Migration paths for juvenile southern bluefin tuna in southern Western Australia determined via acoustic monitoring – summary of 2003-2007 experiments

Hobday, Alistair J. [1,2]*
Kawabe, Ryo [3]
Takao, Yoshimi[4]
Miyashita, Kazushi[5]
Itoh, Tomoyuki[6]

[1] CSIRO Marine and Atmospheric Research, GPO Box 1538, Hobart, Tas, 7001. Alistair.Hobday@csiro.au
[2] School of Zoology, University of Tasmania, Private Bag 5, Hobart, Tas 7001.
[3] Institute for East China Sea Research, Nagasaki University, Nagasaki, Japan
[4] NRIFE, Ibaraki, Japan
[5] Field Science Center for the Northern Biosphere, Hokkaido University, Hakodate, Japan
[6] NRIFSF, Shimizu, Japan

Abstract

Acoustic monitoring technology allows investigation of movement and residence on a scale suitable for both small scale habitat usage and large scale migration studies. Cross-shelf arrays of listening stations have been used in southern Australia for five years to estimate the cross-shelf location of southern bluefin tuna (*Thunnus maccoyyi*) migration paths. We report on these migration paths and residence time in this region, and in a companion paper, the implications for estimates of abundance in a fisheries-independent survey. The significance of the interannual variation in residence time, migration route and cross-shelf location is in the estimation of fish abundance.

音響モニタリングから推定した西オーストラリア州南部におけるミナミマグロ若齢魚の回遊経路　－2003-2007年の実験のサマリー

アリスター・ホブデイ、河邊玲、高尾芳三、宮下和士、伊藤智幸

要約

音響モニタリング技術は、小規模スケールでの環境利用と大規模スケールでの回遊の両方の点において、移動と滞在の研究を可能とした。リスニングステーションを陸棚上を横切るように配置し、オーストラリア南部でのミナミマグロの陸棚上の回遊経路を5年間調査した。本論文で、回遊経路と滞在時間を報告し、別の論文で漁業とは独立した調査による資源量推定との関連を示す。滞在時間、回遊経路、陸棚を横切る位置の年毎の変動は資源量推定に重要である。

Introduction: overview of the acoustic monitoring project

Southern bluefin tuna (SBT, *Thunnus maccoyii*) are an economically important species internationally and in Australia, however, are currently at historically low population levels (Caton 1991; Anonymous 2001). SBT spawn in the northeast Indian Ocean (Farley and Davis 1998). Juveniles move down the west coast of Australia and are found as age-1 and 2-year old fish in southern Western Australia and until about age-5 occur further east in the shelf waters of the Great Australia Bight during the austral summer (Caton 1991). In southern Western Australia an Acoustic Survey has been run since 1995 to estimate the relative abundance of 1-year old SBT. Beginning in about 2000, however, the abundance of juvenile SBT within the Acoustic Survey area declined dramatically. It has been suggested that either (i) changes in the migration behavior of juvenile SBT or (ii) a real decline in the number of juvenile fish may be responsible for the change in the abundance. The acoustic monitoring project was designed to examine the first possibility: migration behavior in southern Western Australia

The two alternative migration hypotheses were that juvenile SBT were now moving inshore of the Acoustic Survey area, or were moving through the area before the Survey has commenced. Examining the SBT migration timing and pathway was thus considered crucial to correctly interpret the abundance indices and assess population trends of this exploited species. Information on behavior and movement of 3, 4 and 5-year old SBT has been successfully obtained using internal archival tags (Gunn et al. 1995), however, these tags do not provide location information on a fine horizontal scale (< 60 nautical miles) (Welch and Eveson 1999; Musyl et al 2001), and so are not suitable for these questions. An alternative approach with finer resolution was required and funded through the Japan-Australia Recruitment Monitoring Program (RMP). This approach, using acoustic tags and moored acoustic receivers that detect tagged fish, had been developed and tested in both Western Australia (Hobday et al., 2001) and South Australia (Hobday, 2002) and is appropriate for SBT movement studies at scales of 1-100 km.

The goal of this project was to determine how quickly juvenile SBT move east along the southern Western Australia coast during the summer, and how close to shore the movements occur. This information will be crucial for interpreting recent declines in estimated abundance of SBT from the RMP Acoustic Survey. Additional information regarding the local environment was expected to yield insight into the movement dynamics.

The successful use of data collected by the acoustic and archival tagging and acoustic monitoring projects in the analysis and interpretation of aerial survey abundance data has been an important achievement of the Recruitment Monitoring Program (RMP, 2002-03 to 2004-05), and subsequently via independent Japan-Australia collaboration (2005-06 to 2006-07). Smart tag technology developed and/or used extensively within the RMP are now tools-of-choice in tuna research programs throughout the world to examine critical questions about habitat preferences, migration and residence patterns, and physiology (Gunn and Block 2001; Heupel et al 2006).

Overall, our principal objectives were to:

- Examine the west-to-east movement rate of age-1 SBT across the acoustic survey area, and the latitudinal range of movements (includes residence times),
- Determine the depth preference of SBT to use as a basis for validating behaviour and depth preference inferred from acoustic survey data (using dataloggers)
- Determine short-term school integrity from the pattern of acoustic detections

In this paper, we summarize the results from the past five years of the acoustic monitoring experiment (2002-03 to 2006-07).

Methods

Station construction

Listening stations consisted of a mooring anchor (125 kg section of railway track), wire cable, VEMCO V2 receiver, timed electronic release, 50 meters of release rope in a PVC canister, and floats. VEMCO temperature-depth recorders (TDR) were attached to the receivers at regularly spaced intervals (the number of TDR tags varying between years depending on the number available). When deployed, the receivers were designed to be at a depth of 20-25 meters, just below the sub-surface floats (**Figure 1)**.

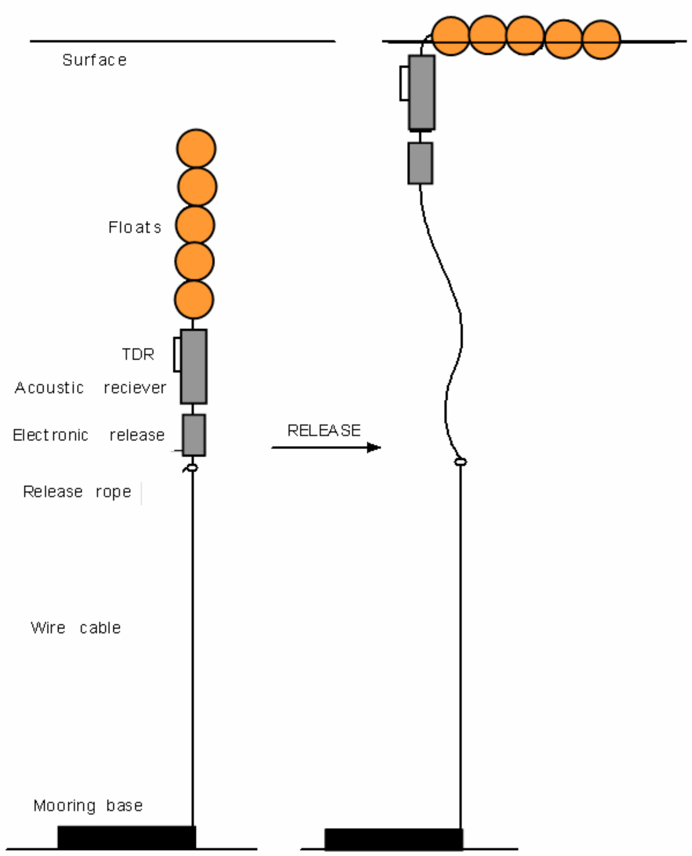


Figure 1. Configuration of the listening station moorings during the sub-surface deployment period (left) and ready for recovery (right).

Receiver deployment

The number of lines and receivers increased from 1 line of 20 receivers (Line 2, 2002-03) to 2 lines of 40 receivers (Line 1 and 2, 2003-04) and since 2004-05 has consisted of 70 listening stations in deployed in 3 lines and 3 hotspots (**Figure 2)**. The stations were deployed in cross-shelf line initiating from the coast at each location. In addition, 3 stations were deployed at each of three hotspots between the western and central lines (2004-05 to 2006-07). Water depth ranged from 55 m at the coast to 115 m at the furthest offshore station (water depth was ~170 m at the edge of this stations detection range). Water depth at the hotspots averaged 52-59 m (Table 1). Stations were separated by approximately 1500 m, which was too large for complete acoustic coverage by the receivers. This spacing decision was based on a desire to cover the width of the shelf; a tag detection range of up to 450 m (V8, V9 and V16 tags) was expected based on previous detection experiments. The actual tag detection range for each station was tested while the receivers were deployed, but is not covered in this paper.

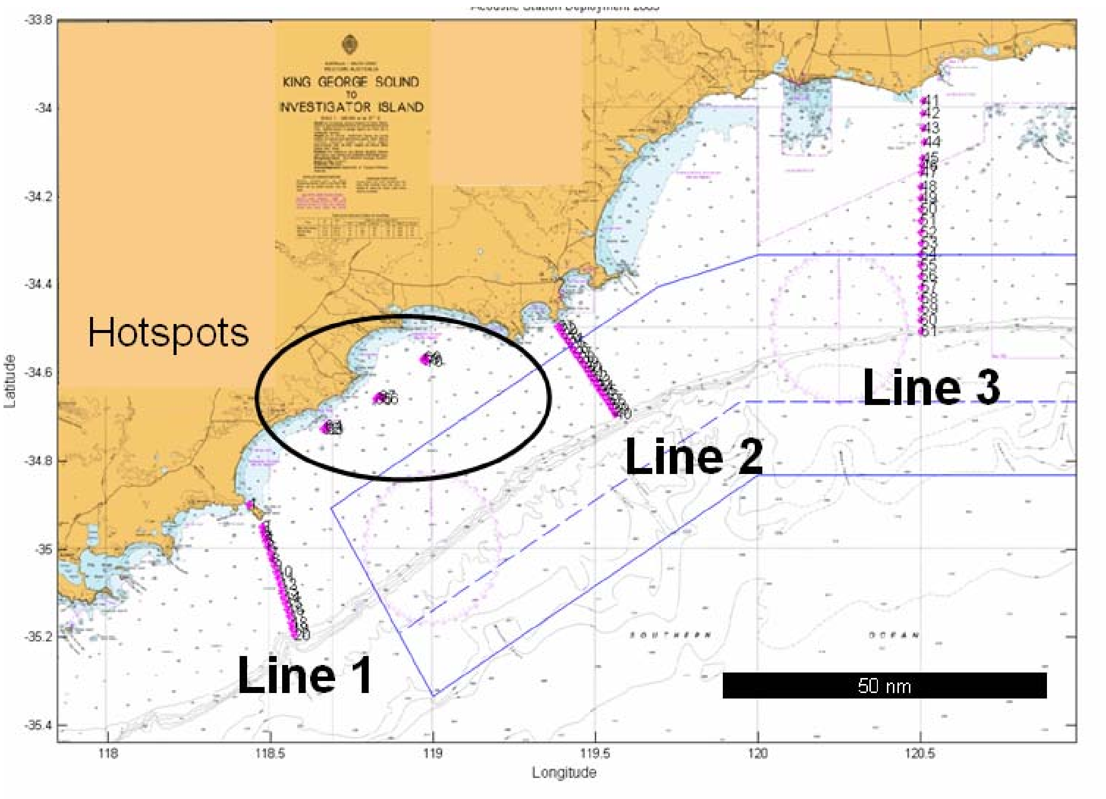


Figure 2. Location of listening stations in the acoustic monitoring experiment. The years in which particular lines and hotspots were covered is described in the text,

The electronic releases on each listening station were programmed to activate after a specified interval. At this time the floats and acoustic receiver would float to the surface, still attached to the mooring anchors via polypropylene rope (**Figure 1)**. All parts of the listening stations (including anchors since 2004-05), are recovered using an attending vessel. Receivers were tested immediately after recovery to ensure that a test-tag could be detected and that the internal clock had not drifted. The data were downloaded using VEMCO software and results analyzed with custom software written in Matlab.

Tag detection range

Validation experiments to determine the *in situ* tag detection range for the listening stations were completed on several occasions during the deployment and tagging operations. These experiments must be completed for every deployment as water depth and ambient noise influence detection range, and are crucial for estimating the detection of tagged fish and the coverage of the listening station line.

Detection tests varied between years, but typically, after the stations had been deployed, two acoustic tags and a TDR tag to determine tag depth were attached to a weighted line that was played out behind the boat for an estimated 50 meters. The actual length of the line was determined from the TDR when it was recovered, as the boat was stationary when the rope was first paid out. The boat then followed a course that passed above the subsurface listening stations at a speed of 2-4 knots. The combination of speed and line-out towed the test-tags at a depth of approximately 10-20 meters. The track of the boat and hence the position of the towed tags during each test was recorded using an underway GPS tracking system. The tags were recovered at the conclusion of each test; however, each test result could only be obtained after the receivers were recovered. When receivers were recovered, the data were examined to see if test-tags were detected. The known location of the tag through time could then be matched to the time of the recorded detection and the distance to the known position of the listening station calculated. It was important to correct the position estimate for the distance between the GPS and the test-tag. Three combinations had to be accounted for in making the position correction, depending on the relative order of the boat, test-tag and listening station.

The results of the detection tests are not discussed further: the important point is that the range of the receivers varies with weather conditions, and the lines of receivers do not allow 100% detection of passing fish. Thus, estimates of migration path are based on probabilities of detection, rather than statistical estimates. This issue has been explored in a paper submitted for publication (Hobday and Pincock, submitted July 2007).

Fish Tagging

The same protocol used for the capture and selection of SBT for conventional tagging (Williams 1983) was followed for the acoustic tagging (Hobday et al. 2001). In brief, fish were caught by poling or trolling at the stern of the vessel and then carried to a tagging cradle and length to caudal fork (LCF) measured. An acoustic tag was surgically implanted in the belly of each fish (see West and Stevens (2001) for an explanation of this procedure), which was also double tagged with conventional orange tags on each side just posterior to the second dorsal fin. The time from capture to release was approximately two minutes. All fish were tagged by a single experienced operator.

Acoustic tags (V8, V9 and V16, VEMCO) were activated and tested prior to deployment. These tags transmitted a coded pulse at a frequency of 69 kHz at random intervals every 20-60 seconds with a predicted lifetime of 365 days (V8) and 700 days (V16). A small number of fish have also been tagged with Starr-Oddi dataloggers to gather fine-scale vertical depth and temperature information. Fish must be recaptured to recover information from the dataloggers. To date, none of these tags have been recaptured.

Results and Discussion

Experimental design

The deployment configuration for each year is shown in **Table 1.** In general, the length of the experiment has increased each year, as the mooring design has improved and in order to ensure that all tagged fish have left the area when the experiment is concluded. The number of tags detected depends on the locations in which fish were tagged. In 2005-06, over 80% of tagged fish were detected; however, they were all tagged between Line 1 and Line 2 (**Figure 2)**. In contrast, a lower overall percentage was detected in 2006-07; however, over 50% of the fish were tagged to the west of the array of receivers.

Table 1. Summary of the experiments for the acoustic experiment in southern Western Australia. HS = hotspots. Locations of the lines shown in **Figure 2**.

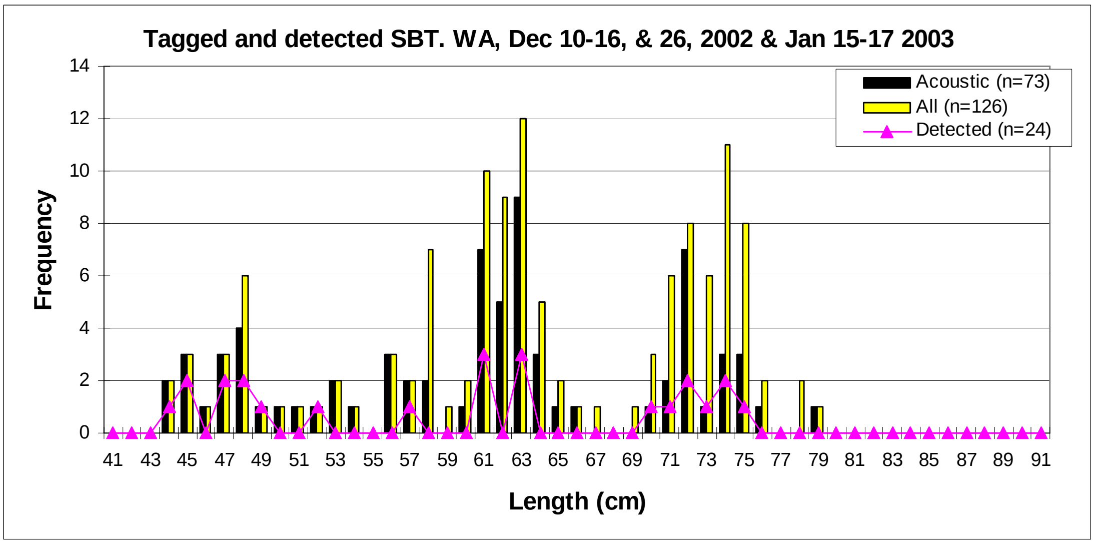
Year	Lines (receivers)	Acoustic Tags deployed	Experiment start date	Length of experiment (days)	% tags detected
2002-03	1 (20)	73	Dec 3, 2002	101	32.9%
2003-04	2 (40)	59	Dec 3, 2003	117	49.2%
2004-05	3 (61) + 3 HS (9)	79	Dec 4, 2004	102	69.6%
2005-06	3 (61) + 3 HS (9)	81	Dec 2, 2005	160	84.0%
2006-07	3 (61) + 3 HS (9)	130	Dec 1, 2006	177	48.5%

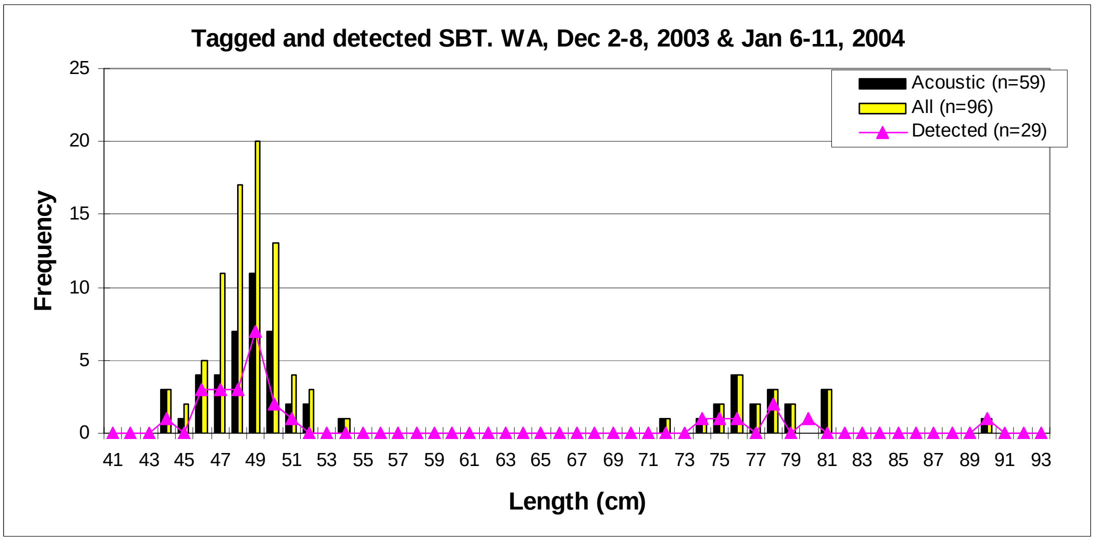
Size distribution

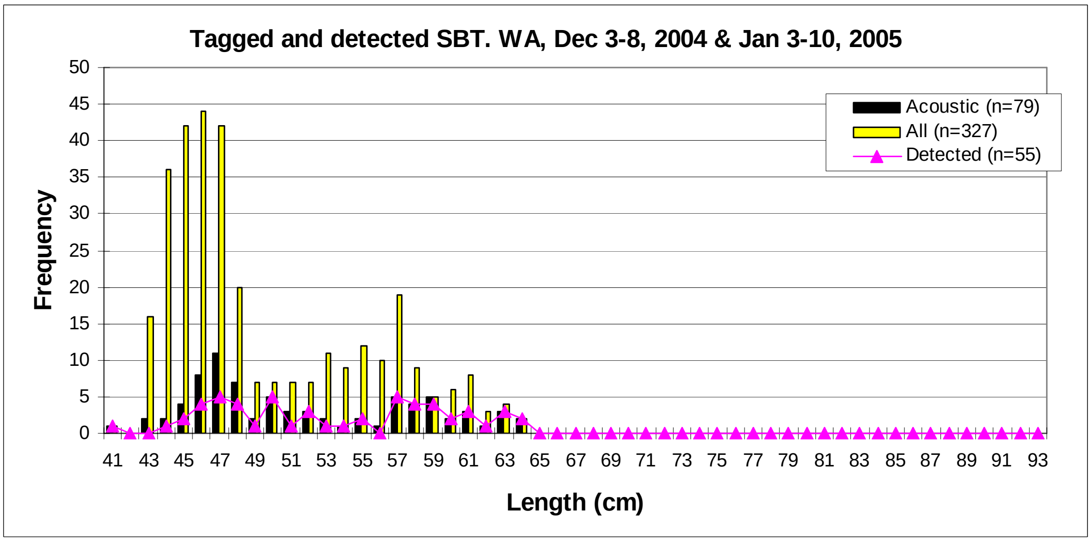
Juvenile tuna implanted with the acoustic tags ranged from 43- 90 cm in length (**Figure 3)**, with the mean size each year between 50.5 and 60.8 cm (**Table 2).** The number of size classes varied by year, and may indicate the recruitment strength of the available tuna. In 4 of the five years there was no difference between the size of the tagged and detected fish. The final year (2006-07) showed a difference because small fish were tagged on the west coast, and only one of these fish was subsequently detected. These west coast fish were the same size as had been detected in previous years (**Figure 3)**, and so this difference is likely due to migration, and not mortality.

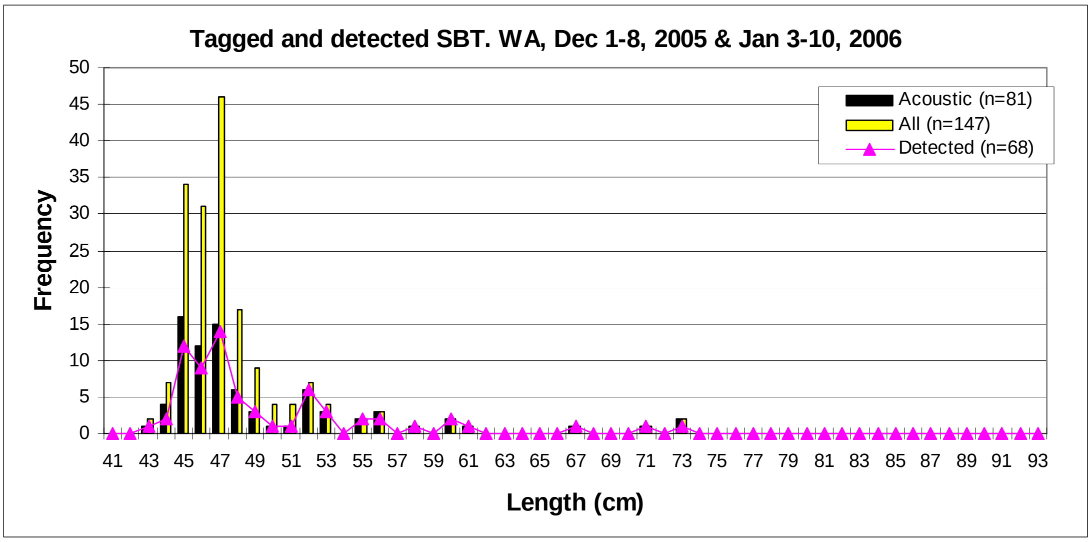
Table 2. Summary of the size of the tagged and detected southern bluefin tuna in southern Western Australia over the five years of the acoustic experiment.

Year	Acoustic Tags deployed	Mean size of all fish tagged (cm)	Mean size of all fish detected (cm)	Difference between tagged and detected sizes (t-test)	Number of size classes tagged
2002-03	73	60.8	59.8	N	3
2003-04	59	57.8	55.6	N	2
2004-05	79	51.4	53.5	N	2
2005-06	81	49.3	49.6	N	1
2006-07	130	50.5	57.9	Y	2


Tagged and detected SBT. WA, Dec 10-16, & 26, 2002 & Jan 15-17 2003
Acoustic (n=73)
All (n=126)
Detected (n=24)
Frequency
Length (cm)


Tagged and detected SBT. WA, Dec 2-8, 2003 & Jan 6-11, 2004
Acoustic (n=59)
All (n=96)
Detected (n=29)
Frequency
Length (cm)


Tagged and detected SBT. WA, Dec 3-8, 2004 & Jan 3-10, 2005
Acoustic (n=79)
All (n=327)
Detected (n=55)
Frequency
Length (cm)



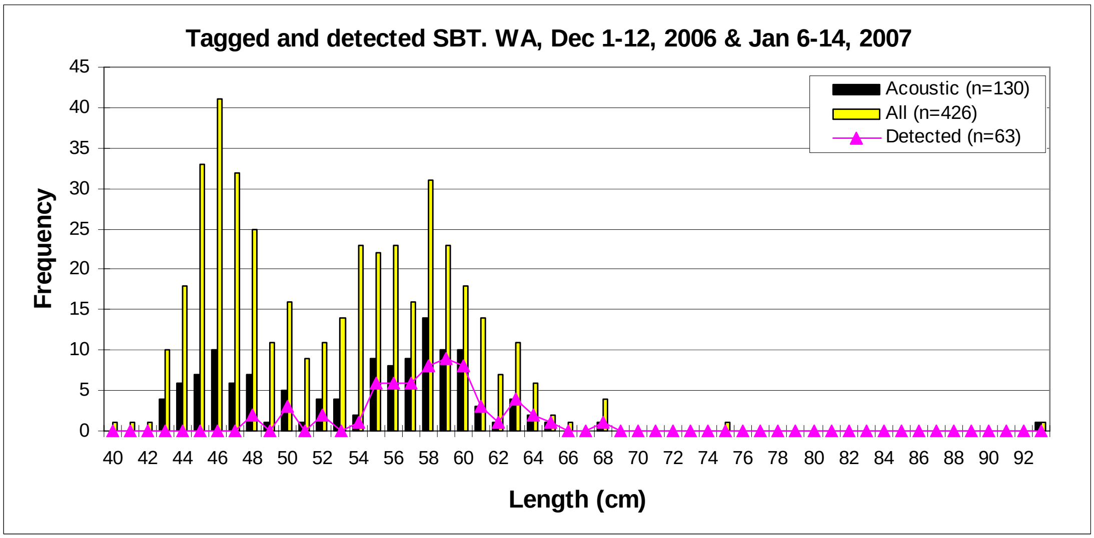


Figure 3. Size distribution of tagged southern bluefin tuna by year. The size distribution of both acoustic and conventionally tagged fish during the two tagging trips each year are shown. The size distribution of the detected fish is also provided for each year. Note the number of size classes each year can be discerned from the size distribution.

Release locations

The location in which fish were released each year varied due to the availability of fish. The general goal was to catch and release fish both inshore and offshore (shelf break), at lumps and away from lumps, and between the lines and to the west of the lines. As can be seen in the following figures, the releases were predominately between Line 1 and Line 2, with the exception 2006-07, where fish were also released much further west. This release was designed to test the migration direction, and the residence time. In 2006-07, releases took place too the west to test specific hypotheses about movements from the west coast to the southern coast, however, 50 tags were still released in the traditional area to allow comparisons with the previous years.

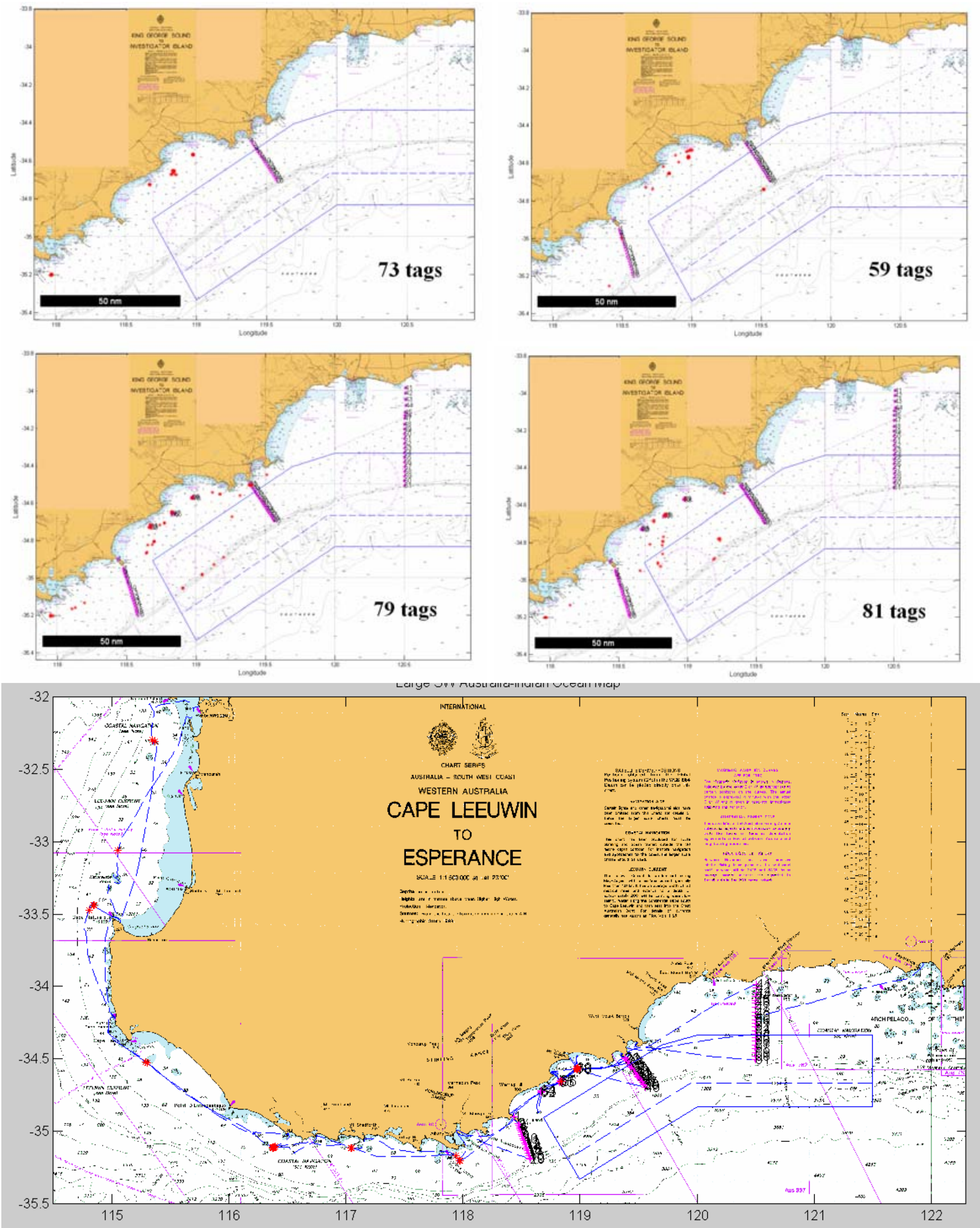


Figure 4. Release locations for acoustically tagged southern bluefin tuna (red stars) in 2002-03 (upper left), 2003-04 (upper right), 2004-05 (lower left), 2005-06 (lower right) and 2006-07 (large lower panel, n=130 tags).

Movement pathways

The movement pathways that could be detected were obviously biased by the number of receivers that were deployed each year. The overall pictures, as in **Figure 5**, are illustrative of the movements observed, but more detailed analysis is more revealing.

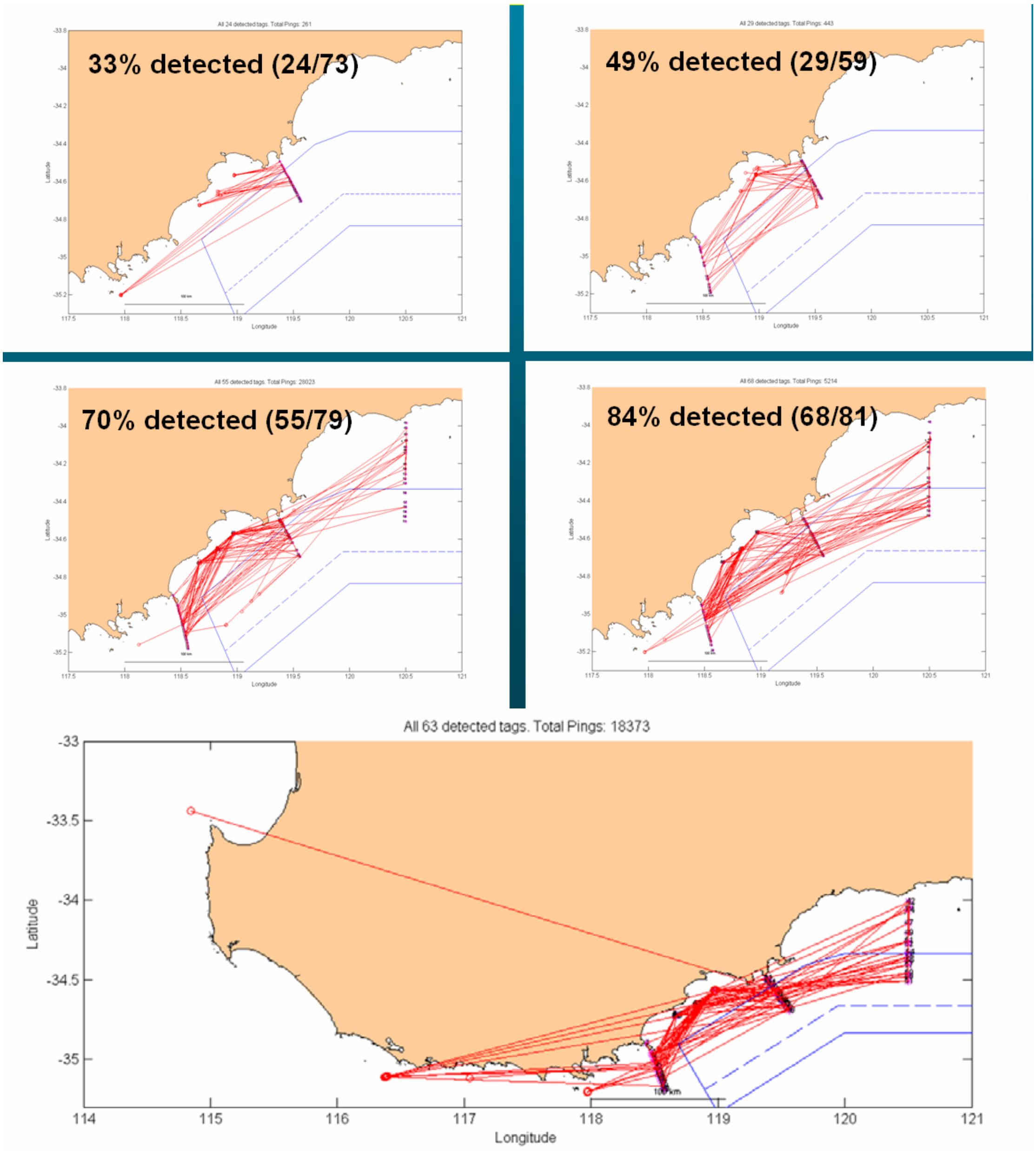


Figure 5. Movement pathways for all detected fish for 2002-03 (upper left), 2003-04 (upper right), 2004-05 (lower left), 2005-06 (lower right) and 2006-07 (large lower panel).

Inshore-offshore pathways

The percentage of fish moving inshore or offshore through the survey area varied by year (**Table 3)**. In some years, the majority of tuna were detected at the inshore half of the receiver line, while the opposite was true in others (**Figure 6)**. This variation in the inshore-offshore detection of fish suggests interannual variation in how fish use the southern Western Australia region. This issue is explored in more detail in Kawabe et al (2007).

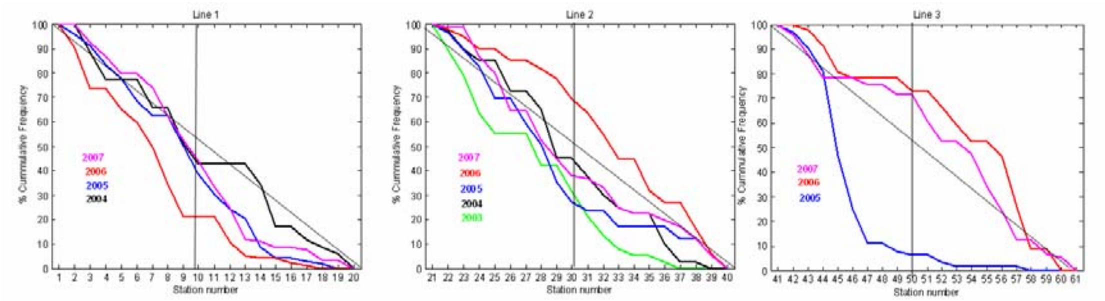


Figure 6. The cumulative frequency plots of detection across each line of receivers (left: Line 1, center: Line 2, right: line 3).

Table 3. The percentage of tagged southern bluefin tuna detected in the offshore half of each line of receivers. If the percentage listed in each cell was less (greater) than 50%, then fish were passing predominately inshore (offshore). The average column is the average across all lines for the year, while the average row is the average of that line across all years.

Year	Line 1	Line 2	Line 3	Average	Pathway
2002-03	-	32	-	32.0	Inshore
2003-04	42	45	-	43.5	Offshore
2004-05	39	27	6	24.0	Inshore
2005-06	21	70	73	54.6	Offshore
2006-07	44	38	61	48.0	~Equal
Average	36.5	42.4	46.7	40.4	

Migration paths

A simple estimate of the direction in which fish were migrating can be made by calculating the last station that fish were detected at: was it to the east or west of the original tagging location. This is only an approximation, as the lines were not close enough to detected 100% of fish that crossed them. On average, from the four years that a sensible estimate could be made (**Table 4),** 62.8% of tagged fish were last detected to the east, indicating the most frequent direction of movement is to the east.

Residence times

Residence time is important as an indicator of how long fish remained in the array area. The residence time calculations can be biased by the number of lines and receivers that were deployed in any year. For example, residence time can be calculated using Line 2 alone (used in 5 years), Line 1 and Line 2 (used for 4 years) or Line 1, Line 2, and Line 3 (used in 5 years), including or removing the inshore hotspots. In this paper, we used Line 2 only, to allow a 5-year time series of residence time to be constructed. We used half-life as an estimate of residence time. This is the time at which half the tags detected in the study remain.

The residence time did vary by year (**Figure 7**; **Table 4)**. In 2002-03 and 2004-05, the half-life in the array area was only 12 and 19 days respectively (using a single line to estimate half life). For the other 3 years, the half life was almost double, at between 34 and 37 days. The implications of the variation in residence time is discussed in Kawabe et al 2007.

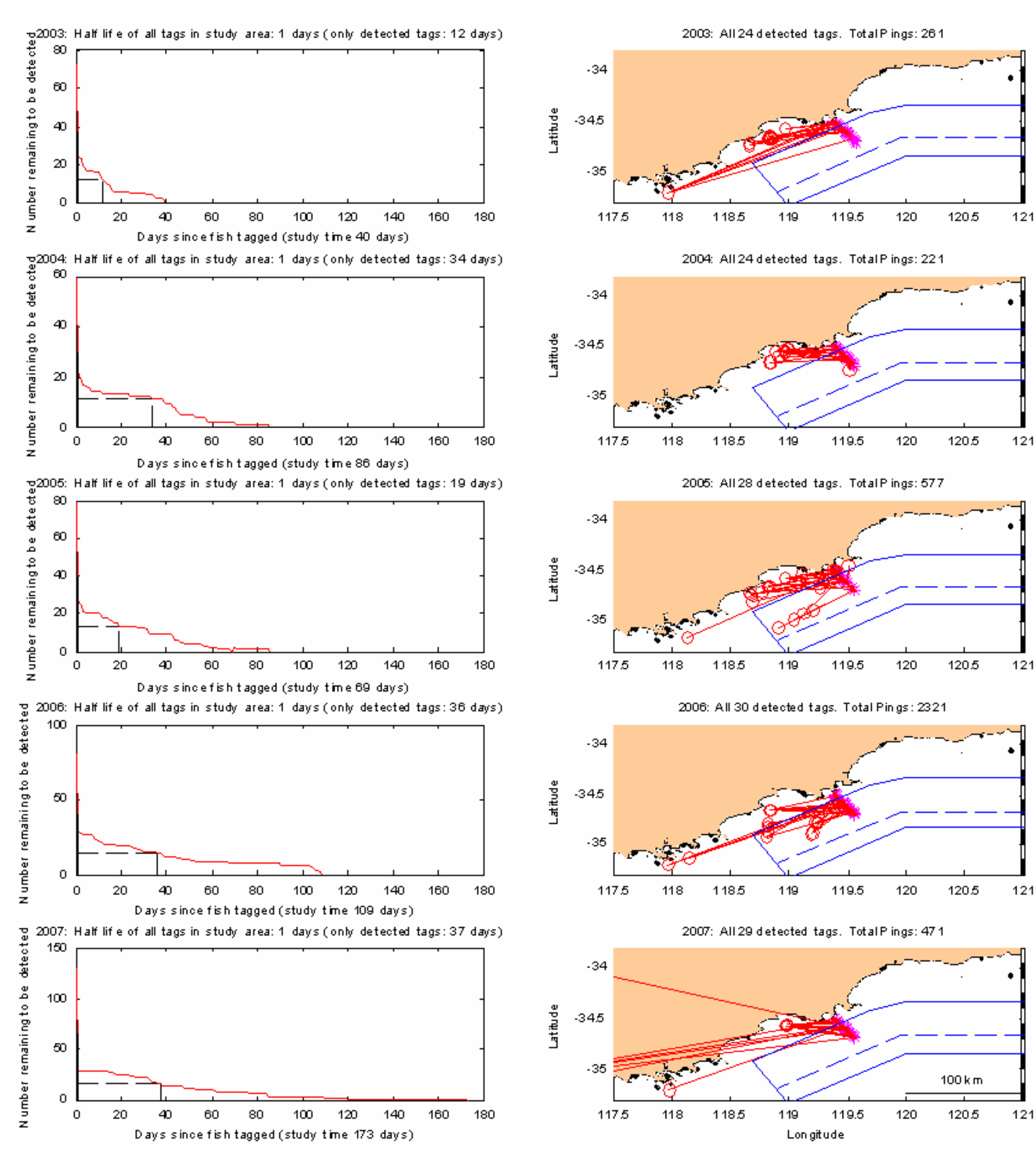


Figure 7. Half life of fish detected in the acoustic monitoring study. The rows represent the years 2002-03, 2003-04, 2004-05, 2005-06 and 2006-07. The left hand column shows the plots of tags remaining to be detected as a function of time. The half life is indicated by the vertical black line. The right hand column indicates the tracks of fish, when only Line 2 data is used.

Table 4. Summary of residence time (half life estimates) for the five years of the acoustic monitoring experiment. The line column indicates which line was used to calculate the residence time. The percentage of fish that were last detected at the eastern line, and the sample size for that calculation is shown in the last two columns. Note that in 2002-03, there was only one line, and so all detected fish were detected at that line, which was to the east of the tagging location.

Year	Line 2	Last detected at eastern line	n
2002-03	12 d	(100%)	
2003-04	34 d	69%	15/25
2004-05	19 d	41%	17/41
2005-06	36 d	60%	36/60
2006-07	37 d	81%	39/48

The number of days that fish were detected at an array also indcates that habitat used varied between years. Of particular interest is that at the hotspots, tuna were present for almost double the time in 2004-05 and 2006-07, compared with 2005-06 (**Table 5)**. The percentage of the days with fish detected at the lines varied between years and lines, but was more consistent within lines. Fish were detected throughout the tagging season, although the detections declined or ceased by the end of each season. An example, for 2006-07, is shown in **Figure 8.**

Table 5. Summary of the number of days southern bluefin tuna were detected at each of the acoustic monitoring locations.

Year	Line 1	Line 2	Line 3	Hotspot 1	Hotspot 2	Hotspot 3
2002-03	-	22.3%	-	-	-	-
2003-04	19.5%	24.6%	-	-	-	-
2004-05	51.9%	36.5%	32.7%	70.2%	52.9%	80.8%
2005-06	24.8%	40.7%	35.8%	6.2%	11.7%	10.5%
2006-07	27.2%	26.1%	27.2%	11.1%	26.1%	46.7%

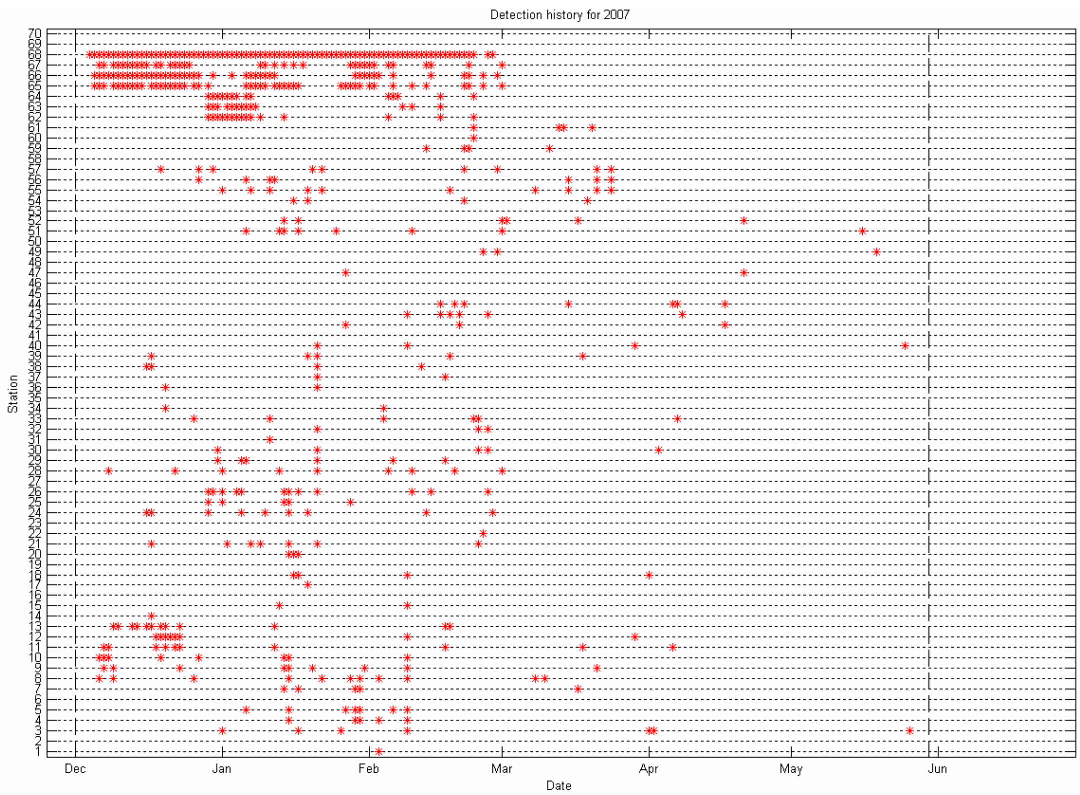


Figure 8. Detections of tagged fish by receiver number for the year 2006-07. The vertical line in June indicated when the receivers were recovered. The location of receiver numbers are shown in Figure 2: Line 1 1-20, Line 2: 21-40, Line 3: 41-61, and hotspots are 62-70.

Conclusion

The purpose of this paper has been to summarize the types of information that has been gathered as part of the acoustic monitoring experiment from 2002-03 to 2006-07. The results presented here indicate that estimates of residence time, migration pathways, and habitat use can be derived. The value of five years of data is apparent given the interannual variation. As the acoustic experiment is modified in future years to test new hypotheses, effort must be made to allow a time series to be continued into the future. This may require tags to be released in the traditional area, as well as in new areas to the west, and that at least two lines be maintained in the survey area. Line 2, with 5 years of data is the most important. It is also adjacent to the piston line survey area, which is important for future calibration of fishery-independent surveys in the area. Line 1 would be the next most important, with 4 years of data. The hotspots and Line 3 are the most flexible, depending on the particular study requirements.

The future of the experiment is addressed in a proposal presented to the CCSBT in a separate paper. In brief, the next crucial questions are focused on understanding the fraction of fish that move through this area, compared to movements towards South Africa from the west coast of Australia. This modification was attempted in 2006-07, and results are still being analyzed. Preliminary analysis shows that fish that were tagged on the west coast did not move to the south coast. This suggests that not all the juvenile SBT population is in southern Australia during the austral summer. This is a major uncertainty, which will impact other population assessments.

Acknowledgements

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References

Anonymous 2001. Report of the sixth meeting of the CCSBT scientific committee. 28-31 August 2001. Tokyo, Japan (available from CSIRO Hobart, Tasmania)

Caton AE 1991. Review of aspects of southern bluefin tuna biology, population and fisheries. In: Shomura RS, Majkowski J, Langi S (eds) Proceedings of the first FAO Expert Consultation on interactions of Pacific tuna fisheries. Noumea, New Caledonia, p 296-343

Farley JH, Davis TLO 1998. Reproductive dynamics of southern bluefin tuna, *Thunnus maccoyii*. Fish Bull 96: 223-236

Gunn, J. and B. Block 2001. Advances in acoustic, archival, and satellite tagging of tunas. Tuna, Academic Press. 19: 167-224.

Gunn JS, Davis TLO, Polacheck T, Betlehem A, Sherlock M (1995) The application of archival tags to study SBT migration, behavior and physiology 1995 Southern Bluefin Tuna Recruitment Monitoring Workshop Report. RMWS/95/8. CSIRO Marine Laboratories Hobart

Heupel, M. R., J. M. Semmens and A. J. Hobday 2006. Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. Marine and Freshwater Research **57**(1): 1-13.

Hobday, A. J. 2002. Acoustic monitoring of SBT within the GAB; exchange rates and residence times at topographic features (Southern Bluefin Tuna Recruitment

Monitoring Workshop Report No. RMWS/02/03). CSIRO Marine Research, Hobart, Australia.

Hobday, A. J., Davis, T. L. O., Gunn, J. S. 2001. Determination of SBT residence time via acoustic monitoring along the southern WA coast (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/01/05). CSIRO Marine Research, Hobart, Australia.

Kawabe, R., K. Fujioka, A. Hobday, Y, Takao, K. Miyashita and T. Itoh. 2007. The effect of the spatial and temporal distribution of juvenile SBT on Acoustic and Trolling Survey abundance estimates. CCSBT-ESC/0709/36.

Musyl MK, Brill RW, Curran DS, Gunn JS, Hartog JR, Hill RD, Welch DW, Eveson JP, Boggs CH, Brainard RE 2001. Ability of archival tags to provide estimates of geographical position based on light intensity. In Sibert JR, Nielsen JL (eds) Electronic Tagging and Tracking in Marine Fisheries. Kluwer Academic Publishers, London, p 343-367

Welch DW, Eveson JP 1999. An assessment of light-based geoposition estimates from archival tags. Can J Fish Aquat Sci 56: 1317-1327

West, G. J., Stevens, J. D., 2001. Archival Tagging Of School Shark, Galeorhinus Galeus, in Australia: Initial Results. Environmental Biology of Fishes 60 283-298.