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Examining the movement and residency of adult SBT in the Tasman Sea and on their spawning grounds south of Indonesia using pop-up archival tags

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Short Abstract to be provided

Pop-up Satellite Archival Tags (PSATs) were deployed on 51 large (156–200cm length to caudal fork) southern bluefin tuna (*Thunnus maccoyii*) in the western Tasman Sea during the austral winters of 2001-2005. Southern bluefin tuna (SBT) were resident in the Tasman Sea for up to six months, with movements away from the tagging area occurring at highly variable rates. In general, SBT moved south into the Southern Ocean, west along the southern continental margin of Australia and then into the Indian Ocean. Three individuals moved east into the central Tasman Sea, with one individual reaching New Zealand waters before returning to the western Tasman Sea. We describe the first observed migration of a SBT from the Tasman Sea to the Indian Ocean spawning grounds south of Indonesia. Individuals spent most of their time on the continental shelf/slope region with an estimated 84 % of time spent in the Australian Fishing Zone. While inconclusive, movement data presented here raise the possibility that SBT estimated to be recruited to the spawning stock are not obligate annual spawners. In general, SBT demonstrated a distinct preference for temperatures between 18-20°C, adjusting depth preferences to reflect changes in the vertical distribution of their thermal preferences. Individuals demonstrated periods of distinct diurnal diving patterns and periods where swimming depths were adjusted to remain at a constant light level over the course of a day. These new data are a significant advance toward greater understanding the spatial dynamics of large SBT and understanding the connectivity between distant regions of their distribution.

KEYWORDS: Southern bluefin tuna, Pop-up Satellite Archival Tag, spawning migration, spatial dynamics, habitat preferences.

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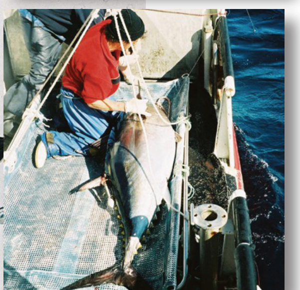

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1. NON-TECHNICAL SUMMARY

Pop-up Satellite Archival Tags (PSATs) were deployed on 51 large (156–200cm length to caudal fork) southern bluefin tuna (*Thunnus maccoyii*) in the western Tasman Sea during the austral winters of 2001-2005. Attachment durations of PSATs on southern bluefin tuna (SBT) ranged 2–206 days and data were received from 46 of the 51 PSATs deployed. Tag attachment durations increased throughout the period of the study largely through improved anchor and tether designs and the implementation of a secondary anchor. However, despite these improvements the single largest hindrance to accumulating long-term data on the movements and habitat preferences of SBT using PSATs in this tagging study was achieving long term attachments.

Individual SBT made large scale migrations between separate foraging areas and to the area of the spawning grounds, demonstrating connectivity within the SBT stock over very large spatial scales within periods of less than one year. Individuals tagged were resident in the Tasman Sea for up to six months, dispersing from this area as late as December. Considerable variability in dispersal rates and movement paths of individuals resulted in individuals tagged in the same area being widely dispersed throughout southern oceans during the austral summer, contrary to the simple movement and spawning models assumed in the current CCSBT stock assessments. These models assume that all individuals older than age 10 spawn on an annual basis, implying all mature individuals migrate annually to the spawning grounds.

In general, SBT moved south into the Southern Ocean, west along the southern continental margin of Australia and then into the eastern Indian Ocean. Five individuals moved east into the central Tasman Sea, with one individual reaching New Zealand waters before returning to the western Tasman Sea. Of four SBT

tracked into the eastern Indian Ocean, one individual was recorded to move north and into the area of Indian Ocean spawning grounds south of Indonesia. This individual traveled in the order of 9,500 km spanning 113 days during it's migration from the western Tasman Sea foraging grounds to the spawning grounds, averaging a movement rate of 84.1 km day^{-1}. Individuals spent most of their time on the continental shelf/slope region with an estimated 84 % of time spent in the Australian Fishing Zone. While inconclusive at this point in time, the movement data presented here raise the possibility that SBT estimated to be recruited to the spawning stock are not obligate annual spawners.

Individuals demonstrated a distinct preference for temperatures between 18–21°C, adjusting depth preferences to reflect changes in the vertical distribution of their thermal preferences. However, SBT demonstrated a clear ability to cope with temperatures outside this preferred range, spending over 10 hours at a time at temperatures lower than 10°C routinely for periods of over two weeks and a minimum of two weeks in temperatures greater than 24°C whilst in the area of the spawning grounds. It is probable that thermal preferences demonstrated by individuals are a reflection of water masses encountered, the extremes of which are determined by the physiological limitations of each individual. Individuals demonstrated periods of distinct diurnal diving patterns and periods where swimming depths were adjusted to remain at a constant light level over the course of a day. Such behaviour may be associated with the vertical migration of prey either directly or via SBT tracking particular light levels most suitable for ambushing or detecting prey. Changes in the behaviour of individuals on both spatial and temporal scales may be associated with changes in prey species targeted and associated changes in the distribution of prey species and/or changes in the thermal properties of the water masses experienced.

Despite the limitations of the technology used to collect these data, determining such aspects of the life history of this species independent of the fishery would be difficult without the use of PSATs. The data presented in this study represent a major step towards reducing uncertainty about the spatial dynamics of SBT – a key uncertainty in management and currently, a poorly understood component of their population dynamics. Deployment of tags in other areas throughout the range of SBT and across wider temporal periods (not only the austral winter) would serve to address problems associated with attachment durations and also help to define the connectivity of SBT in different fishery areas such as the Australian and South African regions. Furthermore, comprehensive data collected across a multi-year period would serve to establish inter-annual variability in SBT habitat preferences and provide important inputs into management regimes such as the spatial management models used in the western Tasman Sea.

KEYWORDS: Southern bluefin tuna, Pop-up Satellite Archival Tag, spawning migration, spatial dynamics, habitat preferences.

2. ACKNOWLEDGEMENTS

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3. BACKGROUND

Southern bluefin tuna (*Thunnus maccoyii*) are a large long-lived pelagic predator widely distributed throughout the oceans of the Southern Hemisphere (Caton 1991, Clear et al. 2000). Genetic evidence, the distribution of reproductively active individuals and the distribution of larvae suggest southern bluefin tuna (SBT) comprise a single population with spawning limited to an area south of Indonesia in the north-western Indian Ocean (Caton 1991, Grewe et al. 1997, Farley & Davis 1998). Fishery and conventional tagging data give evidence for a stable, age dependent spatial distribution of SBT and the age and size composition of global SBT catch suggest ontogenetic changes in migration patterns (Caton 1991). Similarly to Northern Hemisphere bluefin tunas (*Thunnus thynnus* and *T. orientalis*), SBT undertake some of the largest and most rapid migrations of all pelagic fish (Gunn & Block 2001), however a comprehensive understanding of the movements of SBT throughout their complete life history is lacking.

In the Australian region, large schools of juvenile fish (ages 1+ to 4+) aggregate in the Great Australian Bight (GAB) during the austral summer months where they are harvested by a domestic surface fishery. At the same time, similarly aged fish are caught in waters between 0-80°E in the southwest Indian Ocean (Gunn et al. 2003) suggesting the possibility of two migration routes for juvenile SBT from the spawning ground and some spatial structuring within the stock. Juveniles in the Australian region undertake cyclical migrations from the GAB dispersing into the Indian Ocean and the Tasman Sea during the austral autumn months before returning to the GAB in the austral spring (Davis & Stanley 2001, Gunn & Block 2001). Fish older than age five are largely absent from surface aggregations, increasingly becoming dispersed throughout oceanic waters and largely vulnerable to longline catches only.

Adult SBT are assumed to forage throughout the temperate waters of the Southern Hemisphere oceans during the austral winter, migrating to the spawning grounds of the north-west Indian Ocean across the spring and summer months (Shingu 1978, Caton 1991) before returning to foraging grounds in the following autumn/winter. Individuals do not remain on the spawning grounds over the whole season; instead there is a constant turn over of fish with the largest numbers of mature fish occurring in October and February (Farley & Davis 1998).

Catches of SBT in the Australian region of the Tasman Sea are largely the result of bycatch in a longline fishery targeting yellowfin tuna (*T. albacares*) along the southern regions of an eastern Australian tuna and billfish fishery. Longline vessels in the region target particular water masses and frontal zones largely associated with the meeting of sub-tropical waters of the East Australian Current with cooler sub-Antarctic waters (Reddy et al. 1995; Lyne et al. 1998) and these oceanographic features appear to be highly influential on the distribution of tuna species (Young et al. 2001). Oceanographically, this area is similar to the western boundary current systems such as the Gulf Stream and the Kuroshio Current utilized by Northern Hemisphere bluefin species (Polovina 1996, Olson 2001, Kitagawa et al.2004, Block et al. 2005, Wilson et al. 2005; Matsukawa 2006). Yellowfin tuna are thought to inhabit the warmer sides of fronts and eddies while SBT in this region are often caught in the cooler waters of such frontal and eddy systems (Gunn & Young 2000).

4. NEED

Concerns have been raised over declines in the SBT stock for over two decades (Caton 1991) with recent stock assessments suggesting that the current population of SBT is at 5–12 % pre-exploitation biomass (CCSBT 2004). Recent catches from the spawning area support these concerns, indicating a higher proportion of younger fish in catches relative to catches in the 1990s (Farley & Davis 2005). Stock assessment models used for SBT currently make two critical assumptions: first, they assume a knife-edge recruitment into the spawning stock from age 10+ and that spawning occurs on an annual basis. Recent studies have estimated that SBT on the spawning ground begin to actively participate in spawning at ages of 10 to 12 years (Gunn et al. 2003) with the fecundity of spawning females positively related to body size and presumably condition (Farley and Davis 1998). Behavioural differences related to the size of individuals on the spawning ground have also been raised as important factors which need to be accounted for when determining the age and size structure of the spawning stock for assessment models (Davis & Farley 2001). There is currently no information available to confirm the assumption that SBT are annual obligate spawners. Second, current stock assessments assume that SBT belong to one homogenous stock, and thus management actions (e.g. quota restrictions) seek to optimize the health of this stock without regard to spatial heterogeneity observed in catch rates and size composition. The primary reason behind the lack of spatial consideration in the stock assessment models and the management procedures is that almost nothing is known about the fidelity of fish to discrete fishing grounds used by high seas fleets from Japan, Korea, Taiwan and Indonesia, or the mixing rates of SBT between these grounds. What we do understand about the spatial dynamics of adult SBT is derived almost exclusively from interpretation of Japanese longline catch data.

Such interpretations are inherently biased by spatial and temporal variability in effort and targeting practices.

Catch data and mark-recapture data can provide some insight into the movements of SBT; however they are limited for two main reasons. Patterns of relative abundance derived from catch data are entirely fishery dependent and changes in the spatial extent of fishing effort can have direct effects on any interpretations made on these data (Toscas et al. 2001). Additionally, mark-recapture data are heavily fishery dependent and rely on accurate reporting of recapture information and minimal non-reporting of recaptures (Hearn et al. 1999; Gunn 2000). The development of pop-up satellite archival tags (PSATs), which transmit data from the fish without the need for the tag to be recovered, provide fishery independent methods for assessing movement in pelagic fish (Gunn & Block 2001).

While the use of this technology on other bluefin species has been broadly utilized (Block et al. 2001, Marcinek et al. 2001, Stokesbury et al. 2004, Block et al. 2005, Wilson et al. 2005) the deployment of PSATs on SBT has been limited. Data reported from four tags deployed on adult-sized SBT in the region of the spawning grounds north of 20°S (Itoh et al. 2002) described movements away from the spawning ground across a period of a few days to three months. Three individuals undertook south-westerly movements from the spawning ground into the Indian Ocean while the fourth moved into an area south of the Australian continent. Without data of broader spatial and temporal scales, it is difficult to infer anything conclusive of the movement patterns of adult sized SBT from such limited tag releases.

Within Australian waters catches of SBT are managed through the setting of quotas and the demarcation of spatial management zones based on a habitat model[1]. This model currently integrates the thermal preferences of SBT derived from PSAT data with both satellite derived and modeled oceanographic data to determine the spatial distribution of SBT upon which management zones are set. However, at present any variability in residence time, habitat preferences or in the responses of individuals to changes in their environment are not integrated into such calculations. As a result, such models are limited in their ability to accurately predict the spatial and temporal distribution of SBT.

Therefore, critical gaps currently exist in our knowledge and understanding of the movements, residency, regional fidelity and spawning dynamics of adult SBT. These gaps clearly inhibit our ability to accurately assess the state of the stock or comprehensively manage the stock within regional fisheries. Here we report on the results of satellite tagging of large bluefin tuna in the Tasman Sea and their dispersal from these waters into the Southern Ocean, thereby providing an important first step toward greater understanding of SBT spatial dynamics and stock connectivity. Data from a previous investigation into the effectiveness of PSAT technology in determining the movement and habitat preferences of adult SBT (AFMA report R00/0786) have been incorporated with those data collected as part of this study and are also presented here.

[1] A. Hobday & K. Hartmann, CSIRO Marine and Atmospheric Research unpublished data

5. OBJECTIVES

1. Determine the temporal period of residency of southern bluefin tuna in the Tasman Sea each winter.

2. Determine the dynamics of the movement of southern bluefin tuna away from the Tasman Sea and their fidelity to the Tasman Sea foraging grounds.

3. Determine if migrations of adult SBT to the spawning grounds are cyclical in nature and if so the periodicity of this cyclical migration.

4. Determine the spatial scale of areas in the NE Indian Ocean where SBT spawn (and the applicability of then using these data for spatial management of catches in the Indonesian fishery)

5. Determine the temporal scale of residency of southern bluefin tuna on the spawning grounds

6. METHODS

6.1. Tagging operations

Pop-up satellite archival tags (PAT2: n = 11, PAT3: n = 8 and PAT4: n = 33, Wildlife Computers, Redmond USA) were deployed on large SBT in the waters of the western Tasman Sea in the austral winters of 2001-2005. Fish were caught during commercial longline operations with those considered in good condition lead into a tagging cradle and then lifted on board the vessel. Females sampled from the spawning ground demonstrate 50 % maturity at a length of 154cm (Farley & Davis 1998); we therefore chose only fish greater than 155cm length to caudal fork (LCF) for tagging.

In 2001 and 2002 tags were rigged with a single titanium anchor connected via a 400lb monofilament tether to the corrodible release pin of the PSAT. In 2003–2005 nylon umbrella-style anchors (Domeier et al. 2005) were used as primary anchors and an additional double barbed nylon dart tip crimped to 50lb monofilament loop was attached to each tag as a secondary anchor to further secure the PSAT and to minimize any lateral movement of the tag as the fish swam. The monofilament loop of the secondary anchor was placed around the shaft of the PSAT so that the tag could release from the animal should the tag prematurely detach from the primary anchor or the primary anchor release from the fish. The primary monofilament leader on all tags was fitted with a depth release device (RD-1500, RD-1800, Wildlife Computers, Redmond USA), designed to cut the tag off the fish at depths of 1500m (RD-1500) or 1800m (RD-1800), thereby preventing implosion of the tag at depth. The primary anchor was inserted into the dorsal musculature at the base of the second dorsal fin as per Stokesbury et al. (2004). The secondary anchor was inserted into the dorsal musculature in line with the dorsal finlets. Each tag was printed with an identification number, information about a reward offered and where to return the tag. After attachment of the PSAT, the fish and cradle were lowered back into the water allowing the fish to swim away from the vessel. The deployment position was recorded using the vessels' onboard GPS system.

6.2. Data and analyses

We programmed PSATs to record pressure (depth), temperature and light at 60 (n = 50) or 120 (n = 2) second intervals. Tags were programmed to release from the fish after predetermined time periods (30 days: n = 3; 60 days: n = 4; 90 days n = 1; 180 days: n = 7; 300 days: n = 1; 365 days: n = 35), after which they floated to the ocean surface and transmitted their archived data via the ARGOS satellite service (Service Argos, Toulouse, France). Due to limited transmission bandwidth, data collected by the PSATs were summarized into one (n = 1), four (n = 22), eight (n = 20) and 12 (n = 7) hour time periods prior to transmission. The summary data for each time period consisted of distributions of the proportion of time spent within preset depth and temperature bins and temperature-depth profiles. For those PSATs recovered the full archived data set was downloaded from the tag. Only those data collected from tags at liberty greater than 14 days were included in movement and habitat preference analyses (to avoid possible behavioural changes imposed from the process of tagging).

6.2.1. Age classification of SBT

To determine if SBT tagged would be classified as recruited into the spawning stock as per current stock assessments, we derived age estimates for each individual using the cohort slicing method utilised in the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) stock assessments (Preece et al. 2004) which assigns an individual to an age cohort determined with the use of length at age growth curves (Laslett et al. 2002).

6.2.2. PSAT attachment duration

The rate of premature tag shedding was examined by normalizing all tags deployment to a nominal start day and plotting the proportion of tags remaining attached to SBT as a function of days attached. Only those tags that prematurely transmitted data before the intended release date were included. We fitted intercept-free regressions of ln(proportion tags shed) = $\mu\times$(days attached) to examine the shedding rate. Analysis was carried out using the statistical software package R (R Development Core Team 2005).

6.2.3. Potential mortalities

Wildlife Computers PSATs transmit diagnostic information from which mortalities can be inferred. Versions PAT3 and PAT4 identify whether the corrodible tether pin has broken and all versions report the last recorded depth greater than 600 m. We assumed that PSATs that reported very deep final depths (greater than 1000 m) within 2 days of the transmission of data represented mortalities and those that transmitted final depths less than 1000 m or no final depths greater than 600 m represented SBT that had survived, but that the tag had released.

6.2.4. Location estimates

Daily positions derived from each tag were calculated using a combination of light and temperature data based on methods presented in Teo et al. (2004) and Shaffer et al. (2005). Longitude was estimated using proprietary software (WC-GPE.1.02.0000, Wildlife Computers, Redmond USA). Daily estimates of sea surface temperature were derived from SSTs reported by the tag manufactures proprietary software where the depth of the SST was reported to be less than 5m. These were checked for outliers and erroneous measurements identified were replaced with a smoothed estimate of SST based on the three closest SST data points. A loess smoother (Venables & Ripley, 2002) was then applied to the SST data. Remotely sensed SST values (MCSST/AVHRR[2] data) for a defined area either side of each longitude estimate (as per Teo et al. 2004) were then compared to remotely sensed SST values. Sea surface temperature values between 50°S and 10°S for each longitude estimate were gridded into cells of 0.25° latitude and the number of matches to the observed PSAT SST were counted in each latitudinal cell. The cell with the highest number of matches between the PSAT derived SST and the remotely sensed SST was considered to be the most probable position for the day.

To reduce the number of unrealistic matches between SST values, we constrained the distance an individual could move each day by weighting the latitudinal cell frequencies by a function assumed to represent the likelihood of a movement between consecutive positions. A lognormal distribution was used to model the probability of distance moved. This produces a distribution of movement which allows longer distance movements but at a lower probability than shorter distance movements (i.e. long distance movements are down-weighted). The highest weightings were given to movements of approximately 150 km day^{-1} or approximately 0.97 body lengths sec^{-1} based on published estimates of tuna swimming speeds for a 170 cm tuna (Bushnell & Jones 1994, Lutcavage et al. 2000). This process was initialized at the known tag release position. We evaluated the results of our method by comparing the geolocation

[2] See http://podaac.jpl.nasa.gov/products/product102.html for details.

estimates with transmitted pop-up locations where the last estimated position was no more than two days prior to the first transmission date of each PSAT.

To calculate approximate movement distances and movement rates, we also calculated the distance of a simplified and idealized track from the tagging release area, around Tasmania, to Cape Leeuwin and north to the pop-up point. This was calculated using the ‘tracker’ tool in the GIS software Manifold 6.50 (Manifold Net Ltd. Carson City, USA).

6.2.5. Habitat preferences and behaviour

Time-At-Depth (TAD) and Time-at-Temperature (TAT) data transmitted consisted of normalized histograms giving the proportion of time within the pre-programmed summary period that the fish spent within a given depth or temperature range. Aggregate time-integrated indices of the temperature and depth preference were calculated by calculating the median TAD and TAT value in each histogram bin. Empirical cumulative distribution functions were calculated from the median proportion in each bin and used to estimate the expected proportion of time in a given depth or temperature range. To examine broad spatial patterns in depth and temperature preference, the proportion of time in a given depth or temperature range were integrated with location estimates and broad scale differences in the time spent at temperature and at depth were examined.

In order to explore the possibility of correlations between dispersal and oceanic conditions in the Western Tasman Sea a basic comparison of the dispersal characteristics of SBT with SST for the tagging region was undertaken. The median and inter-quartile range of the distributions of latitude and longitude were calculated and then compared with the median SST derived from 8-day MCSST data.

7. RESULTS

A total of 52 pop-up satellite archival tags were deployed on SBT 156–200 cm LCF (mean ± SD: 173.7 ± 9.5 cm) and estimated to be aged 9–20 yr (mean ± SD: 15.3 ± 3.1 yr; Table 1). The cohort slicing method utilized in CCSBT stock assessments assigned 50 of the 52 individuals tagged as recruited into the spawning stock. The lengths of SBT caught throughout the period of this study were relatively stable, with most SBT caught ranging 130–170 cm LCF (Figure 1). Catches in 2003 and 2004 contained slightly higher numbers of smaller SBT (50–110 cm LCF) than other years and 2002 contained higher catches of larger SBT (>200 cm LCF). Of the 52 PSATs deployed, data were retrieved from 44 (84.6 %; Table 1) via Service Argos with a further one PSAT (1.9 %), which failed to transmit, recovered and the data retrieved. Three PSATs are still at liberty and are not due to transmit data until late July and late September 2006.

7.1. PSAT attachment duration

All PSATs detached prematurely, with the number of days tags transmitted prior to the set deployment day ranging 1–362 days. The number of days that tags remained attached varied considerably both within and between deployment years (Table 2, Figure 2) ranging 2–206 days and the proportion of the original deployment period achieved ranged 0.01–0.98. Although variable, the average attachment time of tags per year increased across the study period from a minimum in 2001 of 16.2 (SD ± 46.1) days to a maximum in 2004 of 99.1 (SD ± 12.0) days (Table 2). However, the proportion of time tags remained attached increased from 0.2 (SD ± 0.1) in 2001 to a high of 0.7 (SD ± 0.1) in 2002 before decreasing again across all following years. We note that although the average and maximum number of days attached decreased in

2005 relative to 2004 deployments, at the time of writing, three tags from the 2005 deployments are still at liberty and yet to transmit data. Trends in the overall rate of tag loss (Figure 2) demonstrated a significant negative exponential relationship (Adjusted R^2: 0.97, $F_{1,39}$ = 1,535, $p < 0.001$) and were described by ln(proportion tags attached) = $\mu \times$(days post-deployment). This model estimated the slope coefficient to be -0.02 (SE: ± 0.001) and an attachment "half-life" (the number of days at which 50 % of the tags are likely to remain attached) of 35.4 days.

7.2. Potential mortalities

Of all tags that transmitted data, 11 (24.5 %) did not have a pin breakage reporting mechanism. Of the remaining 34 PSATs, pin breakages were recorded in ten (22.2 %). Tags that reported a pin breakage were on average attached for 118.1 (SD ± 51.8) days post-deployment (median 120.5; range: 53–206; Table 3). A final depth reporting mechanism was not available for three of the 45 tags that transmitted data. Depths greater than 1,200 m were reported from, 11.1 % (n = 5) of fish within two to three days before data transmission suggesting possible mortality in these fish. A further 2.2 % (n = 1) reported a final depth of greater than 1,100 m five days prior to the tag transmitting data (Table 3) suggesting a possible but not definite mortality. Of those SBT considered to be mortalities, tag release occurred 2–25 days post-deployment. Depths greater than 600 m were reported from 62.2 % (n = 28) tags at varying periods prior to tag transmission, however all depths recorded suggested no evidence of mortality. A further 17.8 % (n = 8) did not dive to depths greater than 600 m whilst at liberty.

Table 1. Release and pop-up details for PSATs deployed on SBT in the western Tasman Sea 2001-2005.

Tag	Releases					Pop-up transmissions				
	Date	Latitude (°S)	Longitude (°E)	LCF (cm)	Age (yr)	Date	Latitude (°S)	Longitude (°E)	Time at Liberty	Displacement (km)
2001										
28703	13 Jul 2001	33.42	151.55	170	14	16 Jul 2001	33.38	151.85	3	28.23
28701	13 Jul 2001	35.88	151.57	175	16	19Jul 2001	35.90	153.02	6	130.78
28707	13 Jul 2001	35.22	151.53	190	20	07 Aug 2001	37.32	154.12	25	329.64
28708	13 Jul 2001	35.23	151.53	158	10	27 Jul 2001	37.43	156.62	14	517.90
13274	15 Jul 2001	35.58	151.60	178	19	20 Jul 2001	35.17	152.43	5	88.08
13275	13 Jul 2001	35.60	151.60	200	20	13 Aug 2001	33.72	153.12	31	251.32
2002										
28709	27 Jul 2002	35.02	151.65	157	10	20 Aug 2002	35.07	152.68	24	94.03
13272	27 Jul 2002	35.08	151.65	165	12	06 Sep 2002	36.82	152.10	41	197.89
20926	27 Jul 2002	35.12	151.67	173	15	Failed to transmit				
2003										
13279	10 Jul 2003	35.98	150.96	171	14	06 Aug 2003	34.71	152.27	27	184.75
13273	10 Jul 2003	35.98	150.94	187	20	07 Sep 2003	33.72	153.32	59	332.48
20890	10 Jul 2003	35.97	150.85	200	20	03 Aug 2003	30.81	153.80	24	636.38
30466	10 Jul 2003	35.97	150.85	186	20	14 Oct 2003	35.55	154.75	96	355.35
20914	20 Jul 2003	36.82	150.77	175	16	Failed to transmit				
20924	28 Jul 2003	35.05	151.80	160	10	Failed to transmit				
30465	28 Jul 2003	35.05	151.80	168	13	24 Jan 2004	42.59	123.18	180	2605.49
18564	28 Jul 2003	35.10	150.82	178	19	1 Jan 2004	38.16	122.67	157	2527.83
20891	07 Aug 2003	34.23	151.77	165	12	16 Sep 2003	30.60	154.96	40	503.06
2004										
20925	27 Jun 2004	34.18	151.87	176	17	21 Oct 2004	40.73	149.12	116	768.44
43935	05 Jul 2004	34.13	152.80	174	16	13 Dec 2004	42.80	153.37	161	966.39
43936	05 Jul 2004	34.16	152.88	173	15	15 Jul 2004	30.41	155.79	10	499.19
43937	05 Jul 2004	34.18	152.90	182	20	04 Sept 2004	33.45	157.86	61	465.82
43925	12 Jul 2004	34.67	153.15	175	16	26 Jul 2004	32.55	154.61	14	272.04
43926	12 Jul 2004	34.67	153.15	169	13	03 Feb 2005	17.72	111.07	206	4565.05
43927	12 Jul 2004	34.67	153.15	183	20	14 Jul 2004	33.97	155.24	2	207.34

Tag	Releases					Pop-up transmissions				
	Date	Latitude (°S)	Longitude (°E)	LCF (cm)	Age (yr)	Date	Latitude (°S)	Longitude (°E)	Time at Liberty	Displacement (km)
43928	13 Jul 2004	34.65	153.27	170	14	14 Jan 2005	34.87	111.90	185	3755.83
43929	13 Jul 2004	34.65	153.27	174	16	08 Nov 2004	43.25	150.31	118	990.84
43931	13 Jul 2004	34.65	153.27	169	13	19 Nov 2004	42.55	163.88	129	1272.97
43932	13 Jul 2004	34.63	153.27	169	13	15 Jul 2004	33.59	155.05	2	200.78
43933	14 Jul 2004	34.68	153.23	176	17	Failed to transmit – 172 days data recovered				
43934	15 Jul 2004	34.62	153.15	173	15	29 Jul 2004	34.51	152.11	14	96.12
43945	30 Jul 2004	34.97	151.98	171	14	13 Dec 2004	44.60	146.60	136	1165.91
43946	30 Jul 2004	34.92	151.98	189	20	Failed to transmit				
43943	31 Jul 2004	35.00	151.95	169	13	15 Nov 2004	44.61	158.69	107	1214.10
43941	08 Aug 2004	34.70	152.72	172	15	29 Dec 2004	41.46	144.12	143	1063.88
43942	08 Aug 2004	34.82	152.95	173	15	15 Jan 2005	44.24	146.26	160	1194.61
43939	29 Aug 2004	36.42	152.90	175	16	27 Nov 2004	40.80	133.59	90	1744.86
43940	28 Aug 2004	36.37	152.87	170	14	30 Dec 2004	42.95	149.35	124	791.94
2005										
53269	07 Jul 2005	34.48	151.55	170	14	27 Jul 2005	34.51	153.39	20	168.84
53270	21 Jul 2005	32.24	153.82	177	18	Still at liberty				
43944	21Jul 2005	32.89	153.68	173	15	10 Dec 2005	43.58	147.78	142	1296.10
46336	22 Jul 2005	32.40	153.59	163	11	29 Oct 2005	40.54	137.08	99	1729.24
46337	22 Jul 2005	32.59	153.55	171	14	13 Sep 2005	33.32	155.11	53	166.84
46339	22 Jul 2005	32.63	153.53	172	15	21 Sep 2005	37.21	154.02	61	511.79
46340	01 Aug 2005	35.13	152.15	187	20	02 Sep 2005	34.67	153.43	32	127.59
46342	19 Aug 2005	35.68	153.60	168	13	20 Oct 2005	43.91	147.64	62	1047.71
46343	19 Aug 2005	35.68	153.60	185	20	21 Nov 2005	41.17	150.53	94	667.08
46350	19 Aug 2005	35.68	153.58	178	19	27 Dec 2005	41.60	140.92	100	1280.97
46351	21 Sep 2005	36.22	152.52	157	9	23 Sep 2005	34.82	153.11	2	164.76
46353	21 Sep 2005	36.13	152.40	156	9	Still at liberty				
53263	21 Sep 2005	36.11	152.34	164	11	06 Feb 2006	38.33	140.67	138	1062.77
53264	22 Sep 2005	35.97	153.05	172	14	Still at liberty				

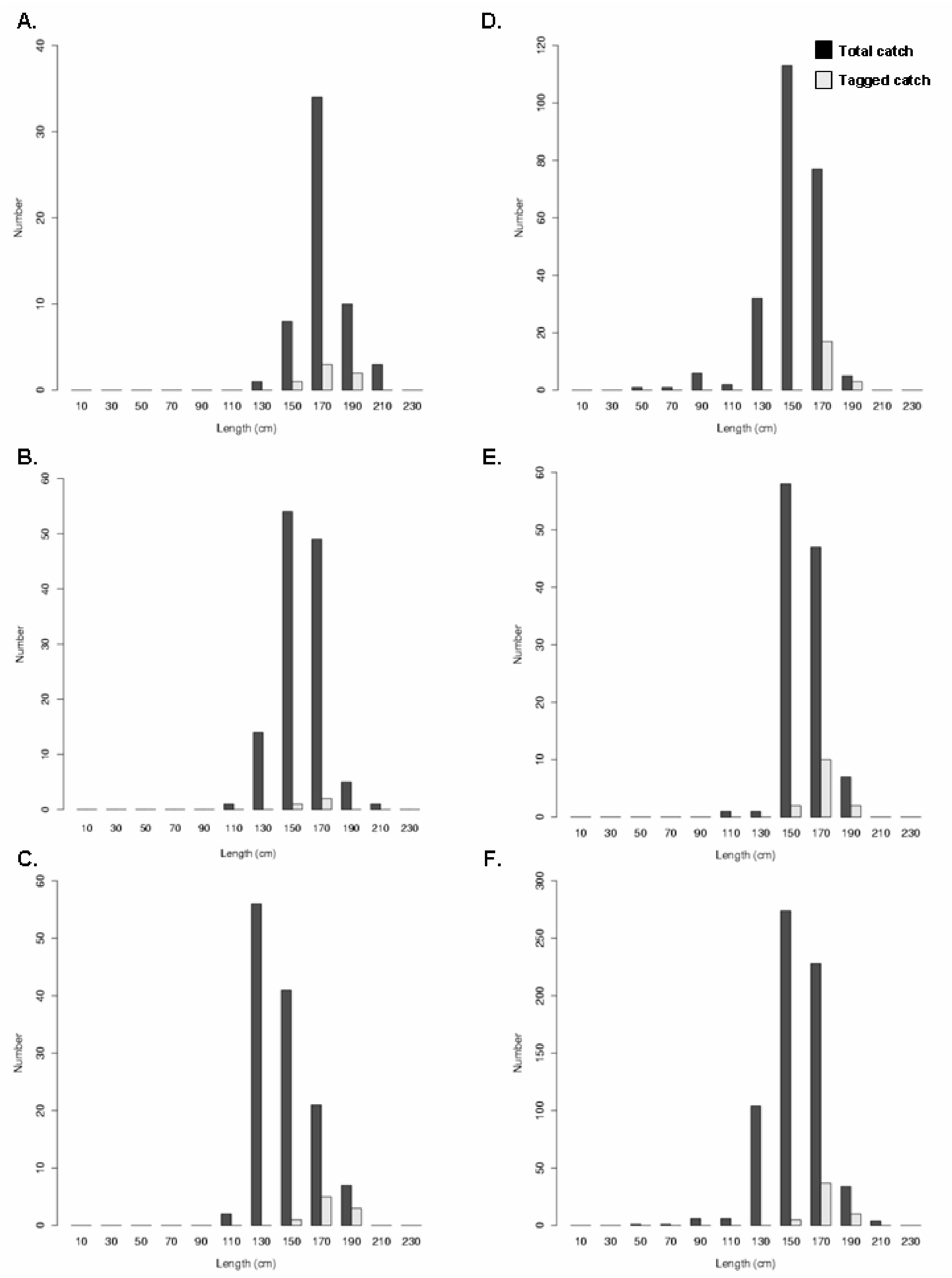


Figure 1: Length distribution of total catches and tagged catches of SBT in the Tasman Sea for (a) 2001; (b) 2002; (c) 2003; (d) 2004; (e) 2005 and (f) all years combined.

7.3. Geolocation accuracy

Adequate light and SST data were available for the calculation of position estimates for 40 tags. Of these PSATs, 36 were at liberty for periods greater than 14 days and position estimates calculated comprised 5.2–92.6 % of the total time tags were at liberty (mean ± SD: 50.7 ± 21.3). Comparison of position estimates calculated via geolocation with a final pop-up position derived from Argos was restricted to 25 PSATs, due to a lack of SST data for latitude calculation, compromised light data resulting in highly erroneous longitude calculation or data transmission failure. The median distance or position error (± SD) between the two final positions was calculated to be 161.9 ± 230.6 km (n = 25, range 23.1–866.3 km).

Table 2. Deployment periods and attachment durations achieved by PSATs deployed on SBT in the western Tasman Sea 2001-2005.

Year (n)	Deployment period		Attachment period		Proportion of period attached	
	Mean ± SD	**Range**	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**
2001 (6)	135.0 ± 103.5	30-300	16.2 ± 46.1	2-31	0.22 ±0.13	0.01-0.42
2002 (3)	60.0 ± 30.0	30-90	32.5 ± 66.1	24-41	0.74 ± 0.08	0.68-0.80
2003 (9)	211.3 ± 127.3	30-364	83.3 ± 63.3	24-180	0.57 ± 0.36	0.10-0.98
2004 (20)	354.8 ± 54.1	180-364	99.1 ± 12.0	3-206	0.30 ± 0.20	0.01-0.64
2005 (14)	364.0 ± 0.0	364	69.7 ± 11.5	2-142	0.21 ± 0.13	0.01-0.39
Total		30-364	70.8 ± 61.0	2-206	0.33 ± 0.25	0.01-0.98

7.4. Migration and residency patterns

Individuals were resident in the western Tasman Sea from June (the earliest in the season fish were tagged) through to December, predominately in an area bounded by 30–40°S and 150–160°E (Figure 3, 4 and 5, Appendix 1). The period spent within this region ranged 34 to 155 days, with individuals moving out of the region as early as

September and as late as December, although most individuals had moved out of the region by October. Five individuals undertook movements east and into the central Tasman Sea, with one moving into waters off the south western coast of New Zealand before returning to the western Tasman Sea and then moving south into an area east of Tasmania. Another two SBT similarly returned to the western Tasman Sea and then moved south to an area east of Tasmania after spending some time in the central Tasman Sea (Figure 3, 4 and 5, Appendix 1) with one moving further into an area north west of Tasmania. The PSATs on the remaining two detached before movement out of the Tasman Sea could be discerned. Individuals were widely dispersed throughout the southern margins during the summer months ranging from waters to the south-east of Australia across to waters south-west of Australia. Of those SBT tracked into the waters south-west of Australia, one travelled into what is regarded as the region of the spawning grounds at 17.72°S, 111.07°E (Figure 3 and 5, Appendix 1). Another two SBT appeared to undertake easterly movements possible initiating a return into more eastern waters (Figure 3 and 5, Appendix 1).

Table 3.Estimated mortality and pin breakage status reported by PSATs deployed on SBT in the western Tasman Sea 2001-2005.

Mortality status	N	Percent number	Pin Breakage	N	Percent number
Yes	5	11.1	Yes	10	22.2
No	36	80.0	No	18	40.0
Possible	1	2.2	Unknown	6	13.3
Not recorded	3	6.7	Not recorded	11	24.5
Total	45	100		45	100

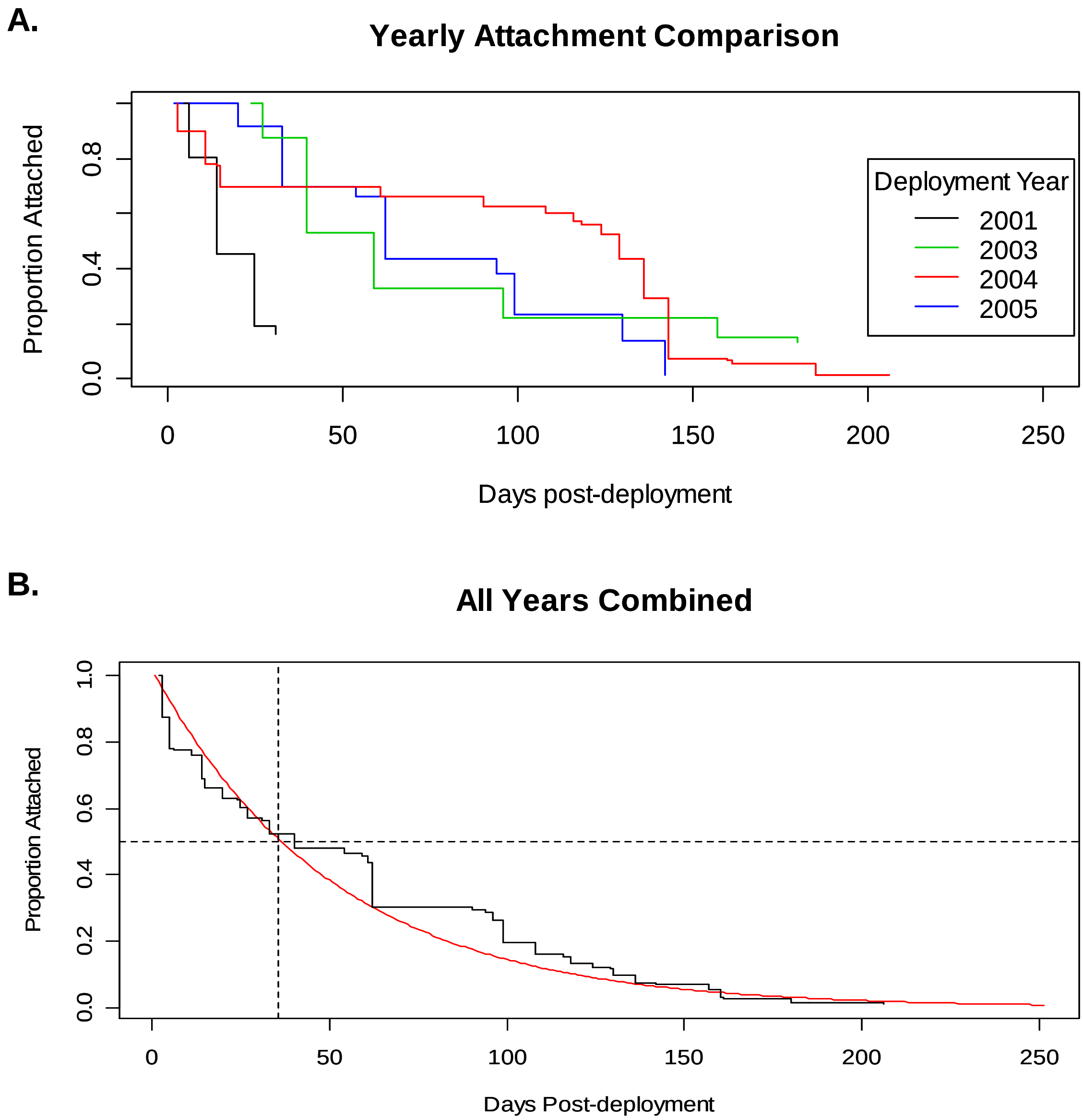


Figure 2. Tag survival curves for (a) each year of deployment and (b) the overall normalized rate of tag loss through time. Tag data from 2002 were not included due to small sample sizes.

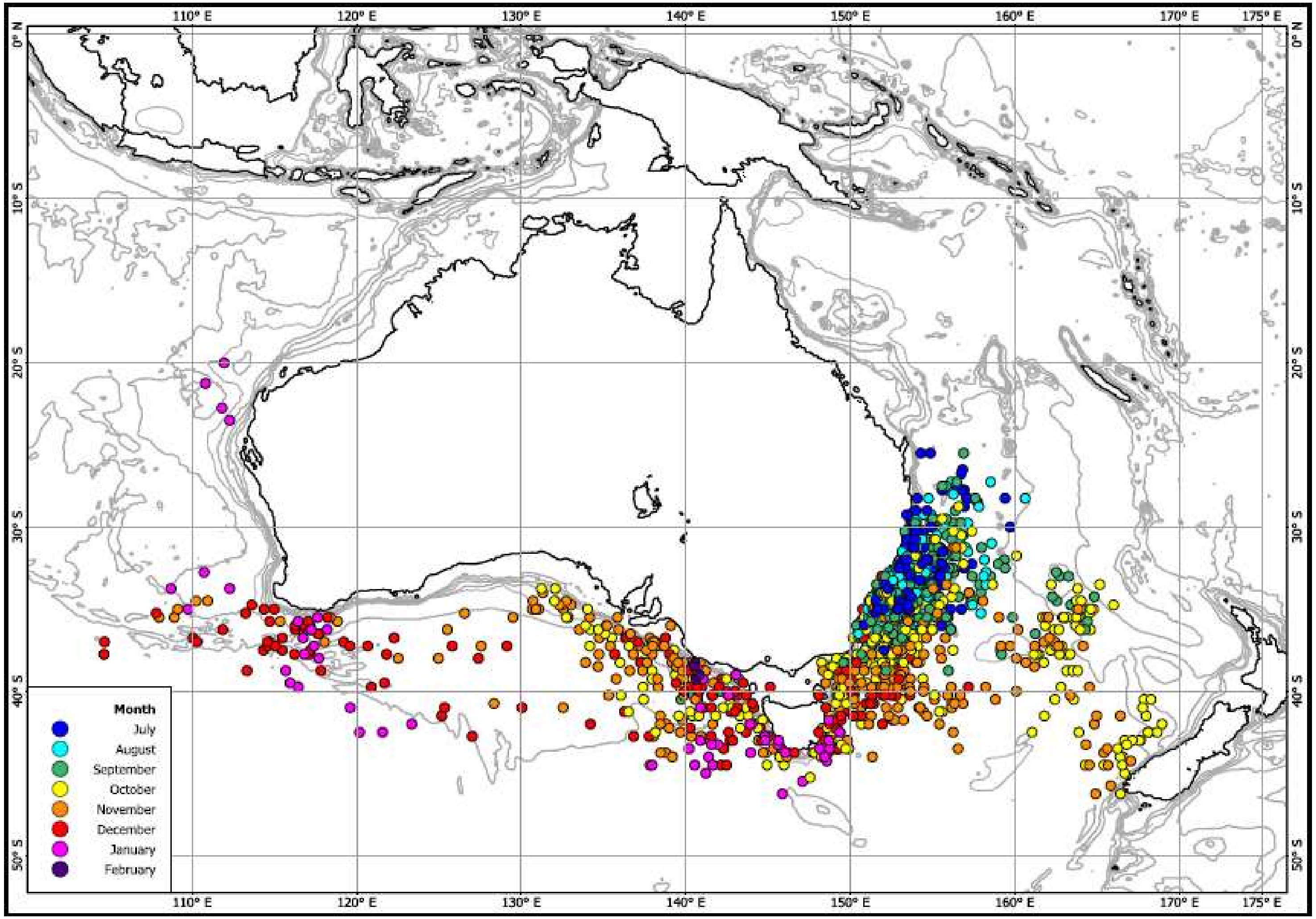


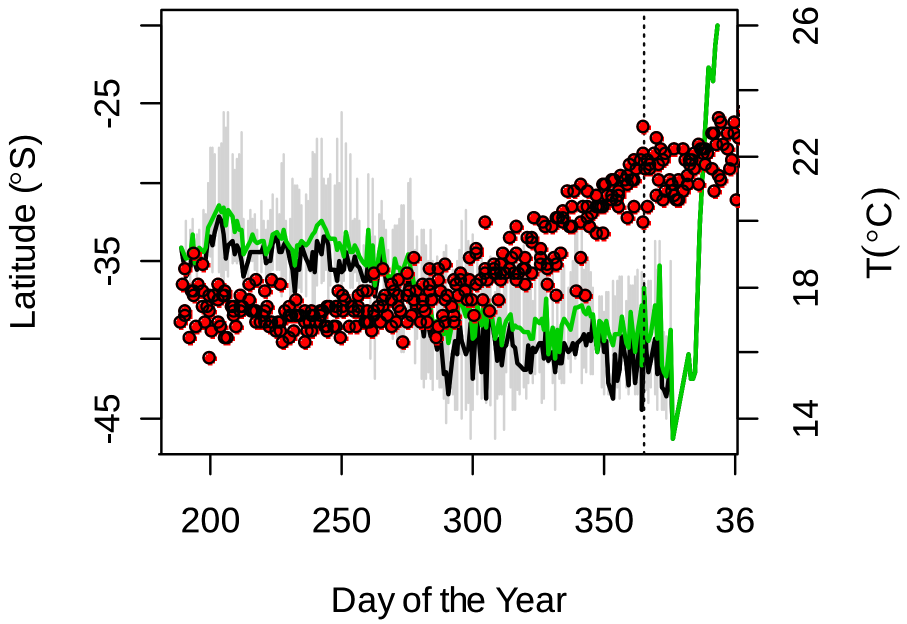
Figure 3. Position estimates of SBT at liberty 2001-2006 by month.

Fish that tracked to the western Australian area were aged 13–19 yr (mean ± SD: 14.8 ± 2.9) and ranged 168-178 cm LCF (mean ± SD: 173.7 ± 9.6). Individuals reached the waters of the western Australian region at varying times throughout November and December, taking 36–84 days to reach the area after departing the western Tasman Sea. Estimating the total distance from the western Tasman Sea to the area of the spawning grounds using an idealized track, the SBT that was tracked to this area migrated a distance of 9,000 km over 113 days, moving at an average of 79.6 km day^{-1}. Movement of this fish along the western coast of Australia from an area south of Cape Leeuwin, Western Australia at approximately 36°S to the tags final pop-up position totaled 1,550 km traveled over a period of 26 days. This is equivalent to an average distance traveled of 59.6 km day^{-1}. Although limited by small sample sizes, no relationship between the size of individual SBT and the extent of their westward movements was apparent.

Individuals also appeared to spend considerable time in an area north west of Tasmania (Figure 3 and 5, Appendix 1). Movements into this region from the deployment area in the western Tasman Sea occurred as early as September and as late as January and on average (± SD) took 26.8 ± 19.5 days (range 3–66 days).

Approximately 84 % of all position estimates calculated were located within the Australian Fishing Zone and were also within one of the three managed Australian tuna and billfish fisheries. The majority of positions of tagged fish (75.1 %) occurred within the Eastern Tuna and Billfish Fishery (ETBF), with 10.4 % occurring within the Southern Tuna and Billfish Fishery (STBF) and 0.3 % within the Western Tuna and Billfish Fishery (WTBF).

A.



B.

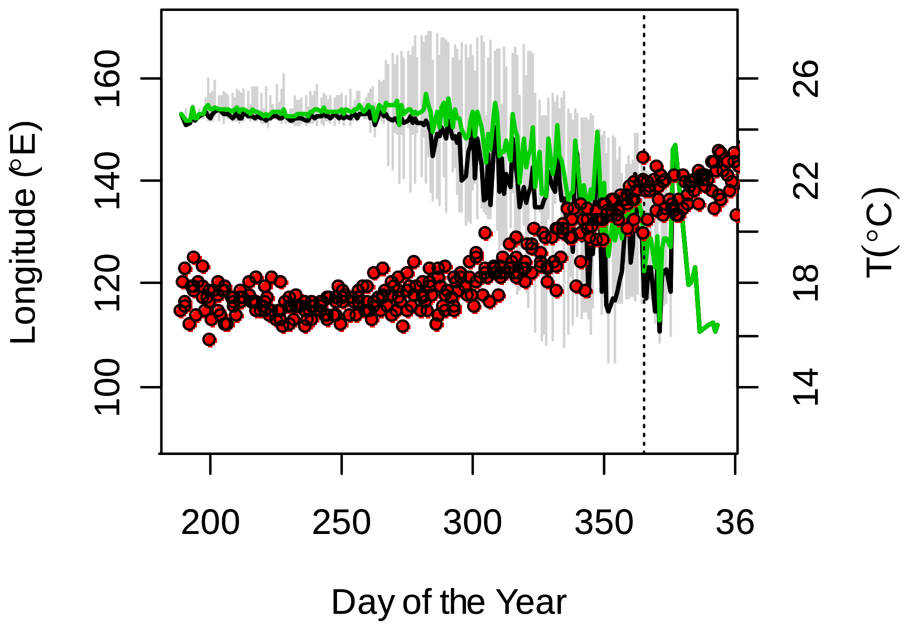


Figure 4. Displacement of those SBT in relation to (a) latitude and (b) longitude. The 1st and 3rd inter-quartiles of latitude or longitude are given in black and green respectively and the range in grey bars. The vertical dashed line depicts January 1. The average SST (MCSST, CSIRO from Jun 2001-Jan 2006) in the region of deployment (bounded by 150-160°E, 40-30°E) is given in red.

A.

B.

C.

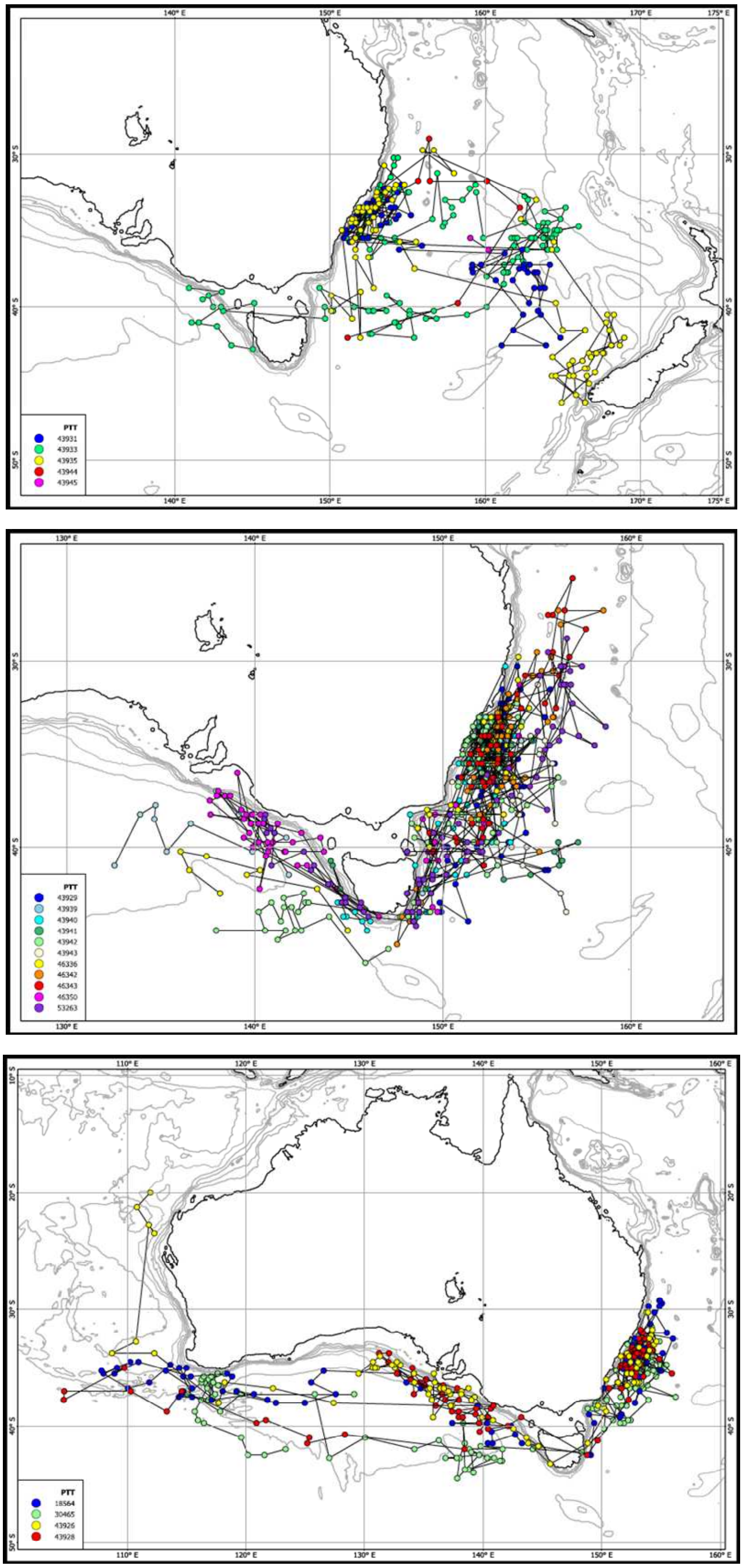


Figure 5. Individual tracks of SBT for which PSATs remained attached for > 14 days separated into regions of movement and residency outside of the western Tasman Sea region: (a) central and eastern Tasman Sea; (b) Southern Ocean and (c) Southern/Indian Oceans.

7.5. Habitat preferences and behaviour

Tagged SBT experienced ambient water temperatures that ranged 2.6–30.4°C (Figure 6) with a median maximum temperature of 18°C (inter-quartile range: 15.4-19.4°C) and a median minimum temperature of 15°C (inter-quartile range: 12.2-17.4°C). The extremes of temperatures experienced by individuals varied from 0.2°C to 19.0°C in difference. A cumulative distribution function calculated using time at temperature of all individuals pooled, estimated that SBT occupy waters at or below 18.5°C 30 % of the time, at or below 20°C 50 % of the time and at or below 21°C 90 % (Figure 6).

Time spent at depth by tagged SBT largely reflected preferences for waters 18–20°C (Figure 6) with most time spent in waters less than 200m and the highest proportion of time spent in waters less than 50m. Individuals spent time in waters deeper than 200m and cooler than 18°C primarily in three localized areas: the western Tasman Sea centered around the deployment area, the eastern Tasman Sea and the region between 135-145°E north west of Tasmania (Figures 7 and 8). Time spent in waters warmer than 20°C was largely associated with those waters close to the eastern Australian coast in the Tasman Sea and within the EAC and warm-core eddy structures and in the region of the spawning grounds in the Indian Ocean.

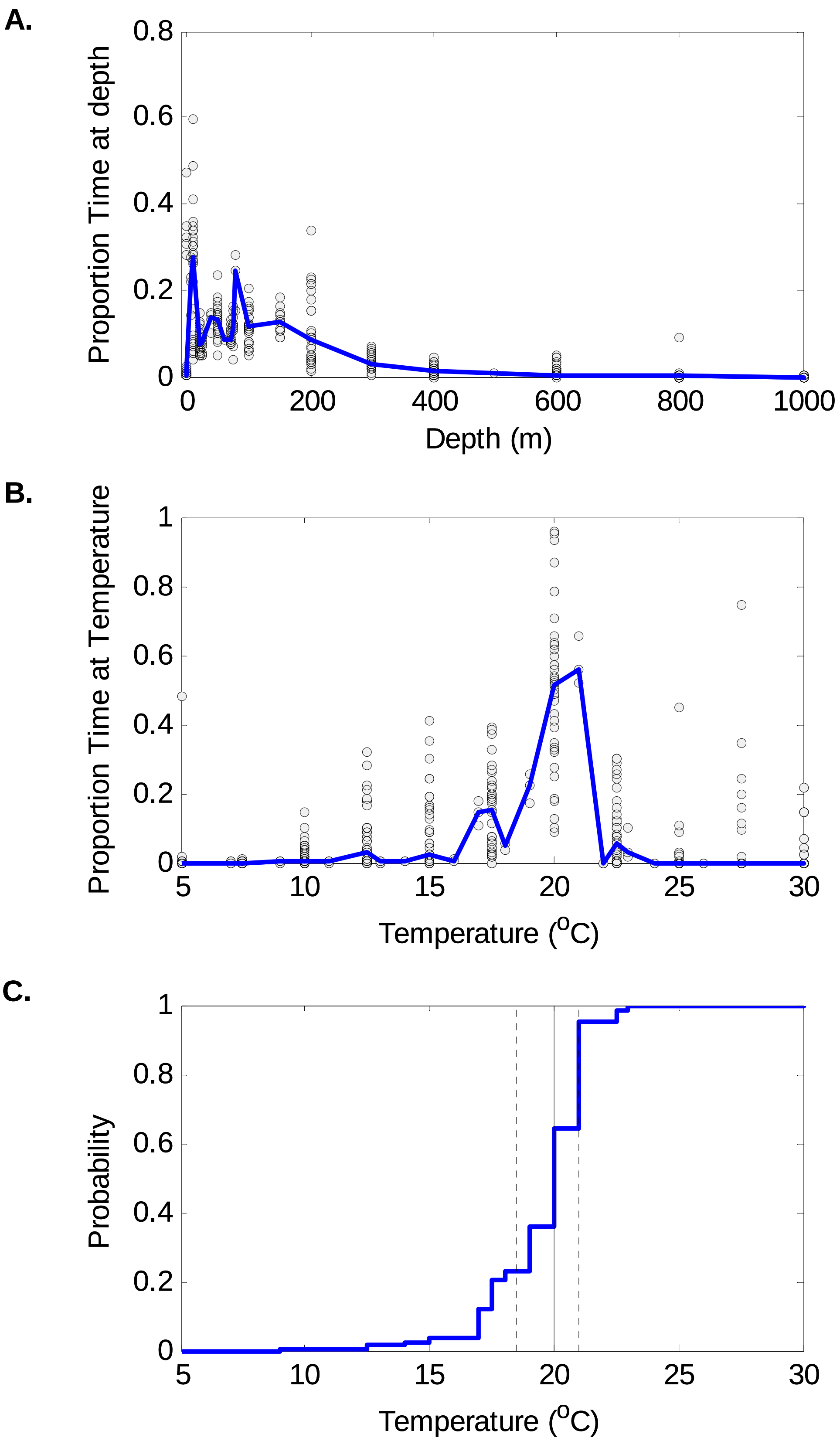


Figure 6. The average proportion of time spent at (a) depth and (b) temperature and (c) the cumulative distribution function of the proportion of time spent at temperature for southern bluefin tuna tagged in the western Tasman Sea 2001- 2005. The median proportion of time spent within each histogram bin is given in blue.

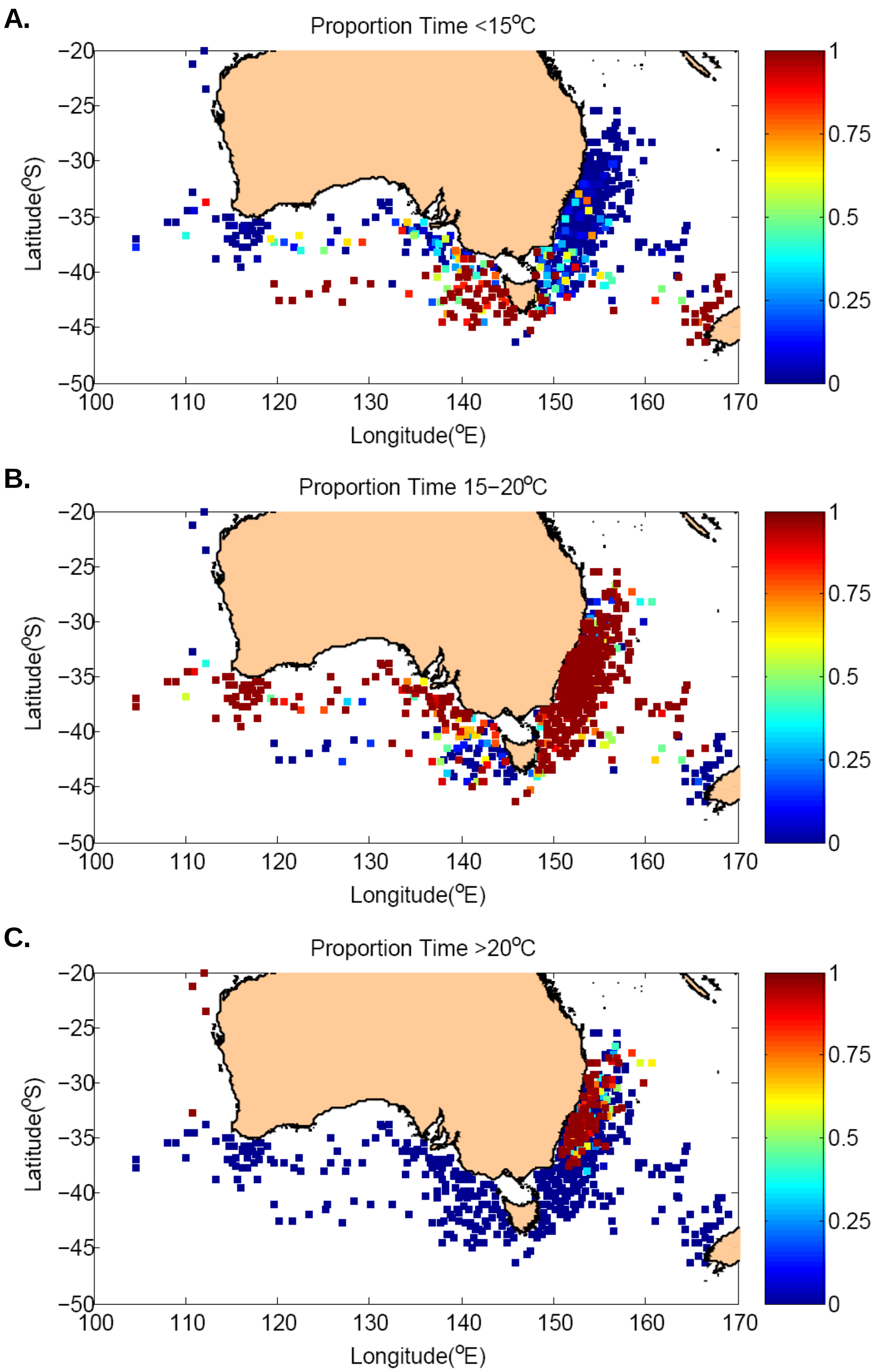


Figure 7. The proportion of time spent in temperatures (a) <15°C, (b) between 15-20°C and (c) in temperatures >20°C. in relation to the estimated position of SBT tagged in the western Tasman Sea 2001-2005.

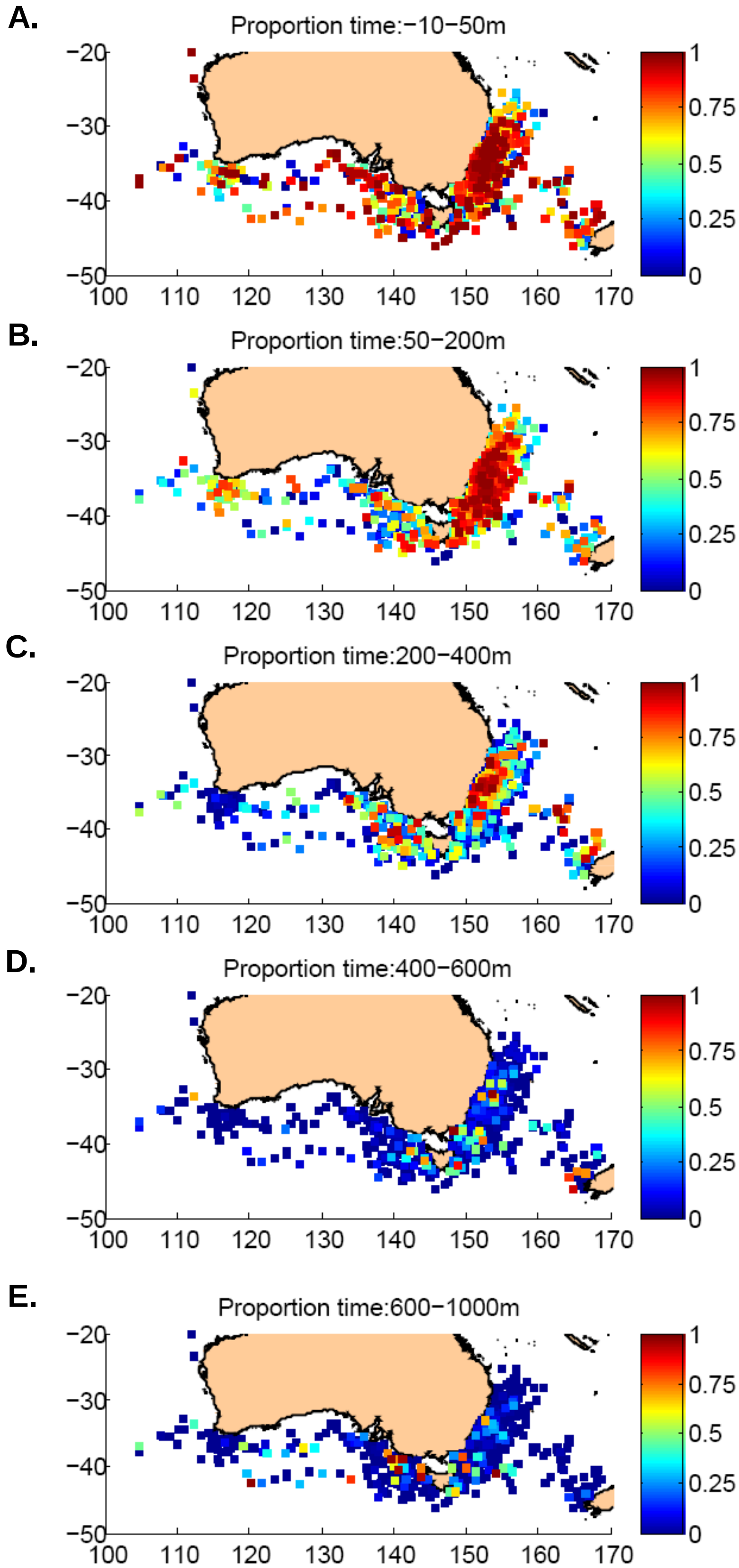


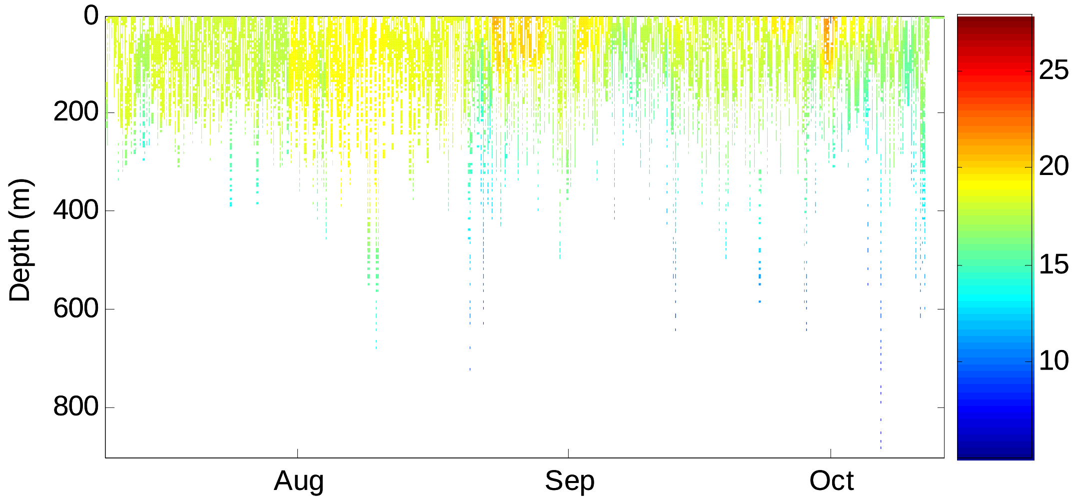
Figure 8. The proportion of time spent in depth ranges (a) -10-50m, (b) 50-200m (c) 200-400m (d) 400-600m and (e) 600-1000m in relation to the estimated position of SBT tagged in the western Tasman Sea 2001-2005.

7.6. Fine scale habitat preferences and behaviour

The two recovered PSATs (30466 and 43933) provided fine-scale depth and temperature data (depth and temperature readings taken at 60 second intervals), collected over 96 and 172 days at liberty respectively (Figure 9). Both SBT spent greater than 90 % of their time in waters shallower than 250 m although time at temperature was highly variable with 30466 spending 69 % of its time in temperature warmer than 18°C while 43933 spent only 37 % of its time in waters warmer than 18°C. Both individuals spent time in waters deeper than 400m and less than 15°C with 43933 spending considerably more time at depths deeper than 400m and colder than 10°C during the summer when it was resident off the west coast of Tasmania.

Lengthy periods of diurnal diving behaviour were demonstrated by both SBT (Figure 10), although episodes of this behaviour were not concurrent on temporal or spatial scales between the two fish. While depths frequented during the day were quite variable (ranging 150 to 600 m), both SBT limited their distribution to waters less than 50 m at night during these periods. Diurnal diving behaviour associated with time spent in waters greater than 400m was observed for periods of up to two weeks at a time and resulted in SBT spending periods of over 10 hours per day in water temperatures less than 10°C and as low as 7°C. Associated with this diurnal behaviour was an ability to remain at more or less constant ambient light levels which resulted in a daily light curve that was almost completely flat (Figure 10).

A.



B.

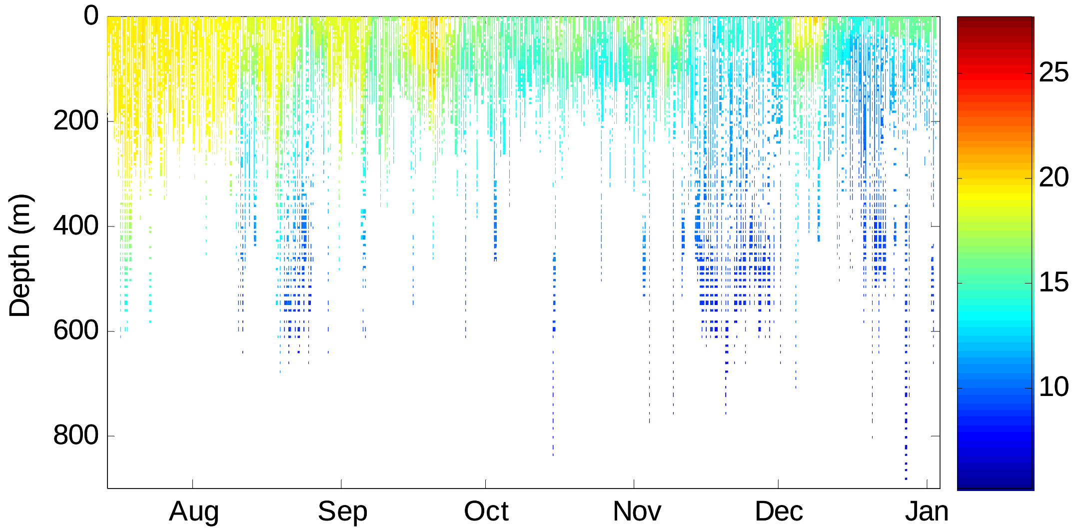
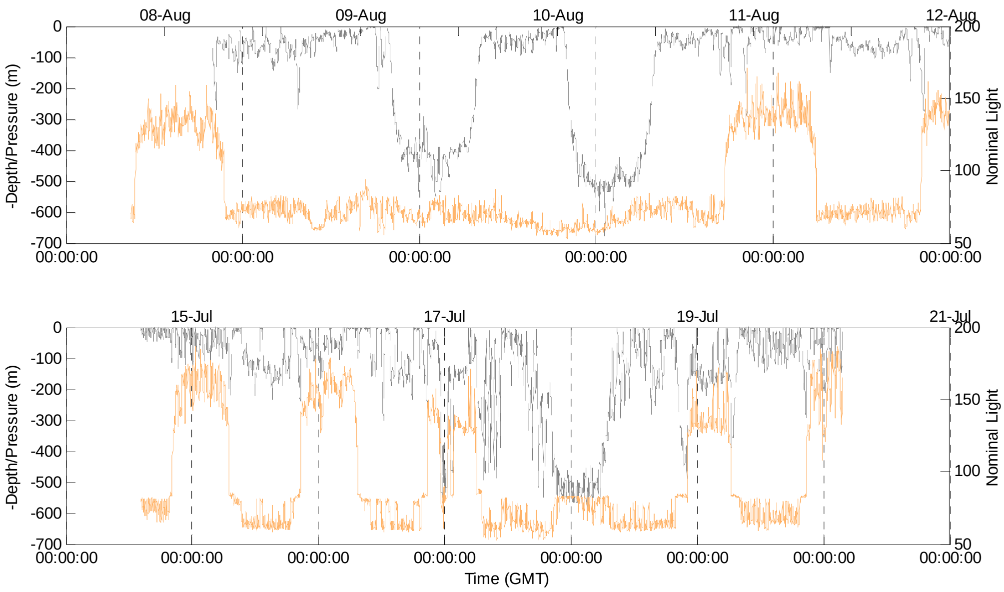


Figure 9. Hourly mean temperature in 5m depth bins from full archival records retrieved from PSATs deployed on southern bluefin tuna in the western Tasman Sea (a) 30466 and (b) 43933.

A.



B.

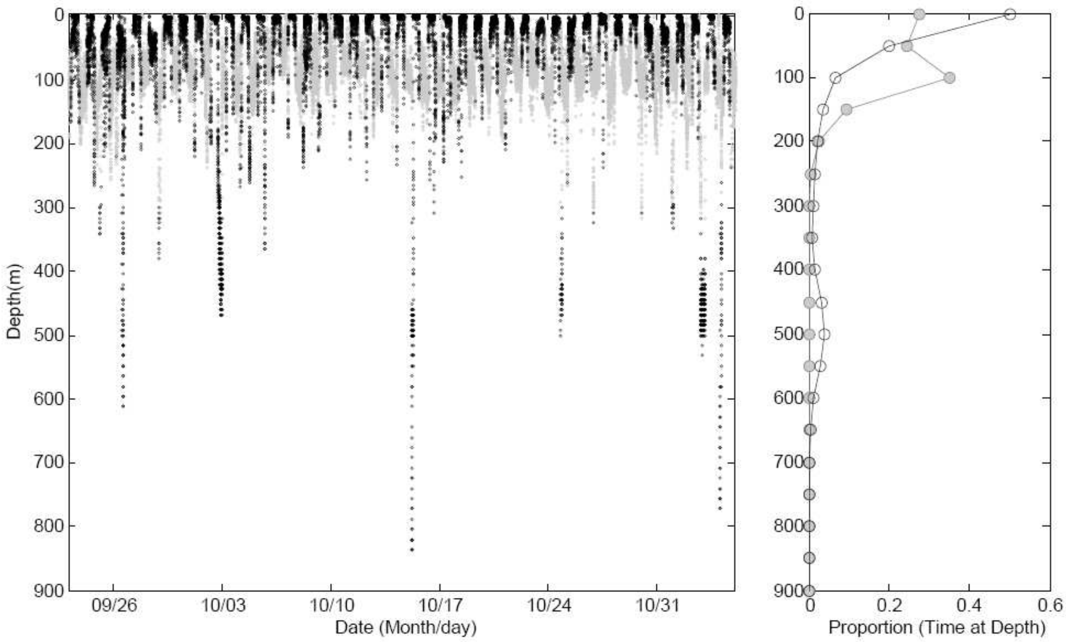


Figure 10 (a) Instances of diurnal diving behaviour resulting in the maintenance of a constant light level in the tag 30466 in August 2004(top) and tag 43933 in July 2004 (bottom). Depth readings are presented in grey and light readings are presented in orange. (b) Detail of a period of diurnal behaviour in tag 43933 (left panel) with depths during the day in grey and at night in black with the proportion of time at depth during the day (open circles) and night (filled circles) on the right.

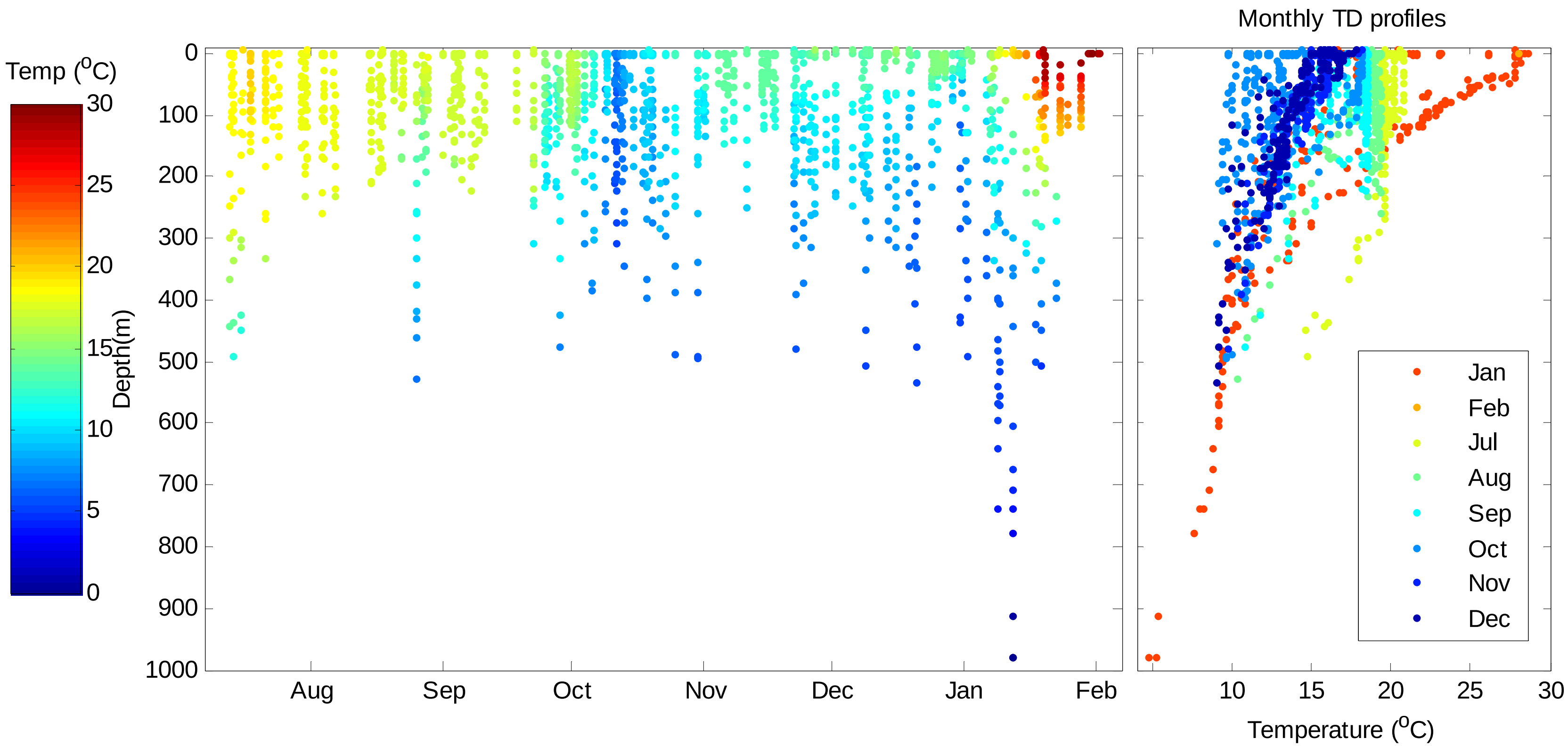


Figure 11. (a) Temperature and depth data and (b) monthly temperature depth profiles of 43926 which migrated from foraging grounds in the western Tasman Sea to the area of the spawning grounds in the Indian Ocean.

7.7. Habitat preferences and behaviour on the spawning ground

The proportion of time spent at depth and temperature demonstrated by the SBT that migrated to the area of the spawning ground (43926) was largely a reflection of the waters experienced during its migration. Whilst in the western Tasman Sea temperatures experienced were largely restricted to 15-20°C and in waters less than 200 m (Figure 11). On leaving the western Tasman Sea foraging area and initiating movement south, variable surface temperatures of 10–20°C associated with colder water masses were experienced. As individuals moved throughout the southern regions of Australia, time spent in waters greater than 250 m increased and in association temperatures experienced decreased with a greater amount of time spent in waters 10–15°C (Figure 11). The depth and temperature preferences of this individual shifted just prior to reaching tropical water masses in mid-January, with an increase in time in the surface waters interrupted by frequent dives to depths greater than 500m. Habitat preferences in the region of the spawning grounds were typified by time spent predominantly in waters less than 150m and as warm as 28°C.

8. DISCUSSION

This study provides the first direct, fishery independent observations of the movement of large southern bluefin tuna across their foraging grounds and beyond in the Australian region. The duration of residency both within and beyond the western Tasman Sea demonstrated by individual SBT was highly variable as was the extent of movement throughout time at liberty. Habitat preferences on spatial scales appeared to indicate thermal preferences associated with suitable foraging and spawning habitats.

8.1. PSAT attachment duration

The single largest hindrance to accumulating long-term data on the movements and habitat preferences of SBT using PSATs in this tagging study was achieving long term attachments. Given the large distances SBT are capable of travelling (as presented in this study) and the duration of attachment required to capture these, improving attachment durations will be important in obtaining a more comprehensive understanding of the movements of this species. The use of a secondary anchor appears to have resulted in a considerable increase in attachment duration, a finding that is supported by a number of other studies utilizing similar secondary anchors[3]. All three stags still at liberty were deployed with secondary anchors.

Determining whether or not the performance of attachments achieved in this study are comparable to those achieved elsewhere on bluefin species is difficult due to a lack of published data; commonly the achieved attachment duration is published but the intended deployment time is not (e.g. Stokesbury et al. 2004, Wilson et al. 2005).

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[3] H. Dewar, National Marine Fisheries Service, personal communication

However, failure of tags to remain attached until programmed release dates has been widely reported elsewhere (Gunn & Block 2001, Domeier et al. 2003, Gunn et al. 2003, Stokesbury et al. 2004, Block et al. 2005, Horodysky & Graves 2005, Wilson et al. 2005, Wilson et al. 2006) and is a common problem in studies utilising this technology.

Maximum attachment durations achieved in this study were considerably shorter than those reported elsewhere (206 days in comparison to 371 days in Stokesbury et al. (2004), 304 days in Wilson et al. (2005) and 261 days in Block et al. (2005)) and may be related to many factors including anchor and tether design used, tag attachment methods used and/or physiological and behavioural differences between species resulting in differences in tissue rejection of anchors or greater wear on attachment points and tethers. However, it must be noted that three tags are still at liberty and are yet to reach their programmed pop-up date. If data transmission is successful from these tags, maximum attachment durations in this study will be comparable to those reported elsewhere.

Pin-breakages were reported in almost one quarter of all tags released in this study. The causes of pin breakages are unknown, although they have been hypothesised to be caused by torque induced stress on the pin or predation (Domeier et al. 2003). Incidences of predation on fish with PSATs have been reported (Kerstetter et al. 2004), possibly either as a result of the PSAT acting as an attractant or the fish being compromised by the tagging procedure and becoming an easier prey target. However, it is impossible to clearly identify the causes of pin breakage definitively without direct observations of the tagged individual.

Wear on monofilament tethers by depth cut off devices has also been hypothesised to be a cause of premature tag release. Abrasion of the monofilament underneath these devices has been documented and thought to be caused by the spinning or rocking of the device on the tether[4]. It is thought that this action gradually wears the monofilament until either the tether is weakened and fails or it is cut in two. The potential for this type of wear on PSAT tethers raises a number of options: finding a means through which movement of the depth cut off device is prevented, development of a more robust tether material which sustains movement of the cut-off device or avoiding of the use of the cut-off device. The use of more robust tether material is at present largely restricted to wire which depth cut-off devices currently used are incapable of cutting. As a result, for most researchers using this technology the most feasible options are to either find a way which minimizes movement of the depth cut off device or to simply cease to use the device. Either of these options must be considered in terms of their cost-benefit to the research being undertaken. Any restraint developed for cut-off devices must themselves be able to withstand considerable periods in marine environments under varying forces and pressure. Removing the cut-off device, particularly in deep diving species increases the chances of structural failure of the tag at depths below which they are able to withstand and a subsequent loss of any data collected. Attempts to stabilise depth cut-off devices on the monofilament tethers of PSATs were attempted on 2005 releases, with further testing planned in 2006/07.

[4] Bruno Leroy Secretariat of the Pacific Community personal communication

8.2. Geolocation Accuracy

The errors calculated around the final position estimates of the PSATs presented in this study compare well to the estimates of geolocation error calculated elsewhere (Teo et al. 2004) and indicate that errors are small enough to allow for robust inference of large scale movements in SBT. Despite the limitations of determining position from light in pelagic animals (see Teo et al. 2004, Neilsen et al. 2006 for a review of these), further improvement to geolocation methodology is likely to improve the accuracy of position estimates. Improving the statistical rigour of calculating location estimates would provide rigorous estimates of uncertainty surrounding location estimates and better statistical methods would also allow for quantification of variability in movement rates between individuals. However, with the exception of the use of Kalman filter models (Sibert et al. 2003, Neilsen et al. 2006) which make strong assumptions about the nature of geolocation errors, statistical applications have yet to be utilised for larger data sets and the most promising published methods have only used simulated data sets (e.g. Royer et al. 2005, Jonsen et al. 2003).

8.3. Migration and residency patterns

Large scale migrations between separate foraging areas and from foraging areas to the area of the spawning grounds were made by SBT, demonstrating connectivity at large spatial scales within the larger size classes of the SBT stock. Such migrations are consistent with those observed in other *Thunnus* species in the Northern Hemisphere (Block et al. 2001; Block et al. 2005) and the connectivity observed in this study is consistent with the results of genetic analyses investigating the stock structure of SBT (Grewe et al. 1997). Daily movement rates observed in this study were similar to those reported in bluefin species elsewhere (Lutcavage et al. 2000, Wilson et al. 2005), however maximum distances observed were noticeably greater, reflecting differences in the stock structure of the species and distances between foraging and spawning grounds.

Considerable variability in dispersal rates and movement paths of individuals resulted in individuals tagged in the same area being widely dispersed throughout southern oceans during the austral summer. All individuals tagged were of similar size to those observed on the spawning ground (Farley & Davis 1998) and only one individual was considered not to be fully recruited to the spawning stock according to methods used in current CCSBT stock assessments. Such a wide dispersion of individuals, a lack of coherency in movements and the temporal period during which SBT were still in the Southern Ocean suggests the possibility that large SBT considered to be reproductively mature may not participate in spawning on an annual basis. However, before definite conclusions can be made on the temporal nature of spawning participation in SBT, more information through the collection of data from longer term deployments is needed to clearly establish the spatial dynamics of spawning sized fish. Further, assumptions associated with the classification of fish into the spawning stock have been suggested to oversimplify the maturity schedules of SBT (Farley & Davis 2001) and are confounded by difficulties in making accurate predictions of age from length data (Caton 1991, Hampton 1991, Eveson et al. 2004). As a result, it is not clear that the proportion of SBT assumed to be recruited to the spawning stock in this study constitute an accurate sample of actively spawning SBT.

The trigger for movement of SBT away from the tagging area in the Tasman Sea may be closely linked to seasonal changes in oceanography. During the austral spring, warm waters associated with the East Australian Current (EAC) extend down the eastern Australian coastline in a series of eddies and frontal zones, producing concentrated areas of productivity which may serve to move suitable foraging areas for SBT southward. Simultaneously, seasonal upwelling events begin to occur in the waters along the Australian coastline to the north west of Tasmania increasing productivity in this region and further west into the eastern margins of the GAB throughout a period encompassing spring, summer and early autumn months (Schahinger 1987, Herzfeld 1997, Kämpf et al. 2004). The area off the south west of Australia is also a region of seasonal productivity, largely driven by mixing between the southward moving Leeuwin Current and wind forced northward currents on it’s northern boundary and cooler waters of the Southern Ocean on it’s southern boundary in the summer months (Pearce et al. 1997). This region of productivity historically has and presently supports a number of fisheries based around small pelagic species and may serve as an important foraging area for large SBT. Sub-adult SBT have been observed to switch preferred prey species between areas of residency (Young et al. 1997) and their movements between areas have been hypothesised to be triggered by a drive to capitalize on concentrations of small pelagic fishes (Young et al. 1996). It is likely that the movements of large SBT are driven by similar requirements to capitalize on patchy prey resources.

8.4. Habitat preferences and behaviour

Individuals tagged in this study clearly demonstrated a preference for waters 18–20°C in temperature, similar to that observed in juvenile SBT (Gunn & Block 2001) and other bluefin species (Block et al. 2001, Marcinek et al. 2001, Stokesbury et al. 2004, Kitagawa et al. 2006). However, large SBT can clearly cope with much cooler temperatures than 18°C for sustained periods, spending periods of over 10 hours at temperatures less than 10°C. It is therefore unlikely that thermal preferences are strictly a reflection of the physiological capabilities of SBT, but are more likely to be reflective of the water masses utilised by forage species the extremes of which are determined by physiological limitations. Tuna are widely documented to associate with fronts and transition zones (Laurs & Lynn 1977, Olson 2001, Sharp 2001, Polovina 2001, Royer 2004), however the factors driving this association are still largely unknown (Kirby et al. 2000). Frontal areas are often associated with biomass maxima, concentrating chlorophyll production and associated secondary productivity and it has been hypothesised that SBT use warm-core eddies and the warm side of fronts as thermal refuge after periods of foraging in colder waters (Gunn & Young 2000). Use of such oceanographic features to trade-off forage availability against thermoregulatory requirements has been postulated for other species of tuna elsewhere (Neill 1976, Sund et al. 1981), while others have hypothesised that this association is strictly related to the aggregation of forage species only (Brill & Lutcavage 2001, Brill et al. 2002, Royer et al. 2004) and is not used for thermoregulatory requirements. Whether or not this association has links to thermoregulatory requirements, the long forays into cool water demonstrated by SBT in this study represent a physiological capability which may allow this species to capitalise on prey concentrations (when they are present) by maximising the amount of time spent in these frontal and eddy regions.

Diurnal patterns in diving behaviour have been observed in a number of tuna species including bigeye tuna (*T. obesus*; Musyl et al. 2003); Atlantic bluefin tuna (Gunn & Block 2001) and Pacific bluefin tuna (Kitagawa et al. 2000) and have been hypothesised to be associated with the vertical migration of the scattering layer (Dagorn et al. 2000; Marcinek et al. 2001; Schaefer & Fuller 2002; Musyl et al. 2003) either through direct tracking of prey or tracking of particular light levels which may be easiest for ambushing or detecting prey (Warrant 2000). Changes in diving behaviour on a diurnal scale associated with relatively constant light levels, as observed in this study, suggest that light may play an important role in determining the foraging depth of SBT.

8.5. Habitat preferences and behaviour on the spawning ground

Although limited, the data obtained from the one individual that was tracked to the spawning grounds provides an interesting insight into the behaviour of SBT both during migration to the spawning grounds and while in the area of the spawning grounds.

The diving behaviour of this individual differed markedly between regions, with the fish demonstrating relatively consistent diving behaviour ranging down to 500m whilst in the Southern Ocean, much deeper diving behaviour in the Indian Ocean and then surface related diving behaviour in the region of the spawning grounds. This cessation of deeper diving and a transition to surface related behaviour appeared to be closely associated with the occurrence of surface temperatures greater than 24°C. Such surface related behaviour is similar to that documented by other SBT in the spawning ground region (Itoh et al. 2002) and is consistent with suggestions that spawning occurs in surface waters (Davis & Farley 2001). Reasons for the change from fairly consistent diving behaviour to depths of 500m to much deeper diving when moving from the Southern to the Indian Ocean are unclear, but may be associated with changes in prey species targeted and associated changes in the distribution of prey species and/or changes in the thermal properties of the water masses experienced. Given the ability of bluefin species to effectively conserve heat, thereby allowing these species to inhabit a much wider thermal range than other tuna species (Carey & Teal 1969), the deeper diving demonstrated by SBT (and in association the increased time spent in cooler waters) in this region may have been associated with physiological requirements to avoid overheating in warmer waters as the individual moved further north.

9. CONCLUSIONS/OUTCOMES ACHIEVED

The data collected as part of this study represent a major step towards reducing uncertainty about the spatial dynamics of a large pelagic predator, the stock of which has been significantly reduced in sized and is still the focus of a major pelagic fishery. At the same time, it raises further questions as to the reproductive schedule of participants in the spawning stock and the location of other important foraging areas for this species in the Australian region. Despite the limitations of the technology used to collect these data (limited attachment durations and therefore data collection periods, variable reporting rates, limited data transmission/reception capacities and inaccuracies in estimating position associated with geolocation methodology), determining such aspects of the life history of this species independent of the fishery would be difficult without the use of PSATs. Current fisheries data or conventional mark-recapture datasets have not been able to provide as detailed a picture of movement. Moreover, in the case of adult SBT, there has been very little conventional tagging from which to infer movements.

Large SBT in the Tasman Sea clearly demonstrate substantial individual variability in the migration pathways they utilise, their residency patterns within the Tasman Sea and beyond and the habitats they utilise (Objectives 1 and 2), reflecting a physiological plasticity which allows for a maximising of resource exploitation in a patchy environment. The results from this study clearly highlight the need for a more comprehensive understanding of the spatial dynamics of this species and the critical gaps in our current integration of movement into stock assessments and management models. As we build our understanding of the habitat preferences of this species and any spatial and temporal variability in these preferences, habitat models used for the spatial management of this resource can be developed further to incorporate this variability. Further information will allow the identification of key habitats utilised by large SBT, providing critical information for the spatial management of this species.

The success of this project in meeting its original objectives was hindered by two key factors: (1) availability of SBT of an adequate size and of a suitable condition for tagging and (2) achieving long term attachments. As a result, we were only able to deploy 34 of the original 60 PSATs anticipated across the 2004-2005 period and we achieved a maximum period of attachment of 206 days with the majority (72 %) less than 150 days. With only one case of a successful tracking of a SBT to the spawning grounds we are unable to determine any clear conclusions regarding Objectives 3, 4 and 5. Deployment of the remaining 36 PSATs in combination with improved attachment rates will serve to resolve these objectives.

Attempts were made to deploy PSATs in the Indian Ocean without success. This was primarily due to a significantly reduced domestic fleet in the region and a lack of encounters with SBT of an adequate size and suitable condition. During tagging operations in 2005, only one SBT was caught and this was deceased. Further attempts at deploying PSATs in the Indian Ocean via the opportunistic deployment of tags on domestic vessels are currently in preparation.

10. FURTHER DEVELOPMENT

Further progress in attachment methods through the use of improved anchor and tether designs has the potential to allow for collection of long-term data. Development of more robust tether material capable of withstanding wear of depth cut off devices or better means to immobilise depth cut off devices should be considered. Current directions of development are centred on immobilizing cut off devices through strategic placement of the devices on the tether and fixing the device to the tether with marine resistant fixatives. Inclusion of swivels in tether designs has also been incorporated in an effort to reduce the torque forces on both the anchor and the tags pin through which the tether is attached.

Additional improvements to the spatial and temporal coverage of movements may also be achievable through careful design of PSAT deployments. Staggered deployments both on spatial and temporal scales may provide a more comprehensive picture of movements, provided fish are accessible to researchers at key periods and areas throughout their migration. Deployment of tags in other areas throughout the range of SBT and across wider temporal periods (not only the austral winter) would serve to address problems associated with attachment durations and also help to define the connectivity of SBT in different fishery areas such as the Australian and South African regions. Utilisation of key areas identified as residency sites across the spring and summer months, such as the area north-west of Tasmania and southwest of the Australian continent may serve this purpose. Further attempts to deploy PSATs in the Indian Ocean on individuals moving to or from the spawning grounds would also serve to extend the spatial and temporal coverage of movement.

Position estimates calculated via light based geolocation methods contain a substantial amount of uncertainty, often placing animals at unrealistic locations from their actual location and thereby limiting the spatial scales at which positions can be interpreted. This uncertainty is exacerbated around the time of the equinoxes due to equal day length at all latitudes and is further compromised by the diving behaviour of the animal causing reduction of light levels at depth. Further development of analyses capable of refining geolocation estimates is required at two levels: (i) in the generation of light attenuation curves to address issues with light collected at depth during dawn and dusk and (ii) in the post-processing calculation and statistical filtering of position estimates. Calculation of position estimates derived via geolocation routinely incorporate the use of physical variables such as sea surface temperature as used in this study, bathymetry and tidal data often improving estimates substantially. However, with the exception of the use of Kalman filter models little has been done to improve the statistical rigour in calculating location estimates. Recently, further development in the calculation of position estimates using Kalman filter models have involved the incorporation of SST matching resulting in substantially improved movement tracks of individuals. However, such models make strong assumptions about the nature of geolocation errors (see Sibert et al. 2003 and Neilsen et al. 2006 for a description of the model), and further work investigating the sensitivity and validity of the results of different state-space models (e.g. Kalman filters and particle filters) should be encouraged.

Development of tag technology focused on improving tag reporting rates and transmission of data would also substantially enhance those data able to be collected from tagged individuals. Of the 52 PSATs deployed as part of this study, six failed to report any data (although one was retrieved and the data downloaded) and all failed to transmit complete records of data summaries. New versions of PSATs recently released onto the market have incorporated advances in antenna technology and data compression and have reportedly improved data transmission rates, thereby enhancing the retrieval of data from surfaced tags. Whether these improvements will resolve data reception problems remains to be seen.

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12. APPENDICES

APPENDIX A: Position estimates of SBT tagged in the western Tasman Sea with pop-up satellite archival tags 2001-2005.

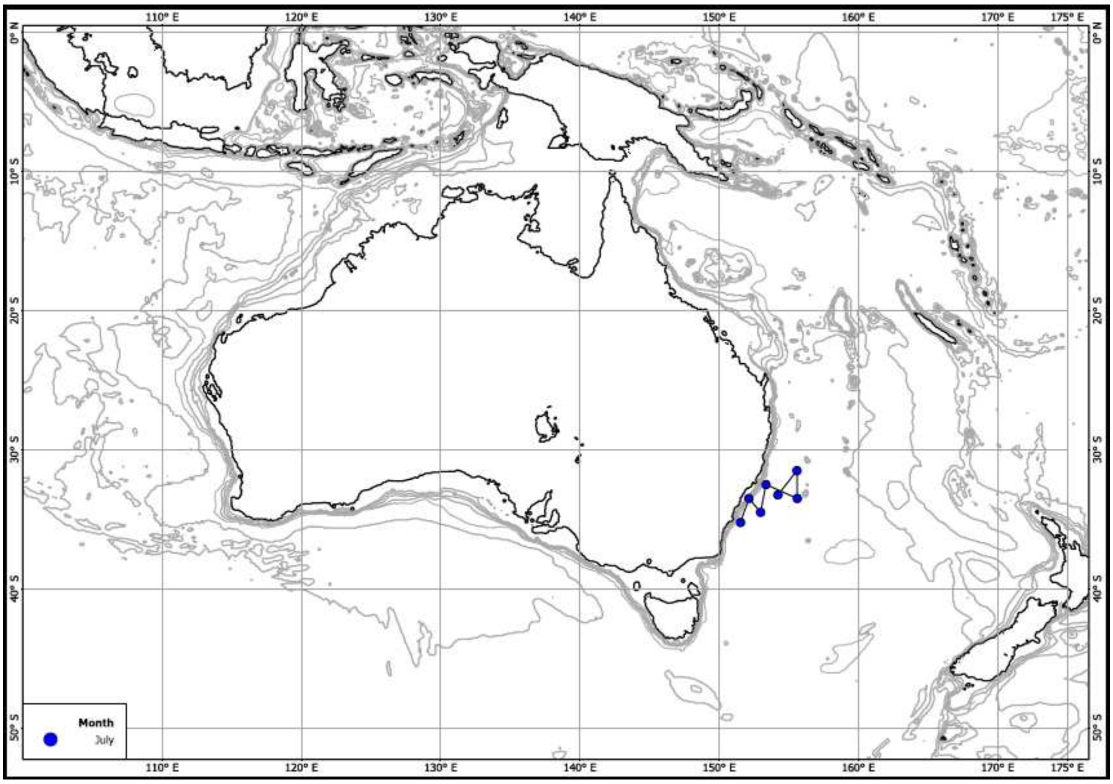

Figure A1. Individual track of 28708, at liberty 13 July 2001 to 27 July 2001.

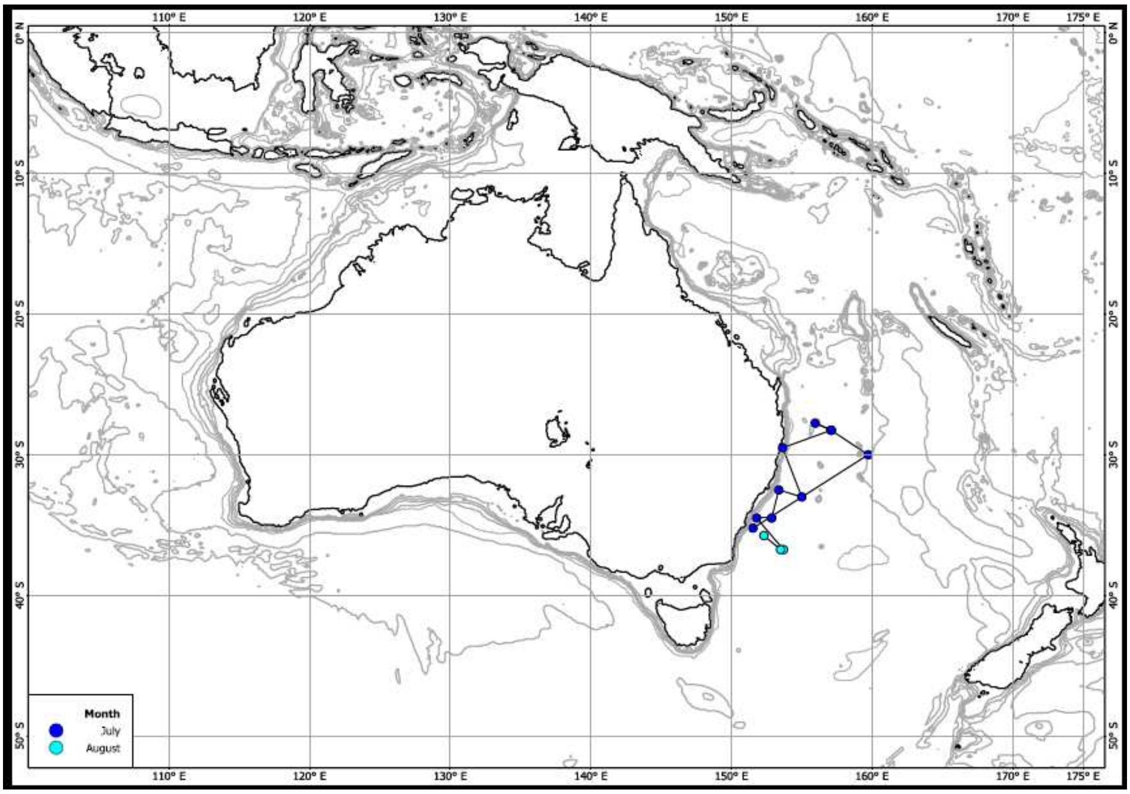

Figure A2. Individual track of 28707, at liberty 13 July 2001 to 07 August 2001.

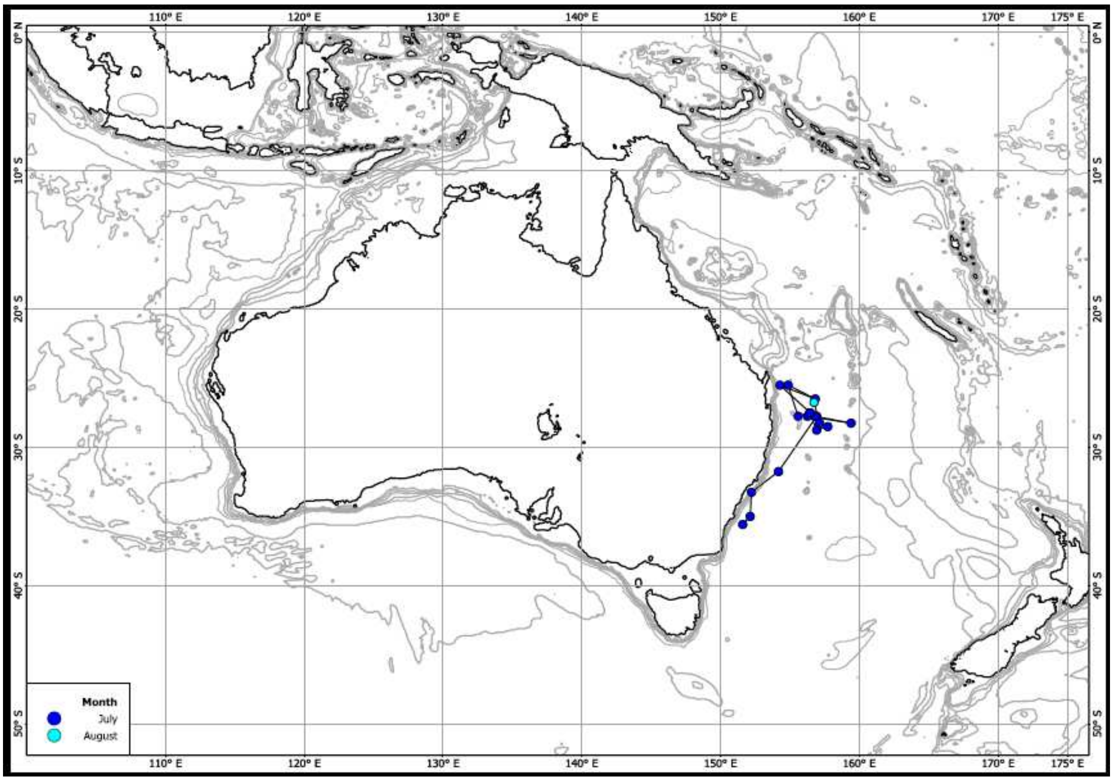

Figure A3. Individual track of 13275, at liberty 13 July 2001 to 13 August 2001.

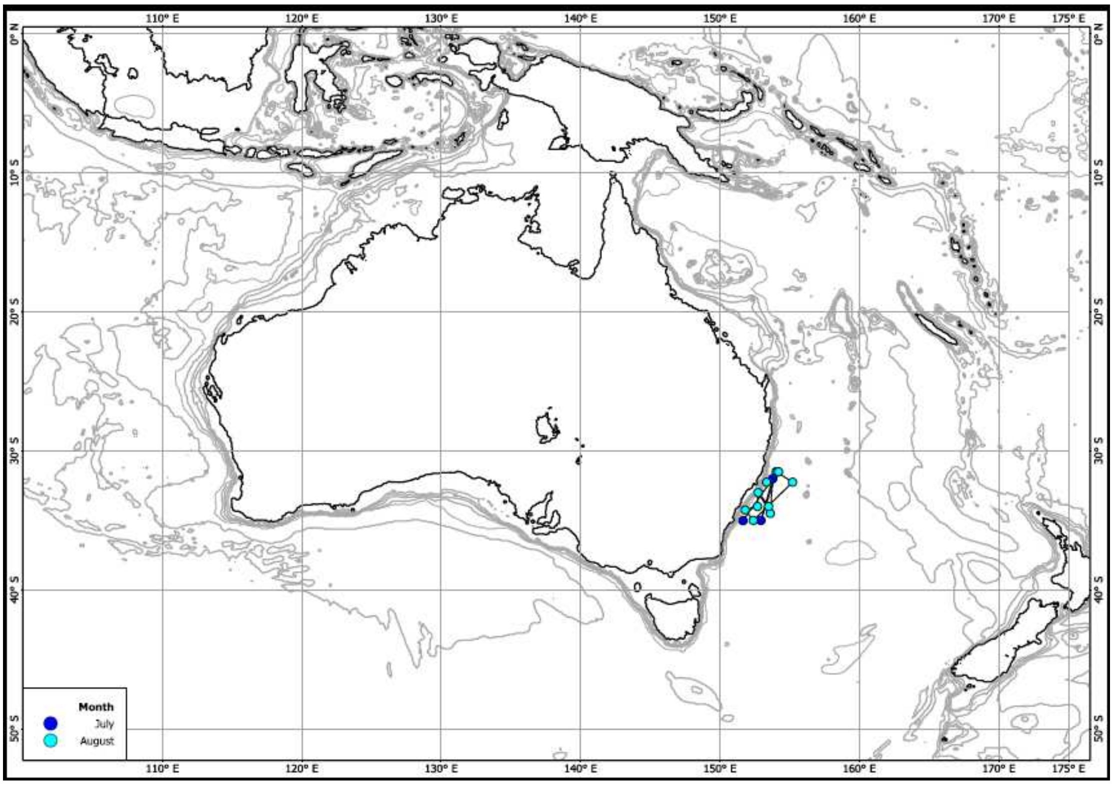

Figure A4. Individual track of 28709, at liberty 27 July 2002 to 20 August 2002.

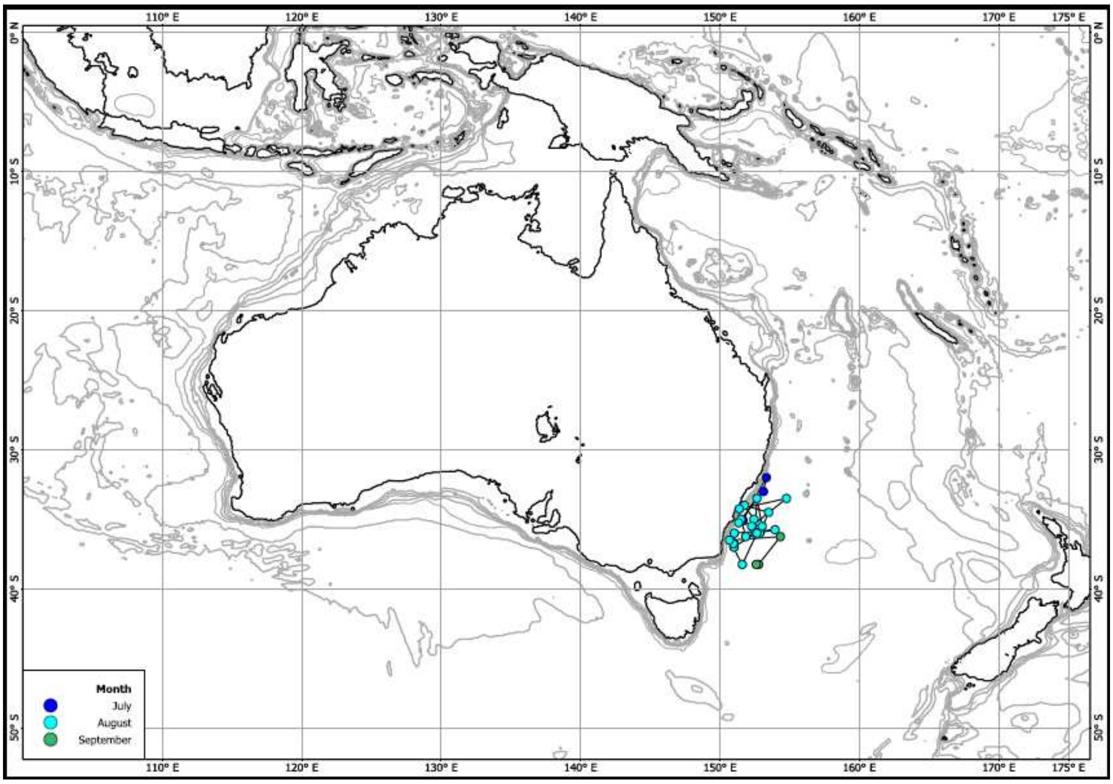

Figure A5. Individual track of 13272, at liberty 27 July 2002 to 06 September 2002.

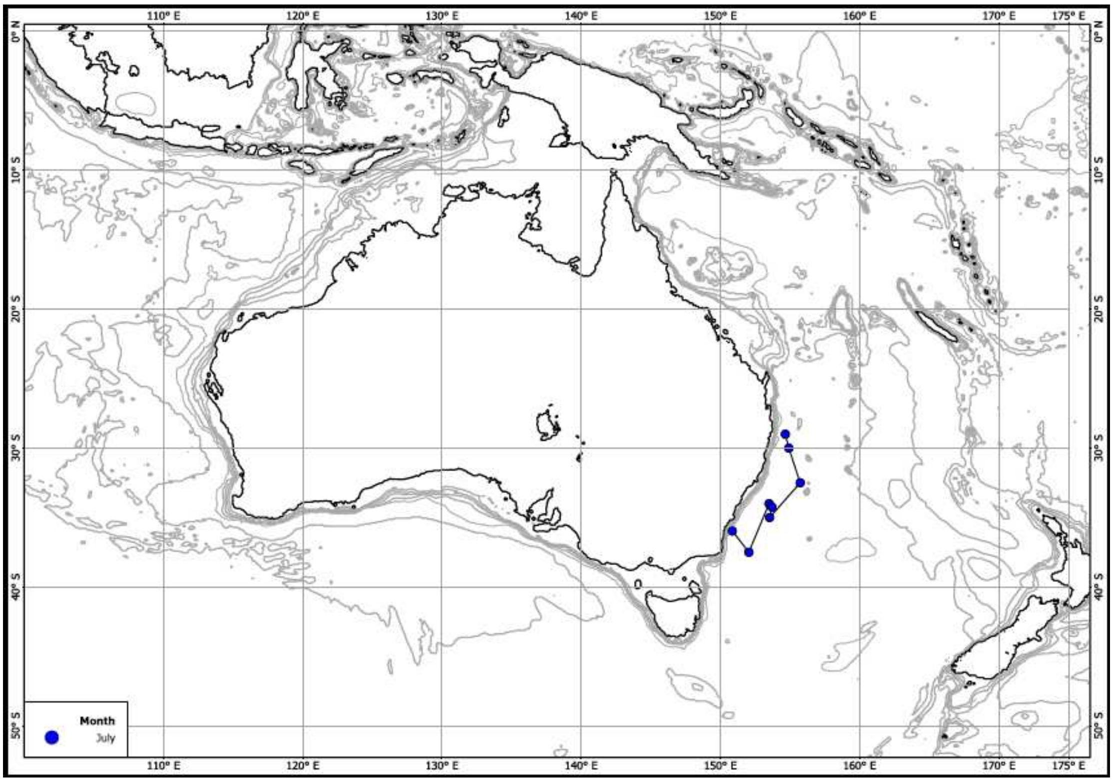

Figure A6. Individual track of 20890, at liberty 10 July 2003 to 03 August 2003.

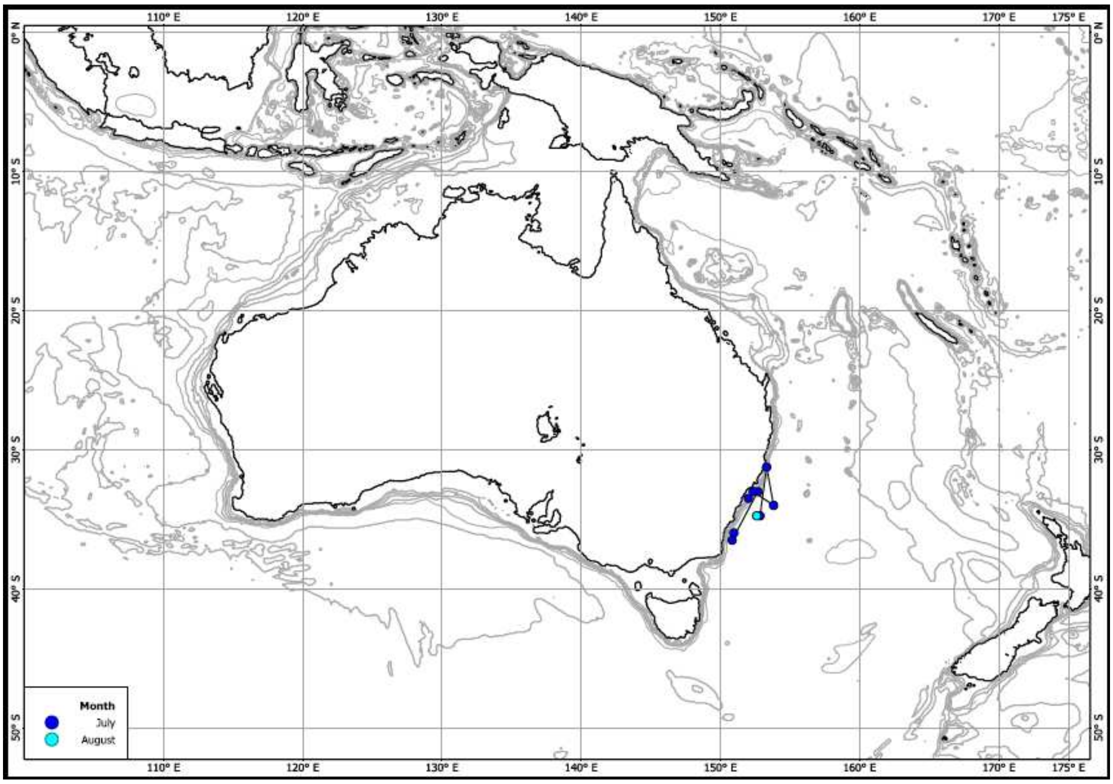

Figure A7. Individual track of 13279, at liberty 10 July 2003 to 06 August 2003.

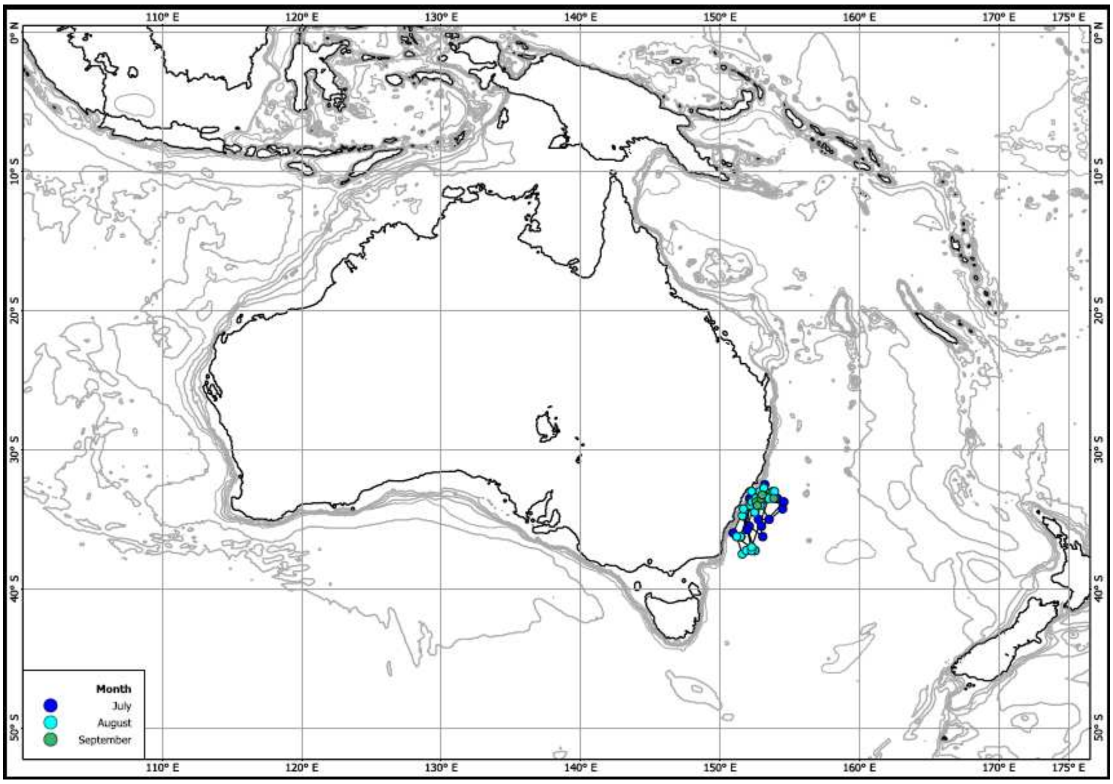

Figure A8. Individual track of 13273, at liberty 10 July 2003 to 07 September 2003.

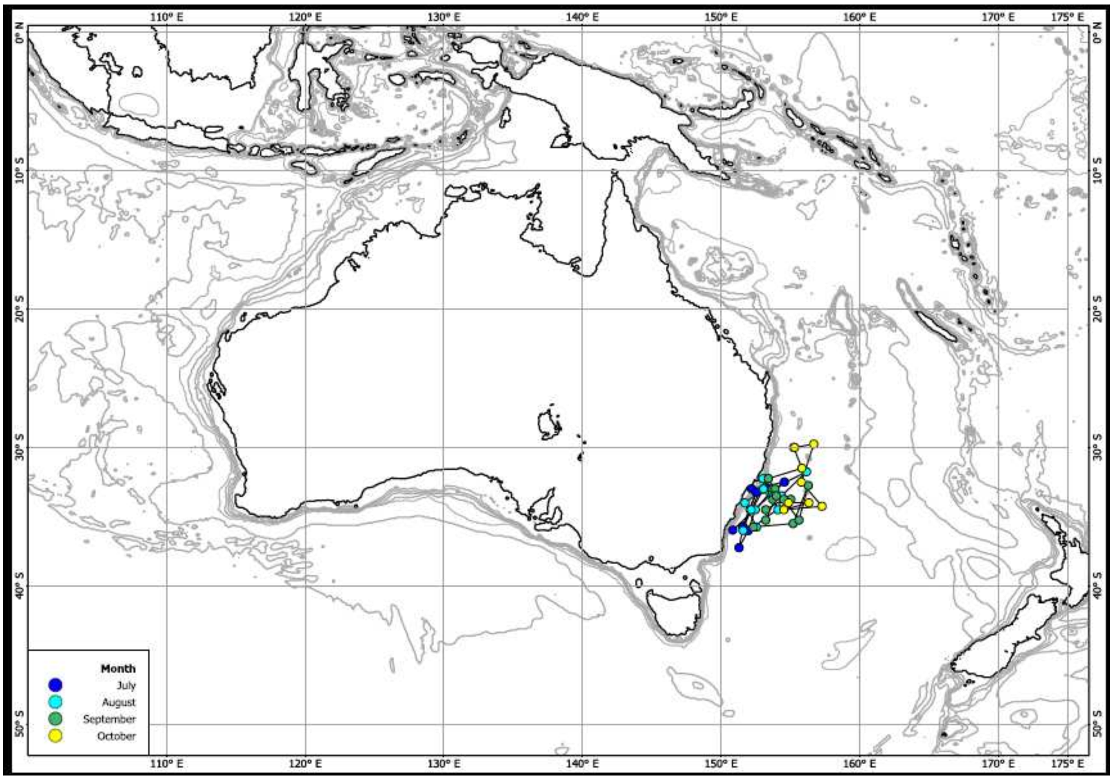

Figure A9. Individual track of 30466, at liberty 10 July 2003 to 14 October 2003.

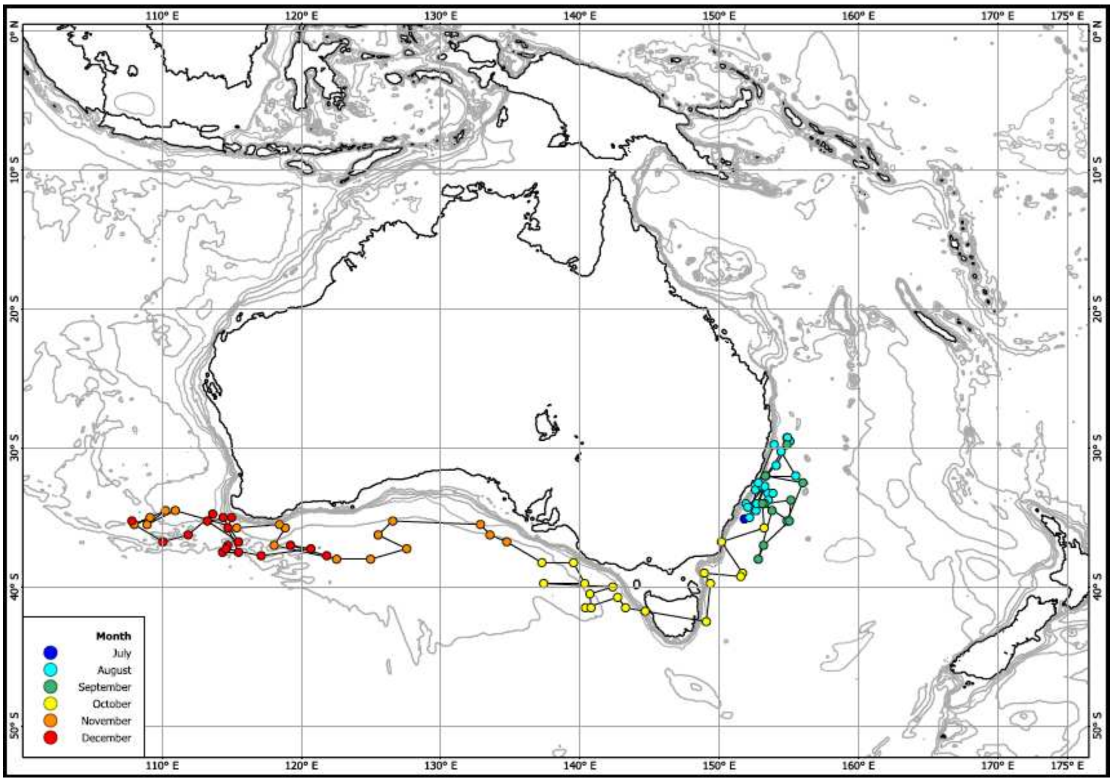

Figure A10. Individual track of 18564, at liberty 28 July 2003 to 01 January 2004.

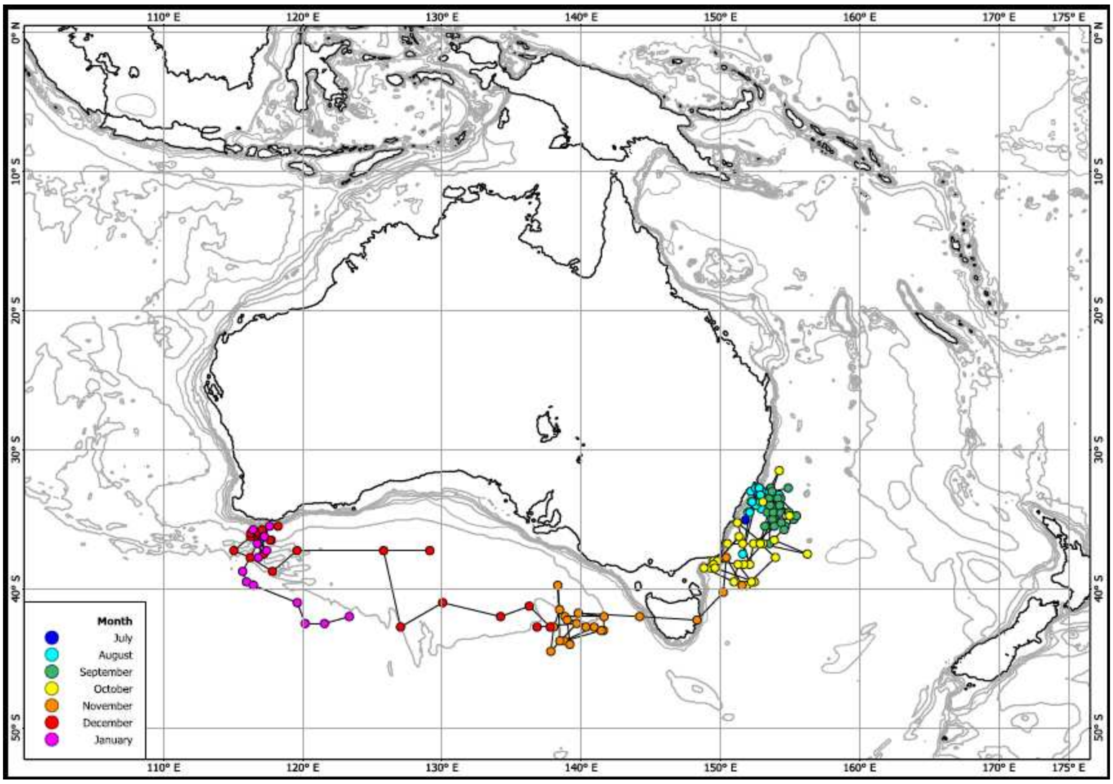

Figure A11. Individual track of 30465, at liberty 28 July 2003 to 24 January 2004.

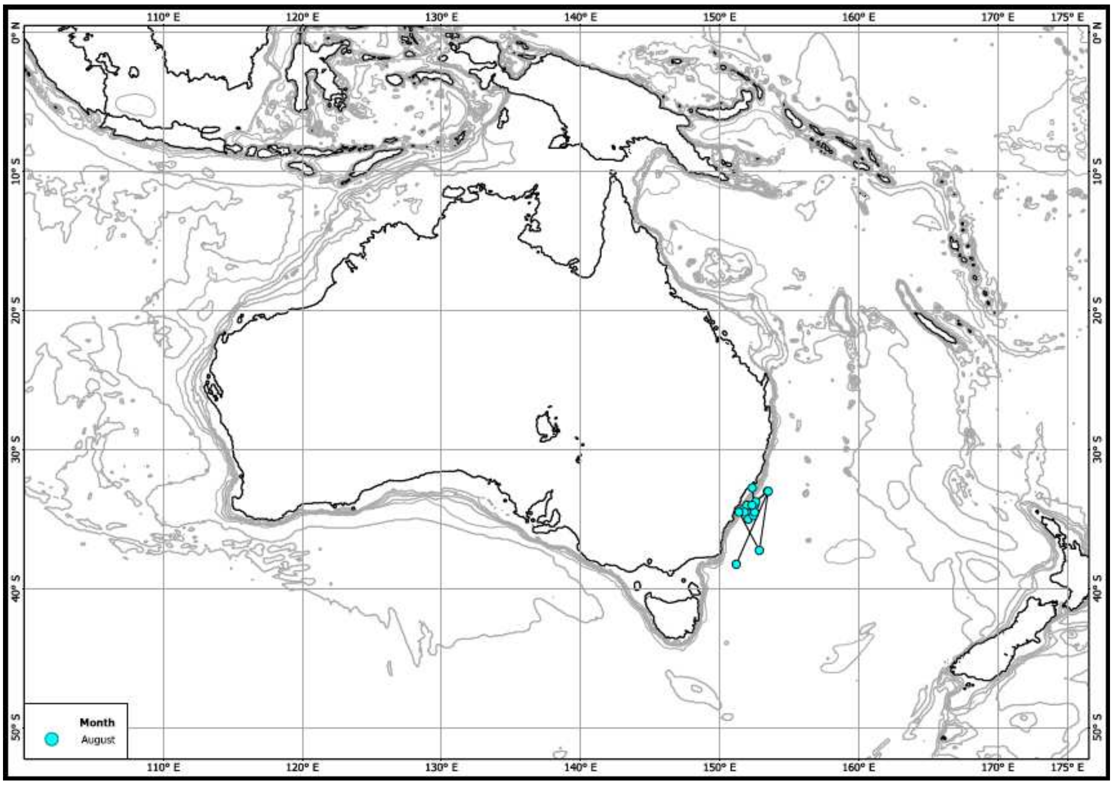

Figure A12. Individual track of 20891, at liberty 07 August 2003 to 16 September 2003.

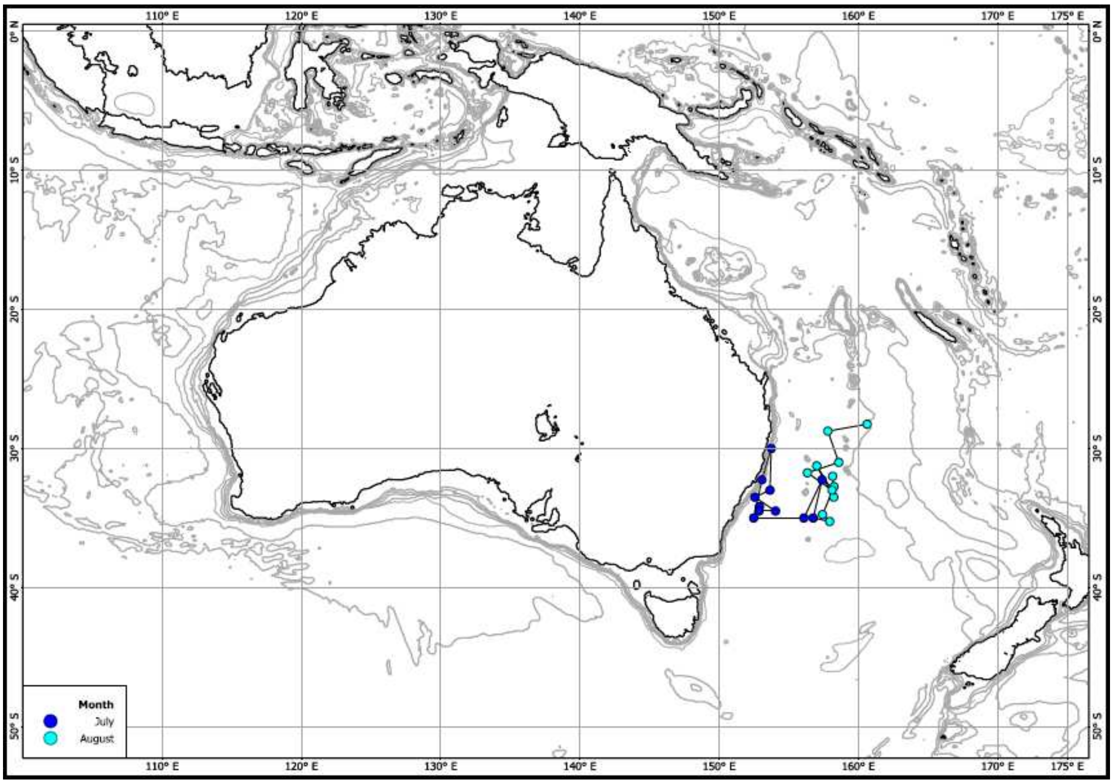

Figure A13. Individual track of 43937, at liberty 05 July 2004 to 04 September 2004.

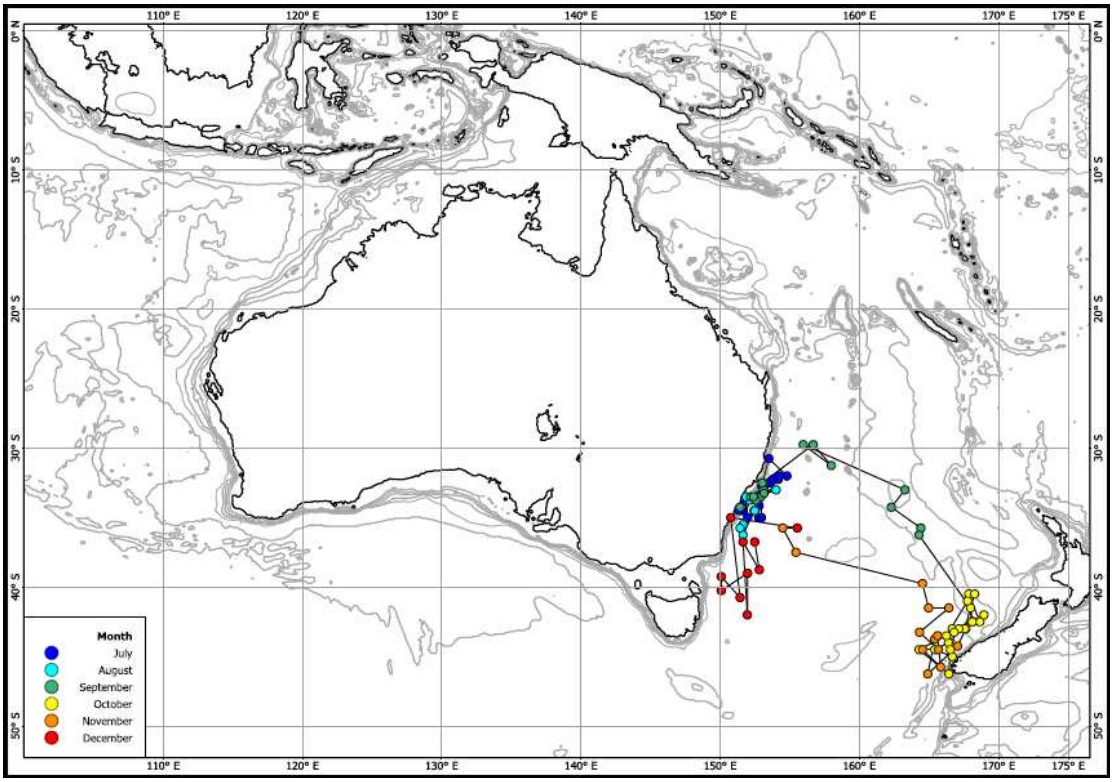

Figure A14. Individual track of 43935, at liberty 05 July 2004 to 13 December 2004.

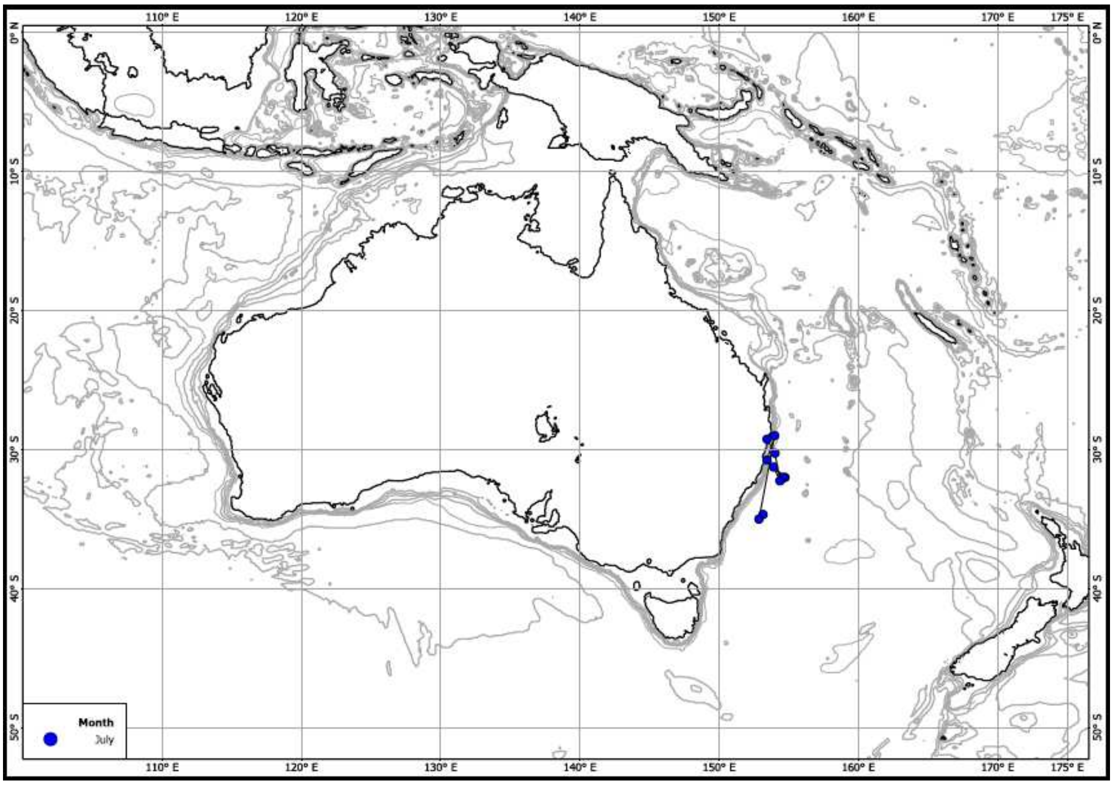

Figure A15. Individual track of 43925, at liberty 12 July 2004 to 26 July 2004.

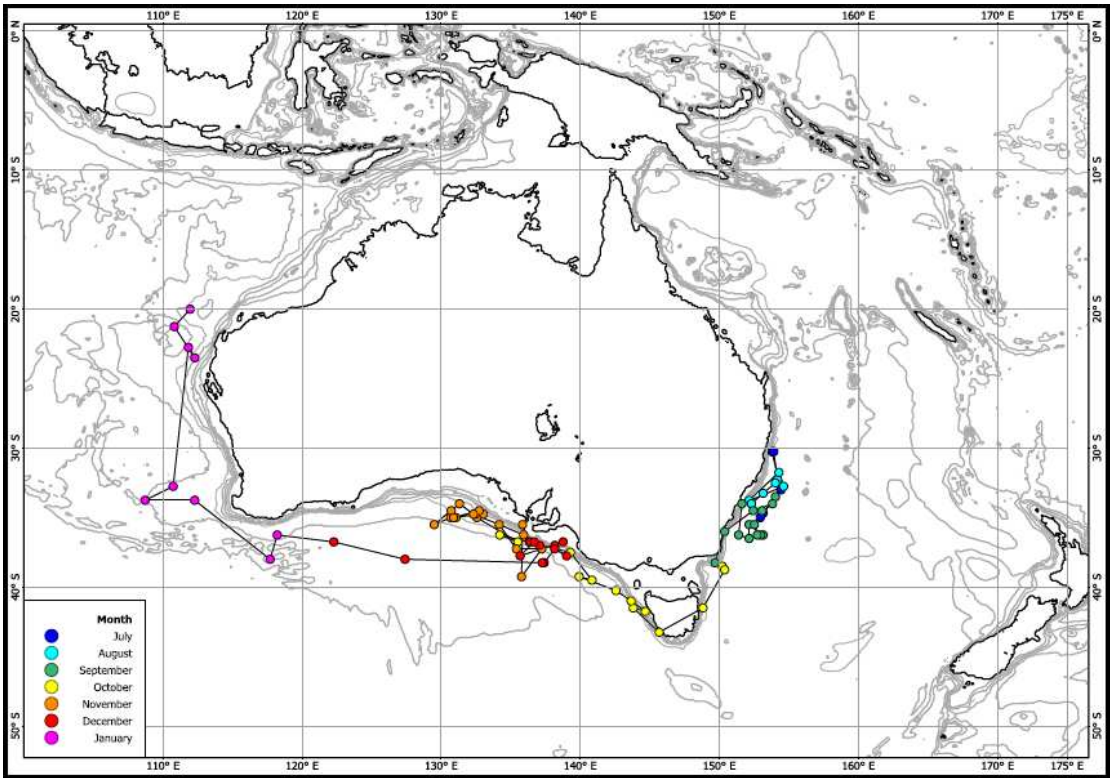

Figure A16. Individual track of 43926, at liberty 12 July 2004 to 03 February 2005.

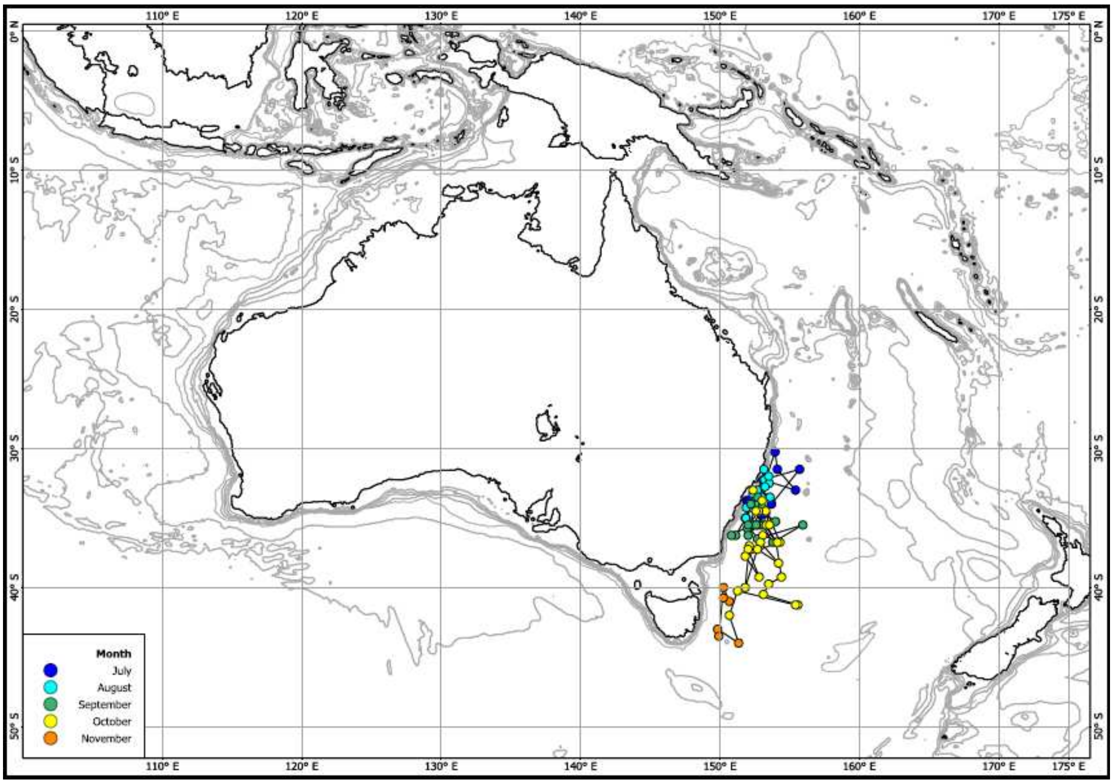

Figure A17. Individual track of 43929, at liberty 13 July 2004 to 08 November 2004.

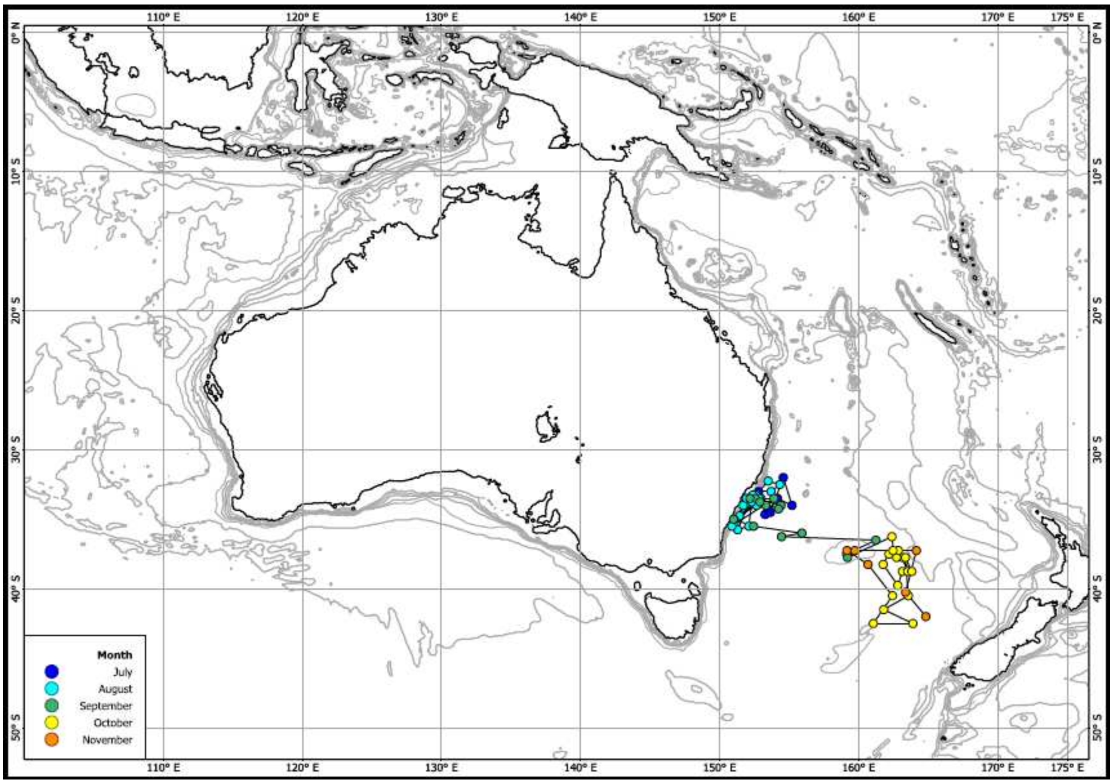

Figure A18. Individual track of 43931, at liberty 13 July 2004 to 19 November 2004.

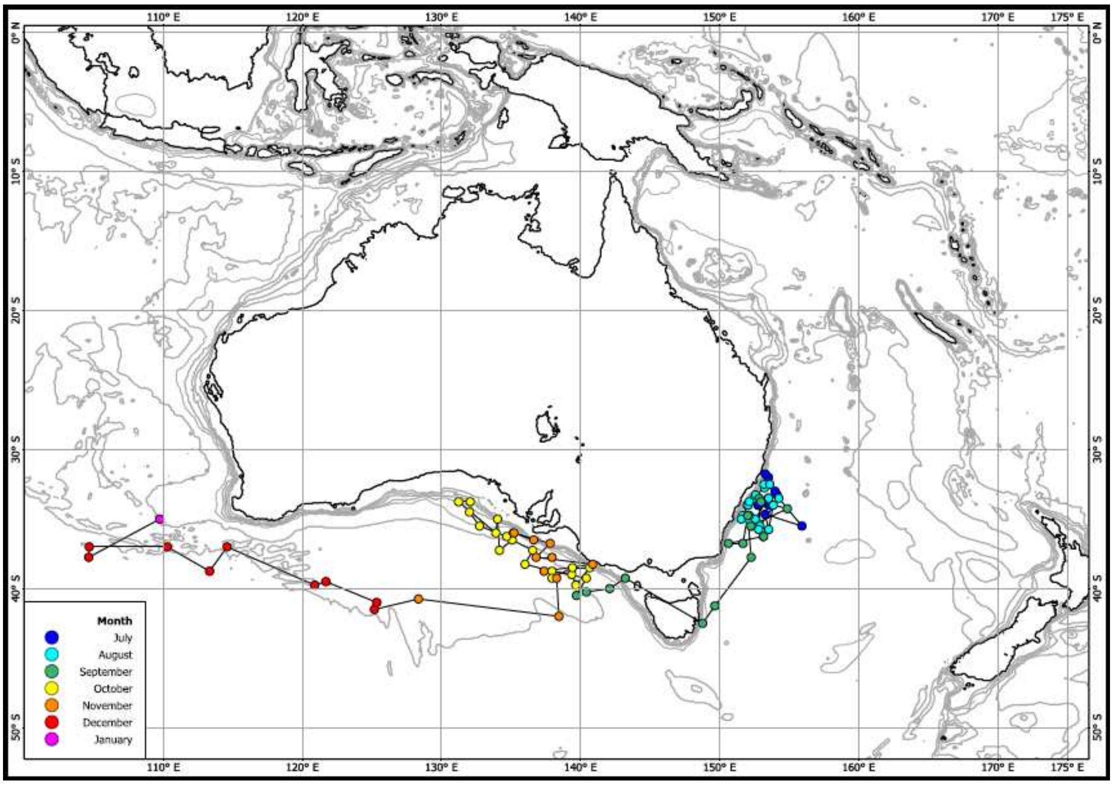

Figure A19. Individual track of 43928, at liberty 13 July 2004 to 14 January 2005.

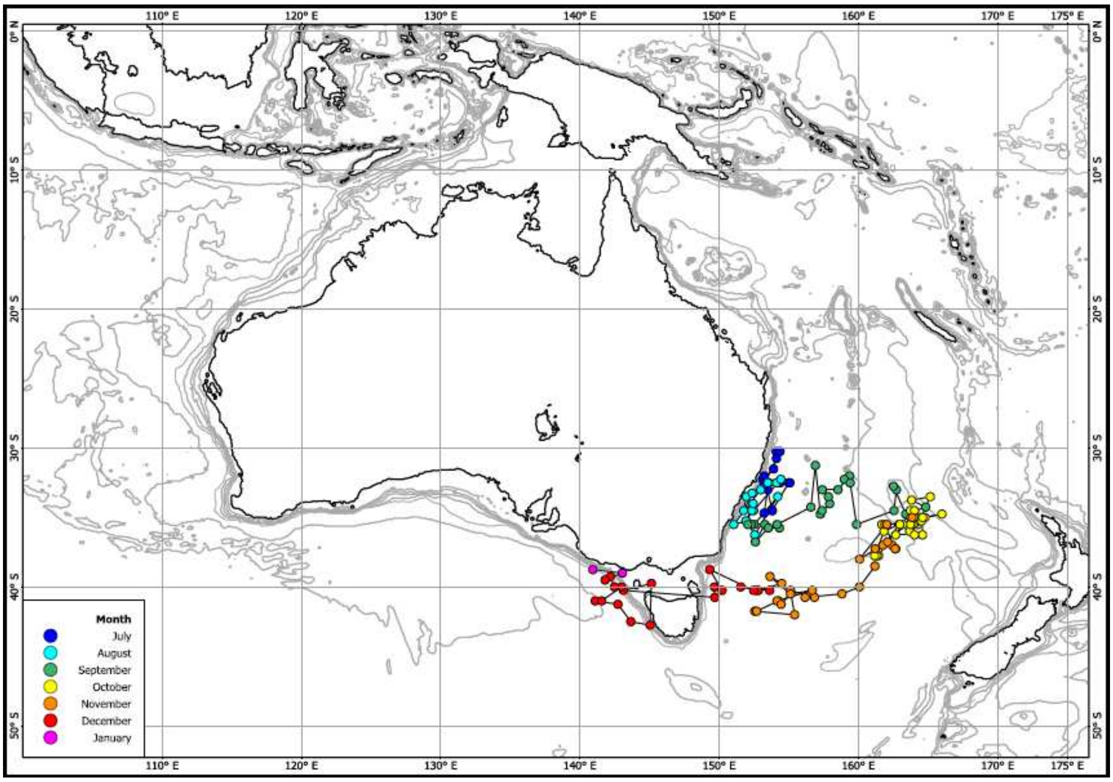

Figure A20. Individual track of 43933, at liberty 14 July 2004 to 02 January 2005.

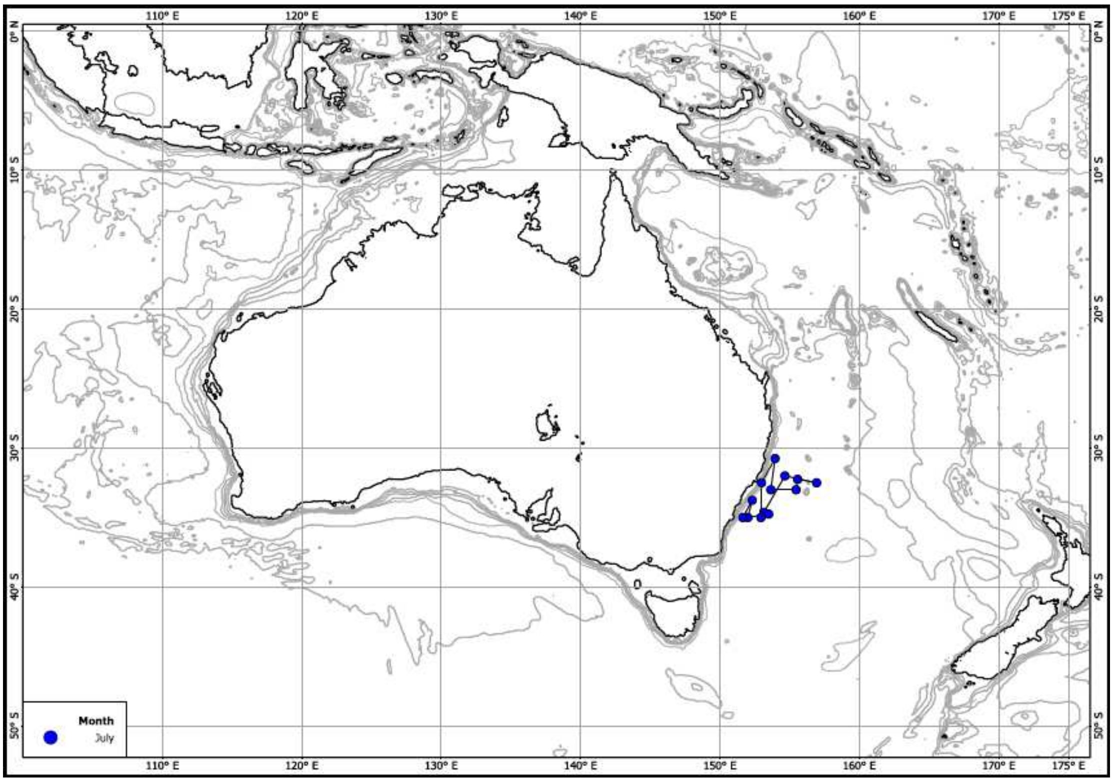

Figure A21. Individual track of 43934, at liberty 15 July 2004 to 29 July 2004.

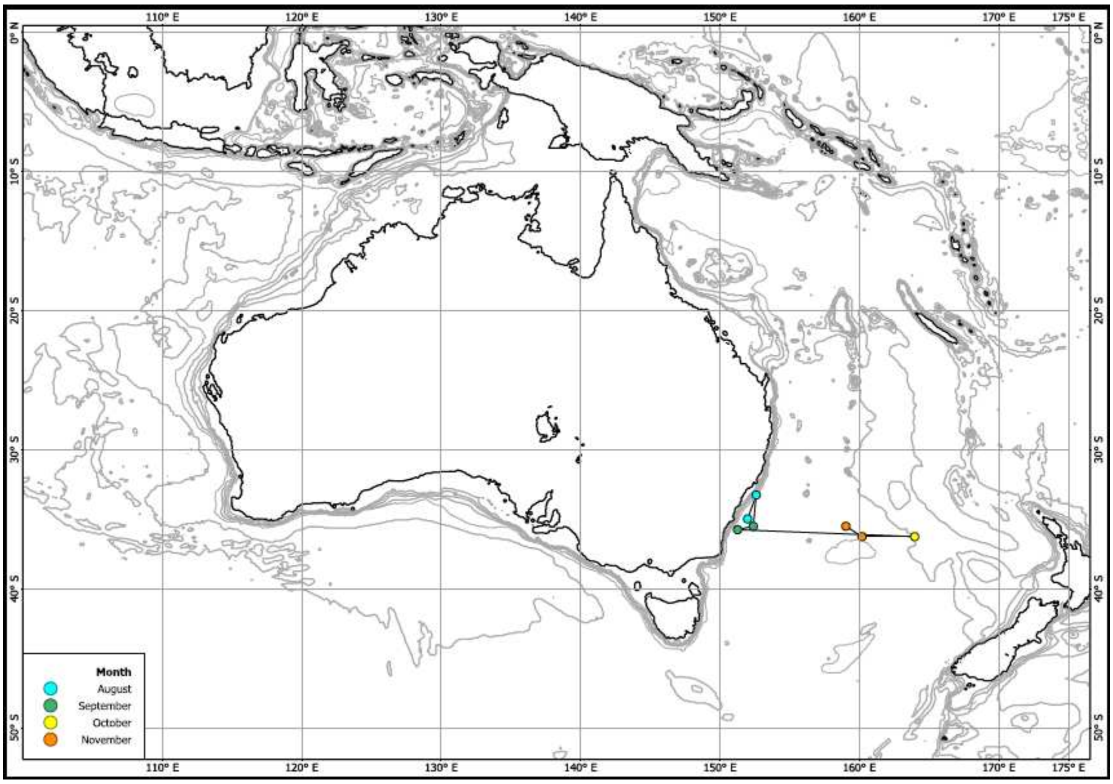

Figure A22. Individual track of 43945, at liberty 30 July 2004 to 13 December 2004.

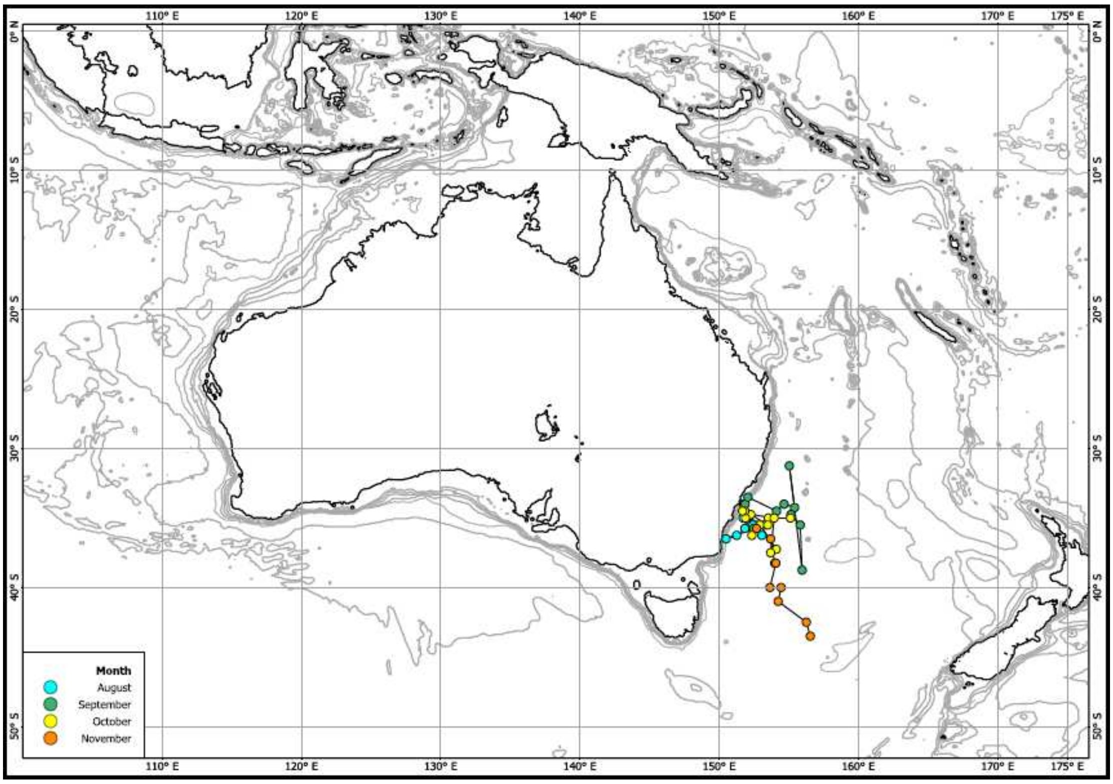

Figure A23. Individual track of 43943, at liberty 31 July 2004 to 15 November 2004.

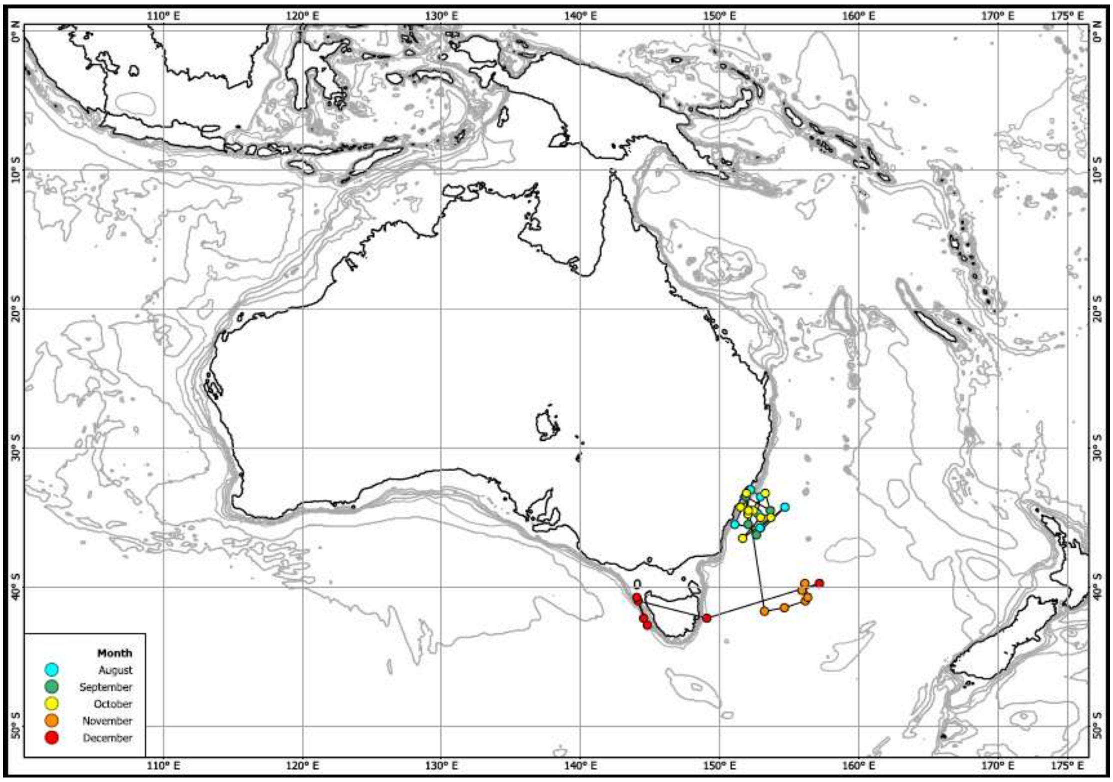

Figure A24. Individual track of 43941, at liberty 08 August 2004 to 29 December 2004.

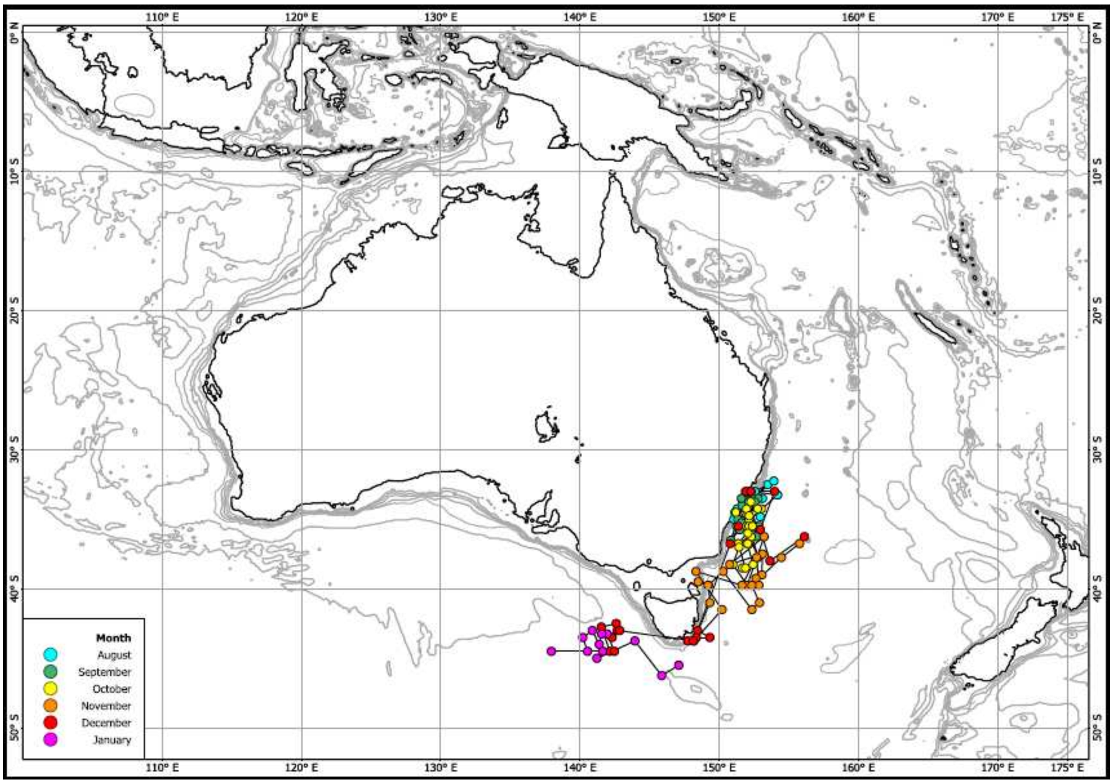

Figure A25. Individual track of 43942, at liberty 08 August 2004 to 15 January 2005.

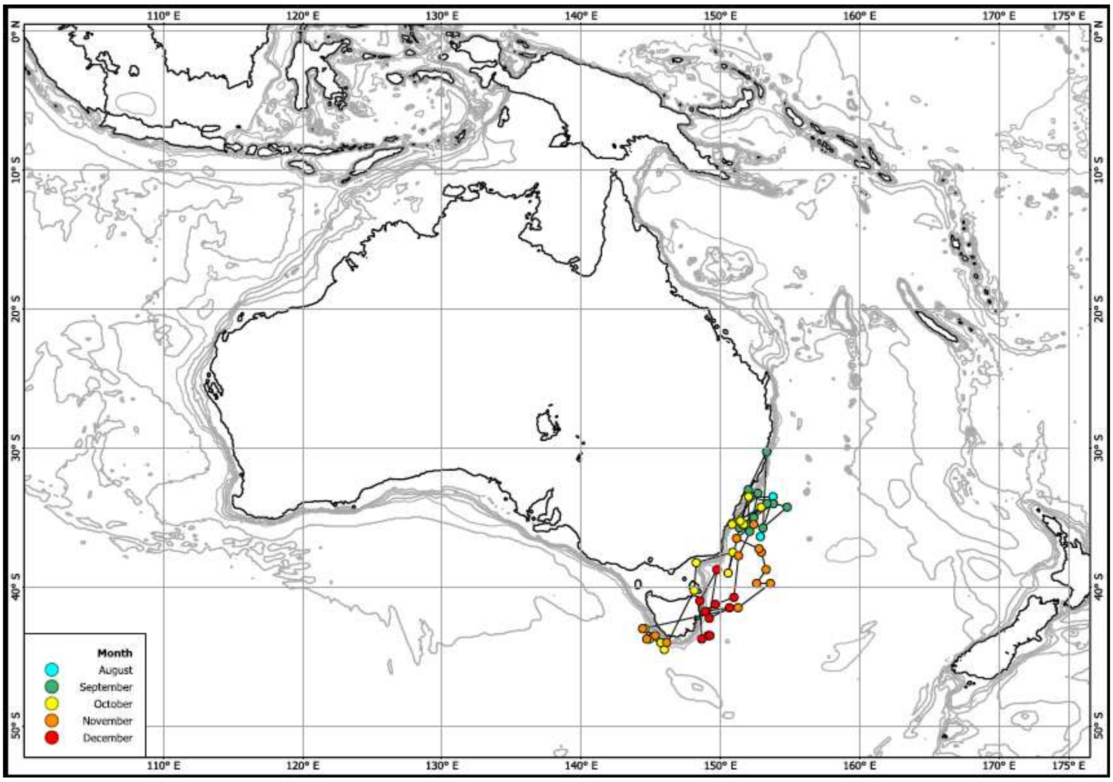

Figure A26. Individual track of 43940, at liberty 28 August 2004 to 30 December 2004.

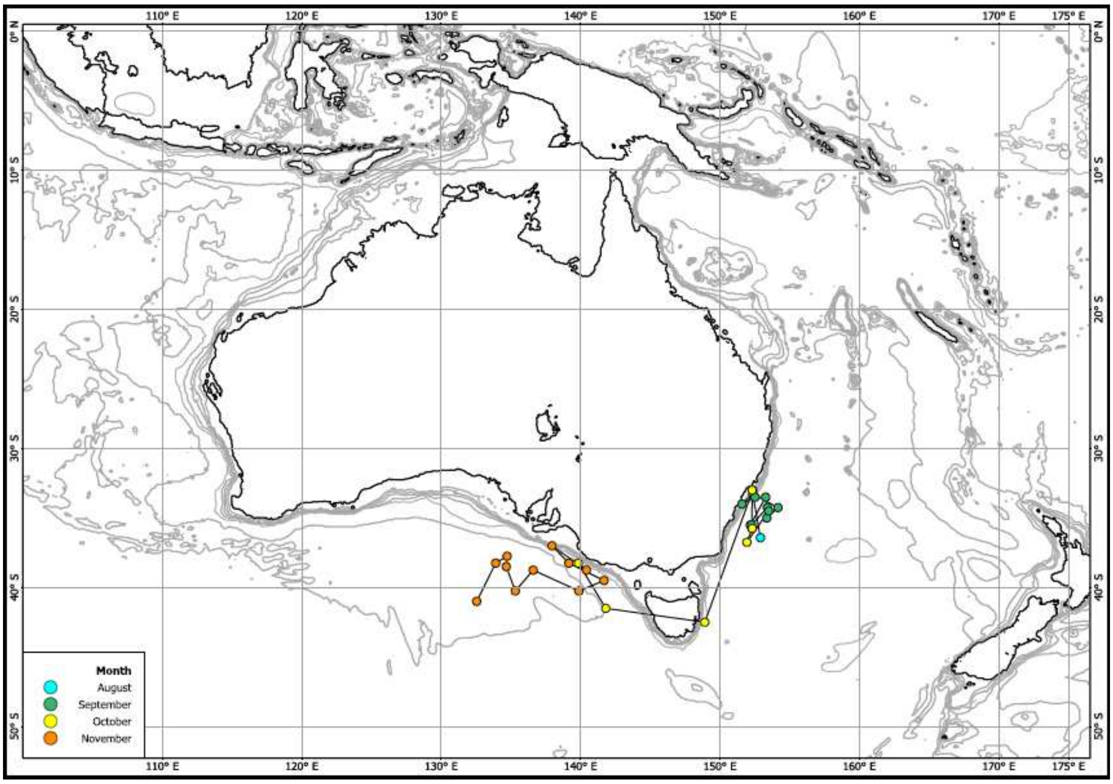

Figure A27. Individual track of 43939, at liberty 29 August 2004 to 27 November 2004.

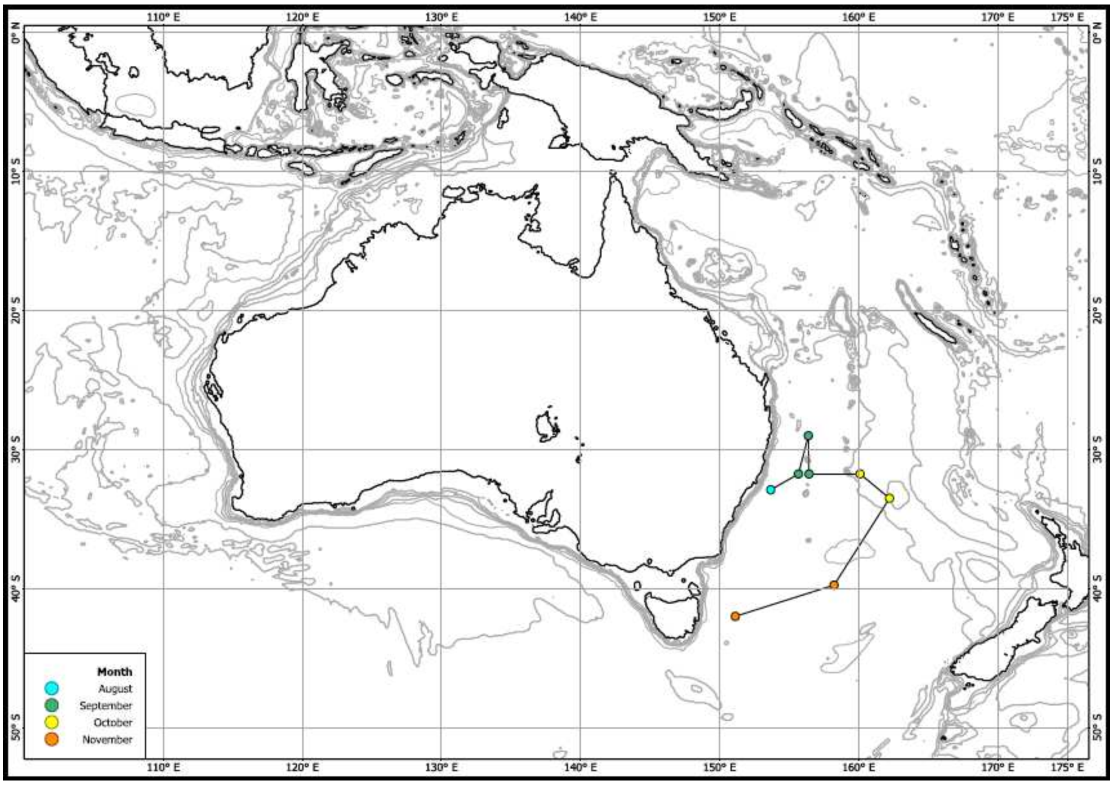

Figure A28. Individual track of 43944, at liberty 21 July 2005 to 10 December 2005.

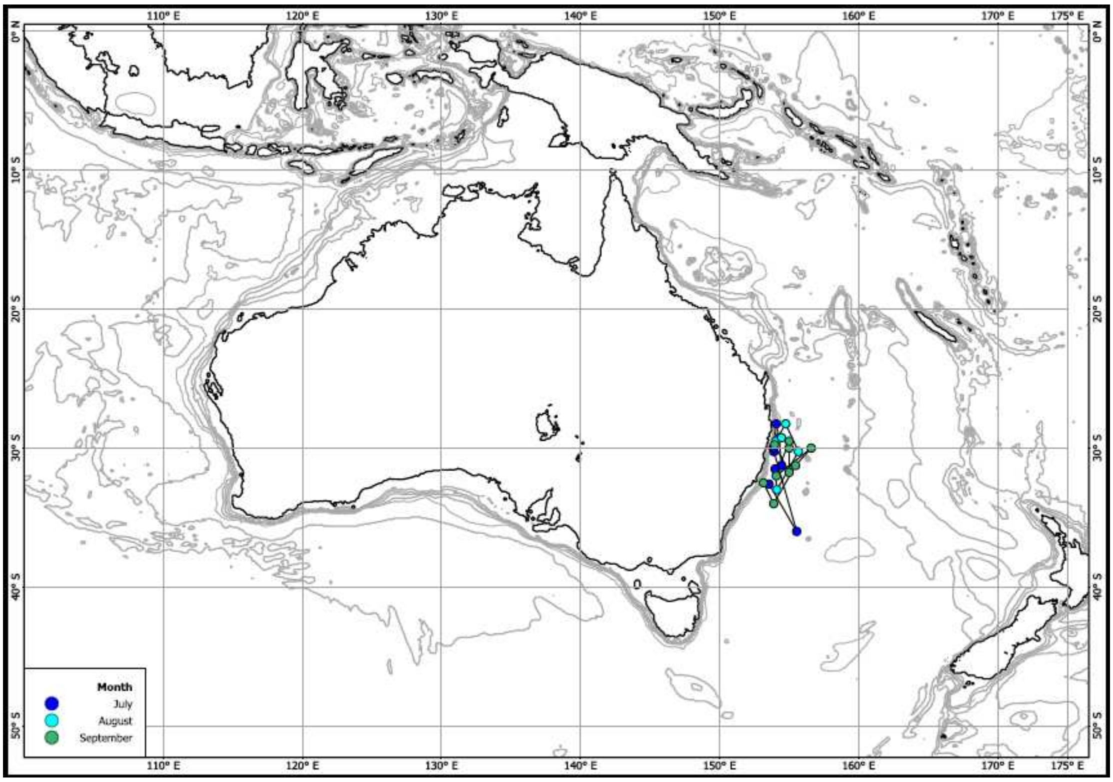

Figure A29. Individual track of 46337, at liberty 22 July 2005 to 13 September 2005.

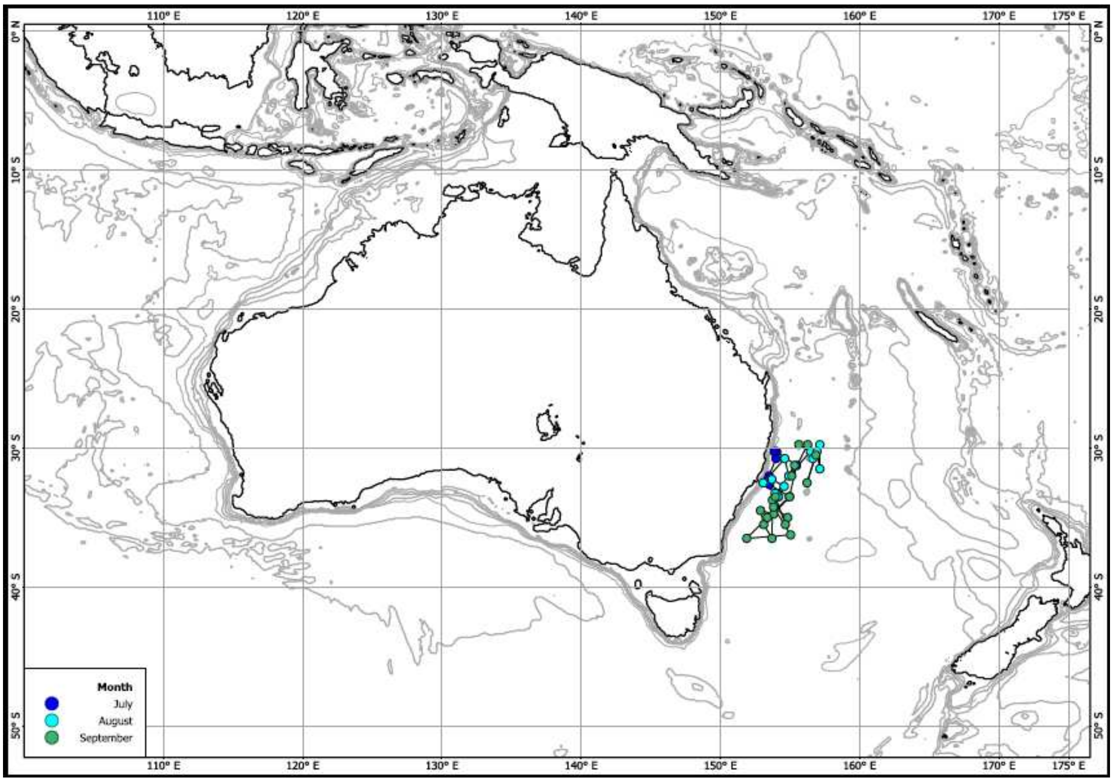

Figure A30. Individual track of 46339, at liberty 22 July 2005 to 21 September 2005.

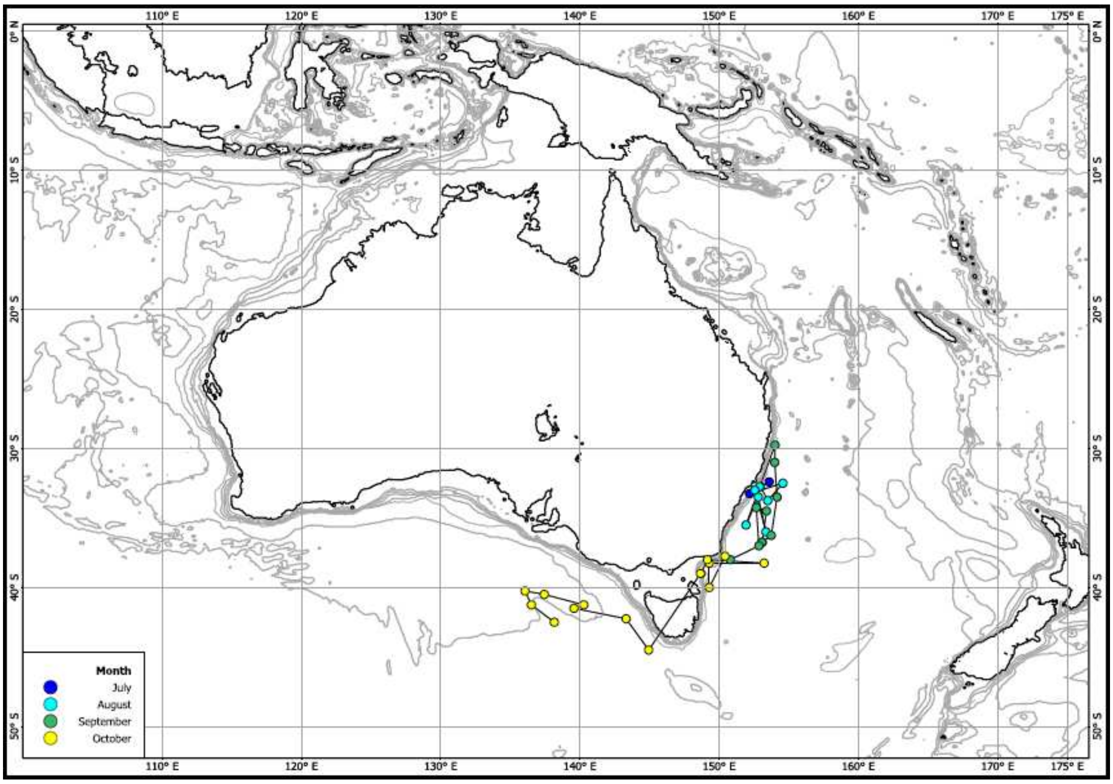

Figure A31. Individual track of 46336, at liberty 22 July 2005 to 29 October 2005.

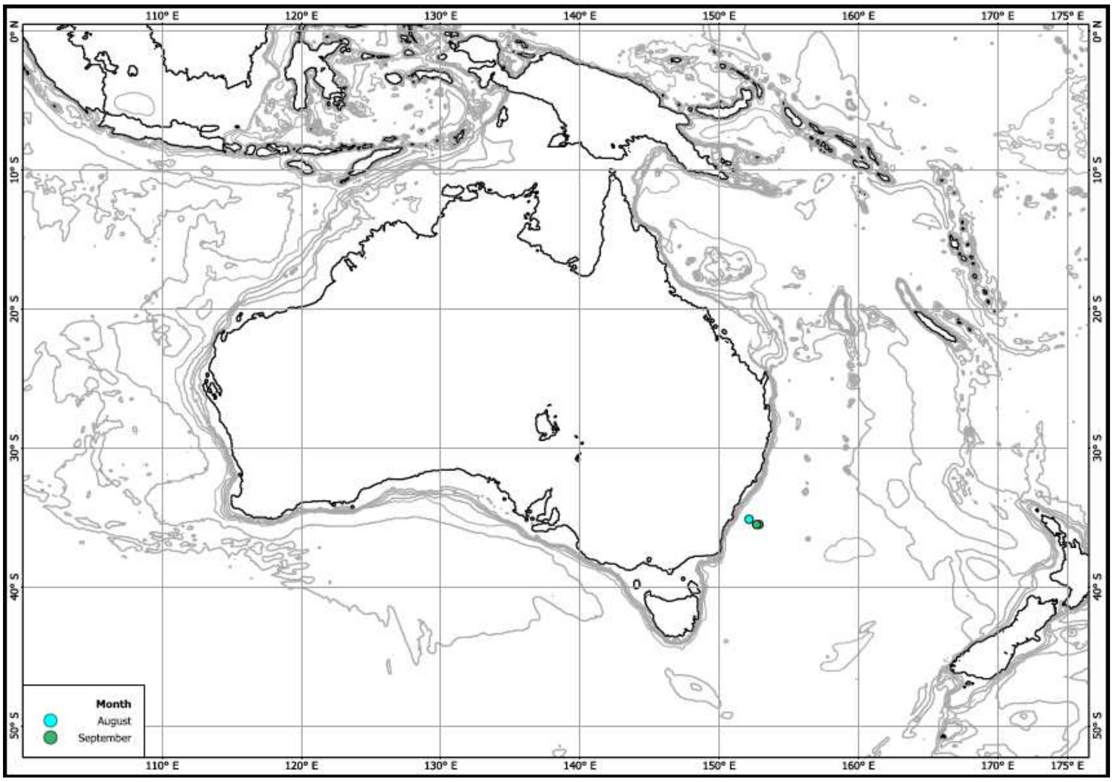

Figure A32. Individual track of 46340, at liberty 01 August 2005 to 02 September 2005.

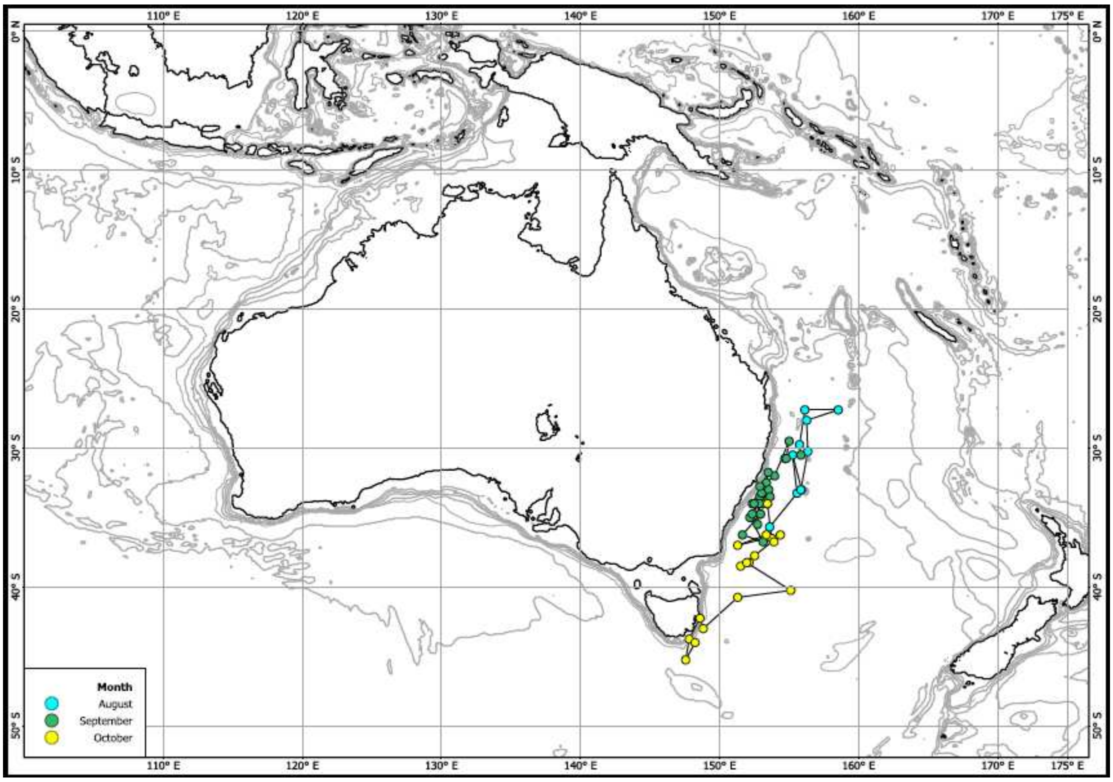

Figure A33. Individual track of 46342, at liberty 19 August 2005 to 20 October 2005.

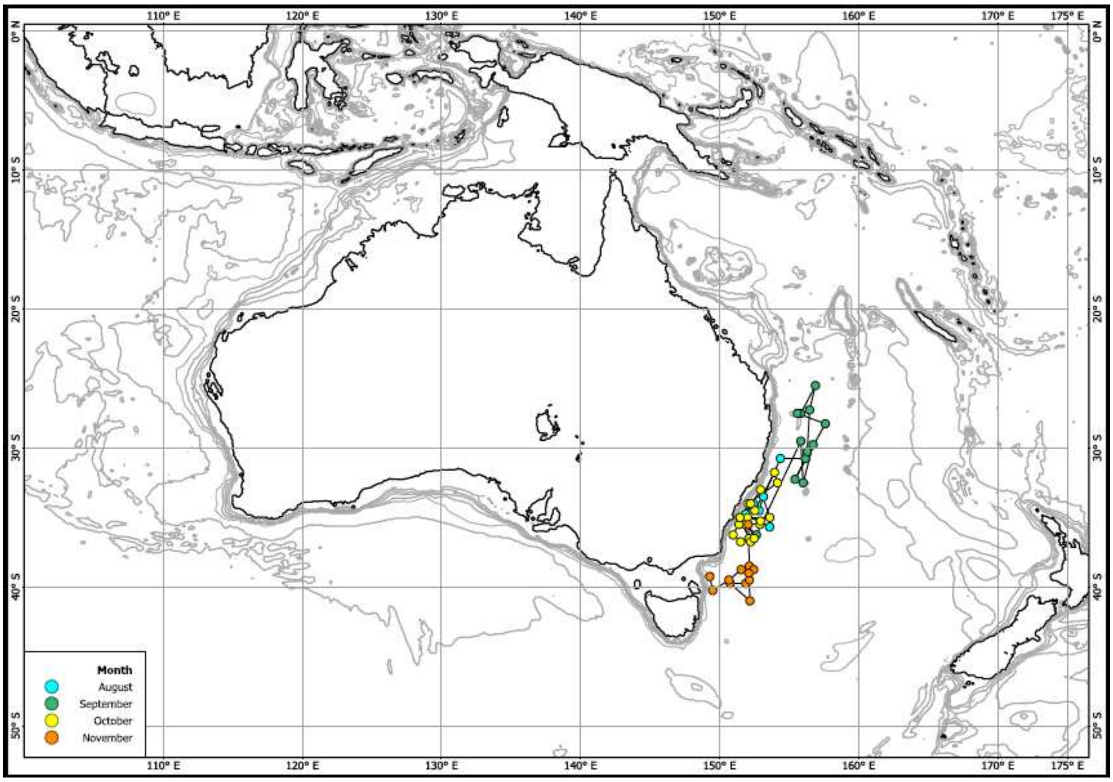

Figure A34. Individual track of 46343, at liberty 19 August 2005 to 21 November 2005.

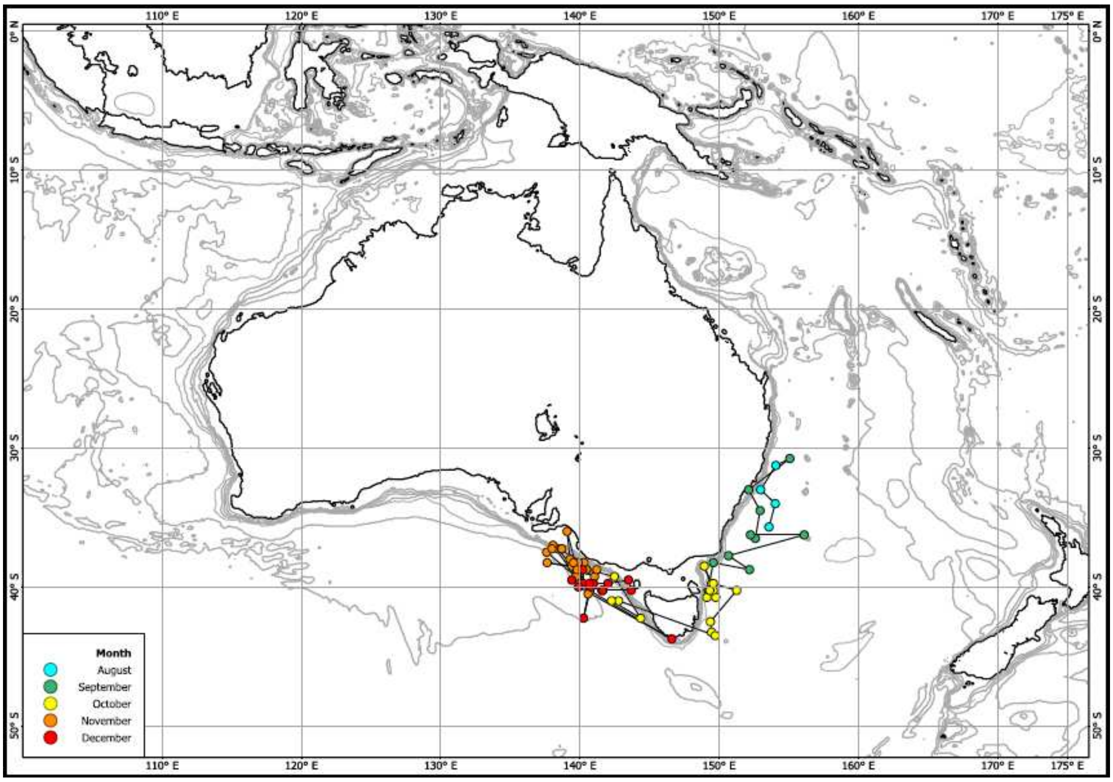

Figure A35. Individual track of 46350, at liberty 19 August 2005 to 27 December 2005.

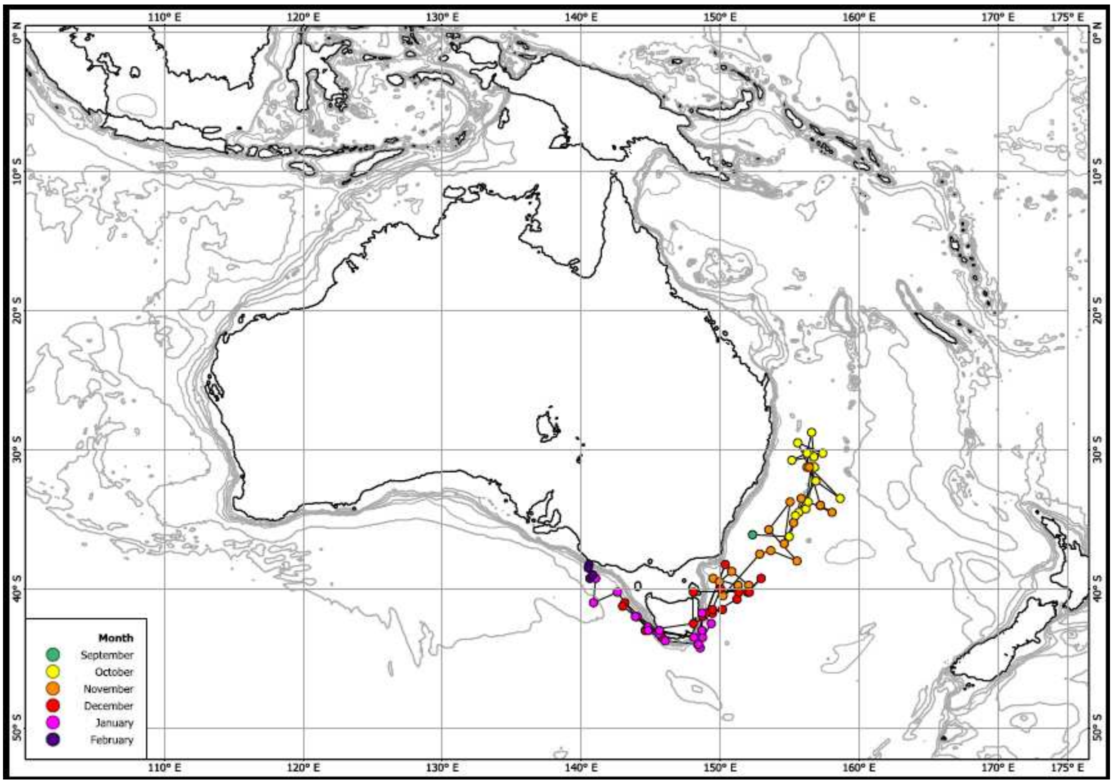

Figure A36. Individual track of 53263, at liberty 21 September 2005 to 06 February 2006.