacares*) at the northern extent of its range. Mar. Biol. 130:119–132.

Brill, R. W.
1996. Selective advantages conferred by the high performance physiology of tunas, billfishes, and dolphin fish. Comp. Biochem. Physiol. 113A:3–15.

Calkins, T. P.
1982. Observations on the purse-seine fishery for bluefin tuna (*Thunnus thynnus)* in the eastern Pacific Ocean. Bull. IATTC 18:123–225.

Carey, F. G., J. W. Kanwisher, and E. D. Stevens.
1984. Bluefin tuna warm their viscera during digestion. J. Exp. Biol. 109:1–20.

Carey, F. G., and R. J. Olson.
1982. Sonic tracking experiments with tunas. ICCAT Coll. Vol. Sci. Papers XVII. 2:458–466.

Cayré, P.
1991. Behavior of yellowfin tuna (*Thunnus albacares*) and skipjack tuna (*Katsuwonus pelamis*) around fish aggregating devices (FADs) in the Comoros Islands as determined by ultrasonic tagging. Aquat. Living. Resour. 4:1–12.

Cayré, P., and F. Marsac
1993. Modeling the yellowfin tuna (*Thunnus albacares*) vertical distribution using sonic tagging results and local environmental parameters. Aquat. Living Resours. 6:1–14.

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[3] Saito, S., K. Shimazaki, and T. Sato. 1981. Distribution of bluefin tuna around the area of polar front in the north Pacific Ocean. *In* Report of the Maguro Gyogyo Kenkyu Kyogikai, in 1980, p. 247–252. Nat. Res. Inst. Far Seas Fish. Pelagic Fish Resource Division, 5-7-1 Shimizu-Orido, Shizuoka, Shizuoka, 424-8633, Japan. [In Japanese, the title was translated by authors.]

Clemens, H. B., and G. A. Flittner.
1969. Bluefin tuna migrate across the Pacific Ocean. Calif. Fish Game 55:132–135.

Collette, B. B.
1999. Mackerels, molecules, and morphology. Soc. Fr. Ichthyol. 25:149–164.

Foreman, T.
1996. Estimates of age and growth, and an assessment of ageing techniques for northern bluefin tuna, *Thunnus thynnus*, in the Pacific Ocean. Bull. IATTC 21:75–123.

Gunn, J., and B. Block.
2001. Advances in acoustic, archival, and satellite tagging of tunas. *In* Tuna: physiology, ecology, and evolution (B. A. Block and E. D. Stevens, eds.), p.167–224. Academic Press, San Diego, CA.

Gunn, J., J. Hartog, and K. Rough
2001. The relationship between food intake and visceral warming in southern bluefin tuna (*Thunnus maccoyii*). Can we predict from archival tag data how much a tuna has eaten? *In* Electronic tagging and tracking in marine fisheries (J. R. Sibert and J. L. Nielsen, eds.), p. 109–130. Kluwer Academic Publisher, Netherlands.

Hill, R. D.
1994. Theory of geolocation by light levels. *In* Elephant seals, population ecology, behavior and physiology (B. J. LeBoeuf and R. M. Laws, eds.), p. 227–236. Univ California Press, Berkeley, CA.

Hill, R. D.,and M. J. Braun
2001. Geolocation by light level. The next step: latitude. *In* Electronic tagging and tracking in marine fisheries (J. R. Sibert and J. L. Nielsen, eds.), p. 315–330. Kluwer Academic Publisher, Netherlands.

Holland, K. N., R. W. Brill, and R. K. C. Chang.
1990. Horizontal and vertical movements of yellowfin and bigeye tuna associated with fish aggregating devices. Fish. Bull. 88:493–507.

Hunter, J. R., A. W. Argue, W. H. Bayliff, A. E. Dizon, A. Fonteneau, D. Goodman, and G. R. Sekel.
1986. The dynamics of tuna movements: an evaluation of past and future research. FAO, Fish. Tech. Pap. 277:vi, 78 p.

Itoh, T., S. Tsuji, and A. Nitta.
2003. Swimming depth, ambient water temperature preference, and feeding frequency of young Pacific bluefin tuna (*Thunnus orientalis*) determined with archival tags. Fish. Bull. 101:535–544.

Kitagawa, Y., Y. Nishikawa, T. Kubota, and M. Okiyama.
1995. Distribution of ichthyoplanktons in the Japan Sea during summer, 1984, with special reference to scombroid fishes. Bull. Jpn. Soc. Fish. Oceanogr. 59(2):107–114. [In Japanese.]

Kitagawa, T., H. Nakata, S. Kimura, T. Itoh, S. Tsuji, and A. Nitta.
2000. Effect of ambient temperature on the vertical distribution and movement of Pacific bluefin tuna *Thunnus thynnus orientalis*. Mar. Ecol. Prog. Ser. 206:251–260.

Koido, T., and K. Mizuno.
1989. Fluctuation of catch for bluefin tuna (*Thunnus thynnus*) by trap nets in Sanriku coast with reference to hydrographic condition. Bull. Jpn. Soc. Fish. Oceanogr. 53: 138–152. [In Japanese.]

Korsmeyer, K. E., H. Dewar, N. C. Lai, and J. B. Graham.
1996. The aerobic capacity of tunas: adaptation for multiple metabolic demands. Comp. Biochem. Physiol. 113A:17–24.

Laurs, R. M., H. S. H. Yuen, and J. H. Johnson.
1977. Small-scale movements of albacore, *Thunnus alalunga*, in relation to ocean features as indicated by ultrasonic tracking and oceanographic sampling. Fish. Bull. 75:347–355.

Marcinek, D. J., S. B. Blackwell, H. Dewar, E. V. Freund, C. Farwell, D. Dau, A. C. Seitz, and B. A. Block.
2001. Depth and muscle temperature of Pacific bluefin tuna examined with acoustic and pop-up satellite archival tags. Mar. Biol. 138:869–885.

Metcalfe, J. D. and G. P. Arnold
1997. Tracking fish with electronic tags. Nature 387:665–666.

Musyl, M. K., R. W. Brill, D. S. Curran, J. Gunn, J. R. Hartog, R. D. Hill, D. W. Welch, J. P. Eveson, C. H. Boggs, and R. E. Brainard.
2001. Ability of archival tags to provide estimates of geographical position based on light intensity. *In* Electronic tagging and tracking in marine fisheries (J. R. Sibert and J. L. Nielsen, eds.), p. 343–367. Kluwer Academic Publisher, Netherlands.

Nakamura, H.
1965. Tuna resources of the world (II), 52 p. Japan Fisheries Resources Conservation Association, Tokyo, Japan. [In Japanese.]

Ogawa, Y., and T. Ishida
1989. Hydrographic conditions governing fluctuations in the catch of *Thunnus thynnus* by set-nets along the Sanriku coast. Bull. Tohoku Reg. Fish. Res. Lab. 51:23–39. [In Japanese.]

Okachi, I.
1963. Studies on the distribution and structure of the fish fauna in the Japan Sea by—catch statistics. II. Supplement of seasonal distribution and fishing condition of the bluefin tuna. Bull. Jap. Sea Reg. Fish. Res. Lab. 11:9–21. [In Japanese.]

Okiyama, M.
1974. Occurrence of the postlarvae of bluefin tuna, *Thunnus thynnus*, in the Japan Sea. Bull. Japan Sea Reg. Fish. Res. Lab. 25:89–97. [In Japanese.]

Orange, C. J., and B. D. Fink.
1963. Migration of a tagged bluefin tuna across the Pacific Ocean. Calif. Fish Game, 49:307–309.

Radovich, J.
1961. Relationships of some marine organisms of the northwest Pacific to water temperatures particularly during 1957 through 1959. Fish Bull. Calif. Dep. Fish Game 112: 1–62.

Shingu, C., I. Warashina, and N. Matsuzaki.
1974. Distribution of bluefin tuna exploited by longline fishery in the western Pacific Ocean. Bull. Far Seas Fish. Res. Lab. 10:109–140. [In Japanese.]

Smith, P. and D. Goodman.
1986. Determining fish movements from an "Archival" tag: precision of geographical positions made from a time series of swimming temperature and depth. U.S. Dep. Commer., NOAA-TM-NMFS-SWFC-60, 13 p.

Stevens, E. D., and F. G. Carey
1981. One why of the warmth of warm-bodied fish. Am. J. Physiol. 240:R151–R155.

Sund, P. N., M. Blackburn, and F. Williams.
1981. Tunas and their environment in the Pacific Ocean: a review. Oceanogr. Mar. Biol. 19:443–512.

Ueyanagi, S.
1969. Observations on the distribution of tuna larvae in the Indo-Pacific Ocean with emphasis on the delineation of the spawning areas of albacore, *Thunnus alalunga*. Bull. Far Seas Fish. Res. Lab. 2:177–256. [In Japanese.]

Welch, D. W., and J. P. Eveson

1999. An assessment of light-based geoposition estimates from archival tags. Can. J. Fish. Aquat. Sci. 56:1317–1327.

Yabe, H., S. Ueyanagi, and H. Watanabe.

1966. Studies on the early life history of bluefin tuna *Thunnus thynnus* and on the larvae of the southern bluefin tuna *T. maccoyii*. Rep. Nankai Reg. Fish. Res. Lab. 23:95–129. [In Japanese.]

Yamanaka, H.,

1982. Fishery biology of the bluefin tuna resource in the Pacific Ocean, 140 p. Japan Fisheries Resources Conservation Association, Tokyo, Japan. [In Japanese.]

Yokota, T., M. Toriyama, F. Kanai, and S. Nomura.

1961. Studies on feeding habit of fishes. Rep. Nankai Reg. Fish. Res. Lab. 14:1–234. [In Japanese.]

Yonemori, T.

1989. To increase the stock level of the highly migrated pelagic fish. *In* Marine ranching (Agriculture, Forestry and Fisheries Research Council secretariat, eds.), p. 9–59. Koseisha-Koseikaku, Tokyo, Japan. [In Japanese, the title was translated by authors.]

Yorita, T.

1976. Bluefin tuna in the Sea of Japan in Hokkaido. Monthly report of Hokkaido Fishery Experimental Station, 33(3): 2–11. [In Japanese.]

Yukinawa, M., and Y. Yabuta.

1967. Age and growth of bluefin tuna, *Thunnus thynnus* (Linnaeus), in the north Pacific Ocean. Rep. Nankai Reg. Fish. Res. Lab. 25:1–18. [In Japanese.]