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Spatial interactions among juvenile southern bluefin tuna at the global scale: A large scale archival tag experiment

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Abstract

The CCSBT Extended Scientific Committee has identified improving the understanding of the contemporary spatial dynamics of the SBT stock as a priority under the Scientific Research Program. This info paper is the project final report of the last large-scale collaborative electronic tagging study of juvenile SBT conducted under the CCSBT Scientific Research Program.

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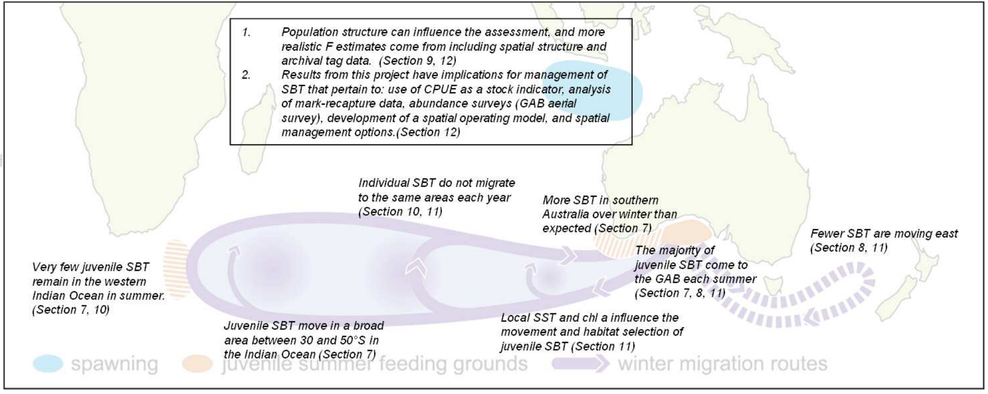

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2. Results from this project have implications for management of SBT that pertain to: use of CPUE as a stock indicator, analysis of mark-recapture data, abundance surveys (GAB aerial survey), development of a spatial operating model, and spatial management options.(Section 12)

Individual SBT do not migrate to the same areas each year (Section 10, 11)

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Very few juvenile SBT remain in the western Indian Ocean in summer. (Section 7, 10)

The majority of juvenile SBT come to the GAB each summer (Section 7, 8, 11)

Juvenile SBT move in a broad area between 30 and 50°S in the Indian Ocean (Section 7)

Local SST and chl a influence the movement and habitat selection of juvenile SBT (Section 11)

Project No. 2003/002

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Cover illustration: Feeding juvenile southern bluefin tuna (David Ellis), archival tag surgery (Alistair Hobday) and spatial dynamic schematic summarizing project findings.

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Acronyms

AFMA	Australian Fisheries Management Authority
CCSBT	Commission for the Conservation of Southern Bluefin Tuna
F	Fishing mortality, or harvest rate, i.e. mortality induced by fishing
GAB	Great Australian Bight; in this report it refers to the area between 128^{o}E and 145^{o}E, and all latitudes south of the coast, unless otherwise stated
GHMM	Grid-based hidden Markov model; a state-space model for estimating tracks. Space is “gridded” into discrete cells, and the states relate to “being within a given grid cell” at each time-step.
HMM	Hidden Markov model; a state-space model for analysis of time-series data. Here used to model movement behaviour in terms of a “resident” and “migratory” state; also see GHMM.
IO	Indian Ocean
M	Natural mortality, i.e. mortality due to non-anthropogenic causes
MP	Management procedure; defined as a simulation-tested decision rule (or harvest control rule), and the requisite methods of data collection and analysis, which together are used to calculate a management recommendation (e.g. total allowable catch (TAC)) for a fishery
OM	Operating model; the simulation model used for testing potential management procedures.
SA	southern Australia, referring to the GAB and Western Australia, between the longitudes 115^{o}E and 145^{o}E
SAfr	South Africa, referring to waters in the Indian Ocean, west of 40^{o}E (or as defined in the specific section)
SBT	Southern bluefin tuna (*Thunnus maccoyii*)
SEIO	South-east Indian Ocean
SST	Sea surface temperature, usually from oceanographic data or remote-sensed (satellite) products, but also calculated at the external temperature measured by the tag in depths less than 5m.
TAC	Total allowable catch

1 Non-technical Summary

2003/002. Spatial Interactions Among Juvenile Southern Bluefin Tuna at the Global Scale: A Large Scale Archival Tag Experiment

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OBJECTIVES:

The final set of objectives are listed here; the rationale for changes during the project are discussed in **Section 5**.

Objective 1: Tag 150-200 juvenile southern bluefin tuna (SBT) per year for 3 years with archival tags throughout the full range of spatial habitats in order to provide a comprehensive understanding of their spatial dynamics;

Objective 2: For each tag returned (expected to be ~20-30%) estimate daily position based on the stored light and temperature data and develop a database for the storage and analysis of all relevant location, temperature and depth data;

Objective 3 (revised): Provide a comprehensive analysis of the evidence for temporal changes in the spatial dynamics of juvenile SBT and analyse the implication of the information provided on mixing rate between the major SBT fishing and their changes over time for the use of combined archival and conventional tagging data to provide fishery independent estimates of fishing mortality for monitoring the SBT fishery.

Objective 4: Provide critical information and contribute to developing a framework for incorporating the archival tag and conventional tagging data within the SBT stock assessment model;

Objective 5 (revised): Integrate the position, temperature and depth data provided by the tags with oceanographic data to develop a seasonal model of residence times and habitat use for regions with consistent temporal patterns across the years.

Objective 6 (revised): Evaluate the implication from the seasonal habit model for the interpretation of future catch and effort data and monitoring strategies.

Objective 7: Evaluate implications of the spatial dynamics of juvenile SBT for the management of the SBT resource (e.g. the potential consequences and benefits of either ignoring or using spatially explicit management actions).

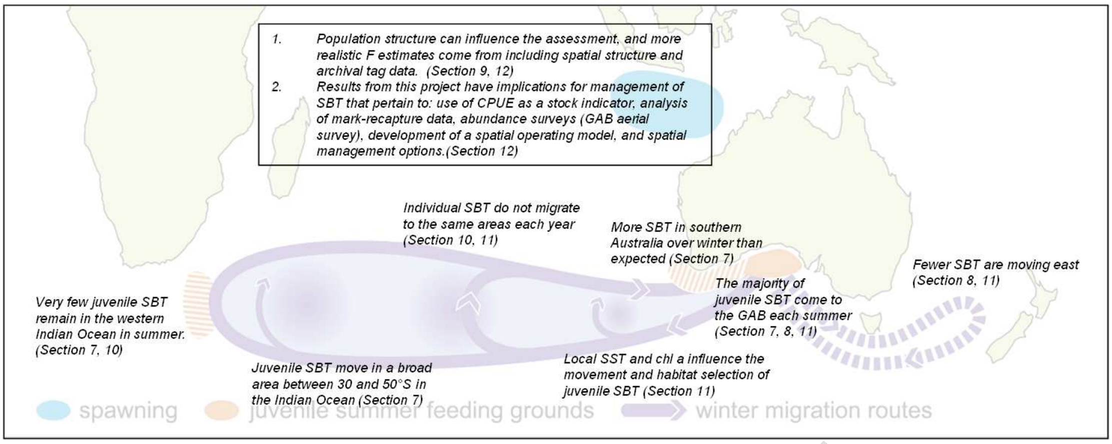
OUTCOMES ACHIEVED TO DATE

This project has led to substantial improvement in our current understanding of SBT movements and spatial dynamics, which should form the basis for improved models, including spatial population dynamics models to underpin future assessments and management procedures for SBT. Uptake of results has been delayed by the CCSBT's recent focus on developing a management procedure for SBT (see Future Outcomes). Results have increased our confidence in the recruitment index based on the aerial survey in the GAB by confirming that the timing and duration are ideal, that the majority of juvenile SBT return to the GAB each summer, and that there is currently no evidence for a large proportion of juvenile SBT remaining off South Africa over summer. This is of benefit to all stakeholders and management bodies, including the CCSBT.

By using information in this report, the fishery can now also address requirements within the guidelines under the strategic assessment provisions of the Environmental Protection and Biodiversity Conservation Act 1999 that "the distribution and spatial structure of the stock(s) has been established and factored into the management response".

Spatial structure of fish populations has long been recognised as a potentially critical factor in a population's overall dynamics, and hence of importance to stock assessments and management. Neither the population model used for southern bluefin tuna (SBT; *Thunnus maccoyii*) assessment and evaluation of management procedures, nor the management of SBT by a global total allowable catch (TAC) take spatial structure into account. In this ambitious project we used archival tags to provide the necessary data to start integrating the spatial dimension into the population ecology and assessment of SBT.

International collaboration between several SBT fishing nations was critical to the deployment and recovery of archival tags for this project. Tags were successfully released in all five desired areas (n = 568) on juvenile SBT (mostly ages 2-4). The recoveries to date (n = 74) represent 13% of releases, and include tags deployed by collaborators. Combined with earlier tag programs, a total of up to 122 tags were available for this project. Tags recorded up to 5 years of data (n=2), 75% of tags covered at least 6 months, and 41% covered at least one year – a marked improvement on the performance of early archival tags. The following schematic illustrates some of the findings discussed in the report.



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The first step in analysis was the difficult task of estimating the daily position of each SBT (latitude and longitude) from the light and depth data recorded by the archival tags. Two different approaches gave broadly consistent results, thus increasing confidence in subsequent use of these location estimates. Clear signals of cyclic seasonal movement are apparent from the estimated tracks. All SBT in our dataset spent each summer (or part of summer) in waters south of Australia (i.e., the GAB and waters south of WA), except one SBT tagged in the Indian Ocean in winter that visited the GAB in the summer following tagging, but spent two subsequent summers in waters off South Africa. The majority of SBT migrated from southern Australia to the Indian Ocean for winter, a much lesser percentage to the Tasman Sea and, somewhat surprisingly, a number of individuals overwintered in southern Australia. Juvenile SBT move in a broad area between 30-50^{o}S in the Indian Ocean; there does not appear to be specific, or narrowly defined, migration routes.

The position estimates were then used in three areas of analyses: 1) a spatial model for analysing mark-recapture data, (2) development of a seasonal migration model, and (3) estimating habitat preference

Two large conventional tagging programs were conducted by the CCSBT in the 1990s and the 2000s to reduce uncertainty in the assessments by providing estimates of mortality rates and abundance. For logistic reasons, juvenile SBT can only cost-effectively be tagged off southern Australia in summer. In such a situation, an analysis that ignores spatial structure can lead to biased estimates of mortality rates and abundance. We developed methods for incorporating archival tag data into a spatial mark-recapture model and applied these methods to simulated data, as well as to SBT conventional and archival tag data from the 1990s and 2000s. The simulations showed that including data from even a modest number of archival tags can substantially improve the precision of movement and fishing mortality estimates, particularly when fish are only tagged in some areas. In the application of the model to SBT data from the 1990s and 2000s, estimates of movement probabilities were unrealistic without archival tag data (e.g. for the 1990s almost no fish were estimated to return to the GAB for summer); realistic estimates were only obtained when archival tag data were included. For the 2000s data, cohort size estimates were consistently higher and natural and fishing mortality estimates were consistently lower with the spatial model compared to estimates obtained from a non-spatial model. Thus, using a spatial model to analyse the 2000s tagging data was critical. A spatial model is also considered important for planning and analyses of future mark-recapture programs for SBT.

We developed a seasonal model of migration (directed, fast movement) and residency (undirected, slow movement) for juvenile SBT. Whilst there is variability amongst individuals in movement dynamics, we quantify the periods of time spent in the resident state in summer and in winter, and the time spent migrating, either out of the GAB or back into the GAB. We have been able to quantify the main departure times from, and arrival times to, areas of high residency, as well as the variability in those times. These results have confirmed that the aerial survey timing and duration are well matched with the arrival and departure of SBT. In addition, all available evidence suggests it is unlikely that there is a large proportion of juvenile SBT resident in waters off South Africa in summer. This substantially increases our confidence in the aerial survey as an index of juvenile SBT abundance. However, the archival tag data to date does not answer the question of whether there are juveniles (age 2-4) that never visit the GAB in any summer; the answer could still be “yes”. A returned tag released off South Africa (of which we have had none to date) may help answer the question, but a definitive answer is most likely, and most cost effectively, obtained by otolith microchemistry.

The migration model results confirm that the high variability in migration paths and timing among individuals and years mean that low spatial (and temporal) coverage of effort remains a serious problem for getting a reliable index of abundance from catch and effort data. A spatial model and spatially explicit CPUE indices are likely to provide a more reliable interpretation of trends in CPUE series.

Habitat preference was determined by considering the combination of (i.e. interaction between) sea surface temperature and chlorophyll *a*. Preference maps show that in most years the GAB is highest preference summer location in the southern oceans. In some years the area off NSW, where a surface fishery used to operate until the early 1980s, also shows up as an area of high preference. Preference maps for the late 1990s show a linking band of high preference around Tasmania and into the Tasman Sea in April to June, which is almost absent in recent years. This could explain why fewer juvenile SBT have been migrating to the Tasman Sea in winter since 2001.

Habitat preference analyses could potentially assist in the standardization of CPUE indices for use in the CCSBT stock assessment process, particularly dealing with regions with no fishing effort. However, habitat preference for the age classes in the longline catches (which are older than the age classes involved in this study) will have to be developed, and variation in preference and environmental conditions over time will have to be considered, before this is possible. Other approaches to CPUE standardisation, such as developing models for estimating catchability by depth, will require substantial additional data collection (e.g. on sub-adult SBT behaviour) and analyses, and we doubt the value of embarking on such an exercise for this purpose, given that it would not resolve the major concerns of (1) operational changes in longline fleet behaviour and (2) lack of spatial and temporal coverage. We do not doubt the value of collecting more data on sub-adult behaviour, which is lacking for SBT, just that we discourage doing so solely for the purpose of CPUE standardisation.

Spatial structure of a population can influence stock status assessments, and results from this project suggest that a spatial operating model for SBT would be preferable to a non-spatial model, both from the point of view of mark-recapture data analyses and the interpretation of CPUE indices. Developing a spatial operating model should be possible, but will not be a straightforward or quick task. Decisions about a range of modelling issues would need to be made within the relevant CCSBT forums. A program for ongoing data collection to inform a spatial model would need to be designed. Given challenges with CPUE interpretation, we also suggest a return to mark-recapture approaches, both for use in the (ideally, spatially explicit) operating model and for potential use in a future management procedure.

Regarding spatially explicit management, there is a strong case for a separate TAC on age 2-4 juveniles in the GAB during summer because of their segregation by age and their strong summer site fidelity. By accident – rather than design – this is the case since the Australian ‘member country’ allocation is currently almost entirely taken by the juvenile surface fishery in GAB. There is currently no evidence of a large proportion of juvenile SBT off South Africa in summer, but if this situation changes and if a sizeable fishery did develop, then spatial management of the juvenile component would need to be considered. This is because there is a strong possibility that juveniles off South Africa would show similar high levels of summer site fidelity as juveniles in the GAB do. The need for spatial management of the winter longline component, i.e. ‘Tasman SBT’ and ‘Indian Ocean SBT’, to avoid localised depletion is less clear because winter site-fidelity of age 5 and older SBT is unknown. Another advantage of a spatial operating model would be the ability to evaluate the need for spatially explicit management.

Overall, we have assembled the most comprehensive picture yet of the cyclical seasonal migration and global movements of juvenile SBT, which will support future spatial assessment (and management where appropriate), as well as process understanding for this species.

2 Acknowledgments

The vision of Tom Polacheck and John Gunn in project development and leadership in earlier phases of this project, and their general leadership in tuna research and management, is gratefully acknowledged. This project was possible as a result of logistical support from New Zealand (coordinated by Talbot Murray) and Taiwan (coordinated by Eric Chang) facilitating release of tagged fish by their observers on commercial fishing vessels. We are grateful to the commercial fishers in Australia and on the high seas who continue to recover and return archival tags, which will be valuable beyond this project. Collaboration with Japanese scientists Ryo Kawabe and Tomoyuki Itoh also allowed release of archival tags during acoustic monitoring experiments in southern Western Australia. The support of the CCSBT secretariat in handling the returns of archival tags as part of the conventional tagging program is also appreciated. We thank the tag manufacturers, Wildlife Computers, for technical tag support. The dedication of a number of CSIRO staff, as recognized in **Appendix 2**, was critical to this project and is much appreciated. Statistical advice from Mark Bravington, geolocation assistance from Chi (Tim) Lam and Anders Nielsen, and general CCSBT insight from Ann Preece enhanced the quality of analyses presented here. Toni Cracknell assisted with the preparation of the final report. Review of sections of this report by Ann Preece, Richard Hillary and Campbell Davies is appreciated.

3 Background

Fishery stock assessments have traditionally been based on assumptions of spatial homogeneity, and spatial considerations have generally not been incorporated into management measures (e.g. quotas are mostly set at a global level). Nevertheless, spatial structure has long been recognised as a potentially critical factor in a population's overall dynamics and something which should ideally be accounted for within the stock assessments where possible, and management where relevant. The underlying inputs into both of these should clearly then also account for spatial structure. The failure to incorporate spatial aspects stems largely from a lack of understanding and absence of quantitative data about the underlying spatial dynamics of the species in question. This in turn largely reflects the absence of effective tools for actually measuring the fundamental elements of spatial dynamics, such as movement, migration, and residence time.

For large pelagic resources, the problems of collecting data on spatial dynamics has been particularly challenging because of the wide range over which these resources occur and the inherent high cost associated with high seas research. In the early 1990's, CSIRO initiated extensive work into the development of archival tags that could provide quantitative data on how fish utilise their spatial environment (e.g. location, depth distribution, preferred water temperatures). This work, in conjunction with related research developments elsewhere, resulted in the availability of highly efficient archival tags that can be deployed in tuna and other species (e.g. Gunn and Block 2001). Extensive testing and targeted deployment of these tags had been conducted with juvenile southern bluefin tuna (SBT; *Thunnus maccoyii*) within the Great Australian Bight (GAB). The results from this early work provided important insights into the SBT spatial behaviour (particularly within the GAB; Gunn 1999; Bestley *et al.*, 2008; Bestley *et al*., 2009) and demonstrated the potential power of these tags to provide the data necessary to start integrating the spatial dimension into the population ecology and assessment of pelagic resources.

Juvenile distribution in summer and winter

All current information – both at the start of the project and at the time of writing this report – suggests there is a single genetic SBT stock with only one spawning ground in tropical waters south of Indonesia (**Box 3.1)**. The species is distributed widely throughout most of the southern temperate oceans (30 - 50°S) except in the more easterly regions of the South Pacific, and encounters a range of oceanographic conditions (**Box 3.2)**. Large numbers of juveniles (ages 1 to 5) are found in coastal waters of Australia, especially the GAB, where substantial numbers are taken by Australian surface fisheries (currently almost exclusively by purse seining for farming purposes). However, juveniles are also found and captured by longline fisheries on the high seas in areas ranging from east of Tasmania to South Africa. Historically, catches of 3- and 4-year-old fish with reasonable catch rates occurred during January, February and March in the South African fishing ground. More recently (2002), there is significant evidence, based on information collected from Taiwan longline vessels, of aggregations of 2-3 year old SBT off southeast Africa during summer months (Gunn and Farley, 2000). In both cases, the occurrence of these juvenile SBT is at the same time as the vast majority of this age group has been assumed to be in coastal Australia (principally in the GAB). The relationship between juveniles captured in these various areas is poorly understood. However, the existence of any large concentrations of juveniles off South Africa during these summer months would have major implications for the analyses and interpretation of the results from the CSIRO/NRIFSF[1] Collaborative Recruitment Monitoring Program[2] (RMP) and the CCSBT conventional tagging program. The domestic SBT industry has also highlighted the need to investigate this critical issue.

Analyses of Japanese longline catch rates for SBT have generally focussed on generating aggregated indices covering the entire stock. Comparison of these aggregated indices with catch rate trends from the different summer grounds indicates a similar overall long-term trend (both for juveniles age 3-6 and the older components of the population). However, there have been substantive differences between the spatial regions over shorter time periods and particularly since the large reductions in catches beginning in the mid-to-late 1980's. This pattern suggests differential exploitation and spatial structuring of the population among the spatially separated feeding grounds, with implications for developing strategies for rebuilding the stock and for setting appropriate catch levels.

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[1] National Research Institute of Far Seas Fisheries, Japan

[2] An aerial survey and acoustic survey formed part of this program, and interpretation of the data from these surveys, as indices of abundance of juvenile SBT, depend on assumptions about the proportion of the population that is in the GAB and whether this proportion is constant over time.

It is known that juveniles conventionally tagged off the south coast of Australia can move large distances and can be recaptured in all of the major longline fishing grounds. However, returns from the South Africa area have been proportionally much smaller than returns from the Tasman Sea and southeast Indian Ocean grounds. The extent to which this represents differential reporting rates or incomplete mixing cannot be determined with existing data. There are also some indications of differential returns from South Africa depending upon whether SBT were tagged in Western Australia or South Australia. Similarly, at the time this project was proposed, none of the archival tag returns from fish tagged in the GAB had shown movements to the fishing area off South Africa. Most of the archival tags indicated 2 and 3 year old SBT had an annual migration between summer feeding grounds in the GAB and winter feeding grounds in either the central and southeast Indian Ocean or the Tasman Sea area. For all the cohorts into which archival tags had been deployed before the start of this project (1990-1999), the majority of fish moved west into the eastern Indian Ocean during winter.

Box 3.1. The biology of southern bluefin tuna

Southern bluefin tuna (SBT, Thunnus maccoyii) are a highly migratory species that occur in waters of the Indian Ocean and south-west Pacific between 30°S and 50°S. In Australian waters, SBT ranges from northern Western Australia, around the southern region of the continent, to northern New South Wales (Caton, 1991). There is a single known spawning ground in the Indian Ocean between Java and northern Western Australia (**Figure B3.1.1**), and SBT are assumed to comprise a single stock based on genetic evidence (Grewe et al., 1997). SBT are captured by longline fisheries on the spawning ground in almost all months of the year, although peaks in abundance occurred during October and February (Farley and Davis 1998). Juveniles move down the west coast of Australia and are found in southern western Australia as age-1 fish (Hobday et al., 2009; **Figure B3.1.1a**), then an unknown fraction, but assumed to be the majority, move to the Great Australian Bight (GAB) where they spend summers for the next 2-5 years, migrating to the southern oceans in winter (**Figure B3.1.1b**). Adult SBT are assumed to forage throughout the temperate waters of the southern oceans during winter, migrating to the spawning grounds of the north-western Indian Ocean from spring to autumn (Caton, 1991) before returning to foraging grounds. While some younger fish have been captured on the spawning ground (e.g. age-5), the age at which 50% of fish are mature is around 10-12 years (Davis and Farley, 2001; Gunn et al., 2008), however, it is unknown if mature fish migrate to the spawning area each year, and how long they remain on the spawning ground. Maximum lifespan is estimated to be 40 years (Gunn et al., 2008).

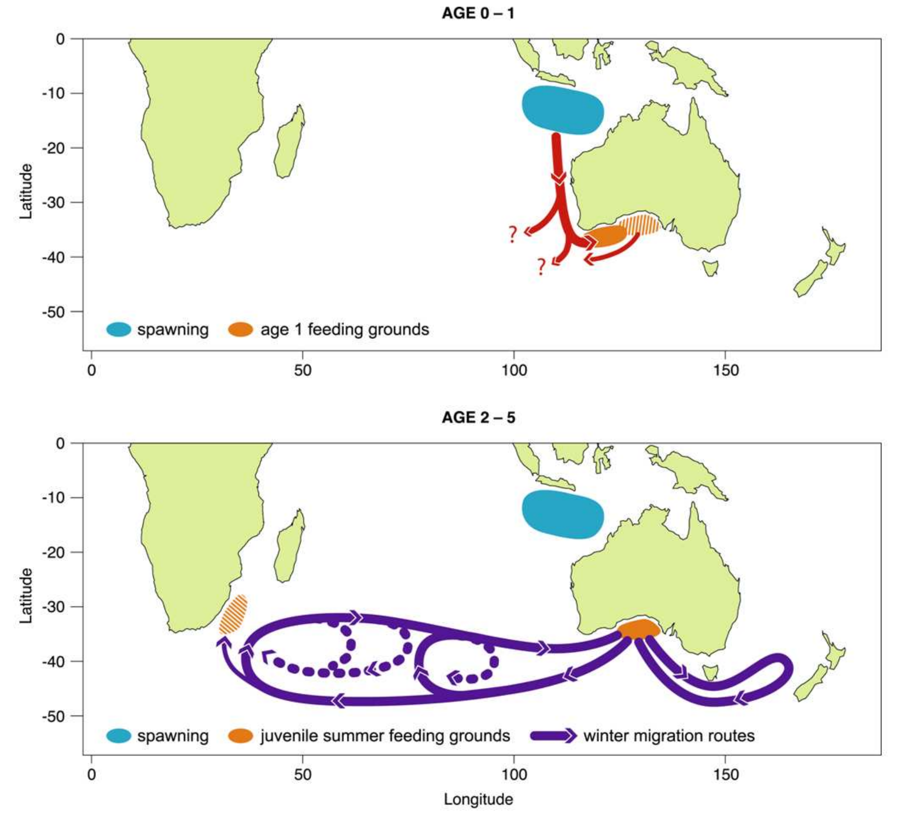

Figure B3.1.1. General movement and distribution of juvenile SBT as understood at the start of this project: (a) age 1 (b) age 2-5.

Box 3.1 – continued.

SBT are able to maintain body temperatures above ambient water temperatures, and are able to exploit rich feeding grounds in the cold waters of the southern oceans. They are generalist feeders on fish, squid, and krill (Young et al., 1996; Itoh et al., 2011).

Photo: David Ellis

SBT are the focus of a large, high value, multi-national, commercial fishery throughout their range. Stock assessments suggest that the current population of SBT is around 5% of the pre-exploitation biomass circa 1960 (Anon. 2010). Much of what is known about the movements of SBT has been determined from conventional tagging studies over the past 40 years and analysis of longline catch data. In more recent years, electronic tagging studies have shed more light on the movements of this species (Bestley et al., 2009; Patterson et al., 2008; Fujioka et al., 2010), information which is now used in several management contexts (e.g. Hobday et al., 2009; Hobday et al., 2010).

Results from this project have contributed substantial additional knowledge as discussed in the main sections of this report.

Conventional tagging program

The Commission for the Conservation of Southern Bluefin Tuna (CCSBT) initiated a large scale Scientific Research Program (SRP) in 2001 for improving the information required to assess the state of the SBT resource (Anon. 2005). One of the primary components of the SRP was a conventional tagging project to estimate fishing mortality rates and thereby current stock sizes. This tagging program was seen as the key element in reducing the uncertainty in the stock assessment. The implementation of this program was seen as a matter of urgency and tagging commenced in southern Australia 2002. The CCSBT Scientific Committee, in recommending a tagging program, recognized that a key uncertainty in the interpretation and analyses of the data would be modelling the mixing of tagged animals within the full population. It recommended that data be collected (including archival tagging data) that would be useful in estimating mixing rates and provide a robust basis for interpreting the conventional tagging results.

The CCSBT SRP conventional tagging program is intended to provide direct estimates of juvenile fishing mortality rates and recent recruitment. It is intended to provide a basis for reducing uncertainty in the stock assessments and to allow more reliable, short-term information for evaluating the sustainability of recent catch levels. However, the robustness and uncertainty associated with estimates of fishing mortality rates will depend upon the extent to which non-mixing can be ignored or to the extent that it can be accounted for within the analyses. The information provided by the conventional tagging program on mixing and spatial structuring will be limited by two factors: (1) conventional tagging cannot provide information on the movements of fish among areas where there is no fishing activity, and (2) mixing rates are highly confounded with the estimation of reporting rates. For the longline fisheries, conventional tag reporting rates are likely to be poorly estimated. As such, independent information on SBT movements will be critically important for the interpretation of the results. Because archival tags provide information on the daily position of individual fish, they are highly informative about movement and mixing rates. This contrasts with information from conventional tags, which only provide information on release and recapture location but no information on where the fish has been in the interim. In addition, although the recovery of archival tags is dependent upon a fish being recaptured in a commercial fishery, the tags provide information on mixing and movements in regions not covered by the fleets.

The large amount of "fishery-independent" movement information available through the use of archival tags can complement and greatly improve the information content and interpretation of the conventional tagging data, and vice versa. This archival tagging project was planned to run concurrently with the conventional tagging program to ensure that differences among years in factors affecting movements (e.g. water temperatures) are not confounded. In addition, the fact that CCSBT was implementing its SRP with both high sea observer programs and large scale conventional tagging programs (beginning in 2002) constituted a unique opportunity for efficiently and effectively conducting a large scale archival project. Thus, the operational costs in terms of archival tag deployment and recovery could be done with marginal increases in cost and the potential for recovery of tags was also maximized.

Changes during the course of the project

In 2000, the CCSBT also agreed to embark upon a process to develop a management procedure for the SBT fishery (Anon., 2000). A management procedure (MP), is defined as a simulation-tested decision rule (or harvest control rule), and the requisite methods of data collection and analysis, which together are used to calculate management recommendation (e.g. total allowable catch (TAC)) for a fishery (e.g. Butterworth *et al.*, 1997; Smith *et al.*, 1999). In the case of the CCSBT, the simulation model used for testing potential MPs was developed from the stock assessment model being used at the time, and is referred to as the operating model (OM). The original target date for adoption of an MP was 2004, but the development process suffered from a number of setbacks, culminating in revelations of substantial data problems in 2005–2006 that undermined confidence in the agreed MP (Anon. 2006; Kolody *et al.,* 2008). As a result, MP implementation was suspended until the implications of the data problems could be formally admitted within the simulation testing process. MP implementation is now expected to begin in 2011 at the earliest (Anon. 2010)

The main data problems relate to evidence of under-reported catches, which may have been substantial over a long period of time (Anon. 2006). There is uncertainty about the magnitude of the unreported catches, although the uncertainty has not been explicitly estimated (Kolody *et al.*, 2008). There is also still uncertainty about how under-reporting occurred, and therefore whether, and to what extent, historic catch-effort data (used to develop CPUE indices) have been affected. This was the main reason for revisions to Objectives 5 and 6 (see **Section 5**).

The uncertainty in total catches affects the analysis of conventional tagging data to estimate abundance and mortality rates; while the tagging data can be used without catch data, only mortality rates can be estimated. In addition, early returns from the conventional tags indicated apparent changes in the spatial dynamics of age 2 juveniles tagged off WA in the 2000s, compared to the 1990s (this is discussed in **Section 9**). This led to a revision of Objective 3 (see **Section 5**).

At the time this project was proposed, the aerial survey for juvenile SBT in the GAB in summer had been suspended since 2000 due to logistic problems of finding trained, experienced spotters and spotter-pilots (Cowling *et al*., 2003). The suspension also allowed for further data analysis and an evaluation of the effectiveness of the survey. This project therefore had no direct objectives relating to the aerial survey. The aerial survey was re-instated in 2005 and now forms part of the CCSBT OM and MP that have recently been tested for anticipated adoption by the Commission in 2011 (Anon. 2010, Hillary *et al.*, 2010). Therefore, although there are no specific objectives relating to the aerial survey, we comment on implications of results for the aerial survey index of juvenile abundance where relevant (**Section 12**).

Overall, despite a general understanding that juveniles move between the GAB in summer and the Indian Ocean or the Tasman Sea in winter (**Box 3.1)**, substantial uncertainties about SBT movement dynamics remained at the start of the project. We address these questions in the following sections of this report, as illustrated in **Figure 4.1**.

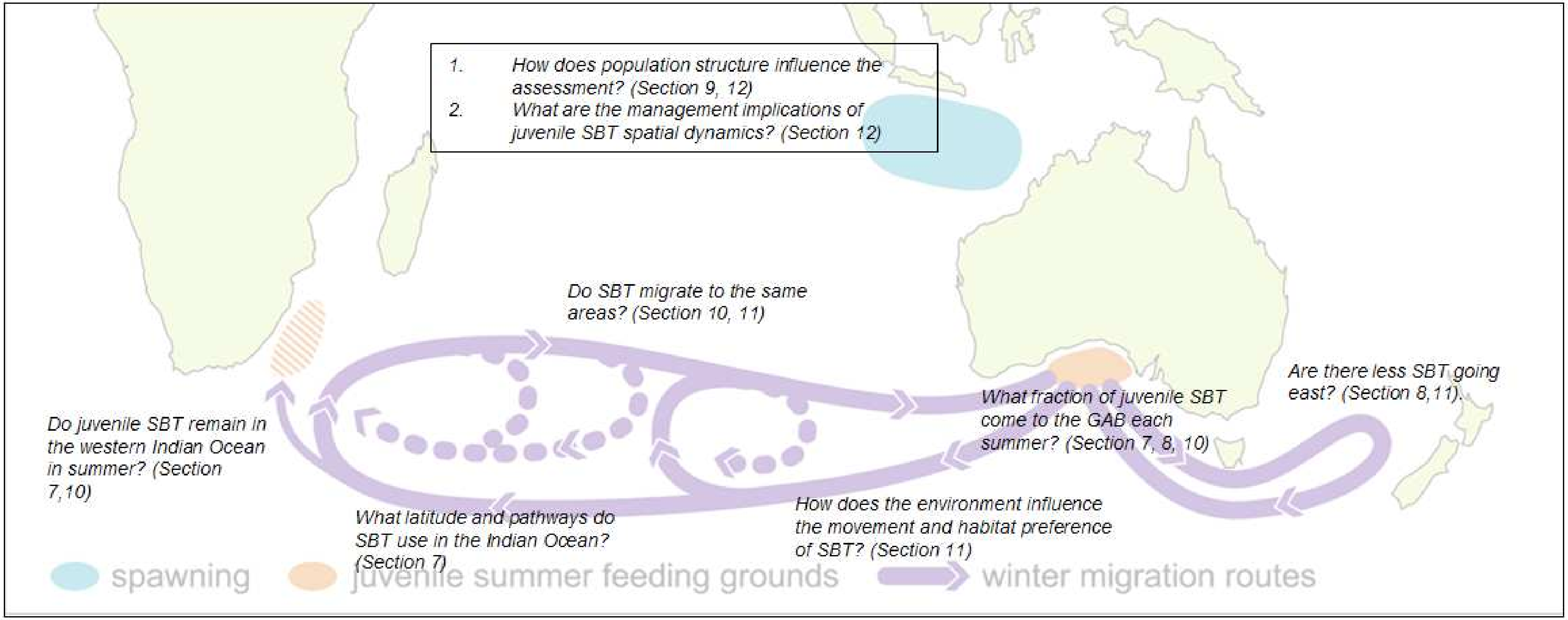

Figure 4.1. Questions regarding the movement and habitat use of juvenile southern bluefin tuna throughout their range that are addressed in this project. The underlying map reflects the general movement and distribution of juvenile (age 2-5) SBT as understood at the start of this project.

Box 3.2. **The ocean environment for juvenile southern bluefin tuna**

The environment experienced by juvenile southern bluefin tuna (SBT) throughout their range can be characterized by temperature, vertical ocean structure (e.g. mixed layer depth) and productivity. While other variables can be used to describe water masses, these three variables provide a suitable summary of the ocean conditions. Temperature, mixed layer depth, and phytoplankton productivity all vary from north to south, with latitudinal zonation evident (**Figure B3.2.1)**. Ocean temperatures are warmer in summer and cooler in winter. The open ocean is deeply mixed in winter, and productivity is generally higher in all areas in summer months.

Juvenile SBT occupy different regions of the ocean at different ages and in different seasons. Very young SBT move south from the spawning ground between Indonesia and Australia to the south west of Australia by age-1, aided by the southward flow of the Leeuwin current (**Box 3.1)**. The Leeuwin Current extends during winter around the southern coast to the Great Australia Bight (GAB) and even to Tasmania (Ridgway and Condie 2004). Age-1 SBT are generally restricted to the continental shelf (water <200m deep) (Hobday *et al.*, 2009) and are resident during summer along the south-west coast of Western Australia (WA), utilizing warm continental shelf waters adjacent to colder upwelling cells (Fujioka *et al.*, 2010). Nutrient-rich and cool sub-Antarctic water periodically intrudes onto the southern WA shelf, leading to elevated chlorophyll concentrations and prey densities (Ward *et al.*, 2006), and SBT forage widely over the shelf (Fujioka *et al.*, 2010). In years when the warm Leeuwin current is the dominant water mass along the coast, SBT are more common in inshore waters foraging around coastal lumps for benthic prey (Fujioka *et al.*, 2010). SBT gradually migrate eastward during the summer, although some fish remain in southern WA throughout the winter.

Age 2-5 SBT are common in the GAB during the austral summer (**Box 3.1)**. The GAB feeding grounds are unique oceanographically, with a very wide (up to 200 km) continental shelf where water depth is less than 150 m. The south coast is the longest east-west ice-free coastline in the Southern Hemisphere, and lies just to the north of the eastward flowing circumpolar currents, although the GAB is isolated from these rich sub-Antarctic currents by the Leeuwin and Flinders currents. Shelf circulation in the GAB is dominated by the Leeuwin current and the west wind drift (**Figure B3.2.2)**. By some descriptions, the GAB is an oligotrophic sea with low productivity (**Figure B3.2.1 and B3.2.2)**, which seems paradoxical given the density of many predators, including SBT, in the region. The southern shelf circulation in the GAB is mainly wind-driven; in winter water flows to the east, in summer water flows to the west (also associated with the Flinders Current). In winter, west of 129°E, the Leeuwin current dominates, east of 129°E, gravity outflow dominates (Hetzfeld 1997). The Leeuwin current is a fast, warm, low salinity current which curls around into the GAB and spreads across the shelf of the GAB as a body of warm water (~20°C), with relatively low salinity. This current then meanders into a series of eddies in the eastern GAB.

Box 3.2. (cont)

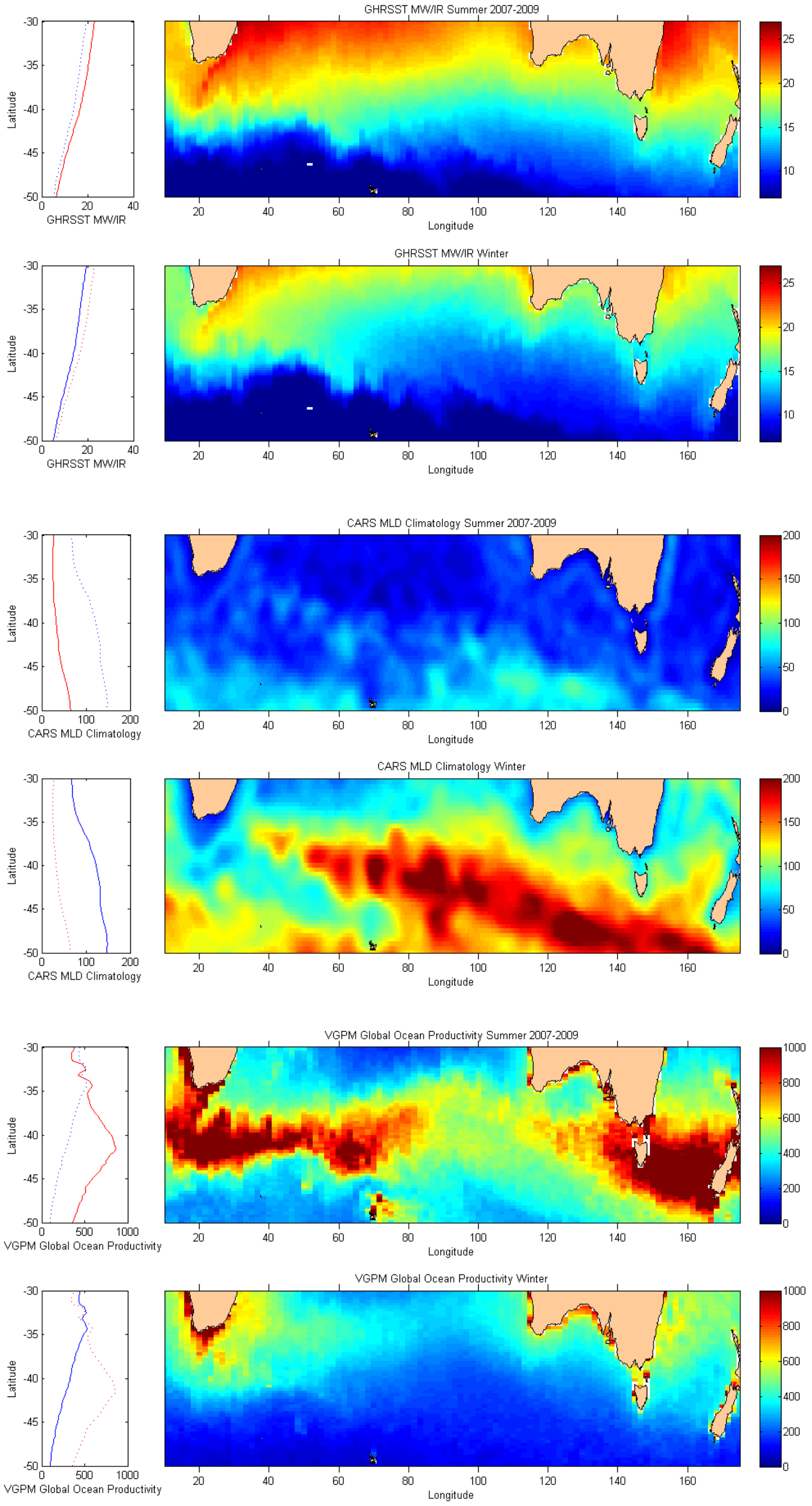

Figure B3.2.1. Environmental variables over the range of juvenile southern bluefin tuna in summer (months 12, 1 and 2) and winter (months 6, 7, and 8), averaged for the period 2007-2009. The plots to the left of each map illustrate the summer (red) and winter (blue) zonal (by latitude) average. Generated with C:\Data\MATLABR11\work\SBT Spatial Dynamics\SBTenvIO

Box 3.2 (cont)

Waters occupied by SBT in the GAB have a very warm surface layer (17–22°C) and a shallow thermocline at 60–80 m (Bestley *et al.*, 2008). Upwelling off western Eyre Peninsula (cool water in **Figure B3.2.2)** is associated with enhanced productivity, including increased abundance of pilchards (*Sardinops neopilchardus*) (Ward *et al.*, 2006), although SBT tend to avoid the most recently upwelled waters (Willis and Hobday 2007). Towards the end of the summer as surface waters cool and upwelling ceases (**Figure B3.2.2)**, most SBT tend to leave the GAB.

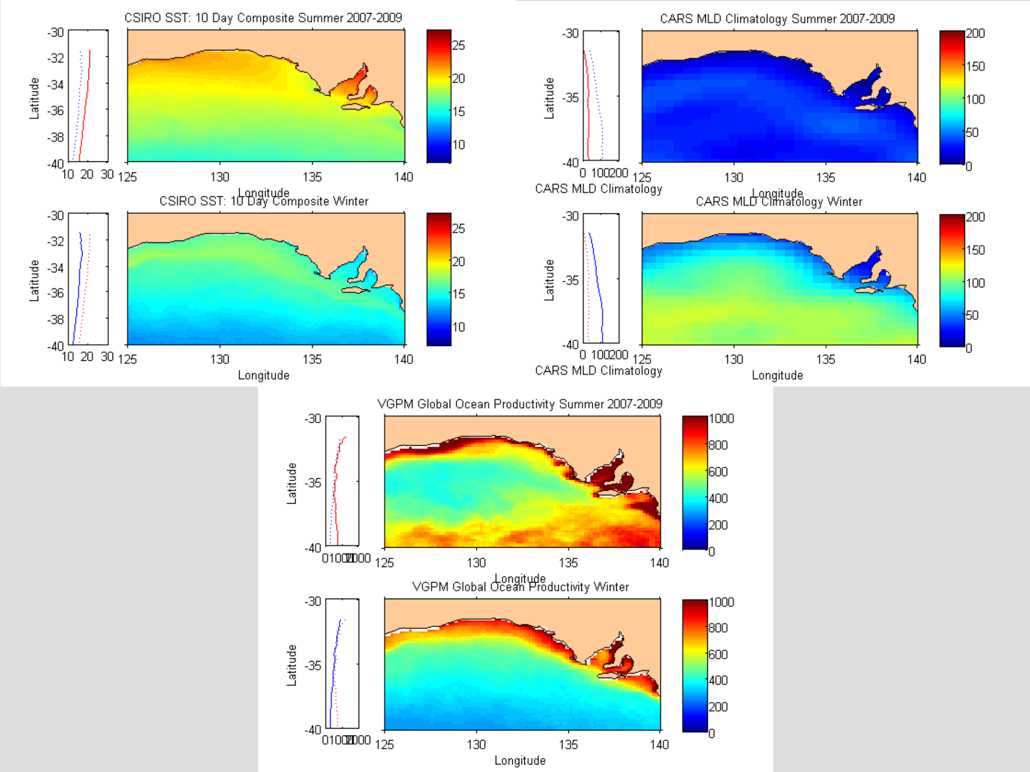

Figure B3.2.2. Environmental variables for the Great Australia Bight in summer (months 12, 1 and 2) and winter (months 6, 7, and 8), averaged for the period 2007-2009. The plots to the left of each map illustrate the summer (red) and winter (blue) zonal (by latitude) average. Generated with C:\Data\MATLABR11\work\SBT Spatial Dynamics\SBTenvIO

During their annual winter migration from the GAB, juvenile SBT may encounter environments of widely varying physical characteristics (Bestley *et al.*, 2008). Some fish move south and east into the Indian ocean, while others move west around Tasmania to the Tasman Sea and New Zealand.

The fish that move to the Indian Ocean will experience the complex near-surface circulation of the south Indian Ocean which is dominated by a series of major circumpolar fronts separating a number of water masses (Belkin and Gordon, 1996; **Figure B3.2.3**), between 30 and 50 S, where SBT migrate.

Box 3.2 (cont)

The Subtropical Frontal Zone (STFZ) is bordered by the North and South Subtropical Fronts (NSTF and SSTF, respectively), and by the Polar Frontal Zone (PFZ), bordered by the Subantarctic and Polar Fronts (SAF and PF, respectively). The SAF is deflected from 45° to 43°S by the mid-ocean ridge and converges with the SSTF north of the Prince Edward Islands to form a combined SSTF/SAF. This front intensifies east of ~50°E as a result of the confluence with the Agulhas Front (AF), and between 52° and 65°E¸ a combined AF/SSTF/SAF (“the Crozet Front”) is observed. The PF continues along ~50°S, passing north of Kerguelen (~46°S), nearly joining the triple Crozet Front. Further east, the individual structure is restored (SSTF, SAF, PF); however, the frontal characteristics towards Australia differ from those further west, largely because of strong air-sea interaction and cross-frontal exchanges in the Crozet-Kerguelen region. The SSTF, squeezed between the AF and SAF, exchanges water with both. The SSTF/SAF interaction results in the Australian SAF being warmer and saltier downstream, while the SSTF becomes shallower and weaker.

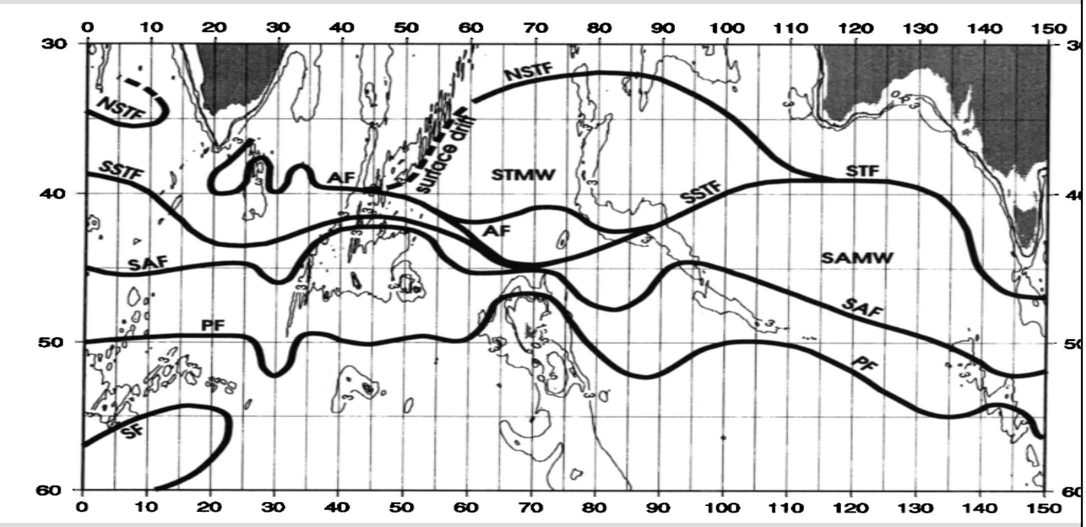

Figure B3.2.3. Circumpolar fronts in the Indian Ocean divide major water masses used by juvenile SBT.

Bestley *et al.* (2008) reported that in the Indian Ocean, based on on-board tag temperature data, juvenile SBT occupy several of these water masses. The northern and southern sides of the NSTF represent subtropical waters and are characterised by surface temperatures of 15–18°C and a thermocline at a depth of around 100– 150 m (Bestley *et al.*, 2008). Around 70–100°E, the Subtropical Mode Water between the SSTF and NSTF occupied by SBT mainly during winter and spring is ~11–14°C and is mixed deeply to 400 m (HAB 6 in Bestley *et al.*, 2008). The coldest waters inhabited by juvenile SBT lie in the most southerly latitudes where water is deeply mixed, between the southern edge of the STF and the northern edge of the SAF, known as the Subantarctic Mode Water. Surface waters may be only 12°C, declining to 7°C below a sharp thermocline at ~100 m (HAB7&8; Bestley *et al.*, 2008).

Box 3.2 (cont)

Fish that migrate to the east of Tasmania from the GAB may also encounter several water masses: the southward flowing East Australia Current, sub-Antarctic water, and the Tasman Sea which is bounded to the north by the Tasman Front. Along the east coast of Australia, the seasonal cycle of SBT habitat is strongly influenced the East Australia Current (EAC; Ridgway and Godfrey 1997). The EAC is a southward flowing western boundary current between 18°S and Tasmania, and is a region of intense eddy activity. The current is generally stronger and closer to the coast in summer (December–March) than in winter. In warmer than- average years, when the EAC moves further south, SBT habitat is compressed to the south, while in cooler years, SBT habitat is found further north than usual (Hobday *et al.*, 2011). Although the signal is weak, El Niño years tend to be associated with decreased strength (transport) of the EAC, resulting in cooler conditions along eastern Australia.

There have been documented changes in the environmental conditions in the major ocean regions occupied by juvenile SBT. The west coast has warmed and the Leeuwin current has weakened slightly (Pearce and Feng, 2007). The GAB has experienced minor warming, but this is difficult to discern given the interannual variability over the same period of time. The EAC has strengthened and warmed, and is considered one of the fastest warming areas in the southern hemisphere (Ridgway 2007). In the Indian Ocean, limited warming and southward movement of the frontal zones has been documented (e.g. Pearce and Feng 2007; Rolland *et al.*, 2010). Changes in other variables, such as chlorophyll have been reported (e.g. Boyce *et al.*, 2010), but remain contentious (Mackas *et al.*, response letters). While no direct impacts on SBT have been documented to date, changes in migration timing and feeding areas in the southern ocean are likely in future, given the projections under climate change.

4 Need

The SBT resource is estimated to be at historically low levels and biological concerns exist about the status of the stock (Anon. 2001, and 2010). The advice from the CCSBT Scientific Committee's stock assessment in 2001 was that under current catch levels (~ 15 000t in 2001) there was a ~50% chance that the stock would continue to decline or increase. The 2002 CCSBT Scientific Committee concluded that there was no basis for changing its previous advice on catch levels.

Reviews of SBT data in 2006 indicated that SBT catches may have been substantially under-reported over the previous 10-20 years (Anon. 2006). Although this substantially increased the uncertainty about the input data – both total catches and CPUE – it did not change the overall assessment about relative stock status; the spawning biomass is still estimated to be at a historically low level. The CCSBT website states its most recent advice as follows: "At its Sixteenth annual meeting, the CCSBT agreed that the status of the SBT stock was at a critical stage and that a meaningful reduction in the TAC was necessary in order to recover the stock and work toward reaching an interim rebuilding target reference point of 20% of the original spawning stock. Consequently, the CCSBT reduced the SBT global TAC for 2010 and 2011 to an average level over the two years of 80% of the previously allocated global TAC of 11,810 tonnes. Accordingly, the average global TAC for each of the 2010 and 2011 fishing seasons will be 9,449 tonnes." (http://www.ccsbt.org/site/total_allowable_catch.php)

The current management practice in the CCSBT is based on a global TAC with no consideration or restriction on where the catch is taken. Genetic studies, along with the fact that there is only one known SBT spawning ground, have led to the conclusion that SBT comprises a single reproductive stock. However, tag return and catch distribution data suggest that there may be substantial spatial structuring and incomplete mixing of SBT among the major feeding areas. Spatial structuring of the stock would have large implications for SBT assessments and for managing the rebuilding of the SBT resource. The combined results from the SRP conventional tagging program and this archival tagging project should provide the basis to evaluate the need for and, if necessary for developing, spatially-explicit population assessment and management response.

There is a critical need for direct and improved estimates of juvenile fishing mortality rates (or equivalently recruitment) to reduce uncertainty in the stock assessments and to provide a robust evaluation of the sustainability of recent catch levels. The SRP conventional tagging program is intended to provide this information. However, in order to achieve this objective, it is essential that sufficient information is available to account for incomplete mixing and the spatial dynamics of SBT in the analyses of the results from the conventional tagging data.

The SRP conventional tagging program has since been suspended, primarily due to serious problems with reporting rates (Anon. 2006), but the data from that program are still of value in the operating model. More importantly, mark-recapture approaches remain important tools for obtaining fishery independent data on mortality rates and abundance; the need therefore remains for future mark-recapture programs.

Catch-per-unit-effort (CPUE) indices are used as indicators of trends in the SBT stock abundance, and form an essential input into the stock assessment models, and more recently the CCSBT OM. It is also a key component in the candidate MPs that have been developed and are currently being considered for adoption by the CCSBT (Anon. 2010). Interpretation of CPUE data is complicated by spatial and temporal variation in the availability and catchability of SBT in relationship to fishing effort. Interpretation of catch rates has been and continues to be a major source of uncertainty in the SBT OM. Two additional complications arose since this project was started: (i) unreported catches with unknown effects on the catch-effort data (Anon. 2006) and (ii) substantial changes in the fleet dynamics and domestic management regulations for the main longline fleet (Japanese fleet) (Anon. 2010; Itoh 2010). The CCSBT Scientific Committee has repeatedly identified the need to develop alternative approaches for modelling and interpreting the SBT catch and effort data, and this need was incorporated into the agreed CCSBT SRP. Both availability and catchability are expected to vary with environmental conditions that modify the habitat suitability for SBT. At the time this project was proposed, techniques of "habitat standardisation" were gaining some favour[3]. Information for habitat-specific CPUE standardization was recognized as an important alternative

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[3] There is potential for confusion because the term "habitat standardisation" has been used to mean "standardising CPUE by using auxiliary information about the species' habitat preference" or to mean, more specifically, "standardising CPUE by accounting for different catchability at different depths". Both interpretations are considered in **Section 12**.

approach for modelling catch rate data at the 2002 CCSBT Scientific Committee meeting. This standardization approach attempts to take into account changes in environmental conditions so that CPUE indices relate to the actual SBT habitat. This should allow the indices to more clearly reflect the actual changes in the abundance of SBT. This is potentially critical as CPUE indices are seen as providing one of the key inputs in the decision-rule-based MP that has been developed by the CCSBT. Thus, it is essential that to the extent possible CPUE indices provide a reliable indication of shorter term trends and that the CPUE signal is not confounded by short-term environmental fluctuations. Archival tags provide a unique tool for collecting the required habitat-specific requirements of SBT. Without such data, these habitat based standardization approaches are intractable. For example the archival tag data on vertical and horizontal distribution allow habitat preferences to be estimated, and CPUE standardization is technically possible.

Although CPUE still forms a key component of the CCSBT OM, the unknown effect of unreported catches on the catch-effort data raises important questions about the reliability of the CPUE indices. Because of this and the substantial changes in fleet dynamics, which are potentially impossible to standardise for (Itoh 2010), the focus on habitat modelling in this project was broadened to a more general rather than CPUE-specific context.

At the time the project was proposed, the aerial survey in the GAB was suspended (2001-2004) partly to allow for further analyses and an evaluation of the value of the survey to provide an index of relative abundance of juvenile SBT. This project therefore had no explicit objectives relating to the aerial survey. Findings presented in Cowling *et al.,* (2003; FRDC report 96/11 and 98/105) led to the aerial survey being re-commenced in 2005, but one question still remained: what proportion of juvenile SBT return to the GAB? We address this question and confirm the choice of timing and duration of the aerial survey.

In summary, this project aims to provide a substantial improvement in our current understanding of SBT movements and spatial dynamics. In particular, the proposal has been developed in response to three specific needs for an improved understanding of SBT spatial dynamics:

1. Estimation of mixing rates for the estimation of mortality rates from conventional tagging;
2. Habitat definition to allow the standardization of CPUE indices for use in the CCSBT stock assessment process, but noting the changes that occurred during the course of this project; and
3. Requirements within the guidelines under the strategic assessment provisions of the Environmental Protection and Biodiversity Conservation Act 1999 that “the distribution and spatial structure of the stock(s) has been established and factored into the management response”.

In addition to these three specific needs, there is a general need to ensure that the current stock assessment models are robust to their implicit assumptions about spatial homogeneity.

5 Objectives

The objectives of this project are as follows

Objective 1:

Tag 150-200 juvenile SBT/year for 3 years with archival tags throughout the full range of spatial habitats in order to provide a comprehensive understanding of their spatial dynamics;

Objective 2:

For each tag returned (expected to be ~ 20-30%) estimate daily positions based on the stored light and temperature data and develop a database for the storage and analysis of all relevant location, temperature and depth data;

Objective 3:

Contribute to the provision of statistically based estimates of mixing rates between the major SBT fishing grounds that can be used in conjunction with conventional tagging data to provide fishery independent estimates of fishing mortality rates for monitoring the SBT fishery;

Objective 4:

Provide critical information and contribute to developing a framework for incorporating the archival tag and conventional tagging data within the SBT stock assessment model;

Objective 5:

Integrate the position, temperature and depth data provided by the tags with oceanographic data to develop a seasonal model of residence times and habitat use;

Objective 6:

Compare the CPUE indices abundance which use this seasonal habitat model as a basis for standardization with current standardized CPUE indices used in the SBT stock assessments

Objective 7:

Evaluate implications of the spatial dynamics of juvenile SBT for the management of the SBT resource (e.g. the potential consequences and benefits of either ignoring or using spatially explicit management actions).

During the course of the project there was evidence from preliminary analyses that there may have been temporal changes in the spatial dynamics of SBT (Polacheck *et. al*., 2006), and changes to Objectives 3 and 5 were suggested. Also, following the revelation in 2006 of substantial unreported catches of SBT and the unknown effects this may have on CPUE, as documented in the publicly available documents of the CCSBT (Anon. 2006), Objective 6 was modified. The revised Objectives 3, 5 and 6 are:

Revised objective 3:

Provide a comprehensive analysis of the evidence for temporal changes in the spatial dynamics of juvenile SBT and analyse the implication of the information provided on mixing rate between the major SBT fishing and their changes over time for the use of combined archival and conventional tagging data to provide fishery independent estimates of fishing mortality for monitoring the SBT fishery.

Revised objective 5:

Integrate the position, temperature and depth data provided by the tags with oceanographic data to develop a seasonal model of residence times and habitat use for regions with consistent temporal patterns across the years.

Revised objective 6:

Evaluate the implication from the seasonal habit model for the interpretation of future catch and effort data and monitoring strategies.

6 Tag Deployment, recovery and data summaries

Key findings

- International collaboration between SBT fishing nations was critical to the project
- Training for tag deployment techniques is critical for success of such programs
- Technologies to support tagging from a range of vessels were developed – portable tagging mattress, tagging box, surrogate tuna
- Tags were released in all five desired areas (n = 568), and the recoveries to date (n = 74) represent 13% of releases. Combined with earlier tag programs, a total of up to 122 tags were available for use in analyses in subsequent project sections.
- Data are quality controlled and archived in a database, facilitating analysis.
- Tags recorded up to 5 years of data (n=2), 75% of tags covered at least 6 months, and 41% covered at least one year.
- Preliminary analyses shows SBT are deeper during the day, spend less time at the surface during daylight, particularly during winter, and maintain a body temperature that is up to 5°C warmer than the surrounding waters.

6.1 Introduction

Critical to the project was the archival tagging of juvenile southern bluefin tuna (SBT) throughout their entire range (i.e. from South Africa to New Zealand). This tagging supported the primary objectives of the project: the estimation of movement and mixing rates of juvenile SBT, and the development of a seasonal model of their residence times and habitat use in different parts of their range. This component of the project was executed with strong collaboration between New Zealand, Taiwan and Australia fisheries agencies and fleets for the release of tags, and cooperation with Taiwan, Japan, New Zealand, Australia and other fishing nations for return of tags.

Here, we report on the tag deployment planning and liaison efforts, tag training activities, the tag deployment and recovery statistics, the database that houses tag data, and present some data summaries that are developed further in subsequent sections of the report.

6.1.1. Tagging preparation: Extension, outreach and permits

An important element in initiating a tagging program for a wide ranging species is to involve potential partners for tag deployment and plan the recovery efforts. While commercial Australian purse-seine vessels operate in the Great Australia Bight (GAB), charter of suitable vessels for tagging in Australian waters was the planned approach in this project. Based on fishing vessel activity in the high seas juvenile SBT range, we also attempted to involve New Zealand, Taiwan, and Japan in the project.

6.1.2. International cooperation

Following initial contacts, Taiwan agreed to deploy tags as part of their observer program, as did New Zealand. Japan did not have an ongoing observer program, and so was unable to release tags, however, pledged to advise their fleet about the tagging program, and provide information and support to aid in the return of recovered tags.

This project was endorsed by the CCSBT. A CCSBT conventional tagging program was also underway, thus the archival tags listed CCSBT details for recovery (address and reward notice). As SBT are a quota managed species, we were granted research mortality allowance to conduct tagging activities, and we reported on any mortality, as well as project status via contributions to the CCSBT annual meetings (**Appendix 3)**.

6.1.3. Domestic activities

Within Australia, we advised the SBT companies operating in the GAB, and requested their cooperation in returning tags. These efforts were supplemented with port and processor visits. Early in the project, CSIRO staff regularly visited Port Lincoln, and talked to companies and industry representatives to emphasise the value of the tags and encourage recoveries. Additionally searches for archival tags during harvesting operations in Port Lincoln were carried out by ProtecMarine staff contracted to recover conventional tags as part of other projects. Tag recovery promotional materials were also distributed to companies and vessels, illustrating the tag types and the value of the reward (**Figure 6.1).**

A$250 REWARD*

- A$250 for returned archival tags
- T-shirt, cap or mug for each dart tag

* or a digital camera of the same value

Southern Bluefin Tuna
ARCHIVAL TAGGING PROGRAM

Remove the tag by making a small cut in the belly in front of the stalk – be careful **not** to cut the stalk. **Do not** try to remove the tag by pulling on the stalk – it will break.

Please return tag with the information below:
Post to: CCSBT PO Box 37, Deakin West,
ACT 2600, Australia
Phone: +61 2 6282 8396 Fax: +61 2 6282 8407
email: tags@ccsbt.org

Date captured ……
Position captured (lat/long) ……
Length/weight ……
Tag number ……
Your name ……
Your postal address ……
Vessel name ……

懸賞金250*
オーストラリアドル贈呈

- アーカイバルタグの返還に 250豪ドル
- 矢形標識 1本につき Tシャツ、コップ又はマグカップ を贈呈

* 又は同じ価値のデジタルカメラを贈呈

ミナミマグロ
アーカイバルタグ（記録型標識）放流計画

アーカイバルタグを魚の腹部から取り出す際は、出ていアンテナの前部を小さく切開し取り出してください。アンテナを切らないように注意してください。アンテナを引っ張り取り出そうとすると壊れてしまいます。

下記のどちらかの住所に、
標識及び漁獲時の情報を送付してください
独立行政法人 遠洋水産研究所
温帯性まぐろ研究室
〒 424-8633
静岡市清水折戸5-7-1
又は、
CCSBT PO Box 37, Deakin West, ACT 2600, Australia
Phone: +61 2 6282 8396 Fax: +61 2 6282 8407
email: tags@ccsbt.org

漁獲日 ……
漁獲位置（緯度/経度）……
体長/体重 ……
標識番号 ……
標識発見者氏名 ……
標識発見者住所 ……
船名 ……

Figure 6.1. Examples of tag reward posters distributed to fishing companies and vessels in Australia and Japan. Versions in Korean, Indonesian, and Chinese were also distributed. Source: S:\Tropical and Pelagic\Pelagic Ecosystems\ST2\Stanley\Reward Posters & Fact Sheets.

Rewards for tags and certificates were paid by CCSBT when they received tags, and to minimise delays in rewards and then CCSBT invoiced the project for these reward costs. Some rewards were initially distributed to the fishing company, rather than the vessel or individual who reported the tag. This caused some concern for fishers who recovered tags domestically and internationally before being resolved with Australian companies, and we think international fishing fleets. We also plan to continue paying rewards and processing archival tags returned after the completion of this project.

6.1.4. Animal ethics permits

Tagging within Australian waters by CSIRO staff is covered under animal ethics permits issued by the Tasmanian Department of Primary Industries, Parks, Water and the Environment. While animal ethics are not required for fish tagging in some of our partner countries, we trained all observers involved in tagging according to best practise animal handling techniques that support our Australian permit conditions.

6.2. Tag training

Training programs in tag deployment for the partner nations, New Zealand and Taiwan, were planned as part of the project. Prior to the release of the first tags, CSIRO scientists Naomi Clear (Taiwan) and Thor Carter (New Zealand) visited each country and provided information on the project and training. Following low releases of archival tags in the first year of intended tag deployment New Zealand (low availability of small fish) and some concern with the tagging technique of the Taiwanese observers, additional training and liaison in New Zealand and Taiwan took place. Alistair Hobday developed and extended the training approach delivered in the previous year (**Appendix 4 and 5**). Larger numbers of observers from each country were included in the sessions, as the exact personnel deployed on vessels that would undertake archival tagging could not be guaranteed by the fisheries agencies of each country.

A total of six training visits by project staff were completed: two in New Zealand, and four in Taiwan (**Figure 6.2)**. These visits are considered to be an important element in the successful deployment of tags in areas not currently accessed by the Australian domestic fleet.

1. New Zealand, Wellington. May 3-6, 2004 – Thor Carter - host Talbot Murray NZ
2. Taiwan, Kaohsing. May 25-27, 2004 – Naomi Clear - host Chienho Liu
3. New Zealand, Wellington. April 19-22, 2005 – Alistair Hobday – host Talbot Murray NZ
    - These observers will use bed-mattresses on board their longline vessels, and so all surgery training was designed to mimic this situation.
    - A group of 6 observers (all new to surgery) trained to implant tags.
4. Taiwan, Kaohsing. April 24-26, 2005 – Alistair Hobday – host Chienho Liu
    - 2 tagging mattresses, 4 tagging kits, 50 tags delivered
    - 5-8 observers trained using dead fish and live yellowfin tuna
5. Taiwan, Kaohsing. March 26-28, 2006 – Alistair Hobday – host Chienho Liu
    - Two observers trained in 2005 released ~47 SBT in the southern Indian Ocean. One of these observers has since left the program. Uncertainty about deployment location of the remaining observers, due to ICCAT and Atlantic Ocean observer levels (15 observers needed for that fleet in 2006) required that additional training be carried out.
    - A total of 12 observers were trained in 2006.
6. Taiwan, Kaohsing. April 24-26, 2007 – Alistair Hobday – host Dr. Shui-Kai (Eric) Chang
    - A total of 14 observers were trained. Only two were present from 2006 (and they have not tagged any fish at sea yet) while the most successful tagger

(present at 2005, and 2006 training) was still at sea (Mr Ming-Shan TSAI), but not in the Indian Ocean.

- A total of 25 archival tags were taken for deployment this year, and reprogramming of 25 was demonstrated (and showed how to reset the clocks), while a further 25 tags were in transit back to Taiwan for reprogramming. Thus, a total of 75 archival tags are available for deployment in the Indian Ocean in 2007. It is anticipated that these will be sent with 3 observers to the Indian Ocean (25 tags each) beginning June 2007.

Figure 6.2. Observers inspect fish as part of training in April 2005; New Zealand (top left) and Taiwan (top right). The Taiwan observer group trained in 2006 (left) and 2007 (right).

Results of the Taiwan training in 2005 were available during training the following year (2006), when Taiwanese observer, Mr Tsai, showed a video of three surgeries involving SBT that looked to be 100 cm or more in length; all were tagged July 2, 2005, according to the video time stamp. The tagging mattress was used in all cases, with head (solid) and tail (clear) covers used.

- Fish 1. Start time: 4:12:45, with fish on mattress and cut beginning. End time 4:13:55, as fish hit water. Surgery technique was satisfactory, with gloves and antibiotic, and stitch all evidenced. However, at the conclusion of the surgery, the crew member lifted the fish by the finger in eye and tail technique to return it to the water.

- Fish 2. Start time: 9:38:50, with fish on mattress and cut beginning. End time 9:41:18, as fish hit water. Surgery technique was satisfactory, and the crew member was told how to lift the fish to return it to the water, however, it was not a graceful entry, but a full belly smack.
- Fish 3. Start time: 9:49:45, with the fish on mattress and cut beginning. The tag was inserted, however, before the stitching could commence, the fish began flapping, and foaming from the gills was evident within 1 minute. Despite calming techniques (patting eye), the fish could not be stitched and the surgery was aborted at 9:52:00. Showing an aborted surgery was very good, and indicates that this observer followed procedures implemented last year, and there was then much discussion about the flapping and aborting a surgery.

Good and poor handling practices based on this video were discussed with all the participants in 2006 and 2007.

This experience with New Zealand and Taiwan illustrated the importance of providing extensive training of observers to deploy archival tags. The reality is that turnover of staff, uncertainty regarding observer allocation to the vessels that are willing to tag tuna, and language barriers make it challenging to guarantee that the trained observer will be in the right place at the right time. Training a larger number of people is a suitable risk management approach, which was successful from 2005 onwards.

6.2.1. Tuna surrogate

Due to the high cost of obtaining live or dead tuna for training surgeons, and the limited number of surgeries that could be completed on each tuna, a tuna surrogate was designed and manufactured at CSIRO (**Figure 6.3)**. This surrogate allowed multiple practise attempts in a timed situation. Replaceable belly implants, manufactured from silicon (ultrasil^{TM}) with shredded coconut added for texture, could be used for each new surgery. These implants could be cut, a tag inserted into the belly cavity, and suturing of the “wound” completed. Holes in the dorsal surface of the surrogate allowed placement of conventional tags. The surrogate[4] was taken to Taiwan on two occasions, generating much interest at customs in both Taiwan and Australia.

This surrogate was a very important development in allowing large numbers of observers to be trained in Taiwan, which was necessary to guard against uncertainty regarding the allocation of observers to tagging vessels. A recommendation regarding the best surgeons was made to the fisheries agency following the completion of training, and was apparently used to help assign observers to vessels that were likely to encounter SBT.

Figure 6.3. Tuna surrogate. Top row. Tommy the Tuna, designed by Alistair Hobday and Russ Bradford, manufactured by Dave Cherry, painted by Lindsay Marshall, with replaceable belly implants designed by Russ Bradford. Bottom row. Tommy the tuna participating in training in Taiwan. Source: C:\Data\Alistair\Pictures and Images\Fish Tuna Pictures\Tuna surrogate

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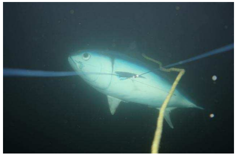
[4] Tommy the Tuna was unfortunately liberated when he escaped from his tether adjacent to the CSIRO wharf while acting as a model for an underwater camera system in March 2010. Tommy was last seen gliding towards Constitution Dock, and as yet, has not been recovered, despite several wharf dive cleanups.



6.2.2. Tag deployment procedures

In Australia, fish capture was by pole and line with the fish landed onto a tagging table (or mat, not shown) (**Figure 6.4**). Fish were then carried to a tagging cradle or mattress (**Figure 6.5**). Illustrations of the surgical procedure are shown in **Appendix 5**. Equipment suitable for use on a range of vessels was designed by the project team, including a portable tagging mattress (**Figure 6.5**) and a self contained tagging box (**Figure 6.6**). Fish tagged by Taiwan and New Zealand observers were captured on commercial longline vessels. These fish were landed directly to the deck or via a tagging cradle, which lifted the fish to the vessel (e.g. **Figure 6.4**). The Taiwanese vessels used a circular dip net, 80 cm in diameter, operated by 3 crew; 2 on the net handle, and a third with a boat hook that lifts the opposite side of the net ring to recover fish. This net was custom made by the observer program. The Taiwanese observers report that the longline snood can be cut and fish dehooked in a gentle fashion, often by feeding the hook through the wound, and not by bringing it out the same way it went in. Hooking in the side of the mouth is more common than the upper or lower jaw, and swallowing the hook is very rare.

Figure 6.4. Fish landing techniques. Upper. Landing of poled fish in the Great Australia Bight onto a tagging table. Lower. Landing of southern bluefin tuna from a longline vessel using a lifting cradle. Pictures by Thor Carter. C:\Data\Alistair\Pictures and Images\Fish Tuna Pictures

Figure 6.5. Fish tagging equipment. Left. Standard tagging cradle. Right. Portable tagging mattress designed in this project for observers in NZ and Taiwan fleets.

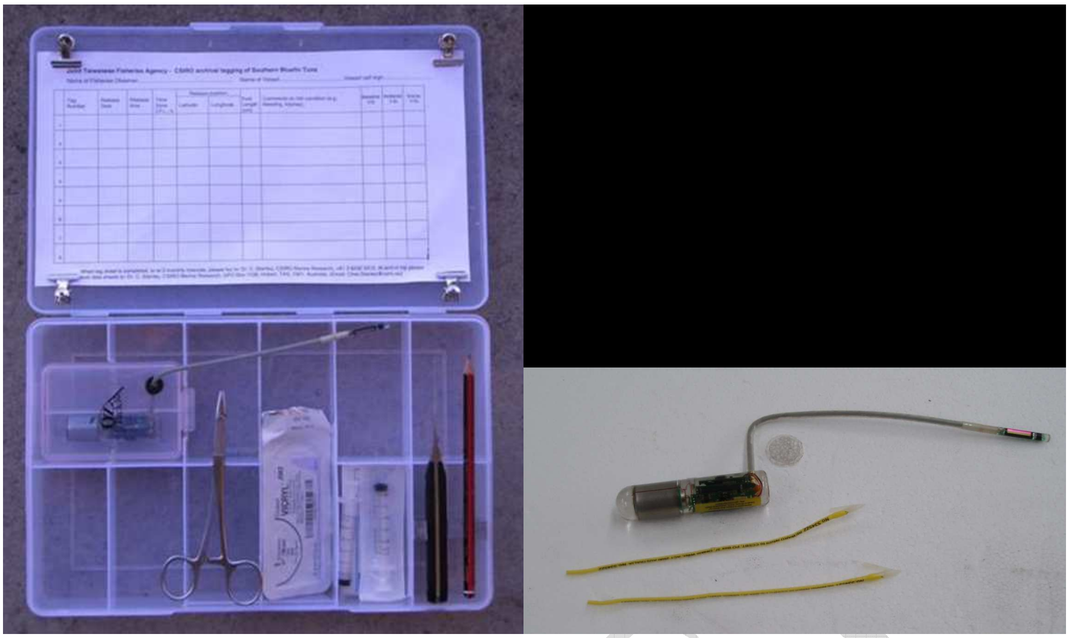


Figure 6.6. Fish tagging kit and tags. Left. Standard tagging kit designed for use by observers in this study. Right. A Wildlife Computers Mk9 archival tag and CCSBT conventional tags.

The tagging procedures developed for this project (**Appendix 5**) have been further extended to cover multiple tag types and species (Bradford et al 2009), and are now used as a formal code of practise for training CSIRO and partner scientists for a range of tagging projects.

The high recovery rates from tagged fish reflect the quality of the fish handling practices, and the value of using trained personnel. In funding future tagging projects, it is worth considering how these high rates (>10%) compare with the much lower recovery rates from some tagging projects that use untrained taggers, such as in recreational fishing catch and release programs (<2%) (Clive Stanley, unpublished data).

6.3. Tag deployment

The first objective of the project was to release 450 tags throughout the juvenile range of SBT, as represented by the following five locations (**Figure 6.7**):

1. the Great Australian Bight (GAB)
2. southern coast of West Australia (WA)
3. high seas in the central Indian Ocean
4. the Tasman Sea, off New Zealand

5. off South Africa

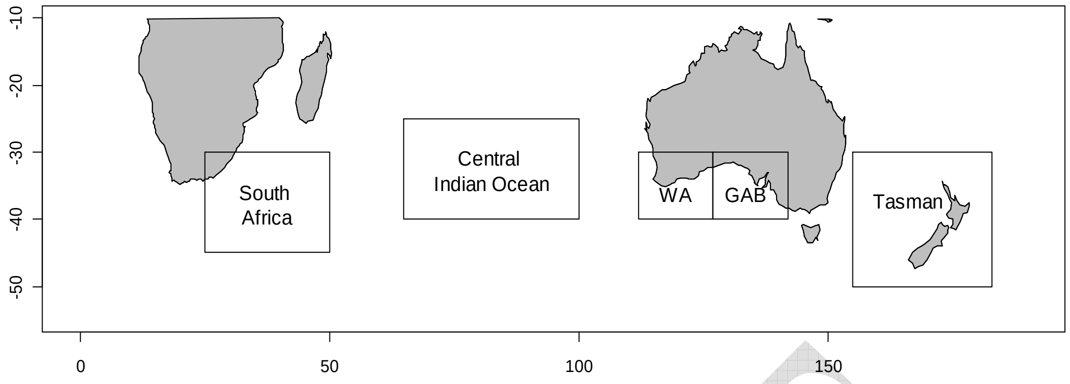


Figure 6.7. The five planned tagging locations for this project.

6.3.1. Australian releases in the GAB and southern WA

Releases in the GAB and southern Western Australia were completed by trained observers on chartered Australian fishing vessels. Fish were attracted to the tagging vessel by trolling and then retained around the vessel using live bait (GAB) or dead pilchards (WA). Fish were captured on a barbless hook, using the pole and line technique, and landed on a mattress or tagging table, before being lifted to the tagging cradle. The eyes of the fish were covered with a wet cloth, the fish measured, and a small incision to the peritoneum made midway between the anus and ventral fins. The tag, sterilized in Betadine, was gently inserted such that the light stalk protruded from the incision, and pointed to the rear of the fish. A general antibiotic was injected into the incision, which was then closed with 1-2 stitches. A pair of conventional tags was inserted in the dorsal side of the fish, one on each side, and the fish was released headfirst from the side of the vessel. The time for the surgery was less than 2 minutes, and the additional handling time was less than 30 seconds (landing to cradle). Additional details are provided in **Appendix 5.**

6.3.2. Indian Ocean releases by Taiwan

Releases in the Indian Ocean were completed by trained observers on Taiwanese flagged vessels. Fish were captured as part of commercial longline fishing operations, and only fish in good condition of appropriate size for the project were tagged. The archival tagging methods were as described for the Australian releases.

6.3.3. New Zealand releases

Releases in the Tasman Sea adjacent to New Zealand were completed by trained New Zealand observers on their domestic vessels. Fish were captured as part of commercial longline fishing operations, and only fish in good condition of appropriate size for the project were tagged. Fish less than 125 cm in length were rarely captured by these vessels, and so releases were limited. The archival tagging methods were as described for the Australian releases.

6.3.4. South Africa releases

A critical component of the project was the deployment of archival tags in area to the east of South Africa – an area where juvenile SBT have been regularly caught during the austral spring and early summer. The initial plan was to have these deployments done either in collaboration with Japanese or Taiwanese research or commercial fishing operations. A number of logistic and administrative problems prevented this from occurring. Consequently, an alternative approach for releasing tags off South Africa was followed using a chartered longline vessel, the Atu-S, operated by Big Catch P/L out of Richards Bay, South Africa (**Figure 6.8)**. This 30 m vessel, with a full range of functioning navigation and communications equipment, was built in 1980 in Japan as a long-line training vessel and operated with 16 crew. The line is set from the stern and hauled from the starboard side. A very low sea-door easily allowed large fish to be landed and, for tagging purposes, released back to the ocean. Arrangements were made for a 30 day charter in November/December 2006.

Figure 6.8. The Atu-S steaming with a following sea.

While weather conditions were far from ideal during the cruise, 16 longline sets were completed. Although historical information on individual sets from commercial and tagging cruises in the late 1990s and early 2000s by Japan and Taiwan were used to determine the area and environmental oceanographic conditions most appropriate for setting, a total of only 13 SBT were caught in the 16 sets. Of these, seven SBT were alive and in suitable state for tagging. However, only one of these was within the target size range for the primary objective of this cruise (juveniles, <125cm). Thus, the cruise resulted in only one archival tag release. Six other live SBT were tagged with either conventional (3) or PSAT (3) tags depending upon their size. The SBT catch rates were extremely disappointing and unexpectedly low. It is not clear if the cruise was simply unlucky or whether these extremely low catch rates reflect that juvenile SBT abundance in this area has become very low (adult abundance at this time of year has always been relatively low as this period is within the spawning season). One indication that juvenile SBT abundances may in fact have declined to low levels is that the number of Taiwanese vessels choosing to fish in this area and season for SBT has been decreasing in the last few years. In fact, only one Taiwanese longline vessel registered to fish for SBT in this area in 2006 and while the vessel had been in the general area at the time, it decided to fish for oil fish and had not caught any SBT.

During the latter part of 2007 and the early part of 2008, the project was successful in having a further 26 SBT archival tagged in waters close to South Africa by observers stationed on Taiwanese vessels.

6.3.5. Deployment summary

In order to achieve sufficient numbers of releases in all planned regions (off South Africa in particular), the number of release years was extended from the original goal of 3 years (2004-2006) to 6 years (2004-2009). Thus, the tag deployment component of the project was completed in 2009 (last release 28 May 2009)[5]. The project exceeded its minimum goal in terms of number of archival tag releases, with 568 releases. All tags released as part of this project were Wildlife Computer Mk9 archival tags (www.wildlifecomputers.com/tdr.aspx; **Figure 6.6**). These tags permit

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[5] Note that we refer to all archival tags released in 2004 through 2009 as being part of the current project; however, releases in the last years were funded by CSIRO, independent of the budget for this project.

multi-year deployments with high resolution data recording from on-board sensors. These tags were to be placed internally, and so the Mk9 configuration we used had the depth, temperature (internal temperature), and wet/dry sensors mounted on the body of the tag while the light level and a second temperature sensor (water temperature) was mounted on a sensor stalk.

A summary of the archival tag releases by year and area is given in **Table 6.1**. The location of releases shows good coverage across the range of juvenile SBT (**Figure 6.9).** The distribution of lengths of all fish at the time of release is shown in **Figure 6.10a**. This implies an age range of between 1 and 5 years old, with most individuals belonging to age class 2 (~75-90cm) or age class 3 (~ 90-105cm).

Table 6.1. Numbers of archival tags released on juvenile SBT as part of this project[5], by year and area of release.

Release year	South Africa	Indian Ocean	WA	GAB	Tasman
2004	0	37	22	38	6
2005	0	48	15	50	0
2006	1	25	39	10	30
2007	25	49	78	24	19
2008	1	0	21	0	22
2009	0	0	0	0	8
Total	**27**	**159**	**175**	**122**	**85**

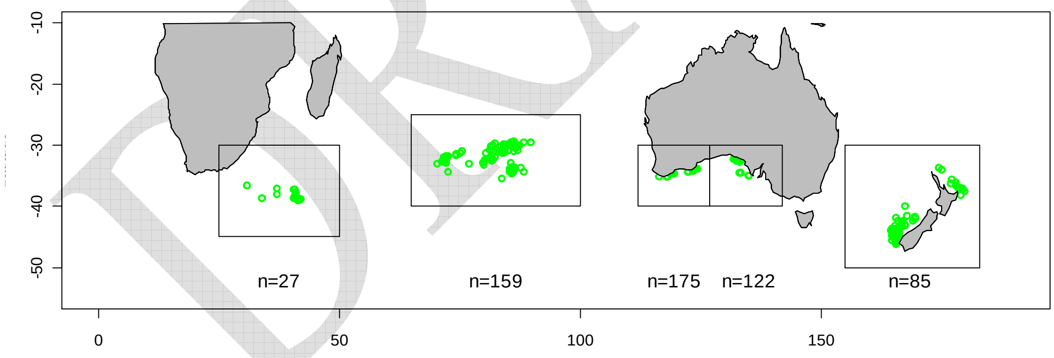
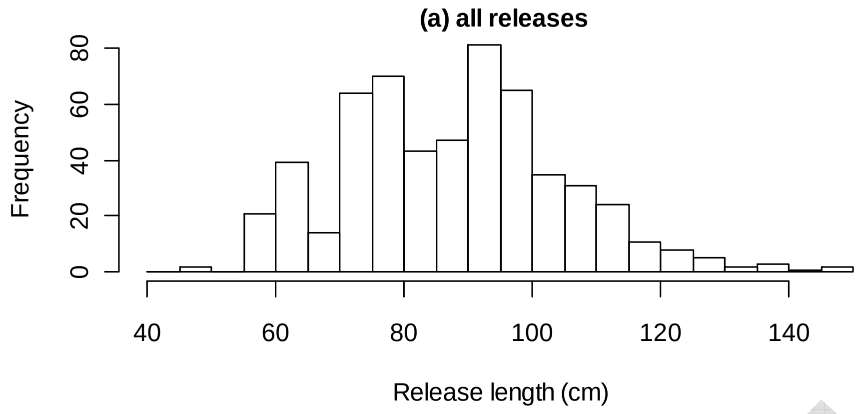


Figure 6.9. Locations of archival tag releases during the project.



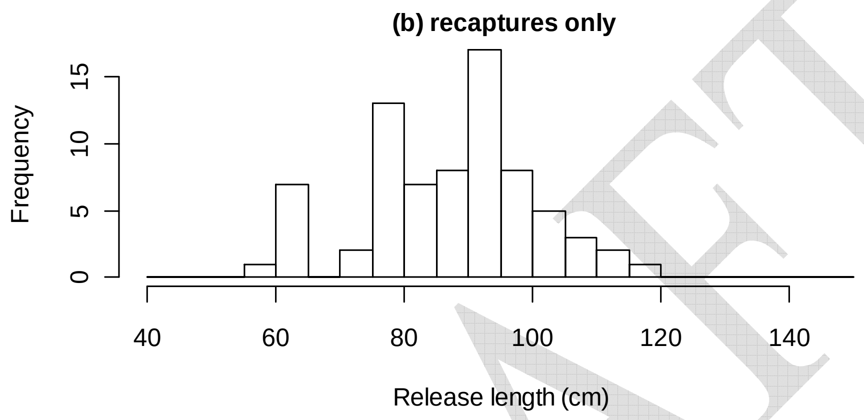


Figure 6.10. Release lengths (cm) of: (a) all 568 fish tagged in the years 2004-2009; (b) the 74 fish tagged that were subsequently recaptured.

6.4. Tag recovery

A total of 74 tags (13%) of those deployed under this project were recaptured and reported as of 10 May 2011, two of which were found on the beach and had no usable data so are excluded from all data summaries and analyses. This recovery rate is somewhat lower than expected (20-30%) at the time the project was proposed (Objective 2). A high recovery rate was achieved for the first three years of GAB releases, but the overall rate was lower because of high seas releases. Additional possible reasons for this are discussed further in **Section 8**. We anticipate that additional archival tags have been recaptured and are in the farms in South Australia and will be returned during harvesting operations. We will continue to reward tag recoveries, process tags, upload the data to the database and, as funding allows, analyse the data after this project has formally ended.

Figure 6.10b shows the distribution of release lengths from all recaptured fish. If we compare this to the distribution of release lengths from all fish released (**Figure**

6.10a), they are quite similar with no indication that the smallest fish tagged were recaptured in lower proportion to the larger fish (i.e., no indication of high tag-related mortality on small fish).

Table 6.2 gives the numbers of recaptures by recapture area, corresponding to the releases in each release year and area. The total percentage recoveries by release year are: 24% for 2004, 25% for 2005, 10% for 2006, 3% for 2007 and 5% for 2008.[6] The majority of the (reported) recaptures have come from the GAB (63 of the 72 tags, 88%). Of the remaining recaptures, 7 have come from the central Indian Ocean, 1 from South Africa and 1 from the Tasman Sea (**Table 6.2**). Maps showing the recapture locations of fish that were releases in each area are given in **Figure 6.11**. The recovery from the releases in the Tasman Sea (New Zealand) are, to our knowledge, the first-ever of archival tags released in this area.

Table 6.2. Numbers of archival recaptures by recapture area corresponding to the releases in each year and area.

Release year	Release area	Number of releases	Recapture area				Total recaptures	Percentage recaptures
			GAB	South Africa	Indian Ocean	Tasman		
2004	GAB	38	11	0	1	0	12	31.6%
	SEIO	37	5	0	1	0	6	16.2%
	Tasman	6	1	0	0	0	1	16.7%
	WA	22	6	0	0	0	7	27.3%
2005	GAB	50	17	0	0	1	18	36.0%
	SEIO	48	5	1	1	0	7	14.6%
	WA	15	2	0	1	0	3	20.0%
2006	GAB	10	2	0	0	0	2	20.0%
	SAfrica	1	0	0	0	0	0	0.0%
	SEIO	25	2	0	0	0	2	8.0%
	Tasman	30	3	0	0	0	3	10.0%
	WA	39	2	0	2	0	4	10.3%
2007	GAB	24	1	0	0	0	1	4.2%
	SAfrica	25	0	0	0	0	0	0.0%
	SEIO	49	2	0	0	0	2	4.1%
	Tasman	19	0	0	0	0	0	0.0%
	WA	78	2	0	1	0	3	3.8%
2008	SAfrica	1	0	0	0	0	0	0.0%
	Tasman	22	1	0	0	0	1	4.5%
	WA	21	1	0	0	0	1	4.8%
2009	Tasman	8	0	0	0	0	0	0.0%
Total		**568**	**63**	**1**	**7**	**1**	**72**	**13.0%**

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[6] The decline in the percentage of returns over time cannot fully be explained simply as the fish tagged and released in later years not having as much time to be recaptured since over 90% of the recaptures to date have occurred within the first 3 years. Reduced fishing mortality on some of the relevant age classes in recent years may be part of the reason, but is unlikely to explain the full difference. Other possible reasons include reduced reporting rates and/or increased natural or tag-induced mortality.

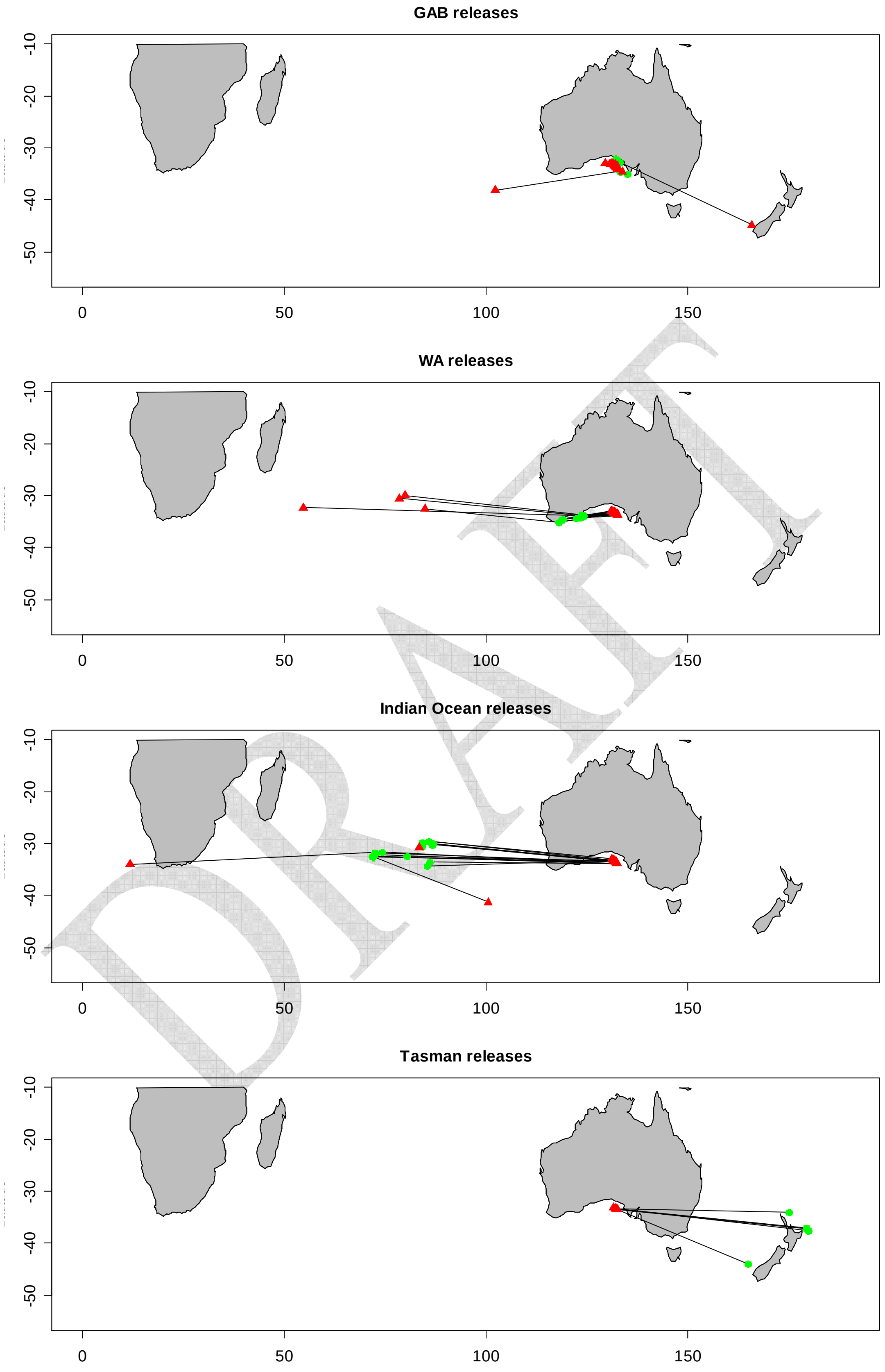

Figure 6.11. Recapture locations (red triangles) of tags released (green dots) in (a) the GAB, (b) WA, (c) the Indian Ocean and (c) the Tasman Sea. There have not yet been any recaptures of tags released off South Africa.

6.5. Preliminary Analysis and Results

The number of tags used in the remaining sections of this report varies depending on the analysis. Reasons for having to leave out tags include lack of geolocation estimates, very short deployment periods, and a few occurrences of problems with sensors, tag damage (e.g. data not retrievable), or the tag recaptured but not actually returned (so data could not be downloaded).

6.5.1. Tag data used for subsequent analyses

In addition to the tags released under this project, a number of archival tag returns from releases on juvenile SBT under previous projects were made available for analysis (**Table 6.3**). These additional tags extend the time-frame back to 1993, though the earlier releases generally have shorter deployment times and less useable data than the more recent releases, making them suitable only for some types of analysis. Full IP with the tags from previous projects, as well as from the additional tags released under the current project that were funded by CSIRO (see footnote 5), remains with CSIRO.

Table 6.3. Numbers of archival tag returns from tags released in 1993 to 2003 under previous projects.

Release year	Release area	Tag type	Number of returns
1993	GAB	Zelcon SBT100	4*
1994	GAB	Zelcon SBT100/150	22*
1995	GAB	Zelcon SBT200	48*
1998	GAB	Wildlife Mk7	34
1999	GAB	Wildlife Mk7	13
2000	GAB	Wildlife Mk7	9
2001	WA	Wildlife Mk7	4
2002	GAB	Wildlife Mk7	6
2003	WA	Wildlife Mk9	4

* The Zelcon tags do not have any tag sensor data (i.e., light, depth, temperature) stored in the database, and only some previously-processed light-based longitude estimates, so their use is very limited. These tags have only been used to explore changes in spatial dynamics in **Section 8**.

6.5.2. Tag output

Each Mk7 and Mk9 archival tag recorded light, depth, internal temperature and external temperature at regular intervals starting at the time of release, relative to

GMT. The light data are used to determine day and night, and hence sunrise, sunset and noon, and are used in geolocation. The external temperature sensor measures water temperature, while the internal sensor measures body temperature, which can be used to identify feeding events. The depth information can be used in studies about diving and vertical habitat use, and is also required to correct the light record for diving behaviour.

The sampling interval varied according to tag type and capability; some of the early tags (released prior to this project) recorded data at 4-minute intervals; the first tags released under this project recorded at 1-minute intervals and later tags were set to record every 20 or 30 seconds. The amount of data for just one tag becomes vast as the period for which it is deployed increases and the sampling interval becomes smaller. For instance, a tag that records every 30 seconds for 1 year will store over 1 million observations for each tag sensor. **Figure 6.12** shows an example of the sensor data for one tag over a 7-day period.

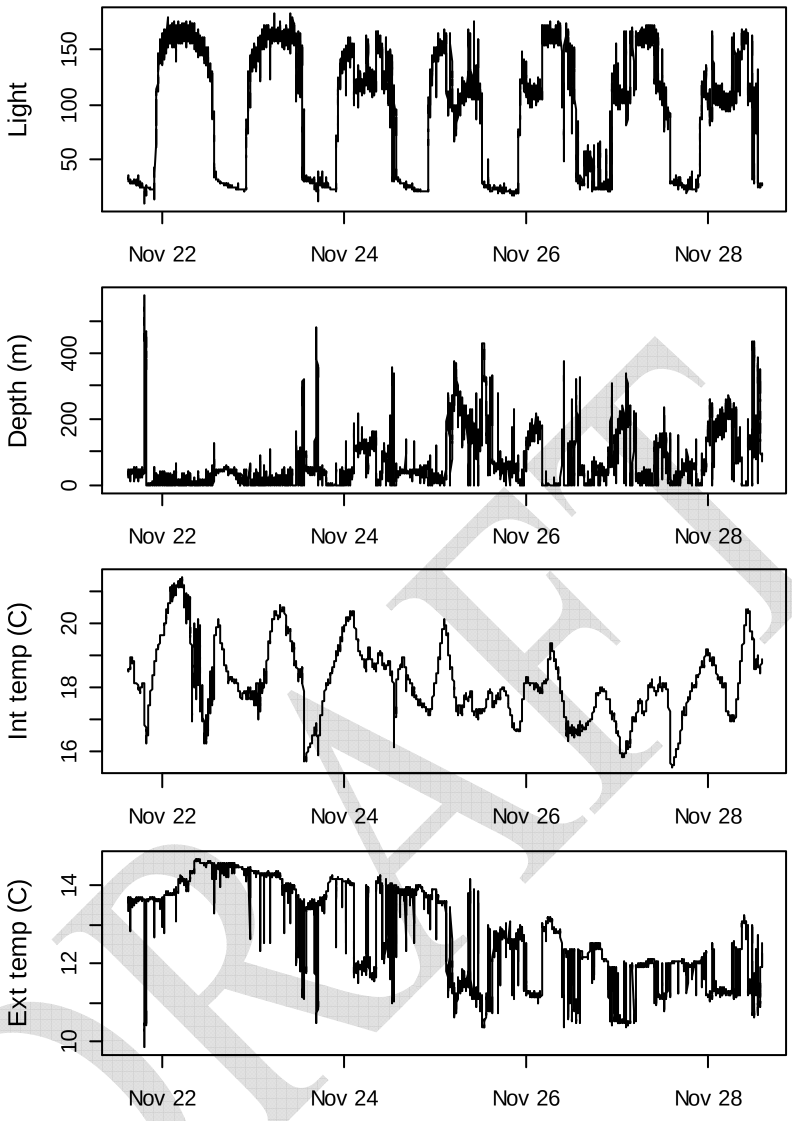

Figure 6.12. Light, depth, internal temperature and external temperature data for tag #791 over a 7-day period. This particular tag was a Wildlife Computers Mk9 tag with a 1-minute sampling interval.

A tag database is essential for handling this data volume (Hartog *et al.*, 2009). Archival and other tag data are handled using an Oracle database initially established for this project (**Objective 2**) and then developed over a number of years at CSIRO to handle a range of tag types and for other species: see details provided in Hartog *et al.* (2009). Tag details were recorded in the database when tag release datasheets were returned from field trips, and then linked to the recovery details when the tags were returned. Preliminary processing can take place, and environmental data can also be matched to tag information and stored in the database, prior to project-specific analyses (**Figure 6.13)**.

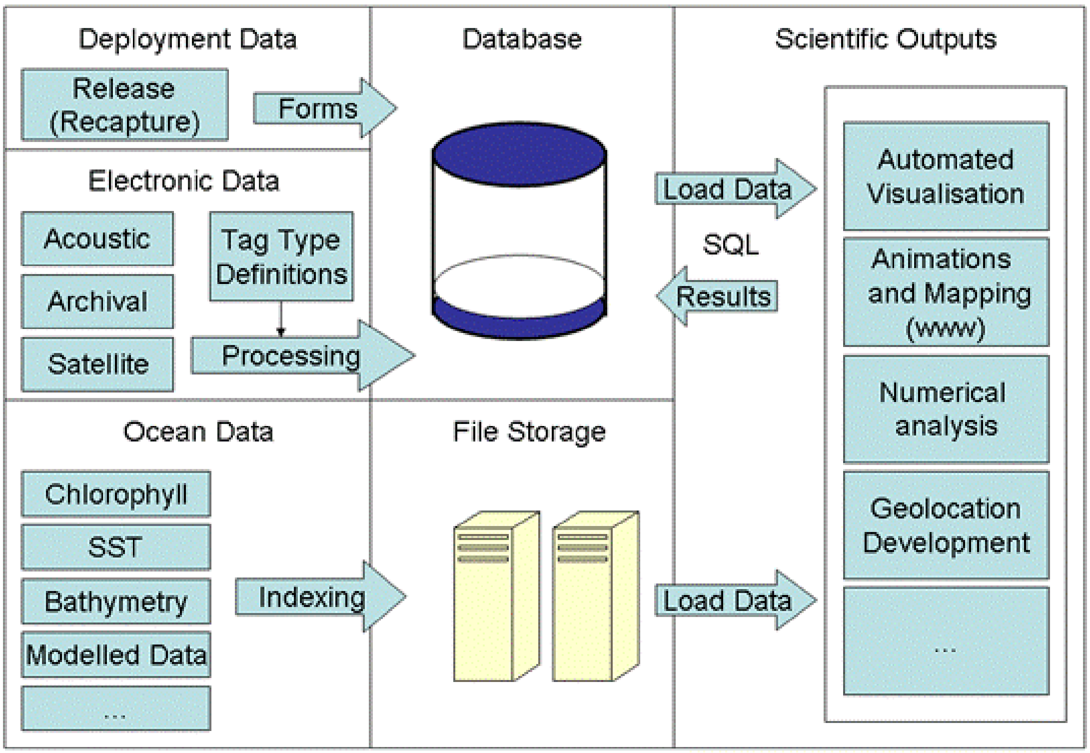

Figure 6.13. Schematic illustrating basic flow of information into the tag database used in the project. Source Hartog *et al.* (2009).

6.5.3. Data pre-processing

When an archival tag was returned, three main steps were involved prior to data upload to the Oracle database, First, the data were downloaded from the tag using proprietary tag software (MK-Host©, by Wildlife Computers). As the downloaded data were in hex format they were decoded using HexDecode© (Wildlife Computers). Finally, some quality control was performed on the decoded data, using the CSIRO program Archtag Viewer to pre-process the archival tag data. These pre-processing steps included:

1. Set start and end of deployment: There is often data logged prior to deployment, as the tag is set up in the office and may therefore be running for days or weeks before surgery on the animal and subsequent release into the water. Similarly, the tag may still be logging after recapture. These data are trimmed from the beginning and end of the data file.

2. Add depth sensor drift correction (where appropriate): Over time, the depth sensor may fail to correctly record depth at the surface. This can be due to excessive diving that compresses the depth sensor housing, or some other fault. Regardless of the cause, we would like to be able to correctly measure depth as zero when an animal is at the surface. This can be achieved by adding a Zero Depth Correction point that tells the software that the depth at the current point is actually zero. More than one correction point can be added, and the software applies a series of linear corrections between the set of points that have been added. The depth sensor should be correct at the start of deployment due to quality control at the manufacturer. The software will assume that the depth at the start of deployment should read zero if a correction point is not added manually at the start of the deployment. Note that this process is only necessary if the depth sensor has an obvious error in the measurement of depth at the end of the deployment.
3. Flag individual sensors as invalid (where appropriate): There are times when sensor readings appear to be outside the possible values that they should be, or they appear to be showing erratic behaviour. In these cases, the sensor(s) were flagged as being invalid. Flagging a sensor as invalid does not delete those readings, but ensures that data stored in the database are flagged as valid or invalid. This step aids in post-processing the data from the database: a user can restrict analysis of the data to only include readings that have been flagged as valid.

One additional pre-processing step was required for the Mk9 tags relating to sensor drift. Some Mk9s (purchased in 2003/4 for this project) displayed drift (to warmer temperatures) of the external temperature sensor. This was evident from a comparison of the internal (body) and external (water) temperatures. In general, SBT internal temperatures are greater than external water temperatures by an average of 4-5°C, when SBT are in the wild. External temperature drift can be identified by large numbers of records where the external temperature is very close to or above the internal temperature. This is physiologically impossible except after deep dives (where there is a lag in the body temperature rising after a deep dive into colder water) or following frozen feeds, as can occur in the farm pens.

Following discussions with the tag manufacturers, Wildlife Computers, the problem was found to be related to an undocumented change in the commercially-sourced thermistors (temperature sensors) used in the external stalks of the batch of Mk9 tags. The temperature drift was due to the combined effects of salt water and pressure at depth, which is why it only became evident after some period of deployment. According to the manufacturers, the problem has since been addressed and is no longer an issue with recent or current generations of Mk9 tags (Wildlife Computers, pers. comm.; http://www.soest.hawaii.edu/PFRP/nov08mtg/nov08mtg_presentations.html). The internal (body) temperature sensor is unaffected and considered to be stable because a different thermistor was used.

We analysed the internal and external temperature readings from tag returns, compared results with Mk7 tags (all known to be unaffected because a different thermistor was used), and identified three categories:

- no external temperature problem (unaffected tags)
- possibly an external temperature problem but not obvious or severe (partially affected tags)
- obvious external temperature problem (affected tags)

Only the external temperature sensor is affected by this particular issue, so even affected tags still contain data on light, depth, and internal temperature which can be used. For the purposes of this project, the affected tags – 16 in total - were flagged as having temperature drift. The partially affected category only manifested bad drift towards the end of deployment when the fish had been captured and were in cages off Port Lincoln. Since we were only using data from the 'wild' deployment period, these tags were flagged as not having temperature drift. This categorisation took into account the kind of analyses we planned to conduct. Any other analyses undertaken in future should re-assess whether this categorisation is appropriate or not.

In theory, it should be possible to develop a correction, but this would be a major task. Instead, we decided to exclude tags with temperature drift from analyses where it could affect results. Temperature drift can affect geolocation if external temperature is used as auxiliary data. We did not use these data in the estimating of movement tracks (**Section 7**). We did use external temperature for an "outlier check" on latitude (**Section 11**), but excluded tags flagged as having temperature drift in developing criteria for outliers. One aspect of migration modelling (**Section 10**) looks at summaries of on-board variables when SBT are migrating or resident. These could be affected, so tags flagged as having temperature drift were excluded. Finally, habitat modelling (**Section 11**) was undertaken using oceanographic products to obtain sea surface temperature, so flagged tags were included.

6.5.4. Deployment times

Of all the tags available for use in this project, 122 had sensor data for at least part of the time they were deployed, and of these, the majority (81 out of 122) had sensor data for over 90% of the time (**Table 6.4**). The number of tags with almost-complete sensor data is greater for release years 2003-2008 (Wildlife Computer Mk9 tags) than for release years 1998-2002 (previous generation Mk7 tags) (**Table 6.4**), suggesting an improvement in tag technology. For most purposes, it is only the time for which a tag recorded sensor data that is of use, so to distinguish between the time between release and recapture of a tag and the time for which that tag recorded sensor data we will refer to the former as its “total deployment time” and the latter as its “operational deployment time”. Note that both the total deployment time and the operational deployment time exclude any time at the end of the tag deployment for which a fish was in a farm cage in Port Lincoln[7].

Table 6.4. Number of tag returns from each release year that have sensor data for at least x% of their total deployment times (x = 0, 50 and 90%). Thus, 122 tags had at least some data (>0%), while 81 tags had data corresponding to 90% of the total deployment period.

Release year	Total returns	x		
		0%	50%	90%
1998	34	29	21	14
1999	13	8	6	3
2000	9	9	6	4
2001	4	3	1	0
2002	6	2	2	1
2003	4	3	2	1
2004	25	22	20	18
2005	28	28	28	26
2006	11	11	11	8
2007	6	5	4	4
2008	2	2	2	2
Total	142	122	103	81

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[7] Fish that have been captured in purse seines in the Australian surface fishery are put into farm (grow-out) cages off Port Lincoln, South Australia, where they are kept for several months before being culled and processed. It is generally at the time of processing that archival tags are found and removed. However, the date of capture in the wild is known for fish within each cage, so we can exclude data beyond this date.

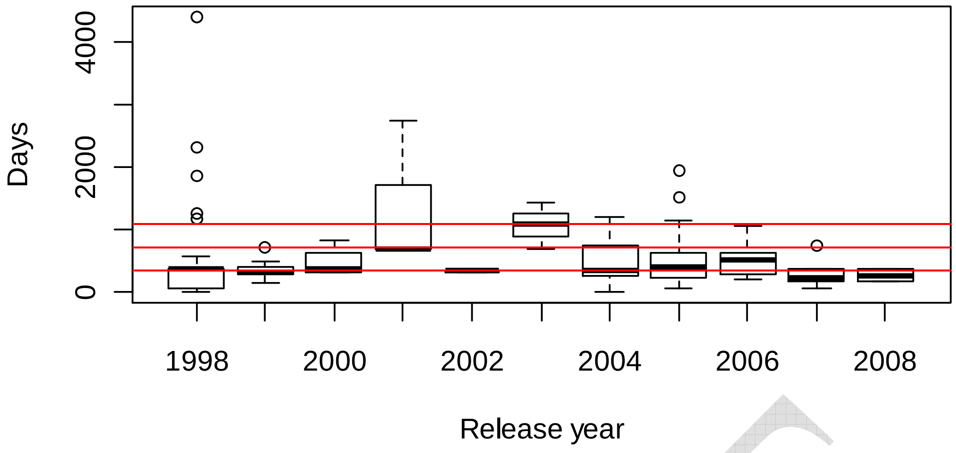
A summary of the operational deployment times shows that there were two tags that recorded data (marked as “valid” in the database) for over 4 years (**Table 6.5**). Over 10% of tags had data for over two years and 42% of tags had data for at least one year. These results are considered to form the basis of a very good data set for analysis, and the success of the project built upon these deployment results.

Table 6.5. Summaries of operational tag deployment times (i.e., durations for which tags recorded valid data) in terms of numbers of tags and percentages.

Duration	< 0.5 years	0.5 – 1 years	1 – 1.5 years	1.5 – 2 years	2 – 3 years	3 – 4 years	4 – 5 years
Number	30	41	32	6	10	1	2
%	24.6	33.6	26.2	4.9	8.2	0.8	1.6
Cumulative %	100	75.4	41.8	15.6	10.7	2.5	1.6

Considering this information by year (**Figure 6.14**) shows that the length of both total and operational deployment times increased over time. For releases in the late 1990s, most tags that were returned recorded data for periods less than a year. It is only in the early 2000s (2003 releases in particular) that longer periods are observed. This could be a combination of improvements in tag technology (e.g., increased battery life; reduced sensor failure), a reduction in recaptures shortly after release (e.g. due to lower fishing rates, different areas and times of tagging) and/or other unknown factors (including chance). The deployment times for 2007 and 2008 are relatively short, but are likely affected by the small sample sizes and the fact that returns from longer deployments are still expected from these releases.

(a) Total deployment time



(b) Operational deployment time

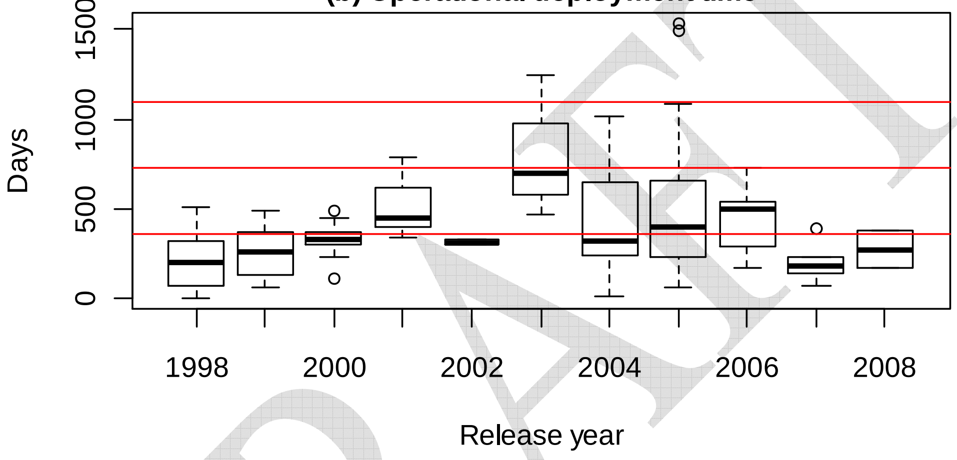


Figure 6.14. Boxplots of (a) total deployment times (times between release and recapture), and (b) operational deployment times (times for which tags had data) by release year. The red horizontal lines indicate 1, 2 and 3 years.

6.5.5. Day-night summaries

Some simple summaries of the tag sensor data over all tags are presented as a precursor to the detailed analysis in subsequent sections. **Table 6.6** shows a) day-time and b) night-time summaries over all tags by month. To calculate these values required determination of which observations occurred during the day and which occurred during the night. While this may sound simple, the date-times stored on the tags correspond to GMT and not to local time at the location of the fish, so day and night must be determined from the light data recorded by the tags' light sensor. To do so is relatively straightforward when a fish remains near the surface so that light levels are maximal and are recorded at a consistent depth (e.g., the first 2 days in **Figure 6.12**); however, when the fish spends extended periods of time at depth, the light record becomes much more variable and difficult to interpret (e.g., the last few days in **Figure 6.12**).

Coinciding with this project, an in-house algorithm for estimating the probability of an observation occurring during the day was developed as an initial step in the development of a CSIRO internally-funded geolocation method (see **Section 7**). A probability of 1 means the observation occurred during the day and a probability of 0 means the observation occurred at night. During dawn and dusk, probabilities would lie somewhere between 0 and 1. This algorithm was applied to all tags and a field was created in the database that stores the probability of day. Thus, for each tag, we calculated daily statistics (e.g., average, minimum, maximum) for each type of sensor data using only observations that had a probability of day of greater than 0.99. Similarly, we calculated nightly statistics for each type of sensor data using only observations that had a probability of day of less than 0.01, thereby excluding (the usually short) periods of dawn and dusk. Note that we excluded any observations that were marked as invalid in the database.

Once we had daily (nightly) statistics for each sensor type and each tag, such as average external temperature and maximum depth, we calculated the average of these by month over all tags[8] to get the values in **Table 6.6a** (b). We excluded any days or nights for which a fish was in a farm cage in Port Lincoln (see footnote 7), since these data are not representative of fish in the wild. Average sea surface temperature (AVG_SST) was calculated as average external temperature for depths less than 5m and proportion of time at the surface (PROP_SURF) was calculated as the proportion of depth values less than 10m.

From the summaries in **Table 6.6** juvenile SBT are found deeper on average during the day, spend less time at the surface during the day (particularly in the winter months), and on average maintain an internal temperature of ~4.5°C warmer than the external temperature in the day and ~5°C warmer at night.

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[8] Excluding those with obvious temperature drift – see **Section 6.5.3** above.

Table 6.6a. Day-time summaries of archival tag data by month. Data summarized over all tags with sensor data, excluding time in farms and excluding tags with obvious temperature drift.

MONTH	AVG_ INT_TEMP	AVG_ EXT_TEMP	AVG_ SST	AVG_ DEPTH	MAX_ DEPTH	PROP_ SURF
1	22.7	18.0	18.6	50.8	180.7	0.44
2	23.4	18.8	19.6	51.6	160.6	0.40
3	23.6	18.7	19.6	50.9	159.3	0.35
4	23.0	17.4	18.2	68.2	179.3	0.29
5	22.0	16.1	16.9	78.2	190.5	0.25
6	21.5	15.8	16.7	85.8	202.7	0.24
7	20.4	15.6	16.5	102.0	228.2	0.22
8	19.8	15.3	16.1	112.5	255.0	0.15
9	20.1	15.0	15.8	106.4	265.0	0.18
10	21.2	15.7	16.4	80.9	252.0	0.29
11	21.7	16.5	17.2	62.0	236.9	0.40
12	22.0	17.2	17.8	60.9	222.4	0.46
Average	**21.8**	**16.7**	**17.6**	**76.0**	**210.7**	**0.30**

Table 6.6b. Night-time summaries of archival tag data by month. Data summarized over all tags with sensor data, excluding time in farms and excluding tags with obvious temperature drift.

MONTH	AVG_ INT_TEMP	AVG_ EXT_TEMP	AVG_ SST	AVG_ DEPTH	MAX_ DEPTH	PROP_ SURF
1	22.6	18.1	18.4	30.1	165.2	0.40
2	23.2	19.1	19.4	28.1	149.2	0.40
3	23.3	19.2	19.5	28.7	151.4	0.39
4	22.6	18.0	18.0	35.4	186.9	0.40
5	21.4	16.5	16.5	42.6	223.4	0.41
6	20.9	16.2	16.3	47.2	238.7	0.40
7	20.0	16.1	16.1	50.2	243.2	0.36
8	19.5	15.6	15.6	46.1	247.2	0.38
9	19.6	15.4	15.5	44.2	253.0	0.36
10	20.6	16.0	16.3	40.8	246.5	0.37
11	21.5	16.9	17.1	33.8	217.6	0.42
12	22.0	17.5	17.7	30.9	194.3	0.47
Average	**21.4**	**17.0**	**17.2**	**38.3**	**210.0**	**0.40**

6.5.6. Time at surface

We already pointed out from comparing **Table 6.6**a and b that juvenile SBT tend to spend less time at the surface during the day than night, particularly in the winter months. This can be seen more clearly if we plot the data (**Figure 6.15a**). The surfacing behaviour of juveniles is of particular interest in the GAB, where the Australian surface fishery operates and where commercial aerial spotting as well as a scientific aerial survey operates (fish must be near the surface in order to be spotted). Thus, **Figure 6.15b** shows the proportion of time spent at the surface during the day and night using only days/nights when fish were in the GAB[9], as determined using the light-based position estimates (see **Section 8**). When only the GAB is considered, we can see that the proportion of time juveniles spend at the surface during the day is greatest in November, averaging ~ 60%, and declines steadily until August (when they spend less than 20% of the time, on average, at the surface during the day), and then increases steadily until November. Note that although juveniles are mainly found in the GAB in the summer months (Dec-May), some fish are still found there during the winter. It is also interesting to note that the proportion of time spent at the surface in the GAB is higher on average during the day than during the night in Nov-Mar, and particularly in Dec and Jan. This reverses in the winter (May-Oct), when fish spend more time at the surface at night than in the day (in the GAB as well as in other regions).

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[9] The GAB was defined here as the area between 125 and 140°E and to the north of 37°S,

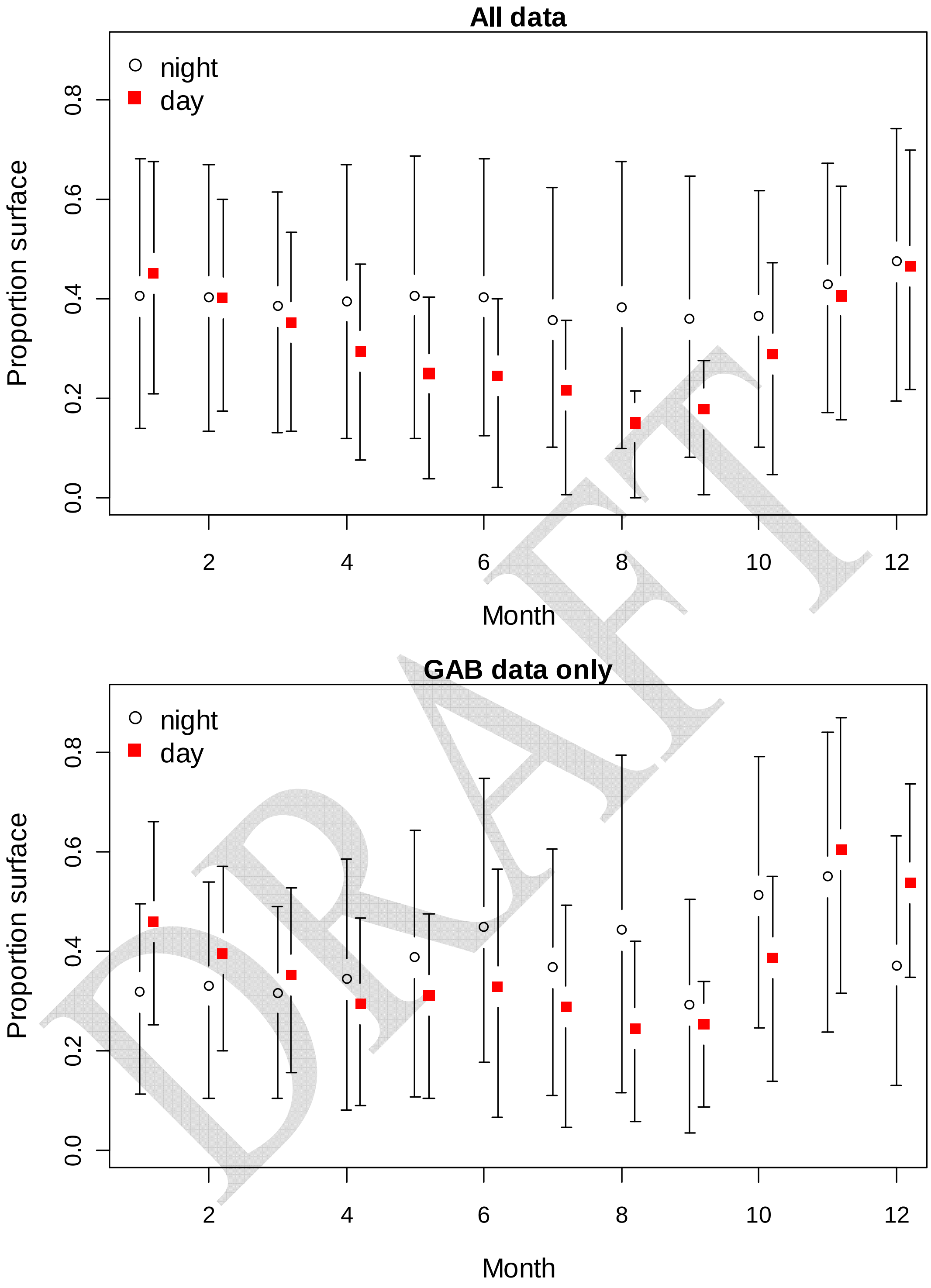

Figure 6.15. Proportion of time SBT spend at the surface (within the top 10m of the water column) during the day and night by month. Points are means of the daily/nightly proportions of time at the surface calculated using (top) all data; and (bottom) only data from the GAB. Vertical lines extend between the 25th and 75th percentiles.

6.6. Summary of main results

This section of the project was successful in releasing archival tags throughout the range of juvenile southern bluefin tuna (**Objective 1**), recovering tags, and establishing a database to hold tag data (**Objective 2)**. It particular, this required international cooperation and significant development of outreach and training with partner countries. We demonstrated through our deployment results the feasibility and viability of conducting archival tagging from longline vessels using trained observers to do the tagging. To date, there have been 17 recaptures from the 159 fish tagged by Taiwanese observers in the central Indian Ocean, and 1 recapture out of 6 releases by observers in New Zealand. To facilitate this tagging by observers on commercial vessels required that we develop appropriate training packages and tools, including a surrogate tuna, codes of practice for handling fish that reflected the ethics permits issued by Australia, and importantly, developed tagging technology that could be easily used in a range of situations, including fish lifting, cradles and mattresses and tag kits. The overall best practise for tagging should include

1. Detailed and intensive training for tag surgeons
2. Release of fish over multiple years
3. Release in multiple areas (see **Section 9**)
4. Outreach for tag recovery
5. Database management for data from recovered tags

The return rate of tags, including several multi-year deployments, supports our contention regarding the success of deployment methods and involvement of trained fishery observers on the high seas. Data from longer release periods are particularly valuable, as possible behavioural effects from handling have disappeared, there is good mixing of tagged individuals, and use of multiple summer and winter grounds can be revealed.

Quality control is conducted on data prior to analyses. Preliminary analysis showed that fish spend more time at depth during daylight and in winter, which will have implications for interpretation of some stock indicators. More detailed analyses are described in the following sections.

7 Geolocation: determining locations of SBT based on archival tag data

Key findings

This section deals with the difficult problem of estimating an SBT's position from the electronic tag data.

- We applied an existing published method and an improved, more rigorous approach to calculation of movement paths. Both approaches gave broadly consistent results.
- Despite considerable challenges of dealing with uncertainty in the latitude estimates for SBT, clear signals of cyclic seasonal movement were apparent, as was the degree of individual variability in movements.
- All SBT in our dataset spent each summer (or part of summer) in waters south of Australia (longitudes of ~115°E-145°E, encompassing the GAB and waters south of WA), except one SBT tagged in the Indian Ocean in winter that visited the GAB in the summer following tagging, but spent two subsequent summers in waters off South Africa.
- The majority of individuals migrated from southern Australia to the Indian Ocean for winter, a much lesser percentage to the Tasman Sea, and, somewhat surprisingly, some individuals overwintered in southern Australia.
- Estimates of location were judged sufficiently precise to facilitate further analysis using behavioural models and to assess habitat preferences in Sections 10 and 11.
- The data generated inform several aspects of SBT research and management including initial assessment of mixing rates and the timing of the SBT arrival and departure from the GAB in relation to aerial surveys of juvenile abundance.
- The results given in this section provide the most comprehensive picture yet assembled of the cyclical seasonal migration and global movements of juvenile SBT and will support future spatial assessment (and management where appropriate), as well as process understanding for this species.

7.1 Introduction

In this section we address the part of Objective 2 which relates to the estimation of daily positions for juvenile southern bluefin tuna (SBT) based on the light and temperature data from the archival tags recovered and stored in the database (see **Section 6)**.

Objective 2:

> For each tag returned (expected to be ~20-30%) estimate daily position based on the stored light and temperature data and develop a database for the storage and analysis of all relevant location, temperature and depth data.

Many methodological advances in light-based position estimation have been developed, both in this project and elsewhere, over the course of this study. Thus, we first briefly review the methods that were available at the start of this project and the methods that have become available since then. We then discuss our choice of methods for this project and detail the considerations which led us to use (or avoid) particular techniques and data for the position estimation. An overview of the resulting track data set generated by this analysis is given and we discuss particular aspects of the derived movements which are important for later sections and the broader goals of the study. In particular we examine the general patterns of migration and give an assessment of individual variability in migration timings (**Section 7.2.3**), consider aspects of schooling behaviour which are relevant to assumptions of mark-recapture models (**Section 7.2.4**), and briefly comment on the migration pattern of one long deployment which is relevant to questions about summer residency of SBT off South Africa (**Section 7.2.5**). Finally, we discuss the movement results in light of the aerial survey conducted over the summer months from which an index of relative juvenile SBT abundance is derived (**Section 7.2.6**).

7.2 Background and Methods

7.2.1 A brief history of tuna geolocation

Geolocation is the process of estimating the location (latitude and longitude) of a tagged animal from the sensor data collected by its electronic tag. Geolocation of free moving animals in the open ocean is a notoriously difficult problem and the inherent errors in the process of arriving at reliable position estimates have presented a major impediment to understanding the movements of fish – as well as other marine species (Gunn and Block 2001; Hill 1994). However, from pre-existing research conducted by CSIRO and others (Gunn and Block 2001; Bestley *et al.* 2008) it was known at the outset of this project that for highly migratory species such as SBT, these errors are less of an issue because the scale of the movements are much larger than the error in the generated tracks - at least in terms of longitude (i.e. the east-west component of movement). As we discuss below, estimation of latitude is more difficult.

The only feasible method of geolocation for the archival tags deployed on SBT in this study is light-based geolocation. Typically an assumed depth-attenuation model is used to calculate surface light levels from depth and light-at-depth data collected by the tag. Light at the surface is then used to estimate latitude and longitude from astronomical equations. The simplest geolocation methods use an estimate of the universal time of midday or midnight to derive a longitude estimate, and an estimate of day length (between sunrise and sunset) to obtain a latitude estimate. However, the entire light record obtained during each twilight event (dawn and dusk) contains information about location, and it is these data that are used in the more recently developed methods.

There are several methods for geolocation based on different approaches and each have their own inherent shortcomings. At the time this project was proposed, the methods available included the following:

- Threshold light method (Welch and Eveson 1999; Musyl *et al.* 2001)
- Wildlife Computers geolocation method (Hill and Braun 2001)
- A sea surface temperature (SST) matching method combined with light-based geolocation (Teo *et al.* 2004)
- A curve-matching method using only blue light (Ekstrom 2007; Ekstrom 2002; Ekstrom 2004).

Threshold light methods first estimate the times of sunrise and sunset, which are then used with astronomical equations to estimate position. Latitude is generally much more uncertain than longitude, so auxiliary data such as SST are sometimes used to improve estimates of latitude (Shaffer *et al.* 2005; Sumner *et al.* 2009). The Wildlife Computers (WC) method (Hill and Braun 2001) uses the entire light curve over twilight, but matches pairs of dawn and dusk curves to improve estimation. This makes the implicit assumption that there is no movement during the time between the two matched events (dawn and dusk, or dusk and dawn); alternatively, one can interpret it as estimating a location somewhere in between what would have been the “pure” dusk and “pure” dawn locations. The SST matching method (Teo *et al.* 2004) relies on first deriving geolocation positions from light only, but then adjusts these by incorporating onboard SST measurements and comparing these to remote-sensing data. Finally, the Ekstrom (2004) method matches a theoretical model of light versus time of day to the relevant portion of a day’s data, but only using blue light (on the basis that blue light is not significantly affected by factors such as cloudiness and atmospheric refraction).

All the above methods have serious shortcomings. The threshold light method is very sensitive to small changes in the recorded light data, so factors such as cloud cover and diving animals that affect the light level are problematic. The WC method often required manual intervention to do the matching of pairs of dawn and dusk curves which introduces the possibility of individual subjectivity in the estimation of movement paths. The SST matching method of Teo *et al.* (2004) relies on three *ad hoc* criteria to match SST derived from the tag to remote sensing SST. This method ignores the latitudinal information in light data and also provides only limited estimates of uncertainty for each derived location estimate. Empirical estimates of geolocation uncertainty have been calculated (e.g. from mooring or simulation experiments; see e.g. Welch and Eveson 1999; Musyl *et al.* 2001), but being from very specific deployments in a particular location with different instruments, these were only of limited use for dealing with data collected from actual deployments on SBT. The individual estimates of location from the methods mentioned above are usually very “noisy”, often suggesting impossible distances moved by the tagged animal. When interpreting the results from these methods, it is usually necessary to leave out obviously unrealistic/poor estimates of location and/or to run a statistical “smoother” through the results.

Around the time this project began, Sibert *et al.* (2003) first used state-space models to "filter"[10] position estimates from these methods and obtain a more realistic track by incorporating some form of movement model. State-space models are a sophisticated statistical technique used in many fields to estimate a dynamic process from noisy data (e.g. radar target tracking, GPS correction, speech recognition, to name a few). They are a recent addition to animal telemetry analysis (Patterson *et al.* 2008). A state-space model consists of two sub-models: (a) a model of the process of interest which cannot be directly or accurately measured. In this case this is the movement, and hence locations, of the tuna; (b) a model of the observation, which models the statistical properties of the observation process. In this case, the observation model is intended to capture the statistical nature of the errors in the geolocation process. After Sibert's (2003) initial method, Nielsen and Sibert (2007) then developed a state-space model to estimate position directly from light measurements of each twilight event. The model explicitly incorporates animal movement to estimate a "most probable track", with two location estimates per day coinciding with dawn and dusk events. Estimates are obtained within a Kalman filter framework (a widely used state-space estimation approach; e.g. Harvey, 1990). This method, implemented in the "Trackit" software package (downloaded from www.soest.hawaii.edu/tagdata/trackit[11]) presents a substantial advance over previous methods, particularly since it takes into account the autocorrelated structure of the light data and estimates uncertainty associated with each location estimate. This method also allows for the inclusion of auxiliary data like SST, but in practice we have found this to be problematic (i.e. the method did not converge to a viable solution when SST data were included).

There are, however, still shortcomings of this approach for the habitat modelling objective of this project. First, Trackit is unaware of land. In the region where it was first used, the Pacific Ocean around Hawaii, it was difficult to determine if this was a problem simply because there is very little land. Around the GAB, Tasmania and New Zealand, it is a potential problem. Second, the method is still based on the assumption of Normal (Gaussian) errors and an assumed structure for autocorrelation in the data. The estimation of four parameters relating to the autocorrelation structure

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[10] The term "filter" is not used here in any technical sense, but rather as an informal description of the process of correcting errors in noisy track data. Note that we do not filter data in term of removing data points but instead statistically arrive at a most likely data point.

[11] Note that this site was no longer available at the time of writing (Aug 2011).

could play a part in the practical difficulties we have found with some tags (some datasets do not converge on a solution, i.e. there is no estimated track).

Finally, the method already assumes a movement model (i.e. the process model) in filtering a track. This is unlikely to be a problem when track estimation is the sole output required, but if we want to develop habitat models with different types of behaviour (e.g. “resident” and “migratory”) related to environmental covariates, then this approach is not theoretically ideal. In theory, the whole sequence of modelling - track estimation, movement/behaviour and preference in relation to environmental covariates – should ideally take place in a single, enormous model. This would allow for the correct propagation of errors through all stages, and would give quantitative estimates of the uncertainty in conclusions. However, such an approach is technically extremely complicated and, most importantly, makes it much harder to run exploratory analyses and check diagnostics. In this report our aim has been to establish what the patterns of movement behaviour and relationships with environmental covariates are, and to see whether our conclusions are ‘qualitatively’ sound (and we conclude that they are; see **Sections 10** and **11**). We are closer to being able to define an appropriate model structure and relationships with covariates, but further work is still required in order to correctly specify such a full model. Whether that is worth the effort, depends on the need for fully quantified uncertainty.

In 2006 CSIRO initiated internally funded research to develop a geolocation method that would:

- be fully automated;
- allow for time-varying depth attenuation to be done within a statistical framework;
- produce a separate and rigorous likelihood for each twilight event, which we call a twilight likelihood

Being able to calculate the likelihood of a candidate position allows statistical filtering of a track through a number of methods: based solely on the twilight likelihoods; including auxiliary data such as SST; or within a more complicated behavioural model. All of these options may be efficiently constructed using a Hidden Markov Model (HMM) approach (Thygesen *et al.* 2009; Pedersen *et al.* 2008). A HMM is a type of state-space model where the unobserved state of the system is discrete rather than continuous as opposed to, say, Kalman filter methods where the states (i.e. locations) are continuous. Note that the hidden state need not be a spatial location, and in fact in a subsequent section, HMMs are again used to estimate a different hidden state – the unobserved behavioural state of individual SBT.

A crucial advance of the CSIRO geolocation work was the development of a robust and rigorous statistical likelihood function for locations. This is essential for obtaining reliable uncertainty estimates of location, which are in turn essential for habitat modelling. For example, if we want to relate movement/behaviour with habitat or environmental covariates, where should covariates be measured? Reliable uncertainty estimates are also essential for making valid choices between alternative models of movement and/or behaviour. The investigation of the mathematical and statistical aspects of this approach has been a major undertaking and has only recently reached a sufficient stage of completion to be applied to real electronic tag data (Bravington *et. al*., 2011; Basson *et. al*., 2011). Manuscripts which comprehensively describe our method are currently being completed for peer-review publication.

It is important to note that the development of the twilight likelihood geolocation method was not part of this project and neither was this study contingent on its development. However, having developed the new approach, it made sense to apply it to the juvenile SBT data to the extent possible in the time remaining. Therefore, in addition to presenting results from the Trackit software, we also present initial results from our recently developed twilight likelihood method to demonstrate its potential. An initial limited comparison between the two methods is given and we discuss options for further work to improve geolocation methods.

7.2.2. Methods adopted for this study

Trackit software

Although this project started electronic tag deployments in 2004, CSIRO had already deployed relatively large numbers of archival tags on SBT in the late 1990s and early 2000s. The intention in this project was always to also consider data from those deployments. Ideally, we wanted a consistent set of geolocation estimates (i.e. based on the same method) for all tags. None of the methods mentioned above (threshold, light curve matching, and SST-matching methods) were ideal for the reasons already outlined. We therefore chose to estimate locations using the Nielsen and Sibert (2007) method, as implemented in the Trackit software package written for the R statistical computing environment.

However, even this was not straightforward because it involved estimation of several parameters from lengthy time-series of electronic tag data, and often the parameter estimation process did not converge. This problem often required multiple runs of the software using different initial parameter values and choosing the best fit when more than one of these runs converged (best fit determined by a set of criteria based on maximizing the objective function value and minimizing the variability of the track). We managed to estimate tracks for 91 of 122 returns using Trackit. Some of the tags that failed in Trackit have long deployments.

Grid-based Hidden Markov Model: Initial application of a new geolocation method

As mentioned above we also applied the new twilight likelihood method to a subset of the SBT tags. The twilight likelihood method produces an estimate of position for each twilight event with an associated likelihood i.e. the probability of the data given any location. These “raw” estimates of location are, however, still very noisy and usually contain point estimates that imply unrealistic/ impossible movement between events. Therefore we require a statistical filter to integrate these independent likelihoods with a movement model suitable for the study animal, in this case, SBT. We developed a track filter based on a HMM similar to that used by Pedersen *et al.* (2011)

Before the track filter can be applied, several complex pre-processing steps were performed. The first of these was to estimate the probability of data being collected during the day or night. This is not as obvious as it may sound. First, the longitudinal movements undertaken by SBT are of a magnitude where the clock on the tag is out of sync with local time and so a simple time-stamp is insufficient for determining the local time. A second more challenging problem is that SBT display complicated and highly variable diving behaviour, sometimes spending several hours at depth during the day, and measured daylight levels can be similar to, or even lower than, those at night. Accordingly a statistical “day-night” filter was developed to estimate the probability of sensor measurement (depth, light, etc.) relating to day or night (Bravington *et al.* in prep.). These estimated probabilities of day and night were used in subsequent analyses to establish whether behaviours are different during night than day (e.g. **Section 6**). Next surface light levels were estimated from raw light-at-depth data (Bravington *et al.* in prep.). After processing the raw tag data with the above steps, a suitable data set, "windowed" around each twilight event, for input into the twilight likelihood geolocation method was constructed. Applying the twilight likelihood method to these data is in itself a complicated step, because the data within each twilight are autocorrelated. Instead of building a complex model of the autocorrelation structure, we apply an empirical approach using mooring data to convert a sums-of-squares surface into an approximate likelihood with the correct confidence interval behaviour (Basson *et al.* in prep.). It is this likelihood for each twilight event that is used in filtering.

For filtering tracks, we defined a discrete spatial domain. In other words, space is 'chopped up' into many small regions, rather than being a continuous surface. The spatial domain is chosen to reasonably encompass the possible locations of each SBT on the globe and is made up of a finite set of gridded locations. This has the following advantages:

- By discretising space, constraints on where the animal can move are easily accommodated. This means that grid cells on land can be explicitly ruled out as a place where SBT can move to. Note that this is not an arbitrary or ad-hoc constraint. Rather, this approach can explicitly utilise the extra information provided by land. For this application we chose a model domain ranging from 20°-50°S latitude and 0°-180°E longitude with a 1°x1° grid square (see **Figure 7.1**). Given the vast distances SBT move, this resolution, while relatively coarse, is more than sufficient to determine overall movement patterns and even regional residency.
- The method has computational advantages in that the uncertainty in spatial location can be integrated over and coupled with a simple movement model. This means that the method is a computationally feasible approach to fitting a spatial state-space model.

- Spatial discretisation allows for pre-calculation of twilight likelihoods on a finite set of locations. This makes our approach computationally feasible compared to other Bayesian filtering methods which would require many more calculations or interpolation of a gridded likelihood surface. However, the computational demands increase greatly as more grid cells are added to the spatial domain.

The spatially discrete or gridded HMM filter (hereafter GHMM) allows for very flexible non-Gaussian error distributions. This is statistically important as the errors in the spatial twilight likelihoods are far from elliptical/Gaussian.

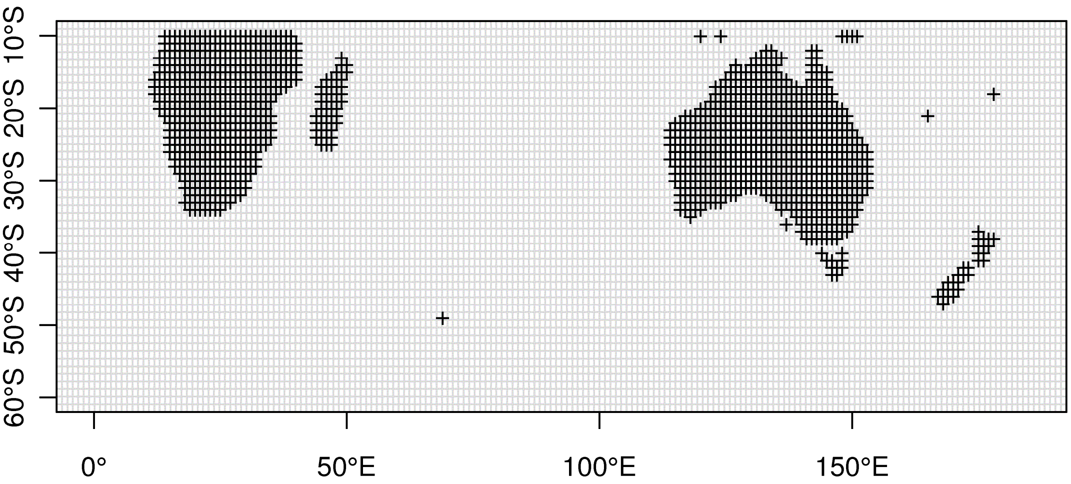


Figure 7.1. Movement model domain. Each grey cross marks the center of a grid cell and black crosses show a land mask which was excluded from the model domain – i.e. SBT were restricted to locations coloured grey only.

The state-space modelling approach (Patterson *et al.* 2008) assumes that our system (i.e. a tuna, or potentially any fish, and the data returned by the tag) are described by two submodels: a process model *f*(.) governing the assumed movement of the fish, and an observation model *g*(.) which gives the likelihood of each position given the light data. Typically, these are written:

$$\mathbf{x}_t = f(x_t, \theta) \tag{7.1}$$

$$\mathbf{z}_t = g(\mathbf{x}_t, \psi) \tag{7.2}$$

where θ and ψ are parameters. For eq. 7.1 we assumed a simple diffusive movement model whereby the probability of movement from cell *i* to *j* is given by

$$f(x_{ji},\theta)=\frac{2\theta}{\pi}\exp\left\{-x_{ji}^{2}\frac{\theta^{2}}{\pi}\right\} \qquad (7.3)$$

known as the ‘half normal’ distribution. Here x_{ij} is the distance (in km) between grid locations *i* and *j*, and θ is a parameter to be estimated. Examples of the probability moving a given distance for different values of θ are shown in **Figure 7.2**.

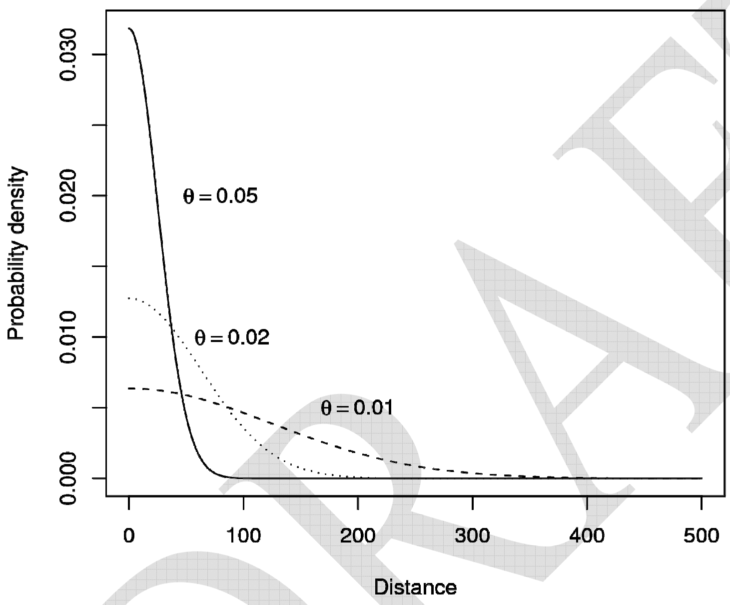


Figure 7.2. Examples of the half-normal generating function used to produce the movement transition matrix (x-axis is in kilometres). Note that in practice values for θ were estimated using maximum likelihood estimation.

Using eq. 7.2**Error! Reference source not found.** we construct a transition matrix **P** which gives the probability of moving from one grid location to any other in one time step; i.e.

$$\{P_{ji}\}=\frac{f(x_{ji},\theta)}{\sum_{i} f(x_{ji},\theta)}$$

where the summation ensures that the sum of all transitions from a given cell equals 1. We can also place further constraints on the movements by explicitly removing locations which are on land (as detailed above and in **Figure 7.1**) and also setting $\{P_{ji}\}=0$ if movement from location *i* to *j* implies unreasonable movement speeds. We set this to be 250 km between successive dusk and dawn events.

For the observation model (eq. 7.2), the likelihood function g() is given by the twilight likelihood method (Basson *et al.* in prep.). The observation model *g*(.) in equation 7.2, gives the probability of observing the data given an underlying process model is given by the light-based geolocation likelihoods. The vector of likelihoods is referred to as $\mathbf{z}_t=\{z_1,z_2,...,z_m\}$ where each z_j is the twilight likelihood evaluated at point *j* at time *t*. Twilight likelihoods were calculated on the spatial grid in Figure 7.1 for each tag.

By combining these two components in a HMM, we can estimate the likelihood of the unknown θ which governs movement. For a HMM, likelihood calculation can be broken down into a set of efficient recursive calculations and full details of the likelihood calculations can be found in Patterson *et al.* (2009) and Pedersen *et al.* (2010). Because there is only one free parameter in eq. 7.3, we used a simple one-dimensional minimisation scheme to estimate θ. Final locations were calculated as a weighted average location per dawn/dusk event by calculating a weighted sum over all possible locations, with the HMM posterior estimates of location as weights.

HMM filtering methods are very flexible and also allow for the incorporation of auxiliary data (such as SST) to improve location estimates and for more complicated behaviour (e.g. resident states and migratory states rather than simple diffusion), but there has been insufficient time in this project to apply more complicated versions of the GHMM method to the SBT archival tag data – though see Pedersen *et al.* (2010) for examples of this applied to adult SBT movement data collected with pop-up satellite tags.

7.2.3. Use of temperature data in geolocation

There is no doubt that it makes sense to consider using auxiliary data to improve longitude estimates, or to make them more compatible with other pieces of information recorded by the tag. However, some care is required when then using such tracks to interpret behaviour in relation to habitat, particularly in relation to the covariate used in track construction. Also, it is not always obvious how best to "match" to (say) SST. Temperature measured on the tag is often when the fish is at depth, so a proxy-SST needs to be constructed by summarising only those readings when the fish was very near the surface. What should the depth range be? What if the animal did not spend any time in the shallow depths during the relevant time? What should the relevant time be (e.g. just before twilight, during twilight, over the whole day?) and what measure should be used (mean, median)? The same set of questions should be asked of the independently measured or modelled auxiliary data being matched to (e.g. SST from an oceanographic product).

The Trackit software can incorporate SST data. We made many attempts to apply Trackit with SST (calculated from the tag as average daily external temperature within 5m of surface), but in all cases we were unsuccessful. The models did not converge and did not, therefore, provide any estimates of location. For this reason, all the location estimates in this project were obtained without auxiliary data, in particular, without SST. As mentioned above, the GHMM method can also incorporate auxiliary variables such as SST, but this extension could not be completed in time for application in this project. For the purposes of habitat modelling (**Section 11**), instead of estimating a track conditioned with auxiliary data, we removed locations that were outliers in a separate step prior to the habitat modelling process (as described in **Section 11**).

7.2.4. Effects of spring and autumn equinoxes on latitude estimation

Around the spring and autumn equinoxes, day-length is almost identical at all latitudes, and the light curves at twilight are also very similar. A comparison of sun angles over time, obtained from astronomical equations, illustrates the problem (**Figure 7.3**). At longitude of 0 degrees on an arbitrary “non-equinox” day, 20 May 2011 for example, the curves of sun angles over time for a range of latitudes are quite different. Note in particular that they are different around twilight (dawn and dusk, i.e. in the region where sun angle = 0), and the day-lengths are also quite different. At the equinox (e.g. 20 March 2011), however, the lines are almost identical for the same latitude in the northern and southern hemispheres (-20, +20, and -40, +40) and also at all latitudes around the times of dawn and dusk; day-lengths are pretty much identical too. This illustrates the difficulty of estimating latitude at and around the spring and autumn equinoxes, i.e. around 20/21 March and 22/23 September.

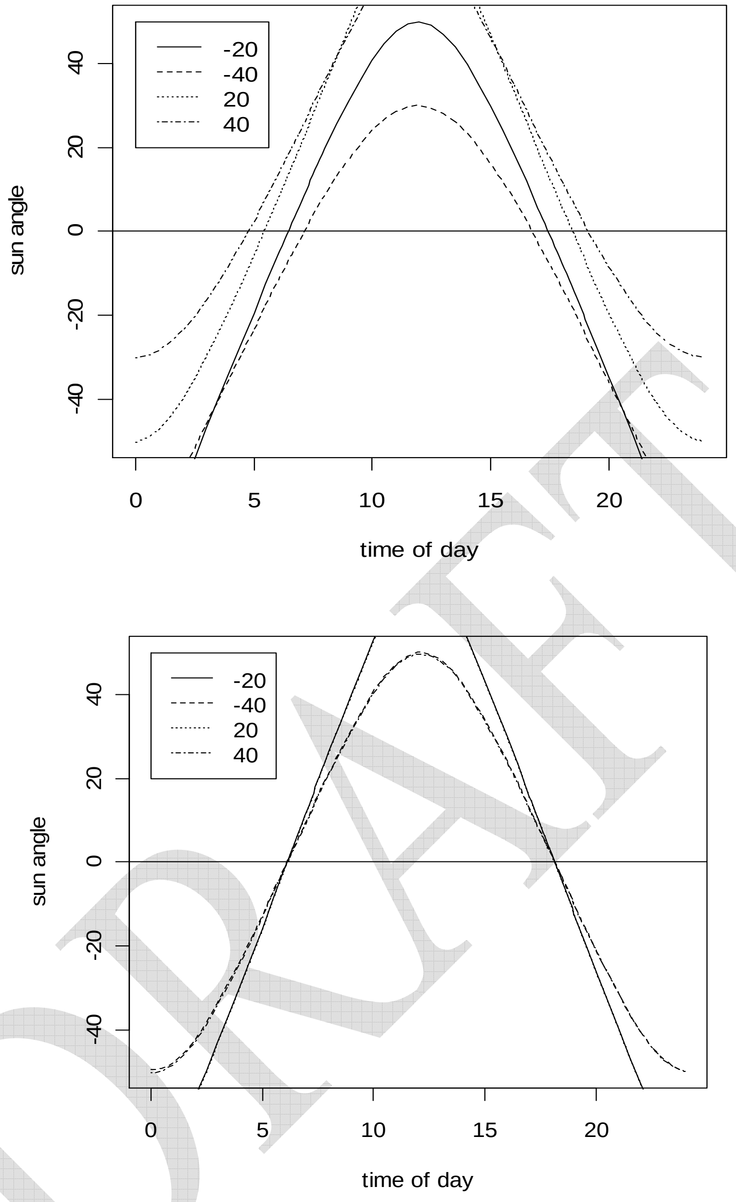


Figure 7.3. Sun angle versus time of day for (left) 20 May 2011 and (right) 20 March 2011 calculated from astronomical equations, at 0° longitude and four different latitudes indicated in the legend.

The way in which the Trackit software filters the location estimates to construct a track means that estimates either side of the equinox are likely to be affected. However, the large uncertainty in location (latitude) estimates around the equinoxes is reflected in the Trackit uncertainty estimates. Trackit estimates the location as a lat-lon pair and longitude could therefore also be affected by the equinox. However, experience with a range of methods and comparisons between longitude estimates from different methods suggest that any effect is likely to be very small. Estimates of longitude from different methods are often almost identical, or at least very similar. The same is not always the case for estimates of latitude.

The GHMM method similarly reflects the additional uncertainty near equinoxes in the raw estimates of location, and because estimates of lat-lon pairs are coupled together by the model, the longitude estimate can also be slightly affected by the equinox. However, the movement constraint in this model and potentially the use of land-masking might reduce this. It is important to bear the issue of spatial uncertainty in mind when interpreting the position estimates, especially the latitude estimates. Nonetheless, we stress that that comparisons between methods have shown very high consistency between longitude estimates. We therefore consider the use of the longitude estimates reasonable in most analyses, but we use the latitude estimates with caution.

7.3 Results and Discussion

7.3.1. Trackit results

We were able to estimate tracks for 91 of 122 archival tags using the Trackit method. The estimated tracks are illustrated in a single figure below (**Figure 7.4**). We note again that position estimates on land are obviously unrealistic and most of the estimates on land are in fact due to latitude estimates around the March equinox (yellow dots in **Figure 7.4**). This can also be seen from a plot of all latitude estimates by month (**Figure 7.5a**); the range of latitude estimates for March/April and September/October is much wider than for the other months. Increased uncertainty over equinox periods was apparent in the estimated standard deviations of Trackit estimates through time (**Figure 7.5**b). An example of one track with uncertainty estimates (95% confidence regions) is shown in **Figure 7.6**. The dashed band surrounding the track is actually a sequence of ellipses, one around each position estimate.

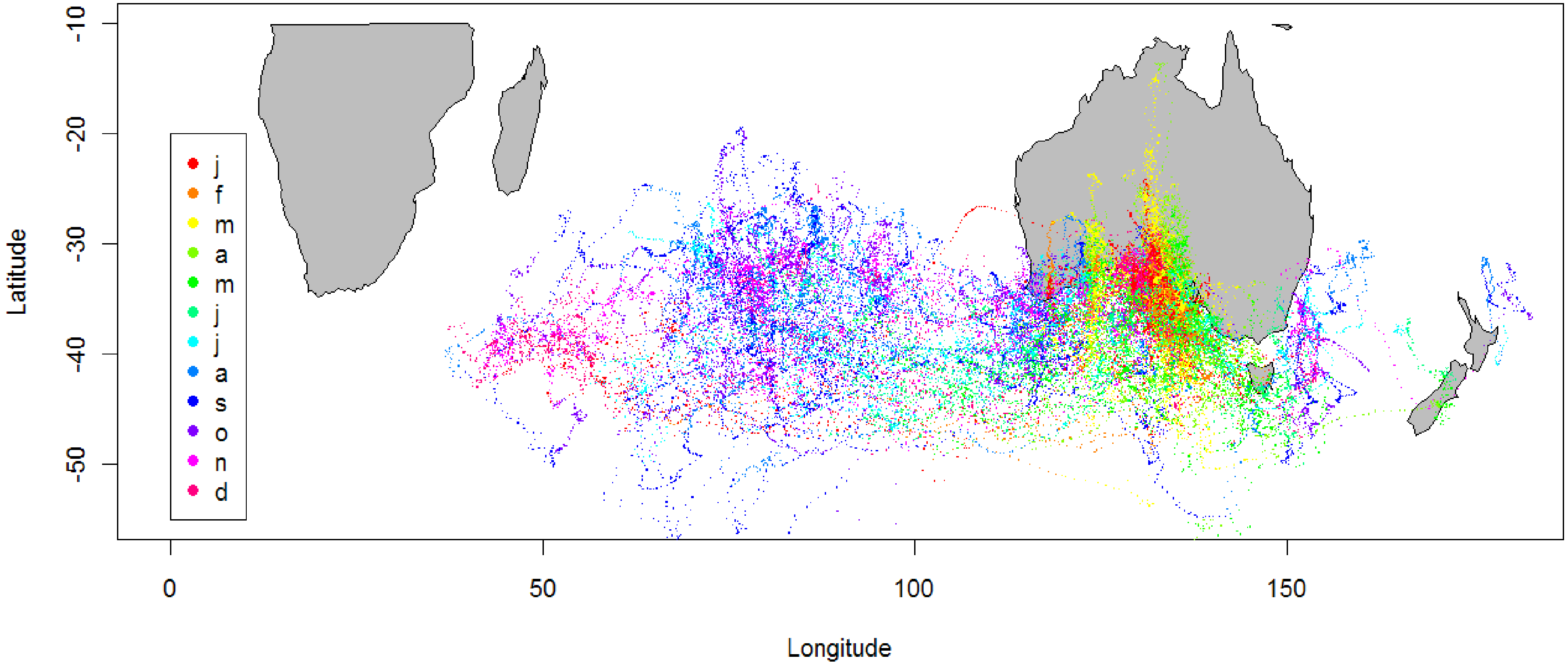
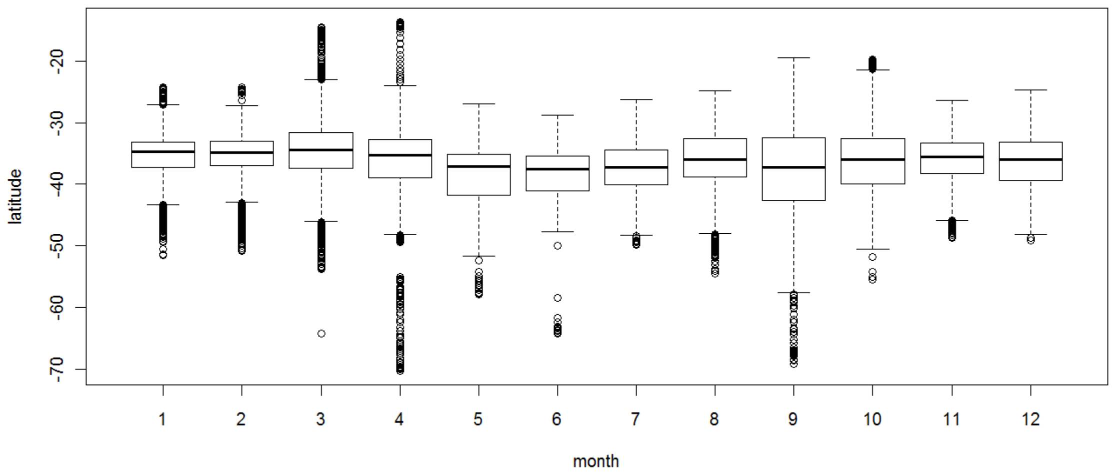


Figure 7.4. Trackit estimates of location for 91 tags, colour-coded by month, and covering years from 1998 to 2008. Estimates on land are obviously unrealistic, but this is because the Trackit software is unaware of land.

(a)



(b)

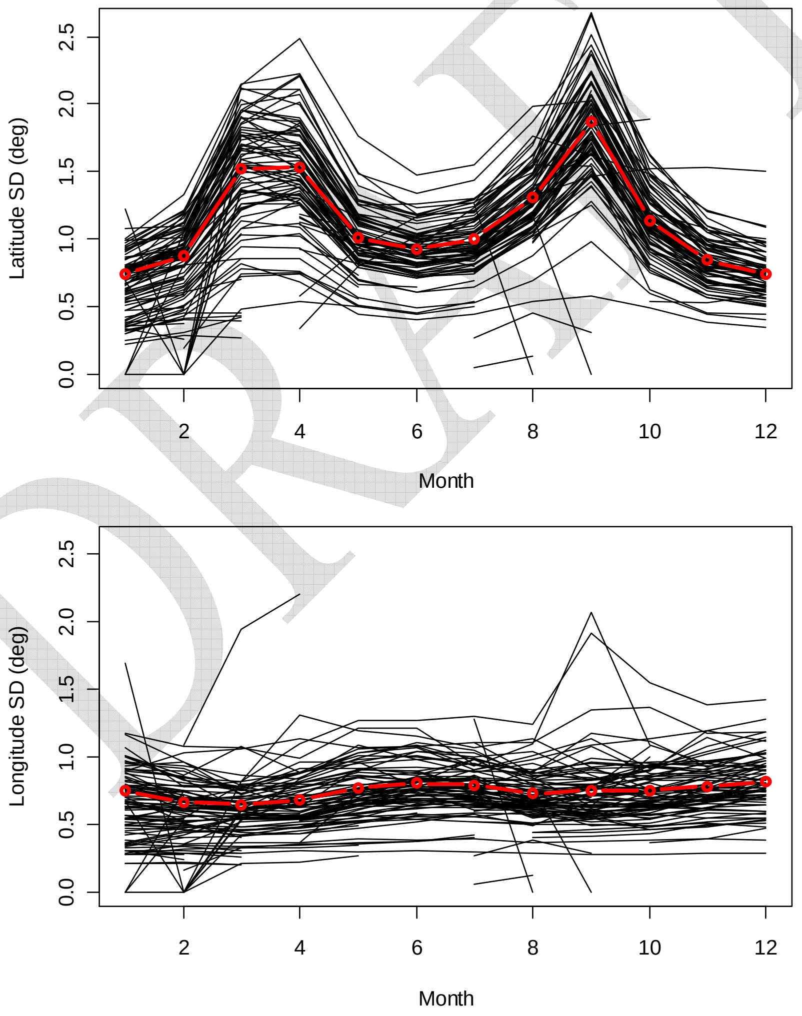


Figure 7.5. (a) Boxplots of latitude estimates by month showing the wide ranges of estimates in March and September, the spring and autumn equinoxes. (b) Estimates of uncertainty in latitude and longitude from Trackit. The black lines show the average standard deviation (SD) across months for each tag; the thick red line shows the average over all tags.

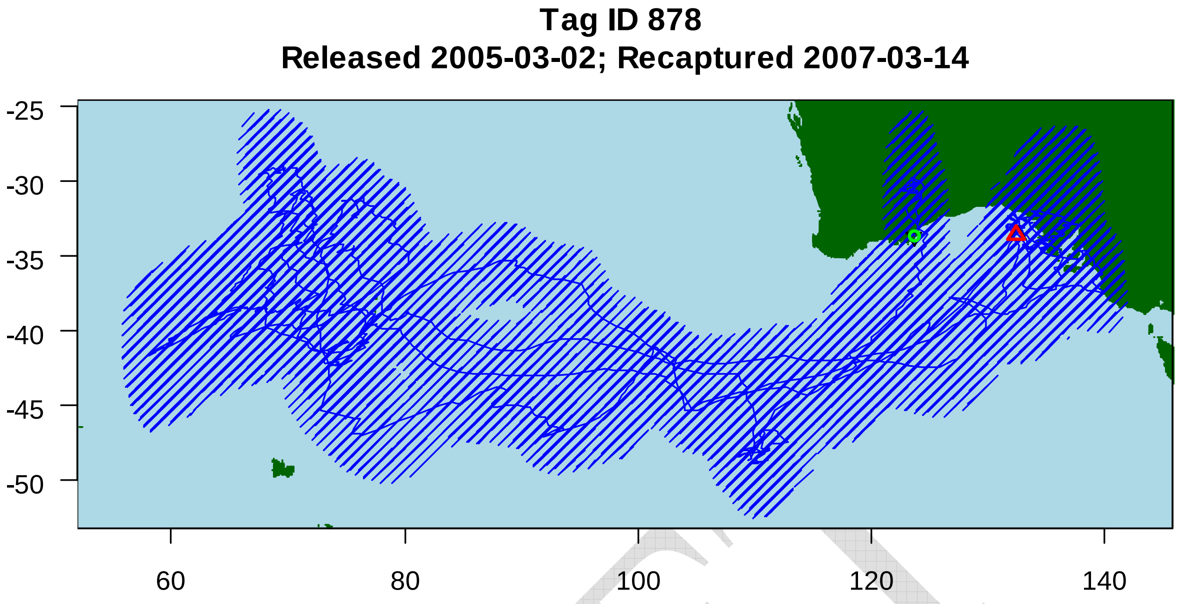


Figure 7.6. Trackit derived track with 95% confidence region shown by dashed area. The tag was released off WA (34°S, 124°E, green circle) and recaptured in the GAB (34°S, 133°E, red triangle).

7.3.2 GHMM results

Estimated tracks were obtained for 48 archival tags using the GHMM method (**Figure 7.7**).

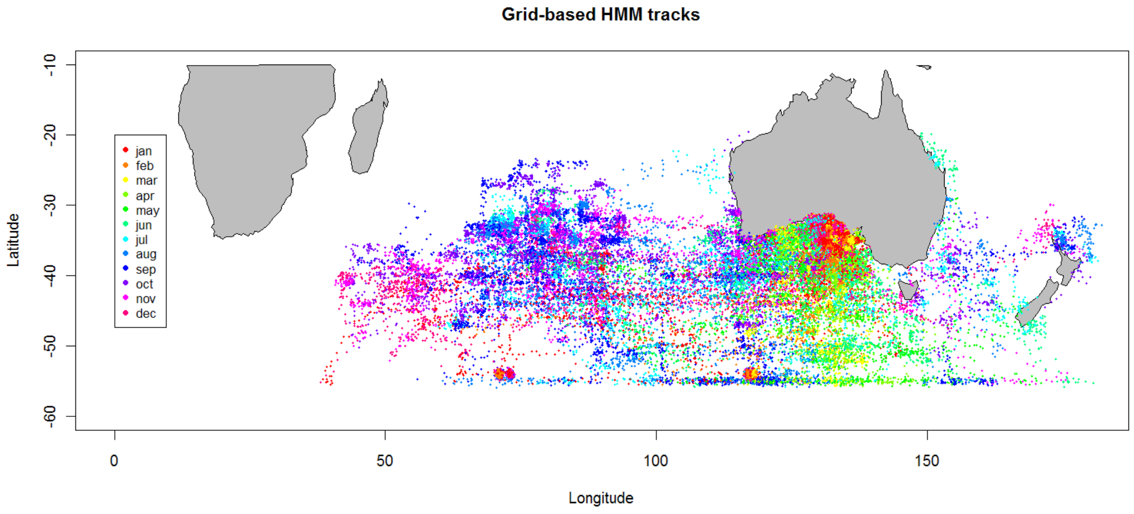


Figure 7.7. Tracks for 48 archival tags from the GHMM method. Locations are coloured by month (and jittered for plotting).

Given its recent development, the GHMM method was employed as a way to examine the consistency of position estimates from two advanced methods, namely GHMM and Trackit. This showed that the GHMM tracks are broadly similar to those from Trackit. As noted in the methods section, both methods have difficulties with locations around the spring and autumn equinoxes, yet the manifestation of this problem differed between Trackit and GHMM. The Trackit software tends to estimate latitudes during the spring equinox to be on land (**Figure 7.4**). The GHMM method avoids this, but often gives latitude estimates further south than realistic. Many of the latitudes that are at the southern edge of the grid (55°S) and also those that suggest northerly movements up the West Australian and Queensland coasts are a result of the March and September equinoxes. The implicit limit on large and unrealistic daily movements sensibly constrains the tracks from making large “jumps”. However, in the presence of sustained periods of uncertainty in the location likelihoods, such as occurs over the equinoxes, there is relatively little information in the likelihoods, and the tracks can wander into implausible locations. Moreover, the same constraint on unrealistically large movements ensures that the track, having ventured there, also takes time to return to move away from these implausible locations (e.g. the southern boundary of the grid). Work on movement of adult SBT (Pedersen *et al.* 2010) indicates that these problems will be substantially reduced when auxiliary data are incorporated into the models in future.

Comparison of Trackit and GHMM tracks for 35 tags showed that longitude estimates from each method are almost identical (e.g. **Figure 7.8**). Ten of the tracks also have very similar latitude estimates, though others can differ substantially (e.g. **Figure 7.8**, tag 786). The comparisons between these two methods again confirm that longitudes can be treated as sufficiently reliable for characterising the large-scale movements that are of interest in this project. Our results suggest, as we anticipated, that latitudes should be interpreted with some caution, particularly for fine-scale analyses, but that they are still very likely to be meaningful for broad-scale analyses.

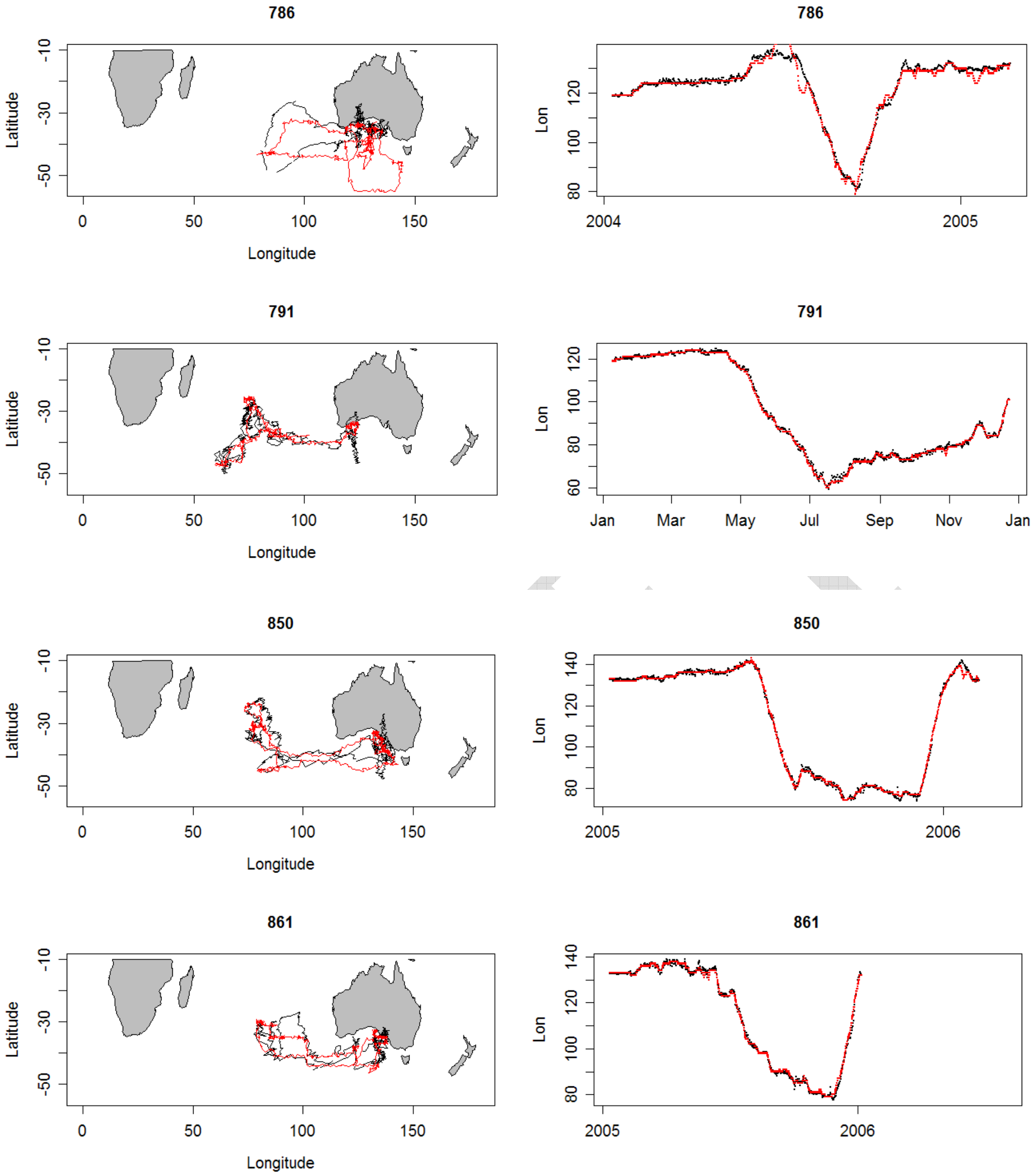


Figure 7.8. Four comparisons of Trackit (black) and grid-based HMM (red) tracks, shown as lat-lon maps (left panels) and as longitudes over time (right panels).

7.3.3 Broad-scale movement patterns

The collection of SBT tracks we have estimated in this project provides a wealth of information on the broad patterns of migration undertaken by juvenile SBT. The longitude estimates clearly show annual cyclical migration from southern Australia (SA), which encompasses the GAB and waters off the south coast of WA, into the Indian Ocean and Tasman Sea and back (Figure 7.9). A large proportion (77%) of the

91 tracks cover at least one summer and one winter, and four patterns of movement between areas in summer and winter can be identified:

- SA – Indian Ocean
- SA – Tasman Sea
- SA – Tasman Sea and Indian Ocean
- SA – SA

A summary of track patterns and numbers of individuals that exhibited those patterns is given in **Table 7.1.** The vast majority of individuals in our dataset switched between SA and Indian Ocean at least once (64%). A smaller percentage (19%) switched between SA and the Tasman Sea at least once. Some individuals (10%) left SA for the Tasman Sea, but in the same winter also migrated to the Indian Ocean. The fourth pattern, where individuals stayed in waters off SA (between 115^{o}E and 145^{o}E), was somewhat of a surprise for juvenile (age 2-4) SBT. A total of 11% (**Table 7.1**) followed this pattern, remaining off SA for at least one winter.

Eight individuals (11%) had tracks covering four seasons (one covered five seasons), and 5 of those switched only between SA and the Indian Ocean. Two individuals went to the Indian Ocean in their first winter and to the Tasman Sea in their second winter after tagging. One individual switched the order and went to the Tasman Sea in the first winter and the Indian Ocean in the second winter after tagging.

The patterns in this dataset show that:

- all individuals return to SA in summer, suggesting high "summer" site-fidelity (BUT see **Section 7.2.5** below regarding one tag that is not in this dataset because it does not have Trackit estimates of location);
- most individuals spend winters in the Indian Ocean, but
- some spend winter in the Tasman Sea or in the waters off southern Australia;
- there appears to be somewhat less strong "winter" site-fidelity (in the broad sense of ocean choice) than "summer" site-fidelity – 3 out of 8 individuals switched between the Indian Ocean and the Tasman Sea in consecutive winters.

These summaries are over all years in the dataset, i.e. 1998 – 2009. In **Section 8** we look at whether these patterns have changed over time, and if there have in fact been some changes in the proportion of individuals going to the Tasman Sea.

Table 7.1. Patterns of tracks which have at least two seasons (one summer and one winter) regarding broad areas: SA=waters off southern Australia (115-145°E), IO=Indian Ocean (20-115°E), T=Tasman Sea (east of 145°E). The left column indicates the areas involved in summer and winter, and columns 2-6 show the sequence over seasons. The first entry in any row of columns 2-6 also indicates where the tag was released. "Number of Tags" indicates how many tags followed each particular sequence, and the total within each set indicates how many switched between the particular areas, irrespective of sequence. The final column gives the percentage of the total that switched between areas (e.g. 60% = 42/70).

Summer, winter areas	1st Summer	1st Winter	2nd Summer	2nd Winter	3rd Summer	Number of Tags	Percent
SA, Indian Ocean	SA	IO				5	
		IO	SA			7	
	SA	IO	SA			25	
	SA	IO	SA	IO		3	
		IO	SA	IO	SA	2	
					Total =	**42**	60%
SA, Tasman Sea	SA	T				5	
		T	SA			1	
	SA	T	SA			4	
					Total =	**10**	14%
SA, Tasman Sea and Indian Ocean	SA	T/IO				2	
	SA	T/IO	SA			5	
					Total =	**7**	10%
SA, SA	SA	SA				2	
	SA	SA	SA			6	
					Total =	**8**	11%
SA, Indian Ocean OR Tasman Sea	SA	IO	SA	T		2	
	SA	T	SA	IO	SA	1	
					Total =	**3**	4%
						70	

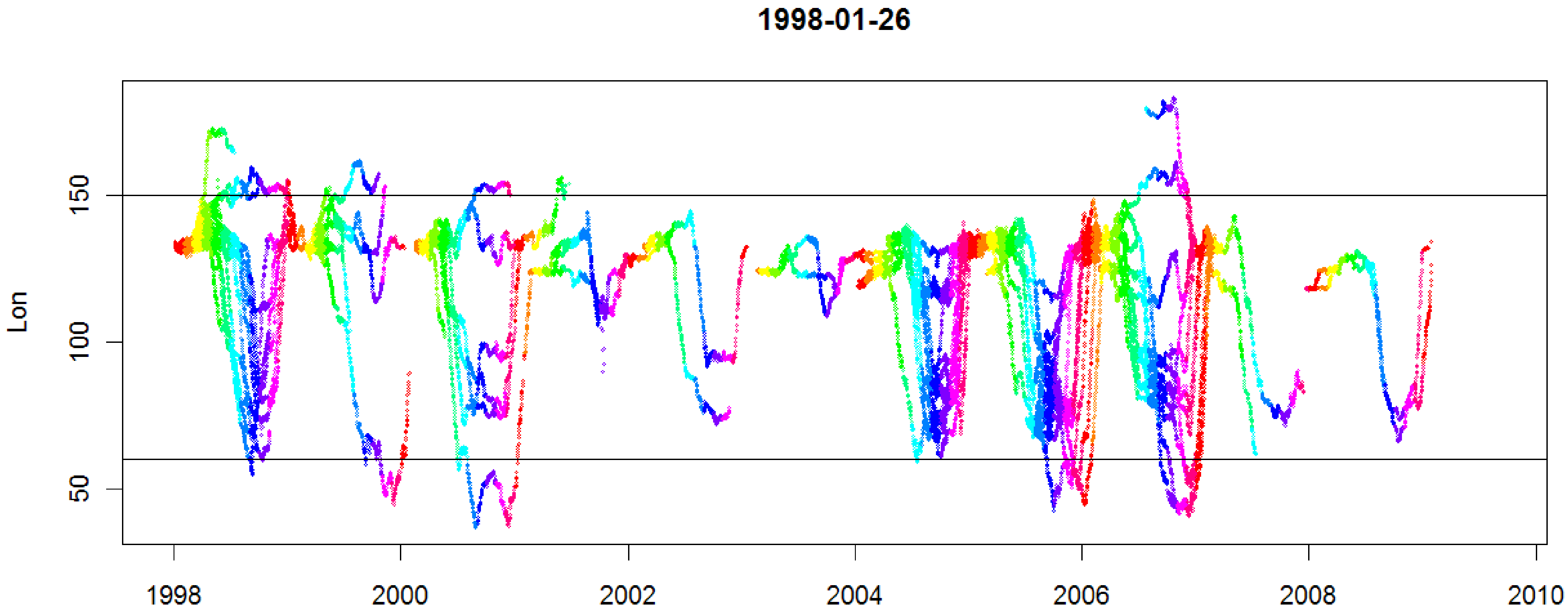


Figure 7.9. Longitude estimates from Trackit software for 91 tags, colour-coded by month. The horizontal line at 150°E is an approximate indicator of the Tasman Sea and the line at 60°E indicates waters off the east coast of South Africa. The region in between covers the Indian Ocean, WA and the GAB,

Table 7.2. Percentage of longitude observations in each month and longitudinal band, where band X implies longitudes (X-5)° to (X+5)°. Cells are blank when there are no estimates of longitude in that longitudinal band and month. Note the percentages given here cannot be interpreted as the proportion of the population (or even of the individuals in our dataset) that is in the GAB in any month because most individuals are likely to be counted in several longitudinal bands in any month (Note: Not all rows sum to 100% exactly because of rounding).

	Longitudinal band														
Month	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
1	<1	2	3	2	1	2	2	2	6	68	13	1			
2				<1	<1	<1	1	1	11	71	15	<1			
3									17	61	22	<1			
4								<1	16	49	32	2	<1	1	
5					0	1	2	4	13	42	30	8	<1	1	
6				1	3	6	7	11	12	32	23	7		2	
7			3	8	8	13	8	8	16	19	12	5	1	<1	<1
8	1	1	1	13	21	18	7	7	13	8	6	5	3		2
9	1	3	4	13	24	20	6	6	12	6	0	5	3		2
10	1	4	4	14	26	10	7	12	9	6	1	6	1		1
11	3	5	5	6	22	9	7	6	13	17	1	7	1	<1	<1
12	2	8	4	2	7	5	5	4	7	48	5	4			

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Individual variability within seasonal patterns

Within the clear seasonal patterns, there is also considerable individual variability in the timings of departure from and arrival back in the GAB, as is obvious from plots of longitude (over time), such as Figure 7.10 for example. Migration patterns are considered in detail in **Section 10**, but we make some initial observations here. Tabulating the percentage of longitude estimates into 10^o longitudinal bands by month, over all years (Table 7.2), shows that the dispersion out of the GAB in autumn is more gradual than the return to the GAB in late spring and early summer. Those that left the GAB departed over a wide range of times and go to a wide range of locations in the Indian Ocean: some stay in the eastern Indian Ocean (~ 100^o E), many go as far as the central Indian Ocean (~ 80^o E), and others go into the western Indian Ocean, off South Africa (~ 60^o E or even further west). We look at these issues in more detail under Migration modelling, **Section 10**.

What follows are examples of tracks illustrating a range of patterns. **Figure 7.10a** shows a group of tags with very similar departure times from the GAB, but quite different over-wintering areas and quite different arrival times (or projected arrival time) back in the GAB the following summer. Tag #72, which was in the water off South Africa, only left in January and would only have arrived back in late February, early March.

Departure times from GAB area can be very different between individuals even in the same year (**Figure 7.10b**). Tag #66 left in about May, tag #2 in late July, tags #3 & #4 in August (tag #3 only going as far as WA), and tag #22 only left in September. Return journeys also start at different times, but this group has quite similar arrival times in December.

Some individuals do not seem to go to the GAB "proper" (i.e. longitudes E of 128^oE) during the summer months (tags #786, #791 in **Figure 7.10c**) even when they're in waters off WA in January. One of these tags (#786) did go to the GAB "proper" but in winter (June-August) and then departed for the central Indian Ocean. Of two individuals tagged in the GAB in April, one remained in the GAB area over winter and the other migrated to the Indian Ocean (tags #776, #779). **Figure 7.10**c also shows very different periods spent away from the GAB or WA by the four tags.

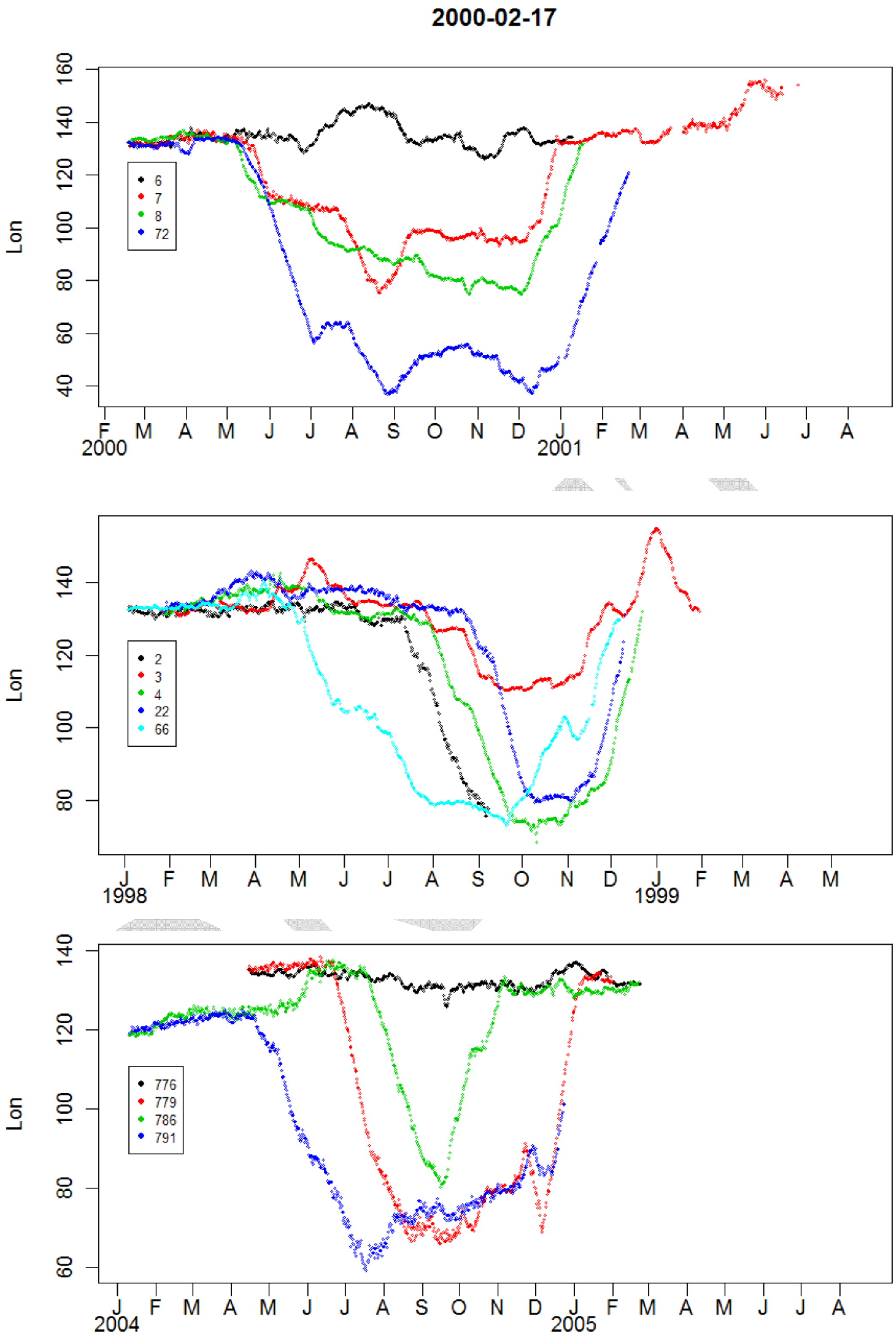


Figure 7.10. Trackit estimates of longitude plotted against time for (a, top panel) 4 tags released in the GAB in 2000, (b, middle panel) 5 tags released in the GAB in 1998, (c, bottom panel) 2 tags released off WA in January 2004 and two tags released in the GAB in April 2004.

A similar pattern of large variability in arrival times in the GAB following winter in the IO is illustrated in **Figure 7.11** for 5 tags released in the Indian Ocean in July 2005. Also note how Tag #965 makes almost an identical journey the year after with a slow meandering to its furthest longitude west, off South Africa, and a fast, direct migration back to the GAB, as indicated by covering the latitudinal range in very little time.

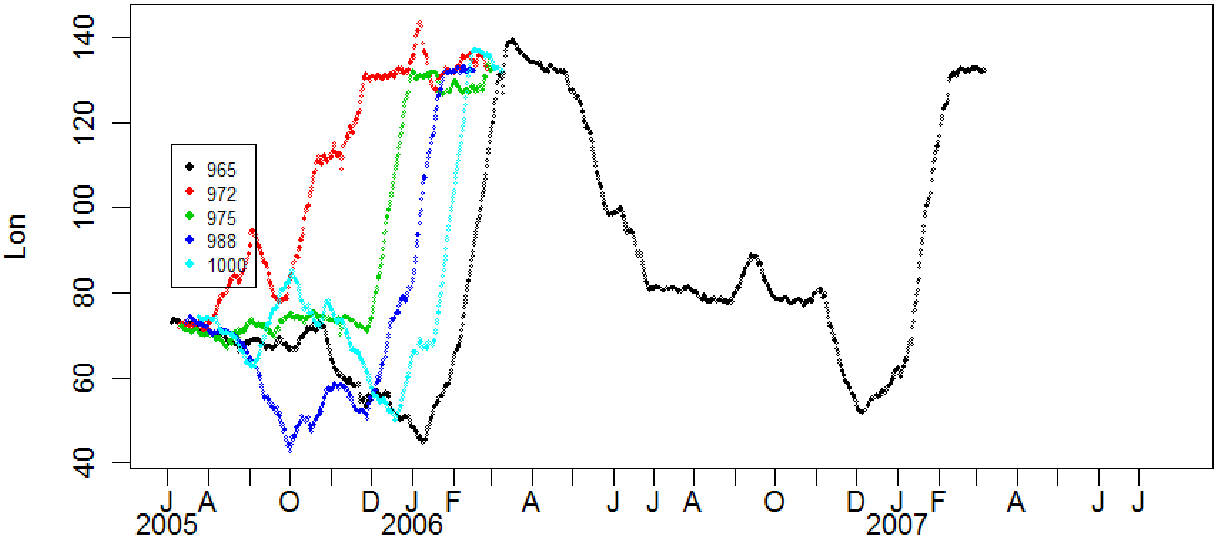


Figure 7.11. Trackit estimates of longitude plotted against time for 5 tags released in the Indian Ocean in July 2005.

7.3.4 Schooling behaviour

Juvenile SBT form schools while in the GAB, but it is not known is whether they tend to stay in the same schools for extended periods of time. This question is of relevance to assumptions made in tag-recapture methods which have been used to estimate mortality rates and cohort abundance of SBT (**Section 9**). There are two basic types of non-mixing that can violate the assumptions of most tag-recapture models, including those that have been applied to the SBT conventional tag data. One type of non-mixing, ("unsystematic" incomplete mixing) refers to situations where fish tagged in the same school or in close proximity on the same day have positively correlated recapture probabilities. This type of non-mixing will lead to underestimates of standard errors of parameters being estimated (more detail is given in **Section 9**).

The archival tag tracks can be used to investigate this issue because multiple fish were often tagged on the same day at the same location (i.e., same latitude and longitude, and most probably from the same school), and there are several instances of groups of returns from a given release day and location (**Table 7.3**). The tracks of these tags show that when the fish leave the GAB (and often even before) they disperse, and can follow very different routes (**Figure 7.12**) This supports evidence from winter recaptures of conventional tags in the 1990s and 2000s which show that tags released on the same day in the same location (in the GAB) can be recaptured at a wide range of different locations in the longline fisheries. This suggests that unsystematic incomplete mixing (e.g., schooling behaviour) is not a serious issue for juvenile SBT.

Table 7.3. Groups of tag returns from releases on the same day at the same location. Only tags that have position estimates available are included.

Release date	Release latitude	Release longitude	Number returns
1994-01-19	-33.2	134.1	2
1995-03-28	-32.9	133.0	9
1995-03-29	-32.9	133.0	7
1998-01-03	-32.8	132.6	10
1998-01-26	-33.1	132.0	8
1998-01-26	-33.3	131.4	8
1998-01-26	-33.3	131.6	2
1999-03-01	-33.3	131.5	10
2000-02-17	-33.6	132.2	9
2001-02-14	-34.1	123.5	2
2003-02-21	-33.9	124.0	2
2004-01-09	-34.6	119.0	2
2004-02-25	-34.3	122.3	2
2004-04-13	-34.5	133.2	6
2004-04-14	-35.0	134.9	3
2004-08-18	-29.5	85.8	2
2005-01-10	-32.6	132.6	3
2005-01-11	-32.6	132.6	2
2005-03-02	-33.7	123.7	2
2005-12-09	-32.5	132.7	3
2005-12-11	-32.2	132.1	2
2005-12-19	-32.7	133.2	3
2006-02-26	-33.8	124.2	3

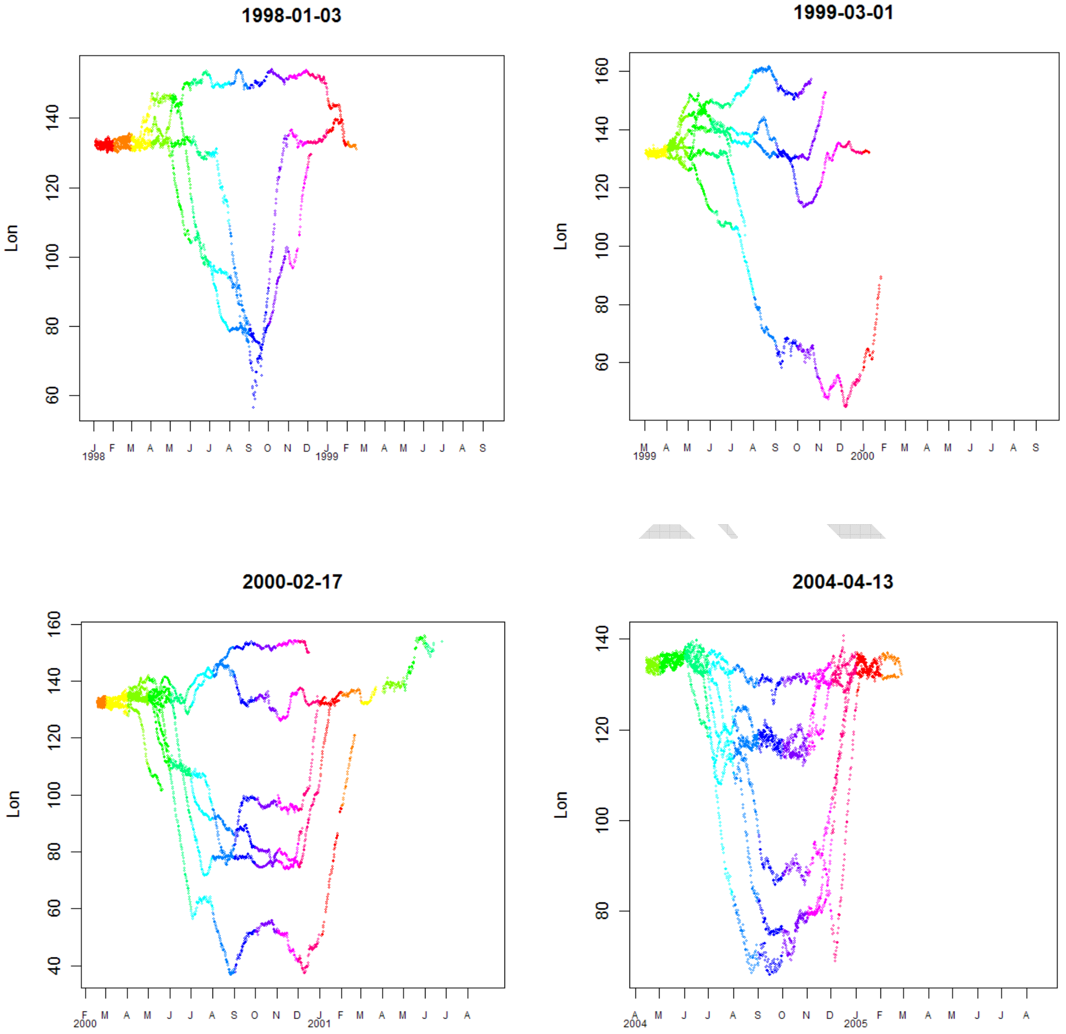


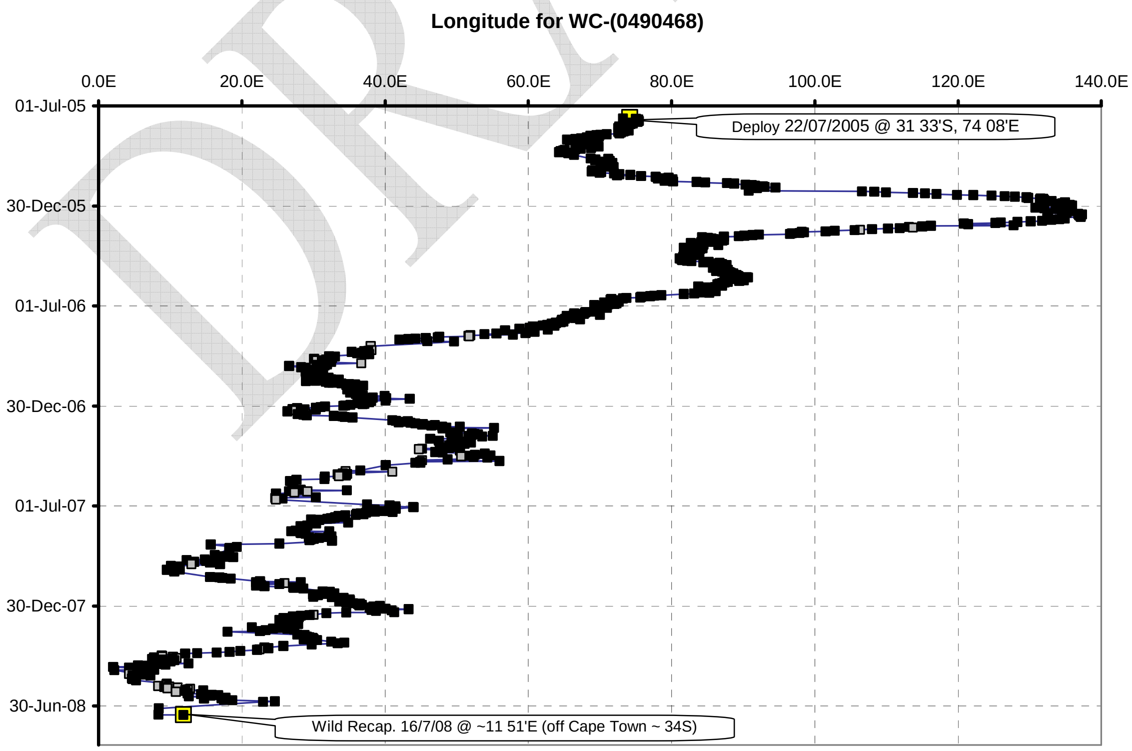
Figure 7.12. Four panels showing tracks (longitude over time) of individual SBT tagged on the same day.

7.3.5 Summer residency off South Africa

There is one tag with a long deployment time of just under three years that shows a very interesting migration pattern. Although we could not obtain a converged solution in Trackit, we obtained longitude estimates from the WC method (**Figure 7.13a,b**). The individual was tagged in the Indian Ocean in the winter of 2005 at a size of 96cm (cohort age 2). It migrated to the GAB in the summer of 2005/06, but only stayed a brief period before returning to the Indian Ocean. For the 2006/07 summer it moved further west to the waters off South Africa and then remained in that region, slowly going further and further west, until mid 2008 when it was recaptured off Cape Town, in the Atlantic Ocean, by a Taiwanese longline vessel. The recapture location was only provided as “off Cape Town” and is therefore approximate based on the light data. This track shows an example of only a brief single visit to the GAB from age 2 onward (we do not know what the fish did in its first summer). The one visit to the GAB means that this tag does not provide firm evidence for the notion of a South African component of the juvenile stock that never mixes with the GAB component. It does, however, support the fact that not all juveniles return to the GAB every summer.

There is one other example of a fish that spent a summer off South Africa from earlier tagging studies. A tag released in the summer of 1999 in the GAB at age 3 moved to waters off South Africa in the winter, and then spent the next summer off South Africa. Around March, it moved into the south-east Indian Ocean where it was caught in July.

(a)



(b)

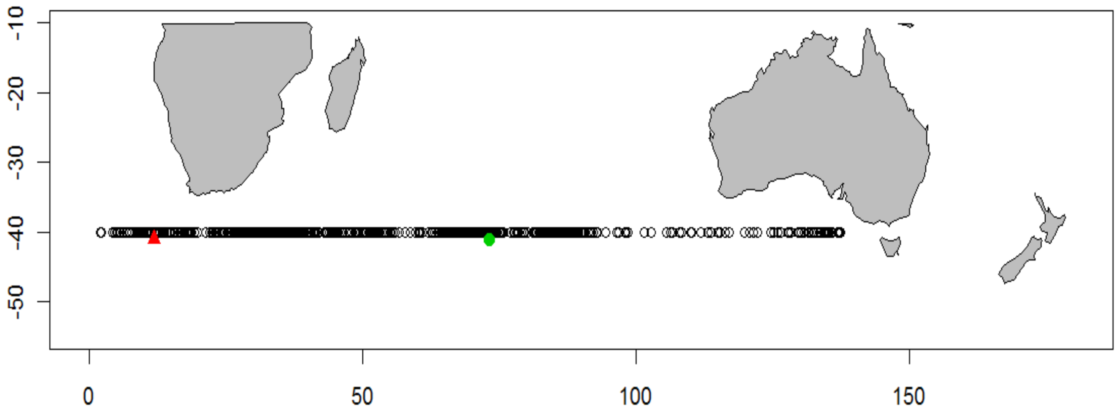


Figure 7.13. (a) Longitude estimates over time for a tag released in the Indian Ocean in July 2005 and recaptured off Cape Town in July 2008. The individual only made one brief visit to the GAB in the first summer after tag deployment, but then remained in waters off South Africa during the subsequent winters and summers. (b) The same longitudes shown on a map (recalling that we do not have latitude estimates). The release longitude (green dot) and approximate recapture longitude (red triangle) are also shown. The most westerly location is estimated at 2°E.

7.3.6. SBT movement relative to the location and timing of the aerial survey

An issue of interest is the arrival and departure of SBT in the GAB in relation to the aerial survey. An aerial survey has been conducted since 1993 (suspended in 1999-2004) with a view to providing a fisheries-independent estimate of relative abundance of juvenile SBT (2-4 year olds) in the GAB in summer (Eveson *et al.* 2010). A set of survey transect lines are flown by aircraft in January through March. Trained spotters record sightings of surface schools (size and location of school, size of fish in the school, and related information). The data are analysed to produce a standardised index of relative juvenile abundance. This index has now been incorporated into the CCSBT operating model and the candidate management procedures being developed (Anon. 2010).

The timing of the aerial survey was initially informed by the timing of the surface fishery in the GAB, and early archival tag returns from the mid 1990s confirmed our understanding of the main periods of residency of SBT in the GAB. The more recent and much larger archival tag dataset available from this project, however, provides an additional source of information to re-confirm this understanding, or to reveal changes we may not be aware of.

To examine the question, we considered each individual separately and calculated the proportion of longitude estimates within the aerial survey longitude range (128 - 134^{o}E) in each month, over all years. We then summarised these results over all individuals. **Table 7.4** shows that the highest mean and median percentages of locations in the aerial survey region occur in January, February and March. The final column shows the percentage of individuals that spent 100% of their time in the survey longitude range in each month. January, February and March again have the highest percentages. This confirms what was previously observed by the survey itself, but it is important to note that we have not considered latitude here because of the large uncertainties and because the autumn equinox is in March, leading to even higher uncertainty. This summary does not reflect whether the individuals were on the shelf, where the survey is conducted, or offshore.

Table 7.4. Medians and means over all individuals and all years of the proportions of longitude estimates that fell within the aerial survey (AS) longitude range of 128 to 134^{o}E in each month, and the percent of individuals that had all their longitude estimates in the AS longitude range for each month.

Month	Median proportion of longitude estimates in AS longitude range	Mean proportion of longitude estimates in AS longitude range	Percent of individuals that had 100% of their longitude estimates in the AS longitude range	Number of individual tags
1	84.9	72.6	42.9	77
2	92.4	70.1	40.8	76
3	70.2	59.5	38.6	70
4	40.8	45.6	13.0	69
5	23.4	35.0	7.4	68
6	10.9	27.9	7.9	63
7	0	17.5	1.5	67
8	0	6.4	1.5	66
9	0	5.4	0	65
10	0	5.4	1.6	63
11	0	12.5	3.3	61
12	42.6	44.6	11.5	61

Concluding Remarks

In this section we took raw sensor data from electronic tags and generated a data set of movement tracks which form the basis for subsequent sections of the report. We compared two sophisticated techniques for estimating locations of free-swimming SBT. Our analysis found that estimates of longitude are considered reliable and are appropriate indicators of migration and distribution patterns for juvenile SBT since SBT migration is predominantly in east-west directions. Moreover, latitude estimates from two different geolocation methods were similar enough to suggest that latitudes are also likely to be informative about broad-scale patterns, with the possible exception of times around the spring and autumn equinoxes. The two sets of tracks allows for sensitivity analyses in analyses where latitudes are used.

From longitudes alone there were very clear patterns of cyclic east-west annual migration of juvenile SBT with most individuals leaving the GAB for winter, but some do overwinter in the region of the GAB and WA (longitudes of ~ 115°E-145°E). However, the majority of SBT in our dataset (i.e. animals tagged in the GAB, WA, IO or Tasman) spent winter, or part of winter, in the Indian Ocean.

All SBT in our dataset spent summer (or at least part of summer) in waters south of Australia (between 115-145°E, encompassing the GAB and waters south of WA), with the exception of one SBT. This individual was tagged in the IO in winter, visited the GAB in the summer following tagging, but spent two subsequent summers in the waters off South Africa where it was caught. This confirms that not all juvenile SBT are found in southern Australian waters each summer. This is, however, only 1 out of more than 100 tags. There is one other such example from a release in 1999 deployed under previous CSIRO investigations of SBT movement. Additionally, the longitude estimates show that the percentage of individuals that spend all their time in the aerial survey longitude range (128-134°E) is greatest during January, February and March, when the survey is conducted. The mean and median percentages of longitudes in that range (over all years and over all individuals) are also greatest in those months. The tracks calculated here also inform our estimates of the extremes of the global distribution of juvenile SBT. The most easterly estimated longitude in our dataset is at 183°E, and the most westerly estimated longitude is to the west of South Africa, in the Atlantic Ocean at about 2°E. This is the first observation that far west from an archival tag, but conventional tags have been recaptured from that area in the past. .

This analysis has captured the large scale movements of juvenile SBT and represents the most comprehensive picture of their migrations yet collected. While large scale movements were clear, the pervasive variability in the timing of migrations by individual fish was equally apparent. These results vastly improve our knowledge of SBT migration and have been able to fill in gaps in our understanding of the spatial dynamics of SBT. In subsequent sections of this report we further quantify these patterns and their associated variability to provide more detailed assessments of behaviour and the relationship between movement, behaviour and environment. Additionally, the tracks estimated here are used to inform spatial mark recapture models (**Section 9)** and we consider the implications of this more accurate picture of SBT movement for fisheries management (**Section 12, and Section 15 Conclusion)**.

8 Recent Changes in Spatial Dynamics

Key findings

- Evidence for changes in the movement patterns of juvenile SBT between the 1990s and 2000s has been emerging over the past several years.
- Conventional tag-recapture data from the 2000s show very low returns from fish tagged at age 1 off the south coast of WA; this was not observed in the 1990s tag-recapture data.
    - One hypothesis is that 1-year-old fish found off WA are no longer entering the GAB in substantial numbers.
    - Archival tag tracks from fish tagged at age 1 off WA (n=8) all show annual summer migrations to, or through, the GAB, so unfortunately do not solve the puzzle.
- Archival tag tracks provide reasonably strong evidence for a contraction in eastward movement of juvenile SBT in the 2000s, with far fewer fish moving into the Tasman Sea (>150°E) after 2001 compared to prior years. The tracks also provide less strong evidence for a contraction in the extent of their westward movement. Changes are possibly in response to:
    - Population decline (there has been a documented decline in SBT abundance and recruitment through the 1990s and into the 2000s);
    - Changes in environmental variables that affect SBT migration (explored in detail in Section 11 “Habitat modelling”).

8.1 Introduction

Historically (beginning in the 1950s), there was a large surface fishery for juvenile southern bluefin tuna (SBT) off the east coast of New South Wales (NSW), but by the mid-1980s this fishery had collapsed (Caton 1991) and the juvenile population in this region has not supported a direct fishery since. Given that we have no evidence for separate stocks for SBT (Grewe et al. 1997), it seems unlikely that the NSW juvenile population was a separate stock that was depleted, as has occurred for species elsewhere (e.g., plaice, Hunter et al. 2003; cod, Hilborn and Litzinger 2009). A possible alternative explanation is that the NSW population was part of the global stock that changed its movement dynamics (in response to population decline), so that NSW was no longer a destination for juveniles.

Evidence for other more recent changes in the movement patterns of juvenile SBT has been emerging over the past several years. During the first two years of this project, some interesting potential changes in the movement patterns of juvenile SBT were noticed in the conventional tag-recapture data. As stated in the abstract of the 2005 CCSBT report that provided an analysis of the most recent conventional tag data (Polacheck and Eveson 2005): "The number of returns from age 1 releases from the 2000 and 2001 cohorts were disproportionately low relative to returns from releases from other age classes and also relative to returns from the 1990s tagging experiments. This suggests either higher tagging mortality or natural mortality or changes in the spatial dynamics for age 1 fish. The spatial distribution of longline returns also suggests a possible change in spatial dynamics with few tagged fish moving into the Tasman Sea."

Both the low returns from age 1 releases and the lack of returns of juvenile fish from the Tasman Sea persisted for several years—until at least 2009. As stated in the 2009 CCSBT report (Eveson 2009): "There continues to be a marked lack of returns, and thus lower estimates of fishing mortality, from fish tagged at age 1 compared to those tagged at ages 2 and above. This phenomenon was not observed in the tag returns from the 1990s releases, and suggests that 1-year-old fish found in WA (where the majority of age 1 fish are tagged) are no longer entering the GAB in substantial numbers. These same 1-year-old fish do not appear to be entering the longline fisheries either. Furthermore, the spatial distribution of longline returns from the 2000s tagging consistently show a much smaller percentage of tagged fish moving into the Tasman Sea in recent years than in the 1990s. These spatial changes have now been observed for 7 years (since 2001), suggesting that they are not simply outliers." Whether or not these changes in the conventional tag returns persisted after 2009 is difficult to evaluate because conventional tagging ceased in 2007.

Further evidence that juveniles may have reduced their movement into the Tasman Sea in the 2000s can be found in the size composition of the New Zealand catch data. These data show that small fish, predominantly ages 3 to 5, almost completely disappeared from the New Zealand domestic and charter fisheries in 2004 and 2005, and were in decline since 2001. The 2006 data showed a small reversal of this trend, which continued until 2009, but in 2010, the proportion of age 5 fish declined to levels similar to 2001 and the proportion of age 4 fish also declined (Patterson et al. 2007).

An original objective of the current project was:

Original objective 3: Contribute to the provision of statistically based estimates of mixing rates between the major SBT fishing grounds that can be used in conjunction with conventional tagging data to provide fishery independent estimates of fishing mortality rates for monitoring the SBT fishery."

In response to the above evidence for changes in spatial dynamics, this objective was revised in January 2007 to be:

Revised objective 3: Provide a comprehensive analysis of the evidence for temporal changes in the spatial dynamics of juvenile SBT, and analyse the implication of the information provided on mixing rates between the major SBT fishing grounds and their changes over time for the use of combined archival and conventional tagging data to provide fishery independent estimates of fishing mortality for monitoring the SBT fishery.

In this section we address the first part of the revised objective, namely, to investigate whether the above noted changes in spatial dynamics of juvenile SBT are supported by the archival tag data collected to date. The implications of our findings for using the conventional and archival tagging data to estimate fishing mortality rates (as described in **Section 9**) are discussed in the section on management implications (**Section 12**).

8.2 What happened to the age 1 WA fish?

Conventional tag-recapture data from tagging experiments conducted in the 2000s show very low returns from fish tagged at age 1 off the south coast of Western Australia (WA). The percent returns from age 1 fish tagged in the Great Australian Bight (GAB) during the same years (2001-2007) is much higher, even when recaptures in the same year as release are excluded (**Table 8.1**). This difference between WA and GAB releases was not observed in the tag-recapture data from the 1990s tagging experiments (**Table 8.1**; **Figure 8.1**). Furthermore, the percent returns from fish tagged at age 2 in the 2000s is very similar for fish tagged off WA and those tagged in the GAB (**Table 8.1**; **Figure 8.2**). This was documented and discussed in detail in Polacheck and Eveson (2007), but the reason for it remains a puzzle. One possibility is that movement dynamics have changed between the 1990s and 2000s so that that age 1 WA fish stopped going to the GAB in large numbers in the 2000s, not only in their first year but also in subsequent years (e.g., they may have migrated directly to waters to the east coast of South Africa and remained there). We can use the archival tag data to investigate this hypothesis.

Table 8.1. Number of conventional tag releases and percent returns by decade of release, release area and release age. The percent returns exclude tags recaptured in the same year as release.

		Number releases			Percent returns		
		Age 1	Age 2	Age 3	Age 1	Age 2	Age 3
GAB	1990s	3005	19538	12902	10.5	12.3	8.2
WA	1990s	25890	3339	88	10.1	10.3	5.7
GAB	2000s	1308	27671	8586	15.2	18.5	11.9
WA	2000s	29761	10705	186	3.5	17.1	12.9

If we do an analogous table as **Table 8.1** for the archival tag data, there does not appear to be the same lack of returns from age 1 WA releases (**Table 8.2**). **Table 8.2a** includes tags released in years 2001 to 2007. Although the percent returns for age 1 WA fish in the 2000s is somewhat lower compared to age 1 GAB returns, the difference is not significant (p=0.30). Furthermore, the fish tagged in 2007 may not have had sufficient time yet to be recaptured and returned, so we redid the table excluding the 2007 releases and the difference disappears (**Table 8.2b**). The sample sizes are so much smaller for archival tags than conventional tags that it is difficult to be conclusive, but still there have been 22.7% tag returns from age 1 WA archival releases in 2001-2006 compared to only 3.5% conventional tag returns. To try and understand why the age 1 WA archival and conventional tagged fish might be different, we checked whether the release years, months, longitudes, or lengths of fish differed significantly between the two tag types, but the distributions of all these factors overlapped considerably.

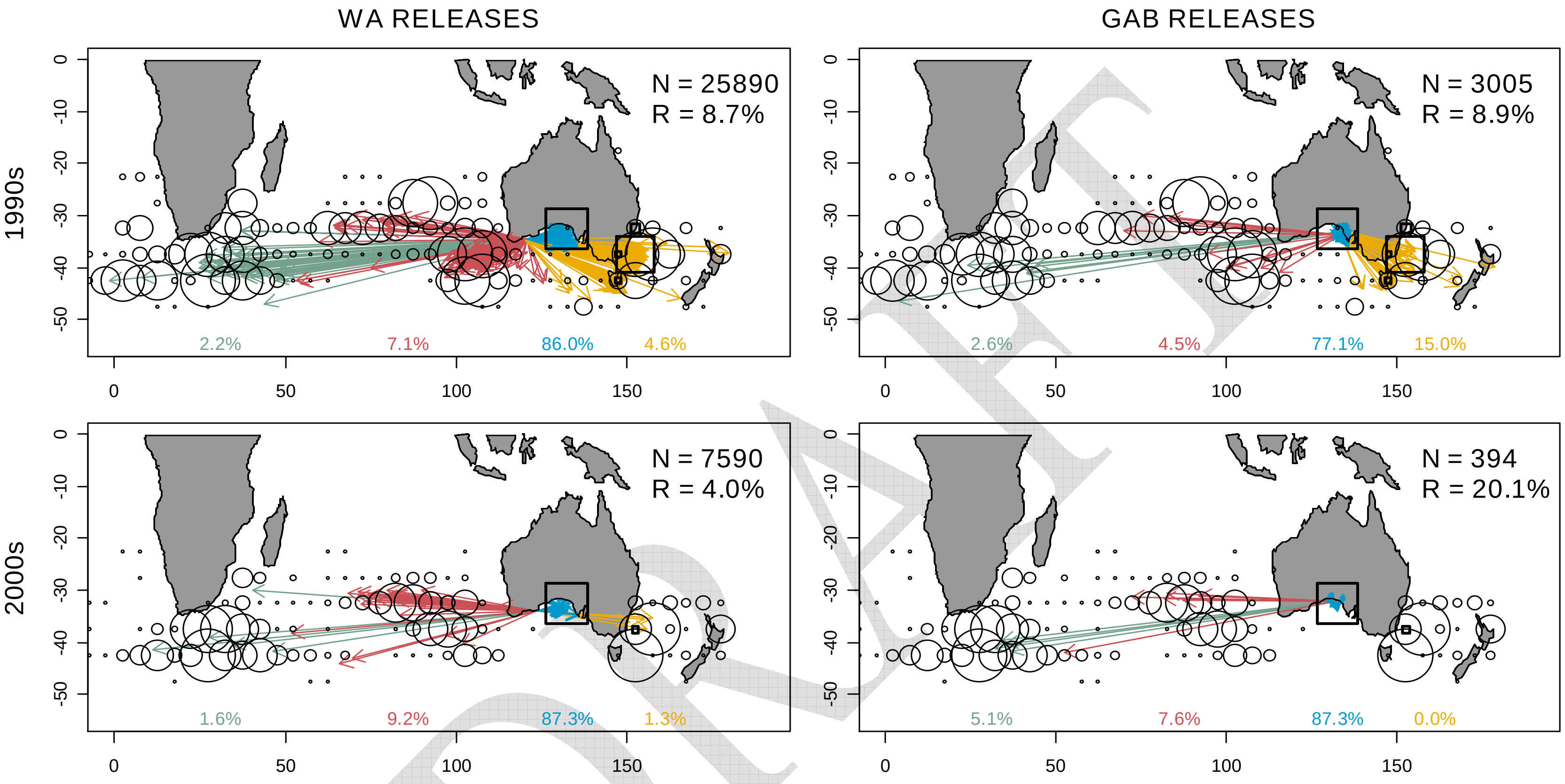


Figure 8.1. Conventional tag releases and returns from SBT tagged in the 1990s (top) and 2000s (bottom) at age 1 off Western Australia (WA; left) and in the Great Australian Bight (GAB; right) and recaptured at ages 2-4. Arrows are direct lines between release and recapture locations; green is recaptures off South Africa, red is recaptures in the central Indian Ocean, blue is recaptures in the GAB and yellow is recaptures in the Tasman Sea (east of 140°E). N = number releases; R= percent returns. The black circles represent fishing effort in the longline fishery (size proportional to number of hooks) and the black squares represent fishing effort in the surface fishery, including effort not targeting SBT (size proportional to number hours searched). The lack of returns of age 1 WA releases in the 2000s compared to the 1990s and compared to GAB releases in the 2000s is evident. Also apparent is the lack of returns of age 1 fish from the Tasman Sea in the 2000s compared to the 1990s.

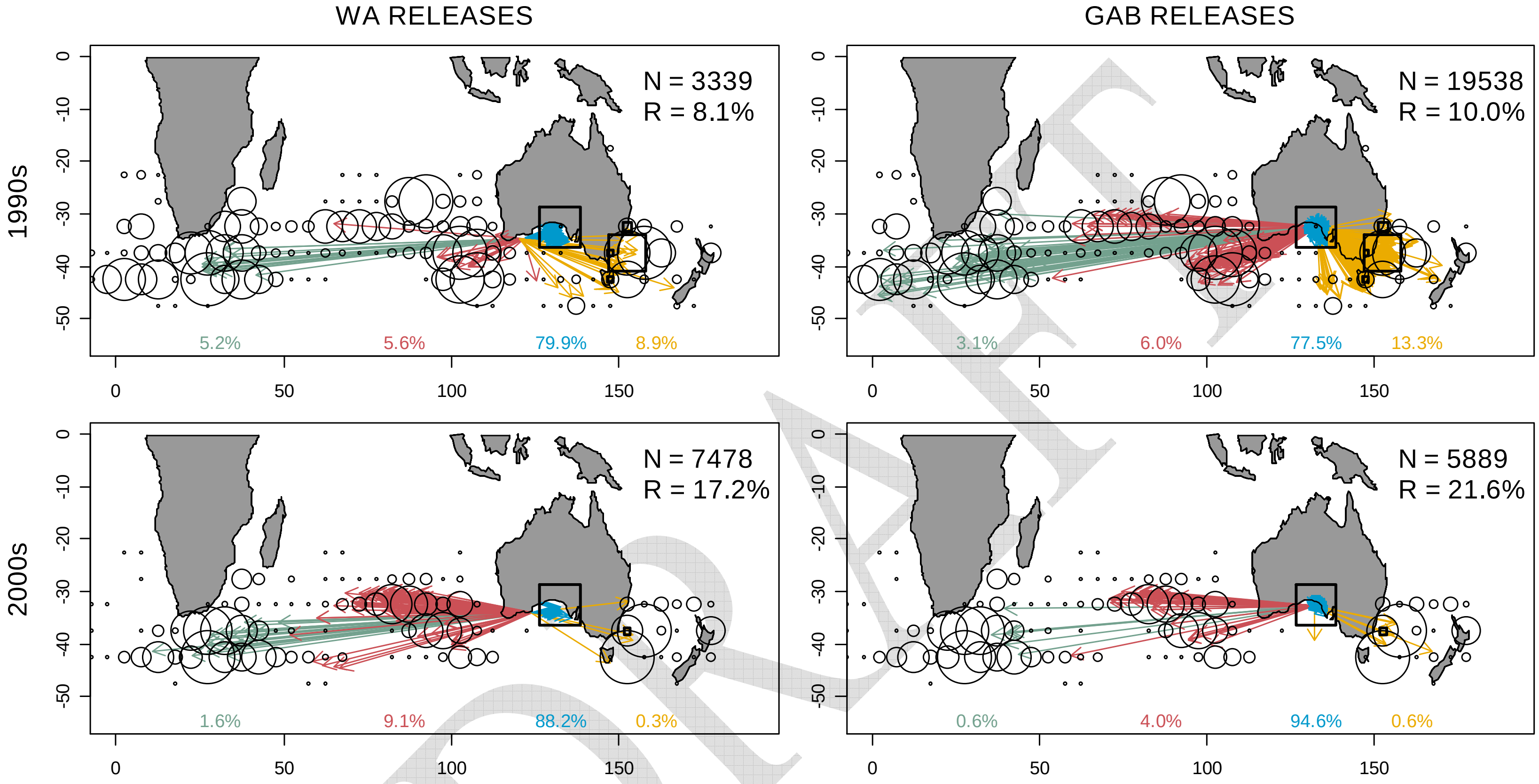


Figure 8.2. Conventional tag releases and returns from SBT tagged in the 1990s (top) and 2000s (bottom) at age 2 off Western Australia (WA; left) and in the Great Australian Bight (GAB; right) and recaptured at ages 3-4. Arrows are direct lines between release and recapture locations; green is recaptures off South Africa, red is recaptures in the central Indian Ocean, blue is recaptures in the GAB and yellow is recaptures in the Tasman Sea (east of 140°E). N = number releases; R= percent returns. The black circles represent fishing effort in the longline fishery (size proportional to number of hooks) and the black squares represent fishing effort in the surface fishery including effort not targeting SBT (size proportional to number hours searched). For a given decade, the percent returns of age 2 releases is similar whether released off WA or in the GAB. The lack of returns of age 2 returns from the Tasman Sea in the 2000s compared to the 1990s is again apparent.

Table 8.2. Number of archival tag releases and percent returns by decade of release, release area and release age. The percent returns exclude tags recaptured in the same year as release.

a. Release years up to and including 2007.

		Number releases			Percent returns		
		Age 1	Age 2	Age 3	Age 1	Age 2	Age 3
GAB	1990s	0	121	341	--	29.8	20.5
WA	1990s	0	0	0	--	--	--
GAB	2000s	10	93	40	20.0	22.6	37.5
WA	2000s	90	55	15	12.2	20.0	13.3

b. Release years up to and including 2006.

		Number releases			Percent returns		
		Age 1	Age 2	Age 3	Age 1	Age 2	Age 3
GAB	1990s	0	121	341	--	29.8	20.5
WA	1990s	0	0	0	--	--	--
GAB	2000s	10	69	40	20.0	27.5	30.0
WA	2000s	44	51	15	22.7	21.6	13.3

Eight of the archival tag returns from fish tagged at age 1 off WA in the 2000s have longitude estimates available (**Figure 8.3**). Although these fish were recaptured, they still may have exhibited some unusual movement behaviour prior to recapture that helps shed light on where the “missing” age 1 WA fish may have gone. Unfortunately, this is not the case—there is nothing particularly unusual or in their longitude tracks to suggest these fish behaved any differently to the majority of the population (e.g., they made annual summer migrations to, or through, the GAB).

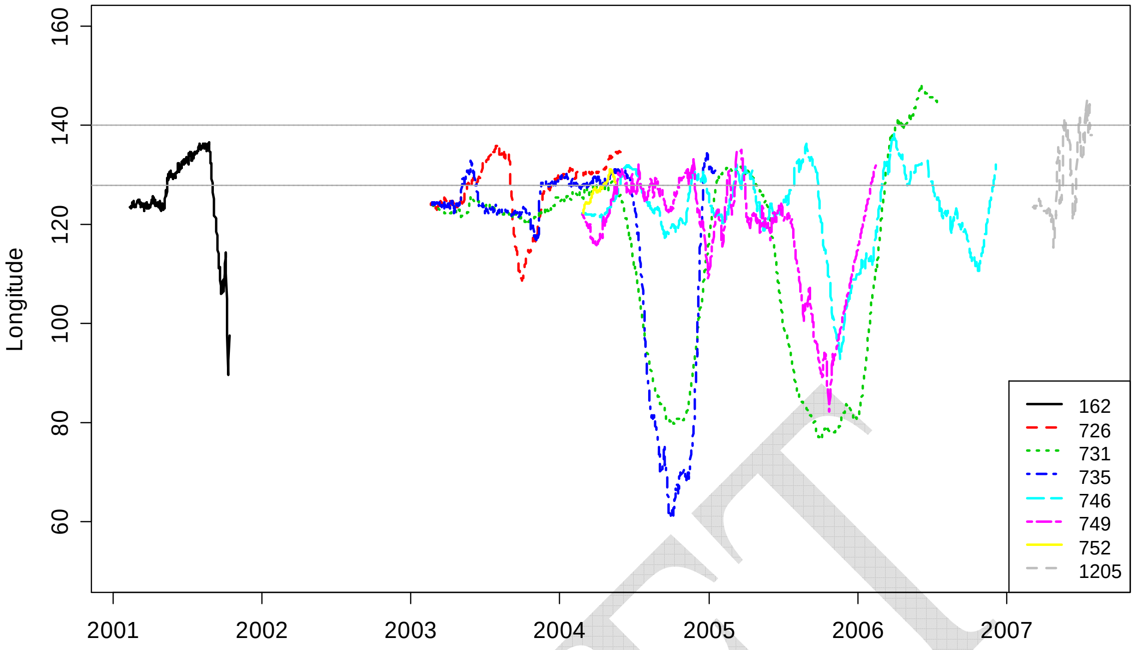


Figure 8.3. Longitude tracks for archival tag returns from fish tagged at age 1 off WA in the 2000s. The horizontal grey lines indicate the eastern and western boundaries of the GAB (128-140°E).

Another possible explanation for the lack of age 1 returns is that natural mortality (or tag-related mortality) of age 1 fish tagged off WA was very high in the 2000s. However, the fact that age 1 fish tagged by the same taggers in the same area at the same time with archival tags did not seem to experience such high levels of natural mortality, and neither did age 2 fish tagged with both tag types by the same taggers in the same area at the same time, this does not provide a more plausible explanation than a change in spatial dynamics.

8.3 Changes in east-west movement

As mentioned in the Introduction, the conventional tag-recapture data for juvenile SBT revealed that the spatial distribution of returns from fish tagged in the 2000s consistently showed a much smaller percentage of tagged fish moving into the Tasman Sea compared to fish tagged in the 1990s. This change in Tasman Sea returns can be seen in **Figure 8.1** and **Figure 8.2**. Consider age 1 releases first (**Figure 8.2**): the percent of tag returns coming from the Tasman Sea in the 1990s for WA and GAB releases was 4.6% and 15.0%, respectively, but it was just 1.3% and 0%, respectively, in the 2000s. Similarly, consider age 2 releases (**Figure 8.2**): the percent of tag returns coming from the Tasman Sea in the 1990s for WA and GAB releases was 8.9% and 13.3%, respectively, but it was just 0.3% and 0.6%, respectively, in the 2000s.

Based on initial archival tag returns from juvenile SBT tagged in 2004 and 2005 as part of this project, Polacheck et al. (2006) found similar evidence of changes in eastward movement of juvenile SBT, with fewer archival tagged fish moving into the Tasman Sea in the 2000s compared to the 1990s. They also found evidence for changes in westward movement of juvenile SBT, with fewer archival tagged fish migrating as far west towards South Africa in the early 2000s as in the 1990s. The archival tags returned to date continue to support these changes to some extent; however, the picture has become more complicated. Up until 2001, all archival tagging of juvenile SBT took place in the GAB. Thus, for greatest comparability, we start by considering only archival tag releases in the GAB for all years.

Figure 8.4 shows the longitude estimates from all GAB releases. There does appear to be a contraction in east-west movement of SBT after 2001, at exactly which point is difficult to say since the data are sparse between 2001 and 2004. Only 3.4% of tracks (1 out of 29) from fish that were released in the GAB showed movement into the Tasman Sea (>150°E) during the months of May through November after 2001, compared to 22% (14 out of 64) in years prior to and including 2001 (**Table 8.3**). Although suggestive of a change, this difference is not statistically significant based on a chi-square test (p-value=0.10). Also, no tracks from fish that were released in the GAB moved into the more western part of the Indian Ocean (< 55°E) during the months of May through November since 2001, compared to 9.4% (6 out of 64) previously (**Table 8.4**). Again, while suggestive of a possible change, this difference is not significant based on a chi-square test.

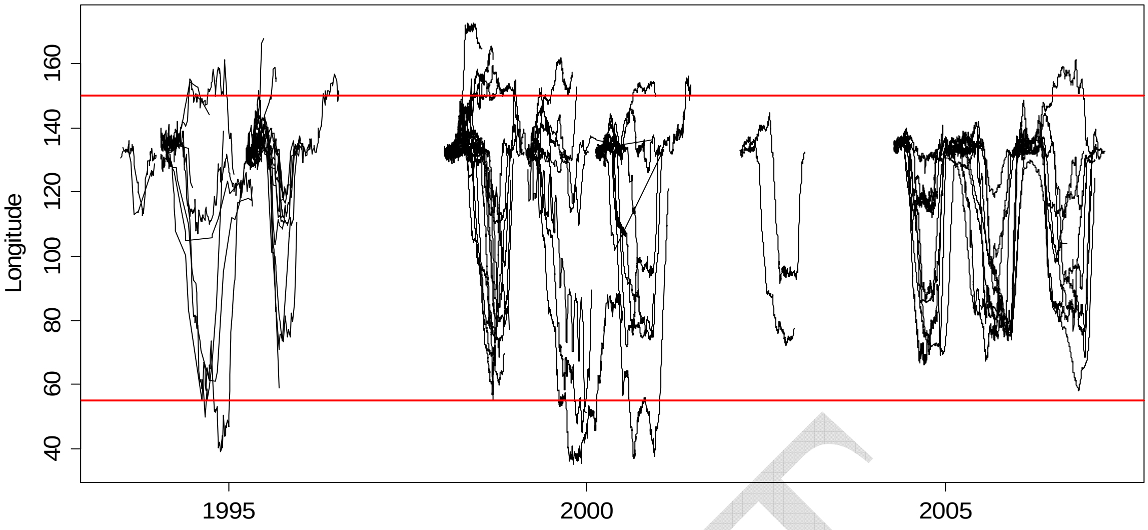


Figure 8.4. Longitude estimates from archival tags released in the GAB. The horizontal red lines mark 150°E and 55°E.

Table 8.3. Number of tracks that go further east than 150°E in May-Dec of each year based on fish tagged in the GAB. (Note that an individual fish can be counted in more than once if its track extends across several years.)

Year	Total	>150°E	Percent
1993	2	0	0.0
1994	8	2	25.0
1995	15	3	20.0
1996	1	1	100.0
1998	17	4	23.5
1999	10	2	20.0
2000	10	1	10.0
2001	1	1	100.0
2002	2	0	0.0
2004	9	0	0.0
2005	9	0	0.0
2006	9	1	11.1

Table 8.4. Number of tracks that go further west than 55°E in May-Nov of each year based on fish tagged in the GAB. (Note that an individual fish can be counted in more than once if its track extends across several years.)

Year	Total	< 55°E	Percent
1993	2	0	0
1994	8	2	25.0
1995	15	0	0
1996	1	0	0
1998	17	1	5.9
1999	10	2	20.0
2000	10	1	10.0
2001	1	0	0
2002	2	0	0
2004	9	0	0
2005	9	0	0
2006	9	0	0

If we include releases from all areas, our sample sizes for the 2000s become much larger. **Figure 8.5** shows the longitude estimates from all tags. In this case, 4% of tracks (3 out of 75) showed movement into the Tasman Sea (>150°E) during the months of May through November after 2001[12], compared to 21% (14 out of 67) in prior years. Given the larger sample sizes, this difference is now statistically significant (chi-squared test p-value=0.01). In terms of westward movement, including all releases actually makes the difference almost disappear, with 6.7% of

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[12] Note that 2 of the 3 tags were released in the Tasman.

tracks going further west than 55°E after 2001 compared to 9% in prior years. This is because several of the fish that were tagged in the Indian Ocean ventured west towards South Africa.

Taking all of the above into consideration, the data lend reasonably strong support for a contraction in eastward movement after 2001; there is less support for a contraction in westward movement. However, further complicating matters is that 77% of fish tagged in 1993-2000 were ages 3 and 4 (23% age 2), whereas only 32% of fish tagged after 2000 were ages 3 and 4 (16% age 1 and 48% age 2). It is possible that there is a greater tendency for older fish to migrate further and this is part of the reason for the observed differences. If we only consider fish tagged at age 3, the same patterns seen in **Table 8.3** and **Table 8.4** hold, but the sample sizes in the 2000s are very small.

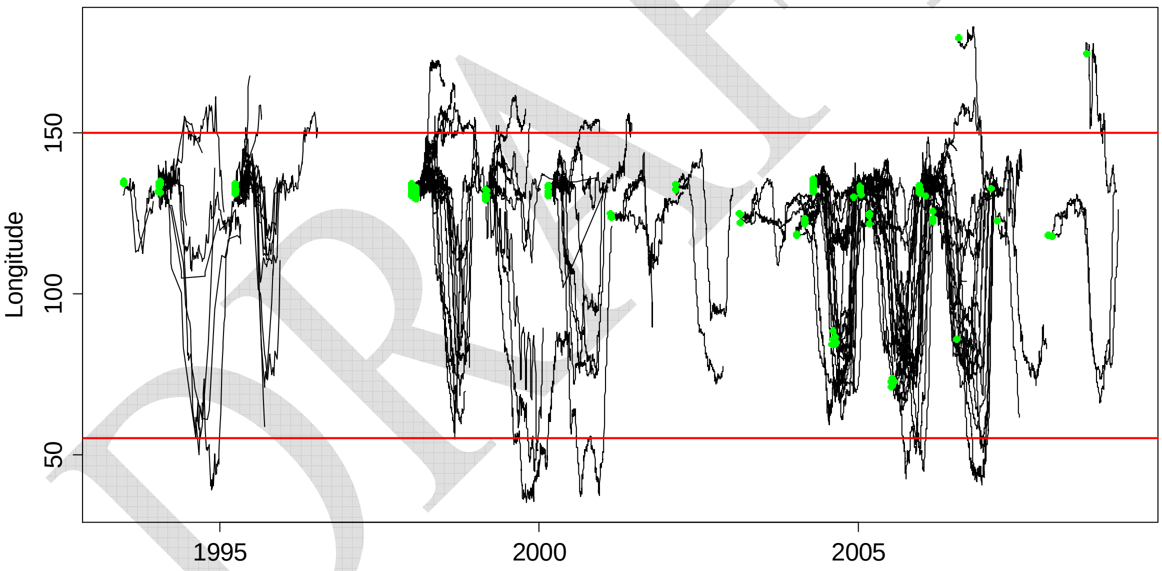

Figure 8.5. Longitude estimates from all archival tags. The horizontal red lines mark 150°E and 55°E, and the green dots mark the release points.

8.4 Discussion

A positive relationship between range size of a species and abundance has been observed in many land species and theories for this have been proposed (Brown 1984; Lawton 1993; McGill and Collins 2003). Range contraction of a number of large pelagic predators, including SBT, in response to population decline has also been posited (Worm and Tittensor 2011). However, the latter study was based on fisheries-dependent catch and effort data and, therefore, needs to be interpreted with caution.

The authors “emphasize the importance of ongoing fisheries-independent tagging and tracking studies to gain further insight into the total ranges of these species and how they might change over time.” The large-scale archival tagging of juvenile SBT done as part of this project is exactly the sort of study they are referring to.

There has been a documented decline in SBT abundance and recruitment through the 1990s and into the 2000s, and cohorts in 2000-2002 were at historically low levels (Anon. 2009). As such, the eastward range contraction of juvenile SBT that appears to have occurred in the 2000s could possibly be in response to reduced abundance; however, this is not the only possible explanation. For instance, warming in surface temperatures has occurred in the eastern GAB and Tasman Sea between the periods 1993-2000 and 2003-2008. Such changes in temperature, as well as in other environmental covariates, may have caused or contributed to changes in SBT migration patterns. This is explored in detail in **Section 11** “Habitat preference modelling”. Also explored in **Section 11** is whether there are any possible environmental explanations for why age 1 fish off WA may have changed their migration patterns in the 2000s compared to the 1990s.

It will be important to continue monitoring the movement patterns of juvenile SBT in future to determine if the changes noted here, both with regard to east-west movement and to the migration patterns of age 1 fish, are temporary, or whether they persist over time. Such long-term monitoring could also help determine whether the changes in movement patterns are in response to changes in population abundance or environmental variables.

9 Including Archival Tag Data in a Spatial Tag-Recapture Model

Key findings

- Methods of incorporating archival tag data into a tag-recapture model for estimating mortality, movement and abundance were developed and applied to simulated data, as well as to SBT conventional and archival tag data from the 1990s and 2000s.
- Key findings from simulations (see **Appendix 6**):
  - Including data from even a modest number of archival tags can significantly improve the precision of movement and fishing mortality estimates, particularly for situations like SBT where fish are only tagged in some areas.
  - When tags cannot be released in all regions, there are situations for which archival tag data *must* be included in order for all parameters to be estimable.
- Key findings from application to SBT data*:
  - For both the 1990s and 2000s, estimates of movement probabilities were unrealistic without archival tag data (e.g., for the 1990s, almost no fish were estimated to return to the GAB for summer).
  - For both the 1990s and 2000s, including archival tag data led to smaller fishing mortality estimates for the South Australia surface fishery (note, however, that estimates for ages 3 and 4 in the 2000s were still very high).
- Comparison of spatial model results with *non-spatial* model results:
  - Fishing mortality estimates were similar for the 1990s, but for the 2000s, estimates derived from the spatial model were consistently smaller.
  - For both the 1990s and 2000s, natural mortality estimates differed most for age 2+, with a tendency to be lower with the spatial model.
  - For the 2000s, cohort size estimates were consistently higher with the spatial model.

** Note that the main objective of our application to SBT data was to illustrate the effect that using archival tag data to inform the movement rates can have on all of the parameter estimates; the actual values of parameter estimates are likely to be biased and must be interpreted cautiously, due to a number of reasons discussed in the text.*

9.1 Introduction

Southern bluefin tuna (SBT) have been subject to high exploitation rates since the 1950s. Recent stock assessments and stock indicators suggest that the spawning biomass is at a historically low level and that the numbers of recruits (i.e., young fish entering the population) have been worryingly low over the last two decades (Anon. 2009). Because the number of young fish in the population largely determines the number of spawners in the future (and, thus, the potential for stock-rebuilding), it is important for effective management of the fishery to have reliable estimates of juvenile mortality rates and abundance. Problems with interpreting catch per unit effort data as an index of abundance are well known. Additionally, catch data for SBT are known to be subject to biases due to under-reporting, potentially large (Anon. 2006). As such, more reliable, fishery-independent data for estimating juvenile harvest rates and abundance are in high demand.

Large-scale conventional tagging experiments have been carried out on juvenile SBT periodically over the past five decades, with the primary aim of estimating juvenile fishing mortality rates and abundance. A fundamental assumption in the use of tagging experiments to estimate these quantities is that tagged and untagged animals are fully mixed throughout the range of the population. This can be difficult to achieve in populations distributed over large geographic areas, such as SBT, and especially when tags are only released in a limited part of the geographic range and/or over a limited time period, again like SBT since almost all conventional tagging of SBT has occurred in the Great Australian Bight (GAB) and off the south coast of Western Australia (WA) where juveniles aggregate in the summer and can easily and cost-effectively be tagged. An objective of the current project is to use the archival tag data to investigate mixing rates of juvenile SBT between the major fishing grounds, and to consider the implications of these investigations for parameter estimates obtained from tag-recapture models.

There are two basic types of non-mixing that can violate the assumptions of most tag-recapture models, including the models that have been applied to the SBT conventional tag data. We follow Polacheck et al. (2006) in referring to these as “systematic” and “unsystematic” incomplete mixing. Unsystematic incomplete mixing refers to situations where fish tagged in the same school or in close proximity on the same day have positively correlated recapture probabilities. There is still a large degree of random mixing among tagged and untagged fish such that, on average, the probabilities of recapture for tagged and untagged fish are the same. This type of non-mixing will not bias the parameter estimates obtained from the tagging model, but the standard errors of the estimates will be underestimated (since there will be more variability in the numbers of tag returns than the model predicts). One method of accounting for this is to use a distribution that allows for overdispersion (i.e., extra variability) in the data (e.g., for a Brownie model, use a Dirichlet-multinomial distribution to model tag returns as opposed to a multinomial distribution – see Appendices 9 and 10 of Polacheck et al. 2006). Systematic incomplete mixing, also called spatial heterogeneity, refers to situations where there is a systematic and repeatable pattern of incomplete mixing between tagged and untagged fish – for example, if all tagging was done in one location and fish in that location tend to remain in one part of the population’s overall range. Such systematic incomplete mixing will generally result in biased estimates of mortality rates and abundance if it is not accounted for within the estimation model (i.e., if a model with an appropriate spatial structure is not used).

We can investigate both sources of incomplete mixing for juvenile SBT using the archival tag data. There are several instances of groups of archival tag returns from tags released on the same day, and the tracks of these tags show that when the fish leave the GAB (and often even before) they disperse and can follow very different routes (see **Table 7.3** and **Figure 7.12** in the **Section 7**). This supports evidence from winter recaptures of conventional tags in the 1990s and 2000s which show that tags released on the same day in the same location (in the GAB) can be recaptured at a wide range of different locations in the longline fisheries. This suggests that unsystematic incomplete mixing (e.g., schooling behaviour) is not a serious issue for juvenile SBT. In any case, an initial period of mixing (of several months up to a year) has been allowed for in the tag-recapture models applied to SBT (e.g., see Appendices 5, 15 and 16 of Polacheck et al. 2006), so fish would need to stay in their same schools for long time periods in order to violate the model assumptions, and we have no evidence of this from the archival tag tracks.

In terms of systematic incomplete mixing, the archival tag tracks we have available suggest reasonably good mixing of juveniles throughout their range; however, most archival returns are from GAB or WA releases, so it is still difficult to fully evaluate the extent of mixing. For instance, there remains a question about whether there is a “resident” portion of juvenile SBT off South Africa that never venture to the GAB. We have not had any recaptures of fish tagged off South Africa, so this question remains partially unanswered. However, we do have one tag return from a fish tagged in the Indian Ocean in the winter of 2005 at age 2 which migrated to the GAB for the summer of 2005/06, stayed only a brief period before returning to the Indian Ocean, and then migrated further west to spend the summer of 2006/07 in waters off South Africa where it remained until it was recaptured off Cape Town in winter of 2008 (see **Figure 7.13** in the **Section 7**). Although this fish’s one visit to the GAB means it does not provide firm evidence of a South African component of the juvenile stock that never mixes with the GAB component, it does establish that not all juveniles return to the GAB every summer. There are also several tracks for individuals that did not go to the GAB “proper” (i.e. longitudes 128-134°E) during the summer months, but remained in waters south of WA.

One way to evaluate the extent to which spatial heterogeneity may be an issue in the tag-recapture models for SBT is to compare the results from a spatial and non-spatial model and see how much the parameter estimates differ. When a spatial model is applied to conventional tag data alone, it has difficulty separating fishing mortality parameters from movement parameters; this is where having archival tag data can be very beneficial because these data are highly informative about movement. Thus, as part of the current project, we have developed a method of integrating archival tag data into a spatial tag-recapture model for estimating mortality rates and abundance.

This integrated spatial tag model makes a major contribution towards another objective of the project, which is to contribute to developing a framework for incorporating archival tag data and conventional tag data within the SBT stock assessment model (or management procedure’s operating model). While the integrated spatial tag model is not a full assessment model (e.g., it does not include all the “usual” data sources, such as catch-per-unit effort data, and only models the juvenile population), it is still very valuable as a fishery-independent method of estimating age- and year-specific natural and fishing mortality rates, and also cohort size if catch-at-age data are included. The likelihood developed for the integrated spatial tag model could also be included in a likelihood-based stock assessment model, *provided that* the assessment model has the same spatial structure as the tag model. Note, however, that the current stock assessment/operating model for SBT is not spatially structured[13], so the likelihood developed here would not easily “slot into” these models (and, in any case, there is little reason for incorporating archival tag data directly into a non-spatial assessment model since the value of these data is the information they provide on movement rates). The issue of whether or not a spatial model should be employed for SBT is discussed briefly at the end of this section, and also in **Section 12**.

The integrated spatial tag model is described in detail in **Appendix 6** (“Using electronic tag data to improve parameter estimates in a tag-based spatial fisheries assessment model“). The appendix also contains results from simulations used to evaluate the benefit of including archival tag data in the model. The results show that including archival tag data can lead to significant improvements in precision of the movement and fishing mortality estimates, particularly when tagging does not occur in all regions (as is the case for SBT). The current section is focussed on applying the integrated spatial tag model to archival and conventional tag data from juvenile SBT tagging experiments conducted in the 1990s and 2000s.

As part of FRDC project 2002/015 (Polacheck et al. 2006), a discrete-space, discrete-time model for estimating fishing mortality, natural mortality and movement rates from conventional tag-return data was developed. Abundance can also be estimated if catch data are included. The model was initially developed under a general spatial framework, but was subsequently modified to accommodate spatial and temporal dynamics resembling those of juvenile SBT (Polacheck et al. 2006, Appendices 11 and 16).

Having position estimates from archival tags that were released at the same time as conventional tags can improve the model in a number of ways. Namely, it can:

- provide valuable information about the appropriateness of the spatial and temporal structure being assumed;

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[13] When this project began, the CCSBT operating model included the conventional tag data from 1990s tagging experiments on juvenile SBT through a very simple likelihood that pooled all releases and recaptures by year. Since that time, a Brownie likelihood for these data has been adopted, which keeps track of and allows for the valuable information about natural mortality in the data to be taken advantage of. Since the operating model is not spatially structured, the tagging data are not broken down by areas of release and recapture. Data from the 2000s tagging experiments are not included in the operating model because of lack of information on reporting rates and also unexplainable differences in returns of fish tagged at age 1 off Western Australia versus in the Great Australian Bight during for this time period (see Section 8).

- help determine whether the assumption that a fish has no memory with respect to its previous movements is reasonable, or whether an alternative hypothesis that fish show site-fidelity is more appropriate;
- provide information to help separate fishing mortality from movement, as this is difficult for the model to do with conventional tagging data alone.

Two general approaches can be used for including archival tag data in the model: 1) a two-stage approach, in which position estimates from archival tags are used to estimate movement parameters, which can then be plugged into the model as known or as priors (i.e. with uncertainty); 2) an integrated approach, in which data from archival tags are incorporated directly in the model through an additional likelihood component. For each recaptured archival tag, the data to be included in the likelihood is the region that the fish was in during each time period between release and recapture. The integrated spatial model is more statistically rigorous because the variance and, therefore, relative weighting of the archival tag data gets correctly accounted for. Plus, there is information not only about movement but also about mortality rates in the archival tag data that gets incorporated with the integrated approach. The integrated approach does, however, require that the archival tag releases correspond to the same release years and ages as the conventional tag data. This is not strictly required with the two-stage approach, provided that movement rates determined from the archival tag data are applicable to the conventional tag data (i.e. movement rates did not change significantly between the time of the archival tagging experiment and the conventional tagging experiment).

The archival tag data for SBT suggest significant changes in juvenile migration patterns have occurred between the 1990s and 2000s, with a contraction in eastward (and possibly the extent of westward) movement (Basson et al. 2009). Moreover, previous analyses of the conventional tag data from the 2000s have found that fishing mortality estimates derived from tags released at age 1 off the south coast of WA are much lower than those derived from tags released at ages 2 and 3 in the GAB (Polacheck and Eveson 2007). This difference was not observed in the 1990s conventional tag data, and the reason for it remains a puzzle (see Polacheck and Eveson 2007 for a thorough discussion). Thus, it made sense to analyse the data separately for these two periods.

For the 1990s, the amount of overlapping conventional and archival tag data is sparse (conventional tags were mostly released in the first half of the decade, and archival tags in the second half—see **Table 9.1**), so incorporating archival tag data directly into the model is not very useful. Thus, we present results from applying the two-stage approach to the data from the 1990s. For the 2000s, the amount of overlapping conventional and archival tag data is much greater, so results from applying the integrated spatial tag model are presented.

Table 9.1. Numbers of a) conventional and b) archival tag releases by age and year of release. Corresponding numbers of recaptures up to and including age 5 are given in italics (age 5 is the maximum recapture age used in the model). Conventional tag releases from WA are omitted for years 2000-2008 for reasons discussed in the text.

a) Conventional tags

RELEASE YEAR	RELEASE AGE					
	1		2		3	
1991	3301	*145*	3209	*361*	811	*87*
1992	2147	*127*	4715	*392*	1110	*88*
1993	4898	*402*	3161	*260*	2909	*197*
1994	9003	*914*	3177	*331*	3737	*264*
1995	8594	*1010*	5968	*897*	2728	*240*
1996	82	*16*	2524	*601*	1516	*349*
1997	884	*109*	593	*131*	553	*143*
1998	-		-		-	
1999	-		-		-	
2000	-		-		-	
2001	-		-		-	
2002	334	*67*	158	*34*	21	*2*
2003	60	*16*	2484	*657*	3251	*617*
2004	622	*78*	3247	*787*	1009	*380*
2005	144	*20*	7856	*1852*	705	*170*
2006	126	*12*	6486	*870*	3124	*581*
2007	22	*2*	7443	*815*	478	*84*
2008	-		-		-	

b) Archival tags

RELEASE YEAR	RELEASE AGE					
	1		2		3	
1991	-		-		-	
1992	-		-		-	
1993	-		29	*2*	1	*0*
1994	-		1	*0*	142	*12*
1995	-		88	*30*	52	*11*
1996	-		-		-	
1997	-		-		-	
1998	-		3	*1*	99	*27*
1999	-		-		30	*8*
2000	-		-		21	*6*
2001	1	*0*	4	*3*	-	
2002	-		14	*3*	8	*0*
2003	29	*3*	-		-	
2004	14	*3*	52	*15*	17	*2*
2005	-		59	*10*	25	*4*
2006	10	*2*	52	*5*	51	*11*
2007	45	*0*	64	*3*	22	*0*
2008	-		54	*0*	33	*0*

9.2 Methods

9.2.1 SBT background

SBT are long-lived (age 30+) and highly migratory (Caton 1991). Mature adults (age 10+) spawn in the Indian Ocean south-east of Java, Indonesia during the months of September to April (Davis and Farley 2001). Newly spawned fish migrate down the west coast of Australia, with 1 year olds commonly found off the west and south coasts of Western Australia (WA) (Hobday et al. 2008). Juveniles predominantly of ages 2 to 4 congregate in large numbers in the warm continental shelf waters of the Great Australian Bight (GAB) during the austral summer (Farley et al. 2007). At the end of summer, they migrate to deep oceanic waters spanning from South Africa to New Zealand to spend their winters before a high but unknown proportion return to the GAB for the following summer (Gunn and Block 2001). Archival tag data has shown that the timing of these cyclic migrations can vary greatly between individuals, but for the most part, juveniles enter the GAB between November and January and leave between April and June. They stop returning as they get older, with very few fish above age 5 found in the GAB.

Commercial fishing for SBT began by Australia and Japan in the early 1950s, and the fishery has undergone substantial changes over time. For our purposes here, we are interested in fisheries that caught juvenile SBT during the 1990s and 2000s, since this corresponds to when the tagging data being analysed were collected. The primary fishery that caught SBT of ages 2-4 during these two decades was the Australian purse seine fishery, catching surface schools off South Australia during the summer (December through March). In addition to the surface fishery, juveniles are also caught by various longline fleets operating throughout the southern ocean, mostly during the winter months. The most significant of the longline fisheries in terms of juvenile catches is Japan, followed by Taiwan, Korea and New Zealand.

9.2.2 SBT spatial model

The spatial model for juvenile SBT consists of four regions:

1. Southern Australia (SA), which includes both the Great Australian Bight (GAB) and waters around Western Australia (WA);

2. South Africa;
3. South-East Indian Ocean (SEIO);
4. Tasman Sea

and two seasons:

1. summer (Nov-Apr), corresponding roughly to the summer surface fishery;
2. winter (May-Oct), corresponding roughly to winter longline fisheries.

The model assumes that the surface fishery occurs only in the summer in SA, and that the longline fisheries occur only in the winter in the remaining 3 regions. Tagging, whether conventional or archival, is assumed to occur only in regions and time periods of fishing. Obviously recaptures can occur only in regions and periods of fishing.

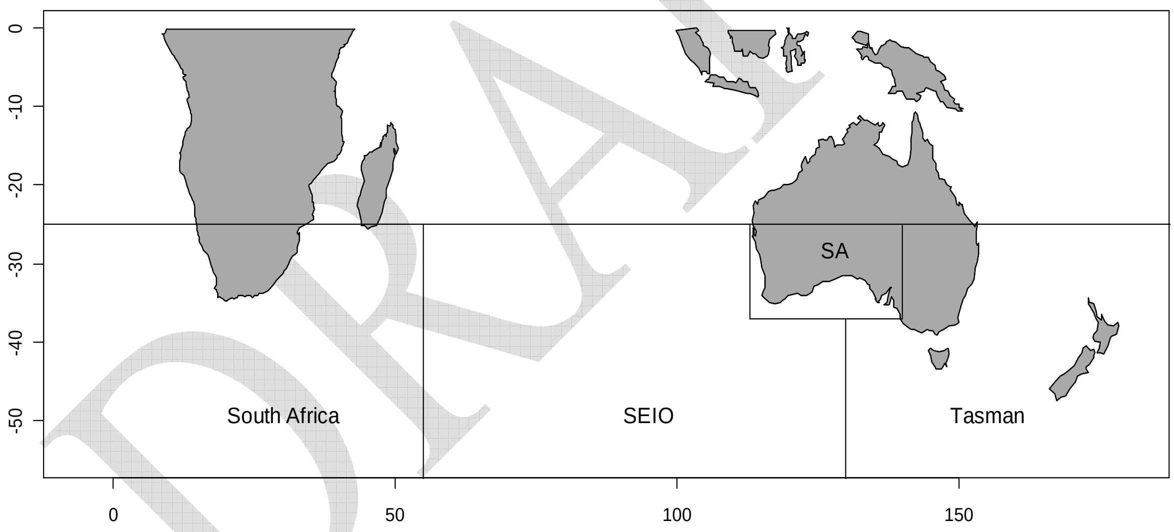

Figure 9.1. The 4 regions defined in the spatial tagging model for juvenile SBT. (SA: Southern Australia; SEIO: South-East Indian Ocean)

At the end of summer, fish in SA migrate to one of the three longline regions. At the end of winter, fish can either stay in their current region or else migrate back to SA (i.e., the model does not allow for direct migration between the longline regions). Movement rates between regions are allowed to vary with age, but are assumed to be the same between years for fish of a given age. Mathematically, these movement dynamics can be described by the following matrices:

End of season 1 (summer) movement probability matrix:

$$\Pi_{a,t} = \begin{bmatrix} 0 & \pi_{a,t,1,2} & \pi_{a,t,1,3} & \pi_{a,t,1,4} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{for odd } t$$

End of season 2 (winter) movement probability matrix:

$$\Pi_{a,t} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \pi_{a,t,2,1} & \pi_{a,t,2,2} & 0 & 0 \\ \pi_{a,t,3,1} & 0 & \pi_{a,t,3,3} & 0 \\ \pi_{a,t,4,1} & 0 & 0 & \pi_{a,t,4,4} \end{bmatrix} \quad \text{for even } t$$

The subscript in $\pi_{a,t,r,r'}$ refers a fish of age a moving from region r to r' at the end of time period t. Each row must sum to 1, so that $\pi_{a,t,1,4} = 1 - \left(\pi_{a,t,1,2} + \pi_{a,t,1,3}\right)$ for season 1 (odd t) and $\pi_{a,t,r,r} = 1 - \pi_{a,t,r,1}$ for season 2 (even t) and $r = 2,3,4$. The 1's on the diagonal of the season 1 matrix reflect the assumption that any fish in regions 2, 3 and 4 during season 1 remain in the same region at the end of the season. The 1 in the (1,1) position of the season 2 matrix is for completeness, but it is not used because the model assumes there are no fish in SA during winter.

9.2.3 Two-stage approach: 1990s

We estimated the parameters of the movement matrices using archival tag tracks available from fish tagged in 1993 to 2000. In doing so, we assumed that the movement parameters are independent of age. Although this may be too simplistic, the data available are insufficient to provide reliable age-specific estimates. Not all tracks fit unambiguously into the spatial and temporal structure being assumed. Thus, we had to use our best judgement in determining region designations for a number of tags. For example, some fish over-wintered in waters off WA, bordering the division between regions SA and SEIO, and we assigned them SEIO for their winter region. Also, fish that ultimately ended up in waters off South Africa during the winter were assigned South Africa as their winter region regardless of how long they spent migrating through SEIO to get there.

Next we applied the spatial model to the SBT conventional tag and catch data from the 1990s, with the movement parameters fixed at those estimated from the archival tag data. The spatial model was already fit to the conventional tag and catch data as part of FRDC project 2002/015 (see Appendix 16 of Polacheck et al. 2006), however in that case the movement parameters were estimated within the model based on information contained in the conventional tag data. We wanted to see how much the mortality rate and abundance estimates differed when archival tag data were used to determine the movement parameters.

The data sets used as input to the model were:

- Tag release and return data from 1991 to 1997 (we do not include tag returns beyond 1997 because it is the last year for which we have information for estimating reporting rates). Specifically, we included data from fish belonging to cohorts 1990 to 1994 that were tagged at ages 1 to 3 and recaptured up to a maximum of age 5 (beyond age 5 the numbers of recaptures becomes very small). The releases needed to be compiled by year, season, age and region of release, and the returns corresponding to each set of releases (i.e., to each year, season, age and region of release) needed to be compiled by year, season, age and region of recapture.
- Catch data from the commercial fisheries corresponding to the same years and ages of tag recaptures; e.g., for the 1990 cohort, catch data were included for ages 1 to 5 (corresponding to years 1991 to 1995). The catch data needed to be compiled by year, season, age and region of capture.
- Estimates of tag reporting rates by year, season, age and region for years 1991 to 1997. These were calculated by taking the weighted average of fishery-specific reporting rate estimates for fisheries operating in a given season and region using the catch-at-age by fishery as weights. The fishery-specific reporting rates were based on tag seeding experiments for the Australian surface fishery and observer data for the longline fisheries (note that there are a large number of alternative options for the fishery-specific reporting rates, of which only one is considered here). The reporting rate estimates were included as known without error in the model.

- Estimates of immediate and continuous tag shedding rates assumed to be the same across years, seasons, ages and regions, as well as taggers. These were derived from double tagging data from the 1990s conventional tag experiments, and were included as known without error in the model.

Details of each of the data sets and how they were compiled can be found in Appendices 4 and 16 of Polacheck et al. (2006). The tag shedding rates are estimated with good precision since all fish were double-tagged, so including them as known without error is reasonable. On the other hand, the reporting rate estimates are highly uncertain. We have chosen to include them as known for simplicity, since the results presented here are only intended to be illustrative. However, uncertainty in the reporting rates can be included through another likelihood component in applications where it is required.

Although the years of the conventional tag-return data (1991 to 1997) do not overlap exactly with the years of the archival tag data used to estimate the movement parameters (1993 to 2000), data from both tag types suggest that movement dynamics of juvenile SBT remained similar from 1991 through 2000[14]. Thus, it should be reasonable to assume the movement parameters estimated from the archival tag data are applicable to the conventional tag data being included in the model.

The spatial SBT model was developed to include both tag-return data and catch data, although it can be fitted using tag-return data alone. The advantage of including catch data is that it allows for abundance by region to be estimated, whilst also contributing information to the fishing mortality estimates. The catch data used here were compiled prior to the independent reviews conducted in 2006 that found evidence of substantial unreported catches of SBT dating back to the 1980s (see Anon. 2006). A number of alternative scenarios for taking into account the unreported catches are being considered by the CCSBT, but these are simply adjustments to the total annual catch statistics. For inclusion in the spatial SBT model, we need to consider how to attribute the unreported catches to regions, seasons and age classes, which is not a trivial problem. As such, we chose to continue using the catch data as compiled for FRDC project 2002/015. Our main objective here is to illustrate the effect that using

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[14] There appears to have been a change in juvenile movement patterns in the early 2000s compared to the 1990s, with fewer fish migrating east to the Tasman Sea after leaving the GAB, as well as some evidence of fewer fish going as far west (Basson et al. 2009).

archival tag data to inform the movement rates can have on the parameter estimates; the actual values of estimates are likely to be biased and must be interpreted cautiously.

9.2.4 Integrated approach: 2000s

Archival tag data can be included directly in the spatial tag model through an additional likelihood component. For each archival tag recovery, the data to be included is the region that the fish was in during each time period it was at liberty. To calculate the probability that a fish will be in a given region at a given time period is relatively simple compared to a conventional tag because all intermediate transitions between release and recapture are known. Thus, under the assumption that fish move between regions at the end of each time period, the probability of a fish released in region r_1 in time period t being recaptured in region r_2 in time period t+3 after having made transitions from r_1 to r_3 to r_1 to r_2 is just Pr(survive r_1 in time period t)*Pr(move from r_1 to r_3)*Pr(survive r_3 in time period t+1)*Pr(move from r_3 to r_1)* Pr(survive r_1 in time period t+2)*Pr(move from r_1 to r_2)*Pr(caught in r_2 in time period t+3). For a conventional tag, all possible intermediate transitions need to be accounted for. The survival probabilities are functions of natural mortality and fishing mortality (which may be age, region and/or time dependent), and the movement probabilities are simply the parameters of the transition matrices (which may be age and/or time dependent). Mathematical details for the archival tag likelihood can be found in Appendix 6.

There are a number of complicating factors when applying the integrated spatial model to real data:

(1) position estimates from archival tags have large uncertainty;

(2) many (most) fish tracks fit do not fit unambiguously into the spatial and temporal structure being assumed;

(3) tracks estimated from archival tags often stop before the fish is caught and the tag recovered (due to a number of reasons such as the light sensor failing, the battery dying, etc).

In terms of (1), longitude estimates are generally much more accurate than latitude and should be sufficient to determine the broad regions needed for the model. In terms of (2), the spatial and temporal structure of the model is clearly an oversimplification of the truth, and it can be difficult to accommodate some of the archival tag tracks within this structure. This was an issue in estimating the movement matrices for the two-stage approach as well. Again, we used our best judgement for each archival tag track to determine the most appropriate region designation in each season. In terms of (3), the model can be modified to accommodate incomplete archival tag tracks by treating each one the same as any archival tag up until the track stops, then treating it as a conventional tag that was released in the last observed region/time period (and recaptured in the region/time period where the fish was caught).

There are also issues specific to SBT data from the 2000s that make applying the spatial tag model to these data complicated. First, we do not have any basis for estimating reporting rates for the longline fisheries in the 2000s, thus we need to make guesses based on estimates from the 1990s. We can estimate reporting rates for the Australian surface fishery based on data from tag seeding experiments conducted in 2003 to 2009, but the very low estimates in some seasons has brought into question the reliability of these estimates. Second, as mentioned in the Introduction, previous analyses of the conventional tagging data from the 2000s showed that fishing mortality estimates derived from fish tagged at age 1 off WA are much lower than those derived from fish tagged at ages 2 and 3 (primarily in the GAB, although some age 2 off WA) (Polacheck et al. 2007). This difference was not observed in the 1990s tagging data. Brownie-type models, on which the spatial model is based, integrate releases from all ages to produce estimates of fishing mortality and natural mortality. Thus, the estimates obtained from applying these models to the 2000s data will have an unclear interpretation. While it is not the most satisfactory solution, we dealt with this problem simply by omitting data corresponding to WA releases.

The data sets used as input to the model were:

- Tag release and return data from 2001 to 2007. Specifically, we included data from fish belonging to cohorts 2000 to 2004 that were tagged at ages 1 to 3 and recaptured up to a maximum of age 5 (beyond age 5 the numbers of recaptures becomes very small). The releases needed to be compiled by year, season, age and region of release, and the returns corresponding to each set of releases (i.e., to each year, season, age and region of release) needed to be compiled by year, season, age and region of recapture.

- Catch data from the commercial fisheries corresponding to the same years and ages of tag recaptures; e.g., for the 2000 cohort, catch data were included for ages 1 to 5 (corresponding to years 2001 to 2005). The catch data needed to be compiled by year, season, age and region of capture.
- A constant reporting rate value was assumed for each region (i.e., independent of year and age) due to lack of information. The values used were: 0.50 for SA, 0.10 for South Africa, 0.25 for the SEIO, and 0.65 for the Tasman. The SA value is an average estimate from the tag seeding experiments conducted in the GAB in the 2000s, whereas the values for the longline regions are based on average estimates for the 1990s, which themselves are highly uncertain. The reporting rate estimates were included as known without error in the model.
- Estimates of immediate and continuous tag shedding rates assumed to be the same across years, seasons, ages and regions, as well as taggers. These were derived from double tagging data from the 2000s conventional tag experiments, and were included as known without error in the model.

The tag shedding rates for the 2000s are estimated with good precision since all fish were double-tagged, so including them as known without error is reasonable. Clearly, the reporting rate estimates are highly uncertain. We include them as known for simplicity, since the results presented here are intended to be illustrative only. If our purpose was to obtain reliable mortality and abundance estimates, then we would need to conduct sensitivity analyses using different reporting rate values.

The catch data were compiled from data contained in the CCSBT catch database. As for the 1990s catch data, we have not made any adjustments for potential unreported catches (for the reasons discussed in the previous section ‘Two-stage approach: 1990s’). We repeat that our main objective is to investigate the effect that including archival tag data in the spatial model has on the parameter estimates; the actual values are likely to be biased and must be interpreted cautiously.

9.2.5 Comparison with non-spatial results

It is of interest to compare parameter estimates from the spatial model with those obtained from an equivalent non-spatial analysis of the same data (equivalent in the sense that if we assumed fishing mortality varied by year, age and region in the spatial model, then we would assume it varied by year and age in the non-spatial model).

Population-wide (non-spatial) estimates of mortality rates and abundance are often of as much, or more, interest than regional estimates; however, we expect them to be biased if spatial heterogeneity in mortality rates exists and full mixing of tagged and untagged fish has not been achieved.

When fitting the non-spatial model for the 1990s and 2000s, we used the same conventional tag and catch data as for the spatial model but summed over regions. We did not include archival tag data since the model does not require estimates of movement between regions. The archival tag data could be included exactly the same way as conventional tag data (release and recaptures numbers by year and age), but the sample sizes are so small compared to the conventional tag data that they would have very little influence in the likelihood. For reporting rates for the 1990s, we used the non-spatial reporting rate estimates used in the current CCSBT operating model (OM). The spatial reporting rates we used for the 1990s were based on the same analyses and assumptions used to calculated the non-spatial estimates in the OM. For the 2000s, we simply used a reporting rate estimate of 0.5, as this was a rough average across regions of the spatial reporting rates that we used for the 2000s.

To compare parameter estimates from the spatial and non-spatial models, it is first necessary to calculate population-wide estimates for the spatial model. Natural mortality is already assumed to be the same across regions in the spatial model, so the M estimates can be compared directly. Population-wide abundance can be calculated simply by summing the regional abundance estimates. To compare the fishing mortality estimates is not as straightforward—we cannot simply sum the F estimates across regions because they need to take into account the number of fish in each region. Thus, we calculate average yearly fishing mortalities for the spatial model as outlined in Appendix 11, section 3.5.1, of Polacheck et al. (2006).

9.3 Results

9.3.1 Two-stage approach: 1990s

The movement probability matrices estimated using archival tag data from tags released in 1993 to 2000 are given in **Table 9.2**. At the end of summer, the majority of fish (67%) are estimated to migrate from SA to the SEIO, with 12% migrating to S. Africa and 21% to the Tasman. At the end-of winter, all fish from the 3 longline regions are estimated to return to SA. The archival tag data contained no concrete evidence of a fish age 5 or less not returning to SA for the summer (for tags released in 1993-2000). There was one tagged fish recaptured off S. Africa in November, but it may still have returned to SA if it had not been caught (a number of fish did not start their return migration until Dec-Jan).

Results from fitting the spatial model to the conventional tag and catch data: (a) fixing the movement parameters at those estimated from the archival tag data (above); and (b) estimating the movement parameters within the spatial model (using only conventional tag data) are compared in **Table 9.2**, **Table 9.3** and **Figure 9.2**. A number of different model parameterizations were considered, but the results presented here are based on the following:

- Natural mortality (M) is assumed to vary by age only (i.e., independent of year and region), and M at ages 2 and above is assumed to stay constant (this is because when fish are tagged at $n = 3$ consecutive ages, only $n - 1 = 2$ M parameters can be estimated).
- Fishing mortality (F) is assumed to vary by year, age and region.
- To account for non-mixing directly following tagging, fishing mortality is allowed to differ between tagged fish in the time period of tagging and untagged fish in that same time period; i.e., for fish tagged at age a in time period t in region r, we replace F(a,t,r) with F*(a,t,r). There are identifiability issues with this model that we overcome by assuming F*(a,t,r) = k * F(a,t,r), where k is a parameter estimated in the model.
- Movement parameters are assumed to be independent of year and age (since this was the assumption made in estimating the movement parameters from the archival tag data).
- Age 1 abundance (P_1) is allowed to vary between years, but the distribution of age 1 fish amongst the 4 regions at the start of season 1 is assumed to be the same each year.

The end-of-summer movement estimates from the model are reasonably similar to those from the archival tag data (**Table 9.2**). However, the end-of-winter estimates suggest very different movement dynamics than those suggested by the archival tag data. For instance, the archival tag data suggest that essentially 100% of juvenile SBT return to SA at the end of winter, whereas the model estimates suggest the majority of fish remain in their winter longline region for the summer. This is most likely because the model has difficulty separating fishing mortality from movement with conventional tag data alone.

The natural mortality rate estimates are higher, especially for age 2+, when the movement probabilities are fixed at those estimated from the archival tag data rather than estimated in the model (**Table 9.3**). The fishing mortality estimates are also significantly affected (**Table 9.3**, **Figure 9.2**). Most noticeable is that the *F* estimates for SA are generally quite a bit smaller with the fixed archival-tag based movement parameters than the model-estimated movement parameters (**Figure 9.2**). This is because when the movement probabilities are fixed, the resulting abundance estimates suggest significantly more fish are in SA in the summer than when the movement probabilities are estimated within the model (**Figure 9.3**); when abundance is higher, a smaller *F* achieves the same number of recaptures. Some of the *F* estimates for S. Africa are very large, and even more so with the fixed archival-tag based movement parameters (**Figure 9.2**); however, the abundance estimates for S. Africa are very small (**Figure 9.3**) so these large *F*’s do not translate to huge catch numbers.

The total age 1 abundance estimates are quite similar using the fixed versus model-estimated movement probabilities, but the breakdown into regions at age 1 is very different (**Table 9.3**). When the movement probabilities are fixed, essentially all age 1 fish are estimated to be in SA in the summer season, whereas when the movement probabilities are estimated in the model, a greater percentage of age 1 fish are estimated to be in SEIO than SA in the summer.

The affect of the different movement probability options on the regional abundance estimates over time is apparent in **Figure 9.3**, which shows that significant numbers of juvenile fish are estimated to remain in the SEIO and Tasman regions in the winter when the movement parameters are estimated within the model whereas essentially no juveniles remain in these regions when the archival tag-based movement estimates are used.

Table 9.2. Movement probability estimates for SBT cohorts from the 1990s: (i) obtained from the spatial model applied to conventional tag and catch data; (ii) based on an independent analysis of the archival tag data.

	From spatial model (no archival tag data)	Based on archival tag data
End-of-summer		
SA to S. Africa	0.09	0.12
SA to SEIO	0.77	0.67
SA to Tasman	0.14	0.21
End-of-winter		
S. Africa to SA	0.00	1.0
SEIO to SA	0.40	1.0
Tasman to SA	0.41	1.0

Table 9.3. Parameter estimates obtained from applying the spatial model to the 1990s conventional tag and catch data for SBT with the movement parameters: (left) estimated within the model; (right) fixed at those estimated from the archival tag data.

				Movement parameters estimated in model					**Movement parameters fixed based on archival tags**				
M				**Age1**	**Age2+**				**Age1**	**Age2+**			
				0.474	0.213				0.503	0.276			
F	**Cohort**	**Season**	**Region**	**Age1**	**Age2**	**Age3**	**Age4**	**Age5**	**Age1**	**Age2**	**Age3**	**Age4**	**Age5**
	1990	1	SA	0.037	0.053	0.084	0.067	0.018	0.014	0.019	0.032	0.027	0.008
	1990	2	S.Africa	0.003	0.006	0.187	0.280	0.176	0.001	0.004	0.223	0.437	0.294
	1990	2	SEIO	0.000	0.004	0.011	0.015	0.019	0.000	0.005	0.014	0.019	0.026
	1990	2	Tasman	0.000	0.137	0.197	0.151	0.340	0.000	0.090	0.122	0.097	0.214
	1991	1	SA	0.019	0.052	0.096	0.124	0.018	0.008	0.019	0.036	0.049	0.008
	1991	2	S.Africa	0.000	0.016	0.106	0.355	0.263	0.000	0.010	0.110	0.559	0.444
	1991	2	SEIO	0.000	0.002	0.020	0.031	0.015	0.000	0.002	0.024	0.040	0.022
	1991	2	Tasman	0.000	0.084	0.060	0.311	0.113	0.000	0.052	0.041	0.222	0.073
	1992	1	SA	0.002	0.038	0.224	0.223	0.125	0.001	0.014	0.083	0.085	0.053
	1992	2	S.Africa	0.000	0.009	0.060	0.296	0.178	0.000	0.007	0.066	0.564	0.359
	1992	2	SEIO	0.000	0.006	0.055	0.045	0.016	0.000	0.007	0.069	0.059	0.023
	1992	2	Tasman	0.001	0.007	0.089	0.079	0.169	0.001	0.005	0.059	0.055	0.123
	1993	1	SA	0.000	0.059	0.626	0.766		0.000	0.022	0.206	0.288	
	1993	2	S.Africa	0.000	0.015	1.511	5.000		0.000	0.010	5.000	1.604	
	1993	2	SEIO	0.000	0.033	0.199	0.064		0.000	0.040	0.254	0.100	
	1993	2	Tasman	0.000	0.005	0.026	0.140		0.000	0.004	0.018	0.132	

1994	1	SA	0.001	0.112	0.962			0.000	0.041	0.280		
1994	2	S.Africa	0.000	0.017	1.136			0.000	0.011	5.000		
1994	2	SEIO	0.000	0.042	0.188			0.000	0.050	0.240		
1994	2	Tasman	0.000	0.003	0.062			0.000	0.002	0.043		
Proportion age 1			**SA**	**S.Afr**	**SEIO**	**Tas**		**SA**	**S.Afr**	**SEIO**	**Tas**	
abundance by region			0.39	0.00	0.48	0.13		0.91	0.00	0.00	0.09	
Age 1 abundance		**Cohort**	**SA**	**S.Afr**	**SEIO**	**Tas**	**Total**	**SA**	**S.Afr**	**SEIO**	**Tas**	**Total**
(millions)		1990	1.17	0.00	1.43	0.38	2.98	2.88	0.00	0.00	0.27	3.16
		1991	1.19	0.00	1.44	0.39	3.02	2.94	0.00	0.00	0.28	3.23
		1992	0.87	0.00	1.05	0.28	2.20	2.02	0.00	0.00	0.19	2.22
		1993	0.45	0.00	0.55	0.15	1.14	1.10	0.00	0.00	0.10	1.20
		1994	0.39	0.00	0.48	0.13	1.00	1.00	0.00	0.00	0.09	1.09

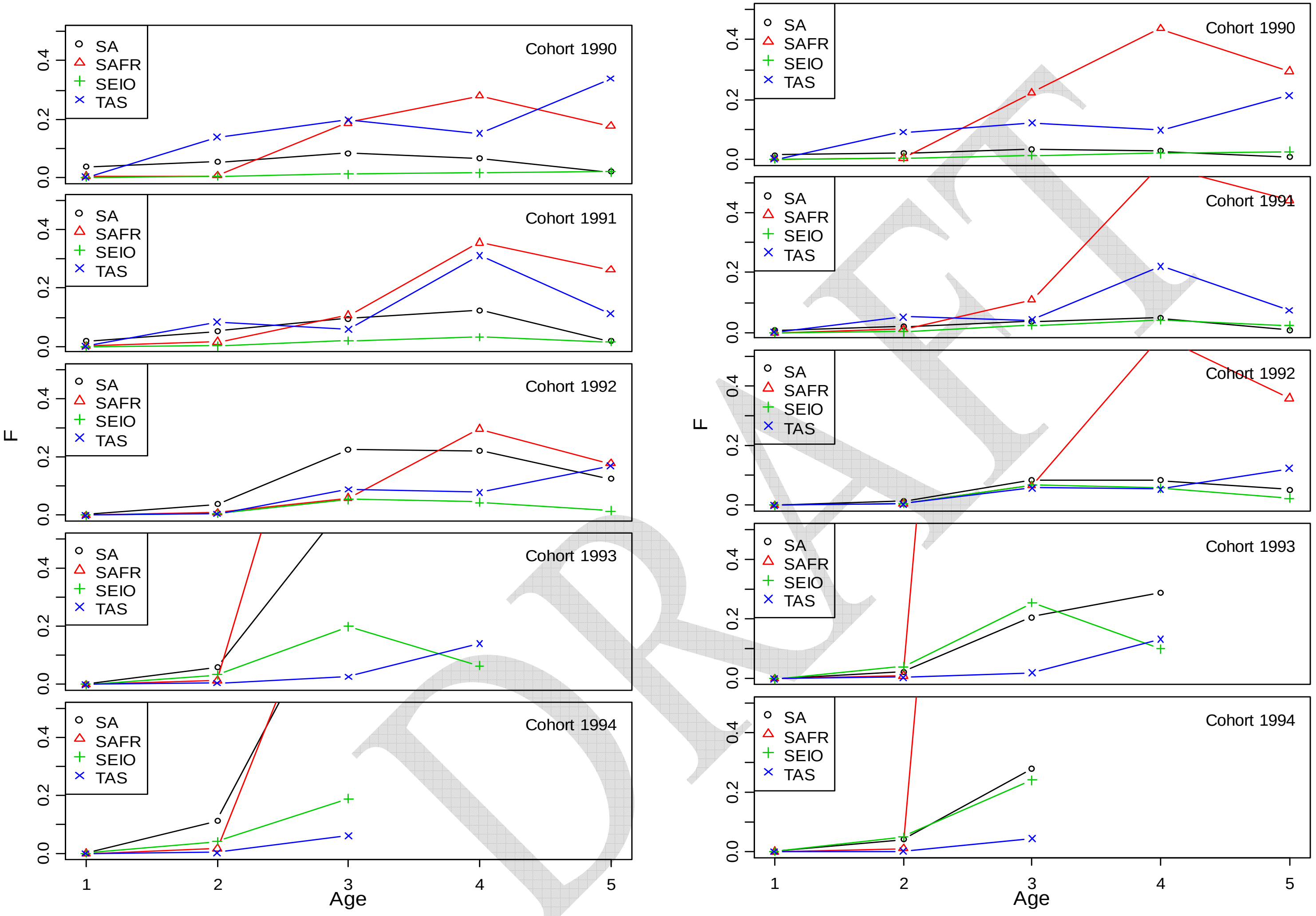

Figure 9.2. Fishing mortality rate estimates obtained from applying the spatial model to the 1990s conventional tag and catch data for SBT with the movement parameters: (left) estimated within the model; (right) fixed at those estimated from the archival tag data.

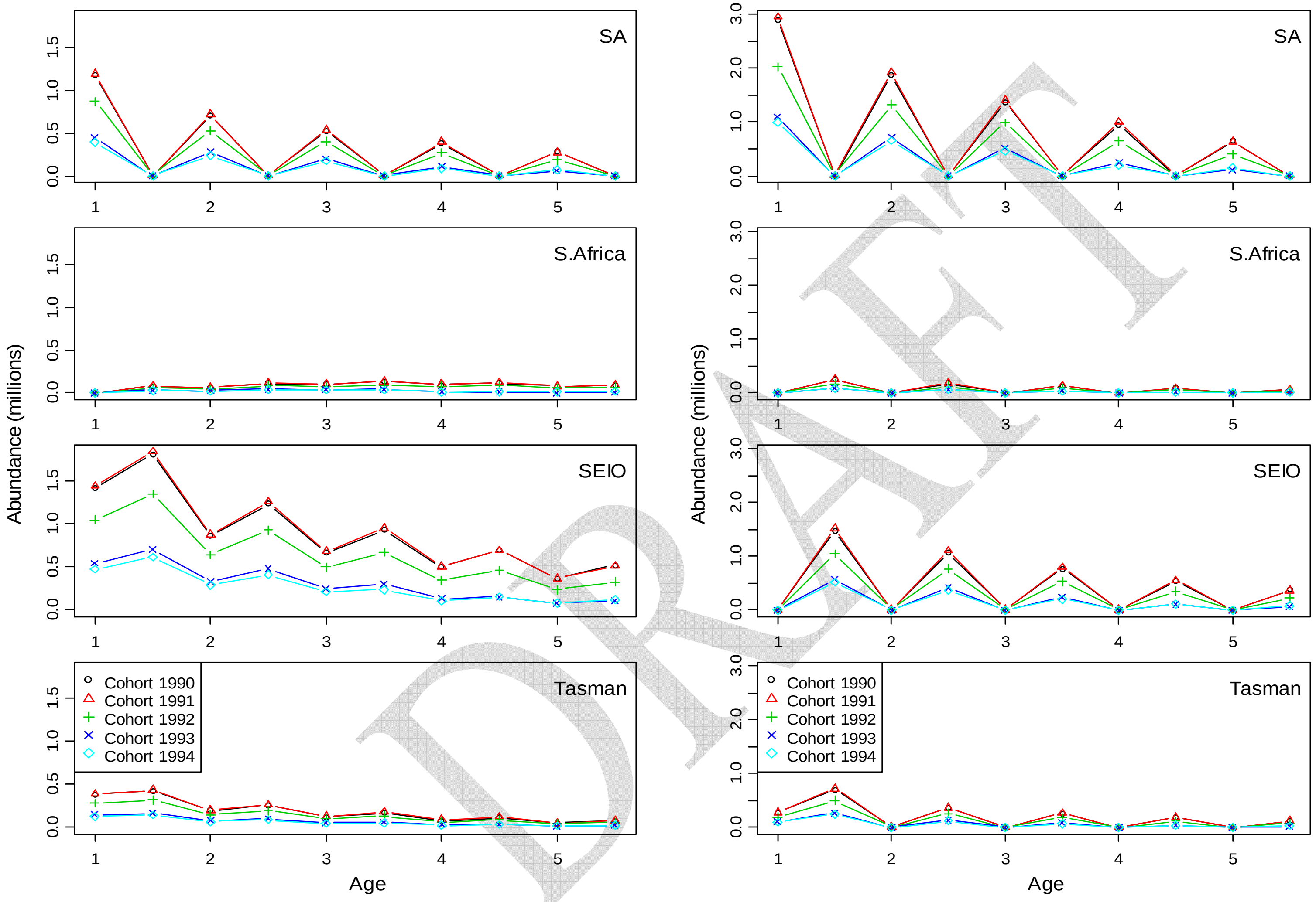

Figure 9.3. Abundance over time (age) by region for cohorts 1990-1994, as calculated using parameter estimates obtained from the spatial model with movement parameters: (left) estimated within the model; (right) fixed at those estimated from the archival tag data.

9.3.2 Integrated approach: 2000s

The spatial model was fitted to the SBT data from the 2000s first using only conventional tag and catch data, and second including archival tag data. A number of different model parameterizations were considered, but the results presented here were based on the following:

- Natural mortality (M) is assumed to vary by age only (i.e., independent of year and region), and M at ages 2 and above is assumed to stay constant (this is because when fish are tagged at $n = 3$ consecutive ages, only $n - 1 = 2$ M parameters can be estimated).
- Fishing mortality (F) is assumed to vary by year, age and region.
- To account for non-mixing directly following tagging, fishing mortality is allowed to differ between tagged fish in the time period of tagging and untagged fish in that same time period; i.e., for fish tagged at age a in time period t in region r, we replace F(a,t,r) with F*(a,t,r). There are identifiability issues with this model that we overcome by assuming F*(a,t,r) = k * F(a,t,r), where k is a parameter estimated in the model.
- The end-of-summer movement probabilities are assumed to be independent of age and cohort (i.e., year). In other words, the proportion of fish leaving SA and going to each of the 3 longline regions is the same for all ages and years.
- The end-of-winter movement probabilities are assumed to be separable into multiplicative age and region effects, meaning that the proportion of fish returning to SA at the end of winter can vary with age, but the relative proportion coming from each of the longline regions is the same for all ages. For example, the relative proportion of fish that return from each of the longline regions may be 0.2 from S. Africa, 0.5 from SEIO and 0.3 from the Tasman. If the total proportion of age *a* fish returning to SA is α_a, then the proportion of age *a* fish returning from S. Africa is $0.2\alpha_a$, from SEIO is $0.5\alpha_a$ and from the Tasman is $0.3\alpha_a$.

- Age 1 abundance (P_1) is allowed to vary between years, but the distribution of age 1 fish amongst the 4 regions at the start of season 1 is assumed to be the same each year.

The parameter estimates are summarized in **Table 9.4** and **Figure 9.4**. When archival tag data are included in the model, the movement probability estimates at the end of summer suggest most fish (91%) migrate from SA to the SEIO, whereas without archival tag data, 75% of fish are estimated to migrate to S. Africa and 24% to the SEIO. At the end of winter, the movement estimates obtained with archival tag data suggest that almost all fish return from the SEIO to SA at age 1 and about 30% return from S. Africa and the Tasman. These percentages decline with age. Without archival tag data, almost all fish are estimated to return from S. Africa at age 1, 85% from the SEIO and none from the Tasman. Again, these percentages decline with age.

Table 9.4. Parameter estimates obtained from applying the spatial model to SBT data from the 2000s: (left) results when only conventional tag and catch data are used; (right) results when archival tag data are integrated into the model.

				Results WITHOUT archival tag data					Results INCLUDING archival tag data				
M				**Age1**	**Age2+**				**Age1**	**Age2+**			
				0.462	0.187				0.490	0.132			
F	**Cohort**	**Season**	**Region**	**Age1**	**Age2**	**Age3**	**Age4**	**Age5**	**Age1**	**Age2**	**Age3**	**Age4**	**Age5**
	2000	1	SA	0.000	0.029	1.281	1.155	0.732	0.000	0.022	1.063	0.468	0.971
	2000	2	S.Africa	0.000	0.002	0.008	0.053	0.078	0.003	0.019	0.049	0.306	0.483
	2000	2	SEIO	0.000	0.012	0.040	0.164	0.186	0.000	0.004	0.012	0.042	0.041
	2000	2	Tasman	0.000	0.024	0.044	0.085	0.349	0.000	0.006	0.011	0.020	0.071
	2001	1	SA	0.000	0.082	3.885	5.000	5.000	0.000	0.067	3.114	0.727	5.000
	2001	2	S.Africa	0.004	0.001	0.055	0.162	0.140	0.046	0.013	0.369	1.028	5.000
	2001	2	SEIO	0.000	0.019	0.509	0.636	5.000	0.000	0.006	0.105	0.105	0.125
	2001	2	Tasman	0.000	0.021	0.090	0.573	0.417	0.000	0.005	0.022	0.114	0.055
	2002	1	SA	0.006	0.337	1.132	2.780	5.000	0.005	0.266	0.922	0.623	2.799
	2002	2	S.Africa	0.000	0.004	0.028	0.087	0.073	0.000	0.035	0.158	0.366	0.304
	2002	2	SEIO	0.000	0.021	0.160	0.541	0.645	0.000	0.006	0.037	0.087	0.063
	2002	2	Tasman	0.000	0.029	0.186	0.246	0.416	0.000	0.006	0.039	0.044	0.056
	2003	1	SA	0.000	0.150	1.108	4.827	0.320	0.000	0.125	0.947	0.727	0.342
	2003	2	S.Africa	0.000	0.002	0.044	0.034	0.034	0.003	0.019	0.358	0.183	0.235
	2003	2	SEIO	0.000	0.028	0.198	0.142	0.207	0.000	0.008	0.045	0.032	0.036
	2003	2	Tasman	0.000	0.017	0.116	0.166	0.276	0.000	0.004	0.028	0.036	0.051
	2004	1	SA	0.407	0.129	0.440	0.980	0.374	0.357	0.107	0.392	0.383	0.418
	2004	2	S.Africa	0.000	0.007	0.030	0.018	0.030	0.004	0.071	0.255	0.108	0.176
	2004	2	SEIO	0.000	0.009	0.039	0.089	0.067	0.000	0.003	0.011	0.022	0.015
	2004	2	Tasman	0.001	0.211	0.450	0.591	5.000	0.000	0.046	0.085	0.072	0.107

End-of-summer movement		**SA to S.Afr**	**SA to SEIO**	**SA to Tas**			**SA to S.Afr**	**SA to SEIO**	**SA to Tas**		
		0.00	0.75	0.24			0.05	0.91	0.04		
End-of-winter movement	**Age**	**S.Afr to SA**	**SEIO to SA**	**Tas to SA**			**S.Afr to SA**	**SEIO to SA**	**Tas to SA**		
	1	0.99	0.85	0.00			0.30	0.99	0.28		
	2	0.57	0.49	0.00			0.18	0.59	0.17		
	3	0.36	0.31	0.00			0.19	0.63	0.18		
	4	0.22	0.19	0.00			0.05	0.16	0.05		
Proportion age 1 abundance by region		**SA**	**S.Afr**	**SEIO**	**Tas**		**SA**	**S.Afr**	**SEIO**	**Tas**	
		0.03	0.00	0.96	0.01		0.03	0.00	0.92	0.05	
Age 1 abundance (millions)	**Cohort**	**SA**	**S.Afr**	**SEIO**	**Tas**	**Total**	**SA**	**S.Afr**	**SEIO**	**Tas**	**Total**
	2000	0.03	0.00	1.11	0.01	1.15	0.04	0.00	1.23	0.07	1.34
	2001	0.02	0.00	0.76	0.01	0.79	0.03	0.00	0.87	0.05	0.94
	2002	0.02	0.00	0.75	0.01	0.78	0.03	0.00	0.95	0.05	1.03
	2003	0.04	0.00	1.40	0.02	1.46	0.05	0.00	1.54	0.08	1.67
	2004	0.05	0.00	1.55	0.02	1.62	0.05	0.00	1.72	0.09	1.86

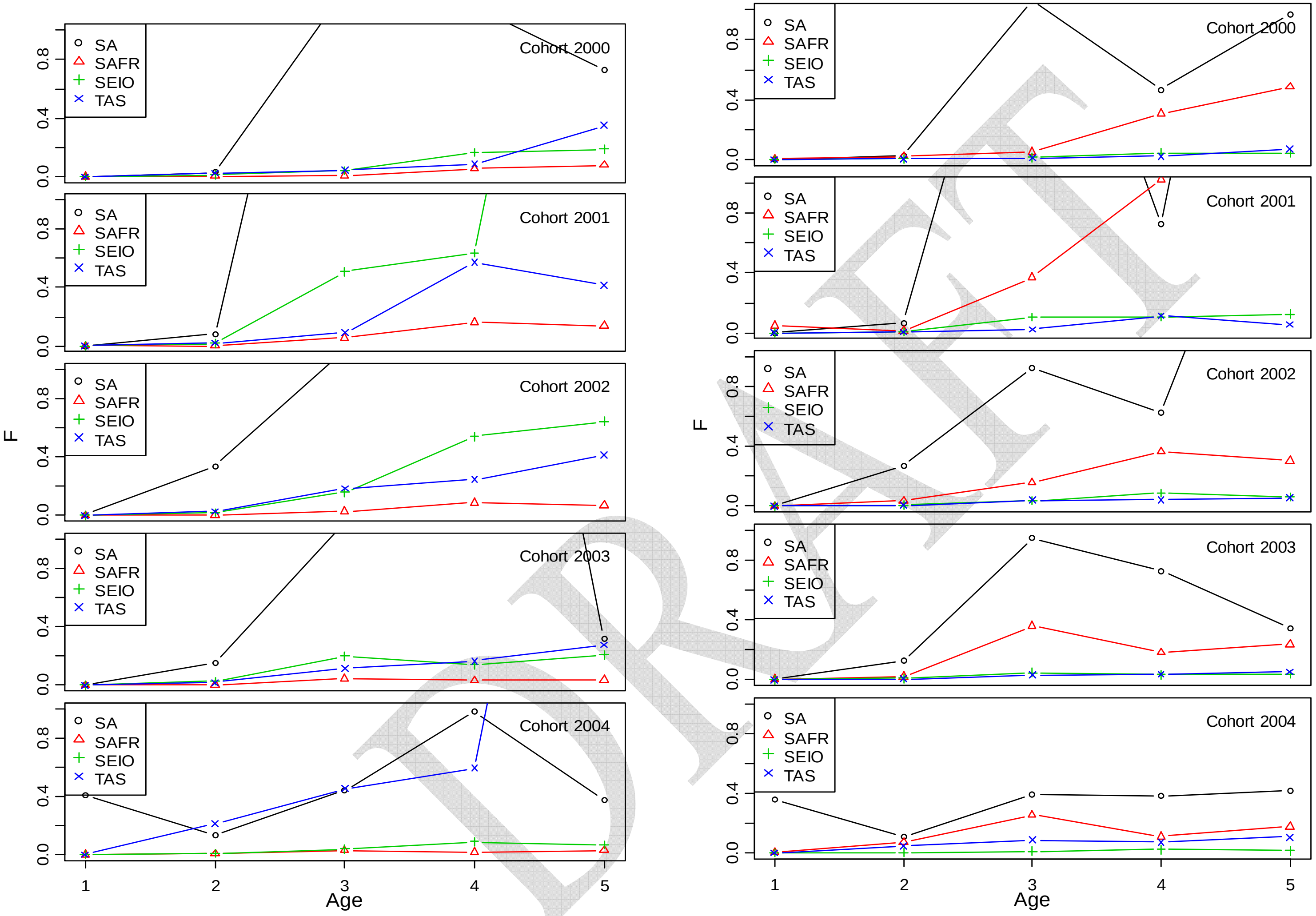

Figure 9.4. Fishing mortality rate estimates obtained from applying the spatial model to SBT data from the 2000s: (left) when only conventional tag and catch data are used; (right) when archival tag data are integrated into the model.

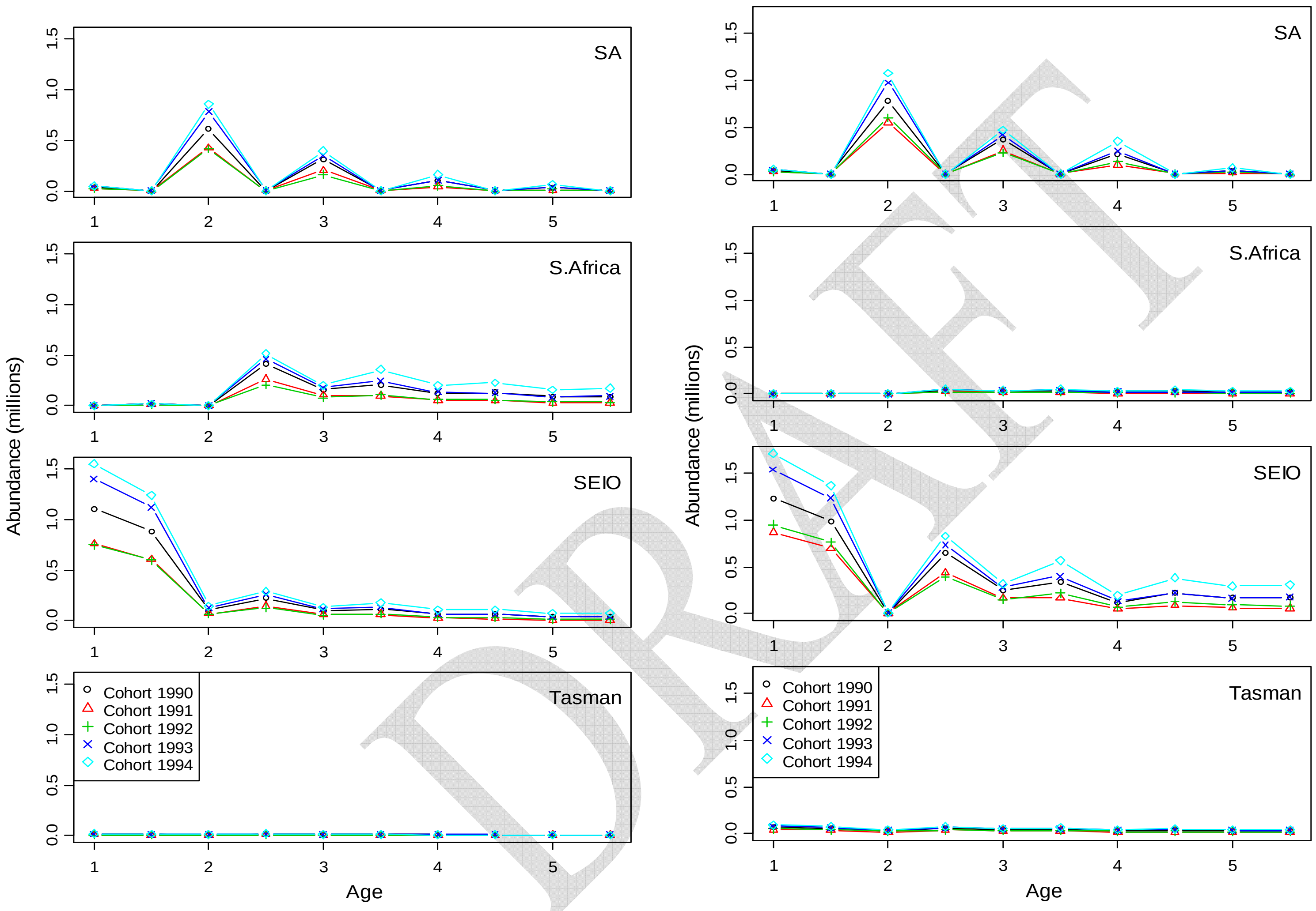

Figure 9.5. Abundance over time (age) by region for cohorts 2000-2004, as calculated using parameter estimates obtained from the spatial model (left) when only conventional tag and catch data are used; (right) when archival tag data are integrated into the model.

The *M* estimates are slightly larger at age 1 and smaller at ages 2+ when archival tag data are included, but in both cases suggest *M* at age 1 is much higher than at ages 2-5 (**Table 9.4**). The *F* estimates tend to be smaller in all regions except S. Africa when archival tag data are included; however, the *F* estimates for ages 3 and 4 in SA are still very high (>0.6 for all cohorts except 2004) (**Table 9.4**; **Figure 9.4**). Some of the *F* estimates for S. Africa obtained when including archival tag data were very high, particularly for the 2001 cohort, but they do not translate to huge catch numbers because the abundance estimates for this region are very small (**Figure 9.5**).

The total age 1 abundance estimates are consistently higher when archival tag data are included (by roughly 0.2 million), but the breakdown amongst regions at age 1 is very similar (**Table 9.3**). However, if we use the mortality and movement parameters to calculate the regional abundance estimates over time (age), we see they are quite different for S. Africa and the SEIO when archival tag data are included (**Figure 9.5**). In particular, the model without archival tag data has substantial numbers of fish off S. Africa at ages 2-5, and relatively few fish in the SEIO.

9.3.3 Comparison with non-spatial results

We first consider the 1990s results. **Figure 9.6** compares the *F* estimates obtained for the 1990s using the non-spatial model with those obtained by averaging the region-specific *F* estimates from the spatial model, both when the movement parameters were estimated within the model using the conventional tag data and when the movement parameters were fixed at those determined from the archival tag data. For the 1990-1992 cohorts, the non-spatial estimates tend to be slightly larger than the spatially-derived estimates, but this is not the case for the 1993-1994 cohorts. Generally speaking, however, there is fairly good agreement between the *F* estimates. The age 1 *M* estimate obtained from the non-spatial model (0.462) is similar to the estimate obtained from both applications of the spatial model (see **Table 9.3**); however, the age 2+ estimate (0.395) is substantially higher. The total age 1 abundance estimates from the non-spatial model (2.8, 2.5, 1.8 1.4 and 1.3 million for cohorts 1990-1994 respectively) are lower than the estimates from the spatial models for cohorts 1990-1992 but higher for cohorts 1993-1994.

We now consider the 2000s results. **Figure 9.7** compares the *F* estimates obtained for the 2000s using the non-spatial model with those obtained by averaging the region-specific *F* estimates from the spatial model, both when archival tag data were and were not included. In this case, there is a consistent tendency for average *F* estimates derived from the spatial model that included archival tag data to be smaller than the non-spatial estimates (as well as smaller than the average *F* estimates derived from the spatial model without archival tag data). The differences for ages 3 and 4 of cohorts 2001-2003 ranged from 0.09 to 0.22. The age 1 *M* estimate obtained from the non-spatial model (0.482) is very similar to the estimates obtained from the spatial model with and without archival tag data (see **Table 9.4**); however, the age 2+ estimate (0.207) is somewhat higher than the estimate obtained from the spatial model with archival tag data. The total age 1 abundance estimates from the non-spatial model (0.99, 0.80, 0.66, 1.37 and 1.48 million for cohorts 2000-2004 respectively) are consistently smaller than those from the spatial model, both with and without archival tag data but particularly with.

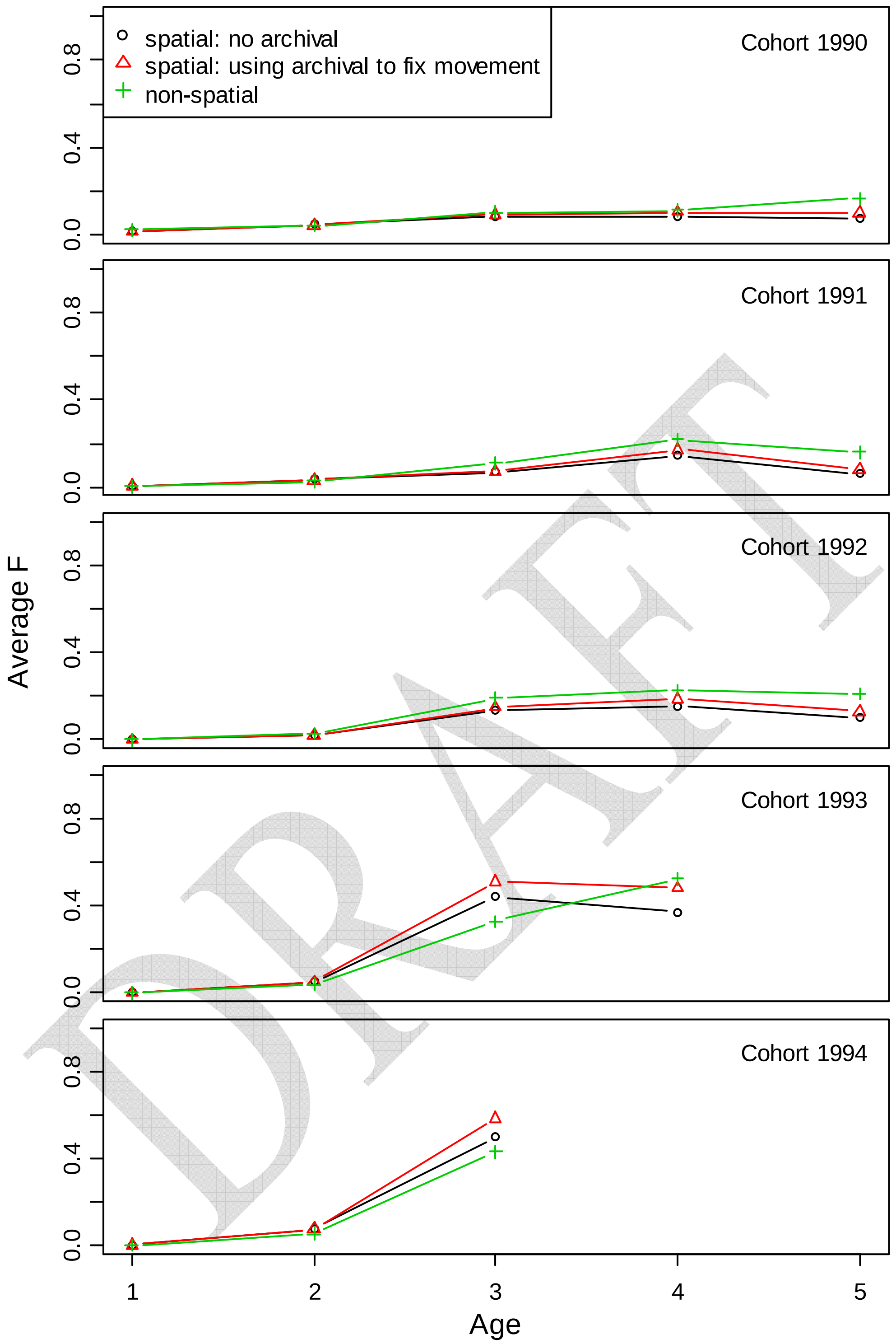

Figure 9.6. Comparison fishing mortality rate (F) estimates obtained for the 1990s using the non-spatial model with those obtained by averaging the region-specific F estimates from the spatial model when the movement parameters were estimated within the model (without archival tag data) and when the movement parameters were fixed at those determined from the archival tag data.

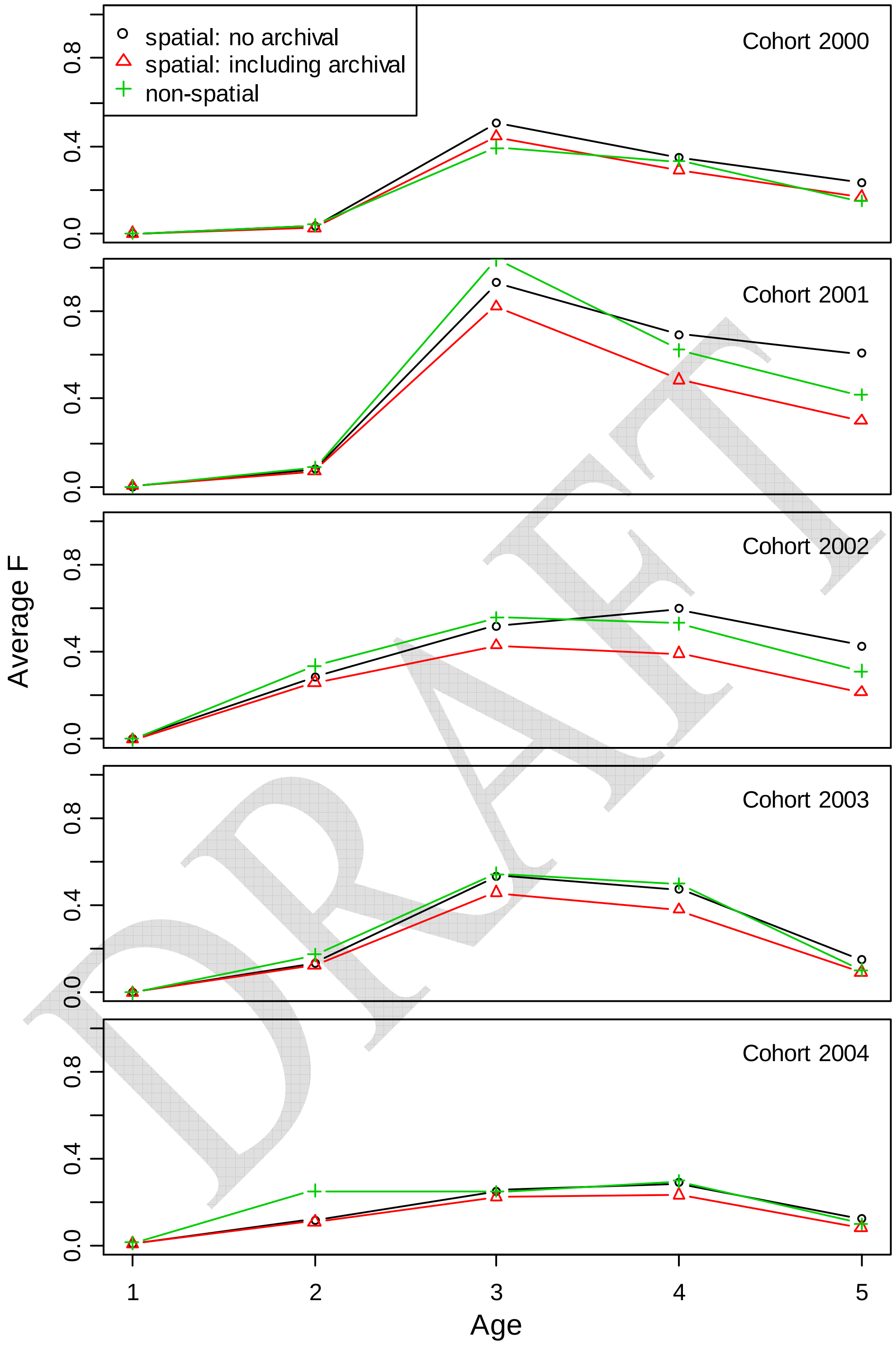

Figure 9.7. Comparison fishing mortality rate (F) estimates obtained for the 2000s using the non-spatial model with those obtained by averaging the region-specific F estimates from the spatial model when archival tag data were and were not included.

9.4 Discussion

In this study we demonstrated how archival tag data can be used, either indirectly through a two-stage approach or directly through an integrated likelihood, to inform a spatial model for estimating mortality rates, movement and abundance.

We applied the two-stage approach to SBT data from the 1990s (since the data were insufficient to apply the integrated approach), and found that the movement probabilities suggested by the archival tag data were significantly different than those estimated in the spatial model with only conventional tag and catch data as inputs. In particular, archival tag data suggest that essentially 100% of juvenile SBT return to SA at the end of winter, whereas the model estimates suggest the majority of fish remain in their winter longline region for the summer. When the movement parameters were fixed in the spatial model at those estimated from the archival tags, many of the other parameter estimates were significantly affected. For instance, the fishing mortality estimates for the SA region (where the Australian purse seine fishery operates) were significantly lower across most cohorts and ages. Based on previous information and inferences about juvenile SBT migration, we expect the majority of juveniles to return to SA but that the proportion is likely to differ with age (since fish stop showing up, at least in the catches, beyond age 5). Unfortunately, we have very few archival tag tracks for fish at ages 4 and 5 in the 1990s so our oversimplified model did not allow for movement to differ with age.

The archival tag data and conventional tag data for SBT cohorts in the 2000s overlapped considerably, so we were able to apply the integrated spatial model to these data. Including archival tag data in the model had a significant affect on many of the parameter estimates. For instance, the F estimates tended to be smaller in all regions except S. Africa. Also, when archival tag data were included, the resulting estimates of abundance by age and region showed many more fish in the SEIO and SA regions, and less fish off S. Africa.

Population-wide estimates derived from the spatial model results for the 1990s and 2000s gave similar overall trends in fishing mortality and abundance compared to estimates derived directly from a non-spatial model; however, there were some notable differences in the magnitude of the estimates. This was particularly true for the fishing mortality estimates for the 2000s: the average estimates calculated from the spatial model results that included archival tag data were consistently smaller (by as much as 0.22) than the estimates obtained from the non-spatial model.

Although we have illustrated the benefits from incorporating archival tag data into the spatial model, we need to keep in mind that the parameter estimates obtained are intended to be illustrative of the potential usefulness of archival tag data. The actual parameter values presented are subject to biases due to a number of issues with the data, including: lack of information on reporting rates (particularly for the 2000s, but also for the 1990s); biased catch data due to under-reported catches (affecting both the 1990s and 2000s data), and the inexplicable lack of returns of age 1 fish tagged off WA in the 2000s (which we dealt with simply by omitting WA releases for the 2000s).

In our application of the two-stage approach to SBT data from the 1990s, we treated the movement parameters that we estimated from the archival tag data as known when we input them to the spatial model. In a more rigorous application, the movement estimates could be treated as priors in the model (assuming, for example, that they are normally distributed with means and variances estimated from the archival tag data). This would allow for them to be updated with information about movement from the conventional tag data, and also for their uncertainty to be propagated through to the other parameter estimates. The integrated approach, which we applied to SBT data from the 2000s, is the preferable approach when sufficient overlapping archival and conventional tag data exist. In this case, all sources of data (archival tag, conventional tag and catch) contribute to the estimation of all parameters (both the point estimates and their uncertainty).

The SBT spatial model as presented here assumes that all fish migrate out of SA at the end of summer. This appears to be roughly true for the GAB, but not for WA (recall that SA encompasses the GAB as well as waters south of WA). The accumulation of more archival tag tracks has shown that, in fact, quite a few fish spend winter in waters off WA. We altered the spatial model to have an alternative movement structure that allows for fish to over-winter in SA but still assumes no fishing takes place in SA during the winter. We applied this alternative model to the data from the 2000s (including archival tag data). A significant percent of fish (27%) were estimated to remain in SA for the winter, but the fishing mortality estimates were largely unaffected. Further investigation of this model was not considered warranted (especially since the age 2+ natural mortality rate estimate went to zero, which is not very plausible). A better alternative may be to split SA into two regions, WA and GAB, where the movement dynamics for WA would be similar to the longline regions (i.e., fish could migrate from the GAB to WA at the end of summer, and fish could either remain in WA or return to the GAB at the end of winter) but fish remaining in WA in the winter would not be subject to fishing.

In terms of the season definitions in the model, the archival tag data suggest they are reasonable, but perhaps oversimplified. The general notion that juvenile SBT migrate to SA for the summer and out of SA for the winter is clearly supported, but the exact timing of these migrations is more variable than might have been expected. Furthermore, the assumption that fish move directly between regions is obviously unrealistic, particularly in the case of a fish migrating between SA and S. Africa, as it must move through the SEIO in getting there. If fish migrate rapidly from SA to their winter region then this assumption is not seriously violated, but the archival tag tracks show that many fish took more than a month to migrate to their ultimate winter region and did not always take a direct route (e.g., some fish headed eastward out of the GAB before turning west towards to the SEIO). There is also the issue of site-fidelity (i.e., fish returning to the same longline region each winter), which would be a violation of the Markov movement model assumption. Site-fidelity is difficult to assess since not many of the archival tags have tracks spanning two winters, however the few tracks that are available show that not all fish return to the same winter region. There may be a tendency towards site-fidelity but, if so, it is not absolute. These are all potential areas for further investigation in future.

10 Modelling juvenile SBT migration behaviour

Key findings

We fitted Hidden Markov Models (HMMs) to the tracks of 60 juvenile SBT, allowing us to distinguish between migrating (directed, fast movement) and resident (undirected, slow movement) states of behaviour.

- There is a clear pattern of cyclic migration of individuals between the Great Australian Bight in summer and the Indian Ocean or Tasman Sea in winter. Most migration out of the GAB occurs in June to August, but it starts in May and continues as late as September. Most migration back to the GAB occurs in November and December, but arrivals begin in October and continue as late as January.
- A wide latitudinal band of the Indian Ocean is used in winter, and there is currently no evidence of specific migration ‘routes’.
- In all months, juveniles are more likely to be in the ‘resident’ state than the ‘migrating’ state, but the highest level of residency is in the GAB in summer (January to May).
- There are regions in the Indian Ocean where more SBT occur in a resident state, but individual SBT do not use the same area each year.
- Current evidence suggests it is unlikely that there is a large proportion of juvenile SBT resident off South Africa.

10.1 Introduction

The work in this section and the next (**Section 11**) relates to revised objectives 5 and 6 of the project:

Revised objective 5:

> Integrate the position, temperature and depth data provided by the tags with oceanographic data to develop a seasonal model of residence times and habitat use for regions with consistent temporal patterns across the years.

Revised objective 6:

> Evaluate the implication from the seasonal habitat model for the interpretation of future catch and effort data and monitoring strategies.

The original objectives[15] included using the seasonal habitat model as a basis for CPUE standardisation, and reflected some of the concerns (at the time the project was proposed) surrounding the interpretation of CPUE data and their use in an index of overall SBT abundance. Concerns included: reduced spatial and temporal coverage compared to the 1970s and 1980s (**Figure 10.1**), the use of aggregated rather than fine-scale data in standardisation, and the absence of environmental covariates in the standardisation. The question was, and remains: does CPUE provide a reliable and representative index of total SBT abundance?

Following the revelations about unreported catches in 2005 (Anon. 2006), the original objectives were revised. Since the “unreported catches” event, there have also been operational changes in the longline fleets, particularly the Japanese longline fleet which forms the basis of the CPUE series used in the CCSBT operating model and management procedures. A decrease in the Japanese quota led to changes in the fleet structure as well as fleet operations, as documented in Itoh (2010). The main observed change has been an extended fishing season, but there has also been a sharp decrease in effort in areas around New Zealand (CCSBT areas 5 and 6, **Figure 10.1a**), in part due to the decrease in quota for Japan (Anon. 2010). There are other factors that may affect CPUE, but that would be harder to detect or correct for. For example, Itoh (2010) notes that the decrease in the number of vessels operating in an area simultaneously may reduce the ability to find good fishing areas because there are fewer vessels exchanging information amongst themselves. Itoh (2010) also comments that the drastic increase in the fuel price in recent years would have weakened the power of search for good fishing areas.

A large amount of work has been done over the past several years in the CCSBT’s CPUE Working Group to explore the standardisation issues further (see e.g. Anon. 2010 and references therein). However, the operational changes and lack of spatial coverage mentioned above present difficulties that are close to impossible to resolve with statistics and modelling of catch and effort data alone. There is also no guarantee

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[15] The original wording of the objectives can be found in **Section 5**.

that there will not be any such changes again in future, so these issues are likely to remain as concerns for the interpretation of CPUE.

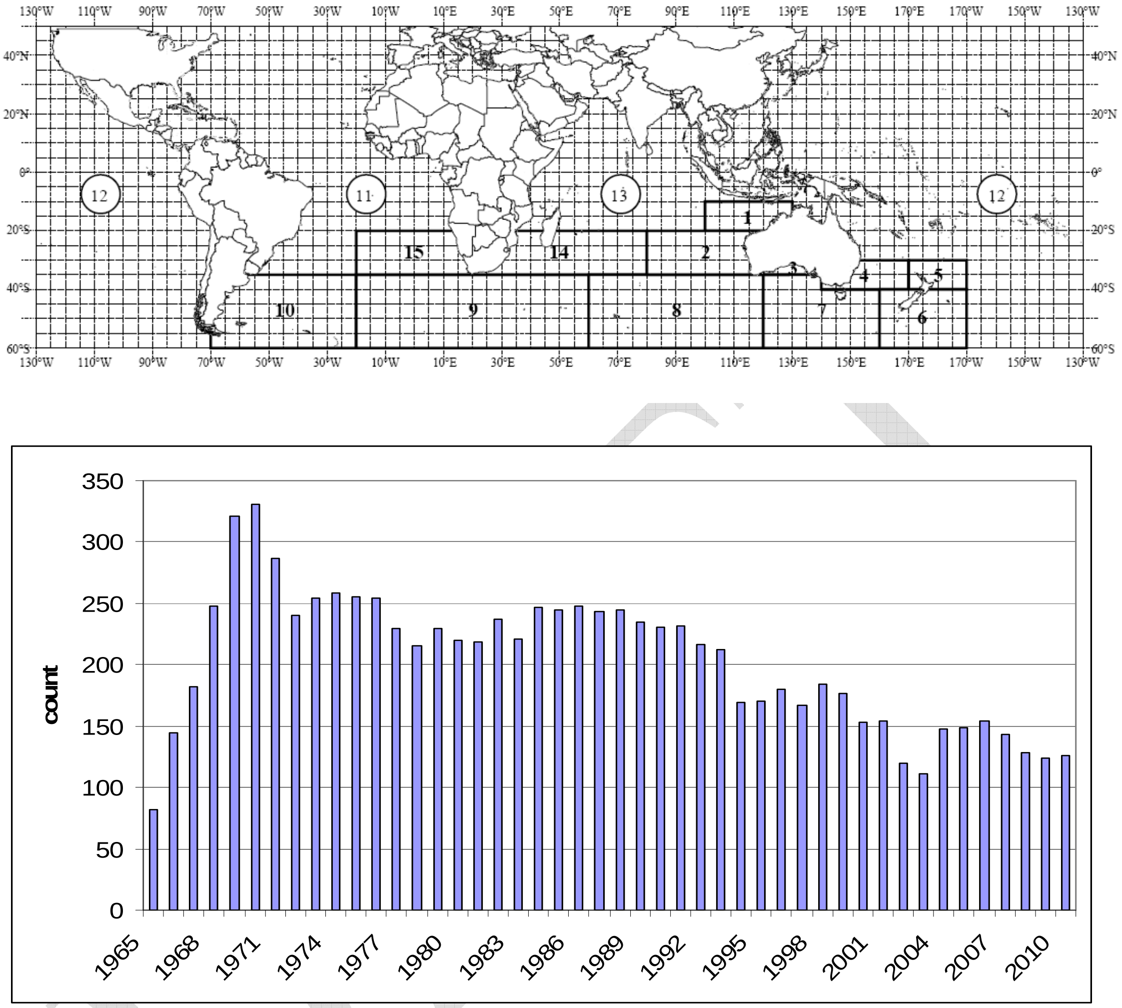

Figure 10.1. a) Map with the 15 CCSBT statistical areas and b) Number of 5° x 5° x month grid cells fished in months 4-9 (April to September) in CCSBT areas 4-9.

In light of this, the analyses in this section aim to understand the migration dynamics of juvenile SBT and, in **Section 11**, some of the observed changes in movement dynamics in relation to possible changes in environmental conditions, rather than focusing narrowly on the interpretation of CPUE. Implications of the results for interpreting future catch and effort data (Objective 6) are discussed in **Section 12**.

The results of **Section 7** showed that while there was an obvious large scale oceanic migration, there was considerable variability in individual movements. Qualitatively it appears that many animals move in at least two “modes” of movement; fast, directed motion (“migrating”) punctuated by periods of slow movements with no clear direction (“resident”). This phenomena has been widely observed in animal movement (Nathan *et al.* 2008) and forms a central tenet of many recent analysis techniques (e.g. Patterson *et al.* 2008, 2009; Pedersen *et al.* 2011). Two previous studies have considered juvenile SBT movements using this conceptual model with smaller data sets (Patterson *et al.* 2009; Bestley *et al.* 2010). In order to develop a model of SBT migration and residency, and to understand the variability in SBT migrations, it is necessary to quantify these patterns in terms of the likelihood of SBT being in a migratory or resident state, how long they occupy either mode, and where they occur in space and time. Thus the main challenge in this section is to develop a method for modelling SBT migration (directed fast movement, i.e. large distances) and residency (undirected slow movement, i.e. small distances). A modelling approach is used because it provides a consistent framework for interpreting the data and ‘classifying’ behaviour as migratory or resident. In the process of developing a model of residency – and migration – times, we try to find answers to questions such as:

How far do juvenile SBT move in a day when they are migrating?

How far do they move on average whey they are resident?

Where are juveniles in the resident state?

Are there specific ‘migration’ paths?

When are most juveniles migrating out of the GAB and back into the GAB?

How long are ‘resident’ periods in the GAB in summer?

How long do they stay in a ‘migratory’ state, and is it the same for leaving and returning to the GAB?

These questions are relevant to the interpretation of catches and CPUE from at least two points of view: availability and catchability. First, the spatial distribution of juvenile SBT in any given month will determine the extent to which SBT are available to the longline fisheries in a particular area in that month. Individual and inter-annual variability in the distribution will imply variability in CPUE in the same area between years, even if population abundance remained constant. Understanding the spatial dynamics of juvenile SBT, and its variability, can therefore inform the interpretation of their catches and catch rates. Second, the ‘behaviour’ of juvenile SBT can affect whether they are more or less likely to be caught on a longline hook, thus affecting catchability (see **Section 12**, Box 2: CPUE). Although we do not explicitly tackle the question of whether, and to what extent, juvenile SBT are feeding in different areas, at different times, while migratory or resident, the modelling in this section and in **Section 11** (Habitat preference) are building blocks towards such an understanding.

10.2 Methods: Hidden Markov Models

We noted in **Section 7** (Geolocation) that, in theory, the whole sequence of modelling – track estimation, movement/behaviour and preference in relation to environmental covariates – should ideally take place in a single, enormous model. This would allow for the correct propagation of errors through all stages, and would give quantitative estimates of the uncertainty in conclusions. However, such an approach is technically extremely complicated and, most importantly, makes it much harder to run exploratory analyses and check diagnostics. In this report our aim has been to establish what the patterns of movement/behaviour and relationships with environmental covariates are, and to see whether our conclusions are ‘qualitatively’ sound, rather than quantifying the uncertainty in conclusions. We have therefore approached the problem in three separate stages. **Section 7** dealt with track estimation. This section deals with movement, or migration modelling. In **Section 11** (Habitat Preference), we address the third step in the process and investigate whether movement behaviour is related to environmental covariates.

The basic aim of ‘migration modelling’ in this project was to estimate when individuals were migrating (directed fast movement, i.e. large distances) and when individuals were resident (undirected slow movement, i.e. small distances). It is obvious from plots of longitude over time (see e.g. **Figure 10.10** below) that there are times when longitude hardly changes at all (e.g. SBT in the GAB), and times when longitudes change rapidly (e.g. SBT migrating west into the Indian Ocean, or east back to the GAB). In particular, the longitudinal distance (in degrees) moved in each 24-hour period should reflect whether an individual is “migrating” (directed fast movement) or “resident” (undirected slow movement). It is important to note that our intention here was NOT to estimate whether an individual was “feeding” or “not feeding”, and the states of “migration” and “residency” should not be confused with, or assumed to imply, a feeding or non-feeding state (see Gunn *et al.* 2001 and Bestley *et al.* 2008 for detailed studies of feeding physiology and ecology).

A modelling framework which is particularly well-suited to this problem is that of Hidden Markov Models (HMMs). We have already discussed HMMs in the context of geolocation (**Section 7.1.2**); here we use the same statistical framework and associated methodology in a somewhat different way. HMMs are state-space models which assume that the observed distribution of the observations (e.g. the longitudinal distance moved) is conditional on a finite number of unobservable or hidden discrete states (Zucchini and MacDonald 2009). This provides a clear link between the concept that tuna move differently given underlying behavioural shifts and the analysis method. Importantly the Markovian aspect of the model directly addresses the temporal-dependence in the data from electronic tags and the fact that sequential observations from a given tag are not independent, but correlated. The HMM allows for transitions from one state to another at each time-step. Results from a model fitted to data include estimates of the probability of being in each of the states at each time-step, as well as the parameters of the distribution of observations associated with each state (here these are the mean and variance of the longitudinal distances moved). The modelling framework provides a statistical, and hence consistent, approach to the analysis, allows for checks of model fits by looking at residuals, and allows for model comparison by looking at quantities such as Akaike's Information Criterion (AIC) (Zucchini and MacDonald, 2009).

There are many ways in which a migration-residency model can be formulated, and several options for quantities to use as observations, or 'input data', to the HMMs. We chose to use the longitudinal distance (in degrees) moved in each 24-hour period as the observations. There are two reasons for this. First, the estimated tracks, and plots of longitude over time, show that juvenile SBT undertake primarily east-west migrations within a relatively well-defined latitudinal range. Longitudinal distance should therefore contain sufficient signal and contrast for successful fitting of an HMM with "resident" and "migratory" states. Second, the uncertainty in latitude, and likely bias around the equinoxes (including many unrealistic estimates on land, for example; see **Section 7**), mean that it would be preferable to avoid using latitude estimates in this phase of modelling. Also, avoidance of estimated latitudes resulted in a larger usable dataset. We also avoided converting from degrees to, say, kilometres as the distance in kilometres (or nautical miles) depends on latitude.

In order to fully specify an HMM the following choices need to be made:

- the number of states;
- the probability distribution of observations associated with each hidden state;
- the form and characteristics of the transition matrix;
- which parameters to estimate, which parameters to assume known;
- whether to fit separate models for each individual or a single model for all individuals.

The verbal description so far hints at two states: a resident and a migratory state. During exploratory analyses we treated easterly and westerly migrations as being similar, by using the absolute values of the distances moved. For SBT with tracks that included migration in both directions (e.g., fish tagged in the GAB that made a return migration), these models did not fit particularly well; there was sufficient difference between distances moved in each direction that one migratory state was insufficient. Instead, a model with one resident and two migratory states was used for these fish. A two-state model was used for those SBT whose tracks included a migration in one direction only. Tags that had short deployment periods (e.g. <6 months; all deployed in the GAB or off WA) often did not show any movement out of the GAB; these would have failed in even a two-state model and were therefore excluded from analyses. Thus, the final sample size was less than the 122 tags with some data available (**Section 6).**

Formally, in this particular application of the HMM, the state-space model assumes that our system (i.e. a tuna, and the data returned by the tag) is described by two submodels: a process model *f*(.) governing the assumed “state” of the fish – migratory or resident – and an observation model *g*(.) which gives the likelihood of each state given the distance moved (in degrees longitude, i.e. the observation). As we saw in **Section 7.1.2**, these are typically written as:

$$\mathbf{x}_t = f(\mathbf{x}_{t-1}, \Theta) \qquad (10.1)$$

$$\mathbf{z}_t = g(\mathbf{x}_t, \psi) \qquad (10.2)$$

where Θ and ψ are parameters; $\mathbf{x}_t$ is a vector of the probability of being in each state at each time step, and z_t is a vector of the likelihoods of each state given the observations (distance moved) at each time step. Due to the dominant east-west signal in the movements, for eq. 10.1 we used both two- and three-state models depending on the data (as discussed above). For the three-state models, the states were labelled “migration east”, “migration west” and “resident”. We assume that the probabilities of switching from one state to another are independent of covariates[16] and constant over time, so that

$$x_t = Px_{t-1}$$

where the transition matrix P is defined as

$$P = \begin{bmatrix} \pi_{1,1} & \pi_{1,2} & \pi_{1,3} \\ \pi_{2,1} & \pi_{2,2} & 0 \\ \pi_{3,1} & 0 & \pi_{3,3} \end{bmatrix} \qquad (10.3)$$

The first row and column relates to the resident state; the second row and column to migration east and the third row and column to migration west. The transition matrix implies that individuals can go from the resident state to either of the migratory states, or remain resident. When in a migratory state, individuals can only remain in that state or transition to resident. Transition between the two migratory states can only be via the resident state, but note this can be for a single-time-step. The values in each row must sum to one, so we can write, e.g. $\pi_{1,3} = 1 - \pi_{1,1} - \pi_{1,2}$ etc. which means only 4 parameters in the transition matrix need to be estimated.

For individuals that only made a migration in one direction, a two-state model with a resident state and only one migration state was fitted to the data (distance in longitude moved per day). In this case the transitions matrix was a two-by-two matrix identical to the top left corner of the 3x3 matrix in equation 10.3.

For the observation model (eq. 10.2), the likelihood function g() is given by a normal distribution ($N(\mu,\sigma^2)$) with state-specific mean and variance, for example for state i and distance moved d_t:

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[16] It is possible to make transition a function of covariates, for example sea surface temperature. We used such model in exploratory analyses, but they did not perform consistently well compared to this simpler model.

$$g_i(\mu_i,\sigma_i,d_t)=\frac{1}{\sqrt{2\pi\sigma_i}}\exp\left(\frac{-(d_t-\mu_i)^2}{2\sigma_i^{\ 2}}\right) \qquad (10.4)$$

These two components – the observation and process models – are combined in an HMM, and this allows for the unknown parameters, and the state probabilities at each time step to be estimated.

A large number of different model formulations, including individual and joint models (i.e. where some parameters are shared by all individuals) were investigated. The set of models that performed best overall, in terms of reasonable residuals and low AIC values (compared to more complicated models), was the set with the following characteristics for the three state version:

- Three states: one resident, two migratory
- Resident state: distance moved in degrees longitude ~ $N(0, \sigma_1^2)$
- Migration east: distance moved in degrees longitude ~ $N(\mu_2, \sigma_2^2)$ $(\mu_2 > 0)$
- Migration west: distance moved in degrees longitude ~ $N(\mu_3, \sigma_3^2)$ $(\mu_3 < 0)$
- Transition probabilities independent of covariates and constant over time (as given in eqn 10.3)

The two state version is very similar, but has only one migratory state, and a 2x2 transition matrix as mentioned. Model fitting and analyses of diagnostics followed the approaches in Zucchini and MacDonald (2009), and build on the work in Patterson *et al.* (2009). Models were fitted to data using a maximum likelihood approach programmed in R (http://www.r-project.org/), and residuals were generated using the approach of Zucchini and MacDonald(2009). The optimisation procedure expects starting values for all the parameters that are being estimated. It is common for models of this kind to have complicated likelihood surfaces and to require some exploration with different starting values to find the global maximum (or at least a satisfactory fit with sensible/realistic parameter estimates). This was done on a subset of tags using simulated annealing (Belisle, 1992); average parameter estimates from these runs were subsequently used as starting values. Any remaining poor fits were again rerun with alternative starting values. In some cases no reasonable fits could be found (in finite time) and those tags were then excluded.

10.3 Results of Hidden Markov Models

Results from the Hidden Markov Models (HMMs) provide insights into many aspects of juvenile SBT movement dynamics. We now return to the set of questions raised in the Introduction and examine each in light of the HMM results.

10.3.1 Parameter estimates

How far do juvenile SBT move in a day when they're migrating?

How far do they move on average when they're resident?

The total sample size was 60 tags. The reduced number of tags compared to the number reported in **Section 6** is because we only chose those that were deployed for more than 6 months, and left the GAB at some stage. Three-state HMMs were fitted to 48 individuals and two-state HMMs to 12 individuals. **Figure 10.2** shows results for two tags and also illustrates how the model works. In each row, the left panels shows the SBT track with the colour of the point identifying the state with the highest probability: black indicates the resident state, green is migrating West (out of the GAB), and blue is migrating East (back to the GAB). The right panel shows the density distributions for each state, in other words, the probabilities of the distance moved (in degrees longitude) associated with each state. For example, for tag 761, when it is moving west (green) the mean distance moved is about -1.5° longitude (the negative sign indicating movement west).

For tag 761 which was released in the GAB in summer, we can see that after it left the GAB, migrating East, it was resident in several places off WA and again at about 108°E, after which it continued migrating East as far as about 90°E where it spent some time in the resident state; by definition, the model interprets that part of the track as resident because the distance move in longitude is close to zero, even though the estimated latitudinal movement is not. We can also see from the track that the return to the GAB (blue part of the track) has fewer 'stops' in the resident state along the way.

A similar story can be constructed for tag 972, though its track is a little more complicated. Note how the model switches from migrating east to migrating west in the track that loops southward off southern Australia and off WA.

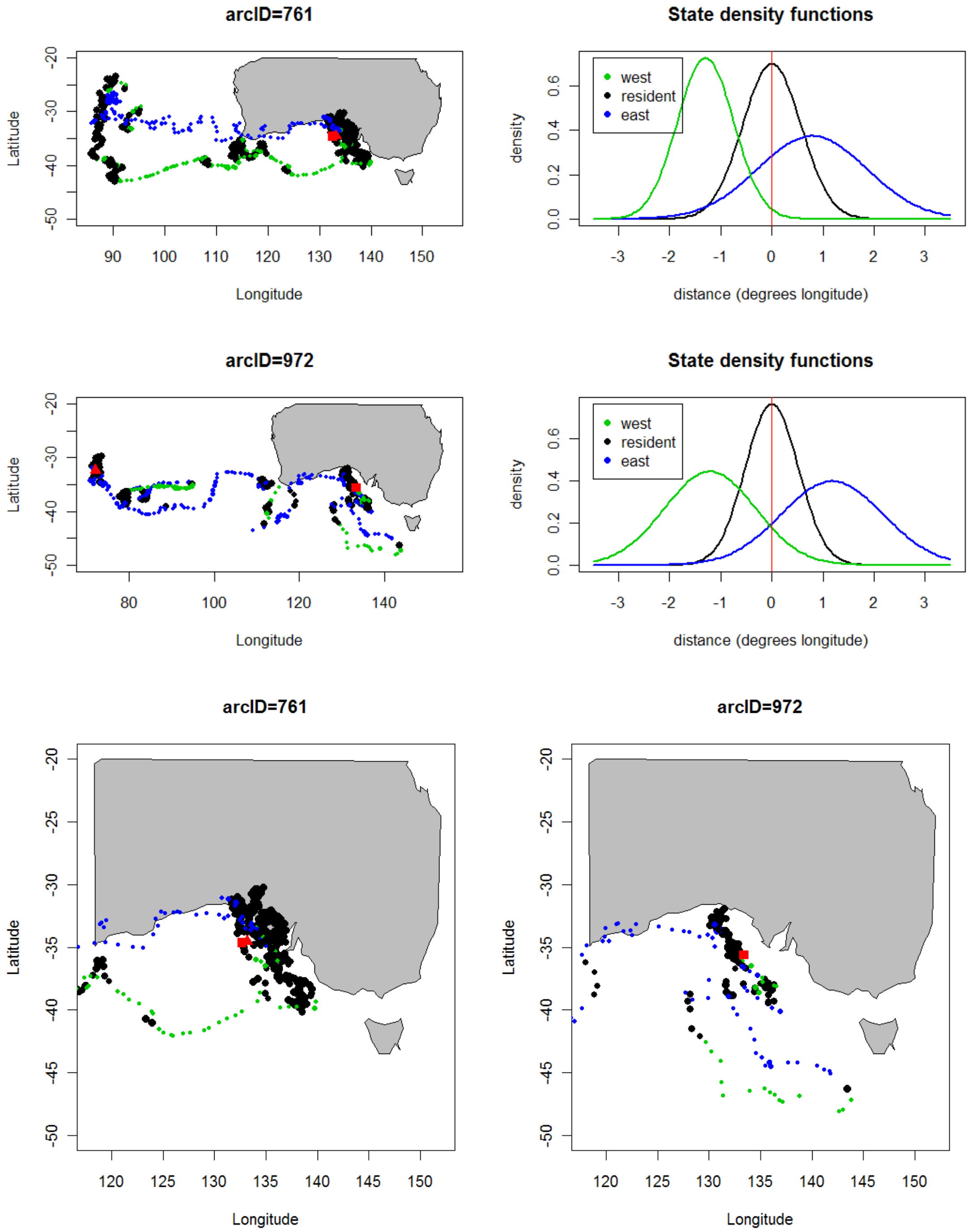


Figure 10.2. Results of HMMs for tag 761 (top row) and 972 (middle row). In top and middle rows, the left panels show the SBT track with the colour of the point identifying the state with the highest probability: black=resident, green=migrating West, blue=migrating East. The right panels show the probability distributions for each state, similarly colour-coded. The bottom row shows detail of the tracks and estimated state just for the GAB. The red triangles show the release location and the red squares the recapture location (tag 761 was recaptured very close to where it was released).

The final two panels show details of the track just for the area in the GAB. Tag 761 shows that the model sometimes switches to the migrating state while in the GAB, and when it is not necessarily the start of the main migration - this can be seen in some of the blue and green dots within the large cluster of black dots. The extent to which this occurs relates to how much overlap there is between the three density distributions for the three states.

A simple diagnostic for checking model fit is to look at the overlap of the density distributions. Ideally these should have reasonably well separated peaks. If they overlap fully, then it is likely that there are too many states in the model, or our choice of distribution may be inappropriate. The two examples above are of good model fit from this point of view.

The convergence and pseudo-residuals of models, as defined in Zucchini and MacDonald (2009), were also checked to ensure acceptable fit. **Figure 10.3** shows a set of diagnostic plots for one tag. The plots indicate acceptable model fit because the uniform pseudo-residuals are close to uniformly distributed and similarly, the normal pseudo-residuals are close to normally distributed. The qq-plot of the normal pseudo-residuals is also very close to linear as expected.

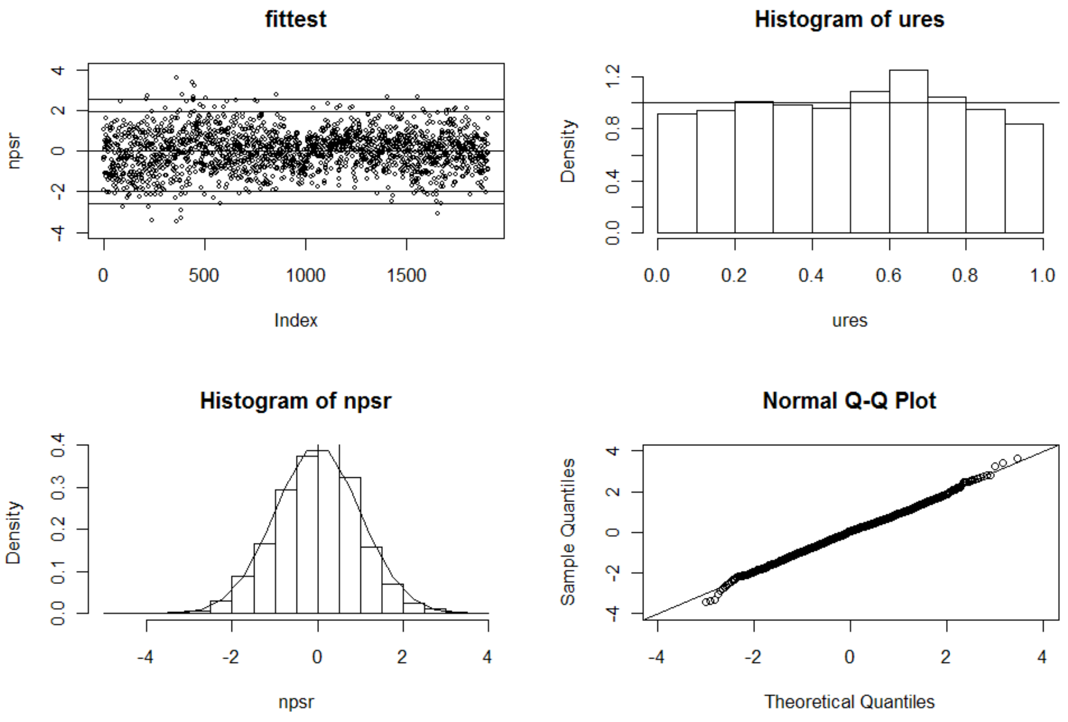


Figure 10.3. An example of residuals that indicate good model behaviour. (i) Normal residuals with lines at the 1, 5, 95 and 99 percentiles; (ii) histogram of uniform pseudo-residuals; (iii) histogram of normal pseudo-residuals and (iv) qq-plot of the normal pseudo-residuals.

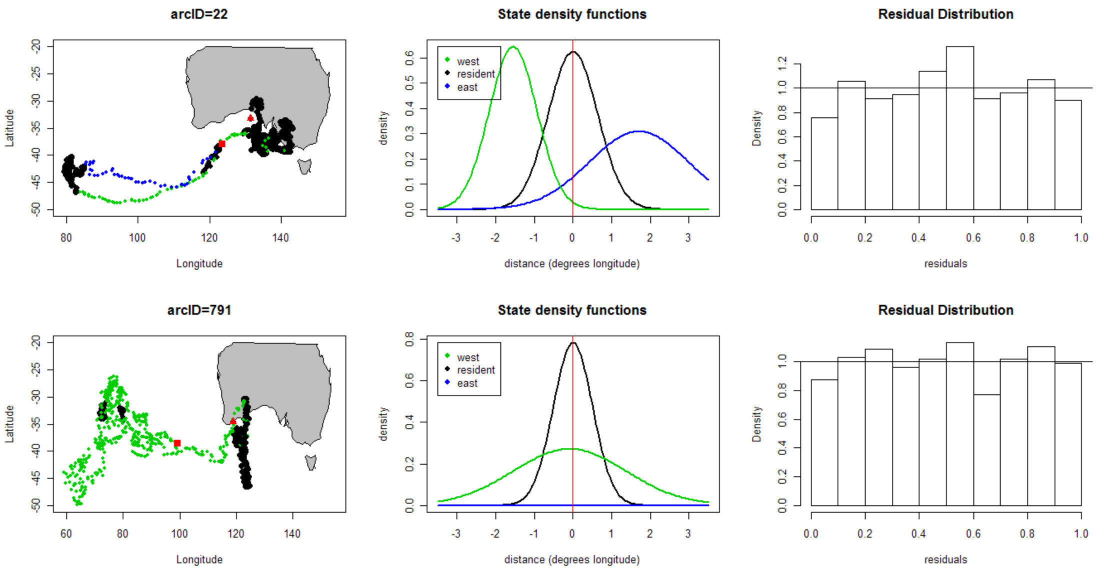


Figure 10.4. a,b. Example of results for (a, top row) tag 22, showing a good fit and (b, bottom row) tag 791, showing a poor fit. Left panels in each row show the SBT track with the colour of the point identifying the state with the highest probability: black=resident, green=migrating West, blue=migrating East (red triangle and square mark release and recapture locations respectively). The middle panels show the probability distributions for each state, similarly colour-coded. The final panel shows a histogram of the uniform pseudo-residuals. See text for discussion of fits.

Two more examples are shown in **Figure 10.4.** The top row (tag 22) is an example of a good fit of the model to the data. The track looks sensible, showing high probabilities of being in resident state (in black) when there is little movement in the longitudinal direction, and high probabilities of being in the migratory states (green going West; blue going East) when there are larger longitudinal movements. By implication, a low probability of being in the resident state implies a high probability of being in either of the two migrating states. The estimated distributions of distances moved for each of the 3 states have means that are well separated, and the histogram of uniform pseudo-residuals is close to uniform.

In contrast, the bottom row (tag 791) shows an example of a poor fit of a three-state HMM. Some sections of the track seem sensible (e.g. resident state (black) while south of WA, and the start of the westerly movement (green) out of the GAB), but other sections in the Indian Ocean show up as “migratory” when it seems to be hardly moving longitudinally. The reason becomes clear when we note that the distributions (central panel) overlap entirely. The distribution for ‘migrating east’ has such a large variance that it shows up as a horizontal line in the middle panel. This suggests there is insufficient contrast in the data for the model to separate the resident and migratory states. This was true for a two-state model as well, so tag 791was excluded from subsequent analyses. It is interesting that the uniform pseudo-residuals are quite close to a uniform distribution; this highlights the importance of not just relying on the residuals to identify poor model fit.

Comparing the estimated HMM parameters between individuals allows for an assessment of the uniformity in movement behaviour. Two sets of parameters are estimated for each individual (i.e. each HMM):

- the state distribution parameters, i.e. means and variances the distance moved (in degrees longitude) for each of the three states
- the transition probabilities between states

Summaries of the estimated mean distances moved per day for the two migratory states (**Table 10.1**) show reasonable consistency, but still quite a large level of variability between individuals. The medians for easterly and westerly migration are similar, but easterly migration has a larger average and 75th percentile. This is consistent with the visual impression from many tracks that migration back to the GAB is faster than migration west into the Indian Ocean.

Although we could summarise the variance estimates of the movement distributions in a similar way, it is more meaningful to present them in terms of the mean + 2 standard deviations (SD), i.e. the 95th percentile of the normal distribution. This can be interpreted as an upper “extreme” of the distance moved per day (**Table 10.2**).

Table 10.1. Summary of the 60 estimated mean distances moved per day (in degrees longitude) for the two migratory states. In the lower half of the table the statistics are given in terms of km by multiplying degrees longitude by 50nm x 1.85 km/nm (noting that the median latitude in the dataset is 37^{o}S, and 50% of estimated latitudes are between 33 and 41^{o}S, implying 1^{o} of longitude being between 45 and 50nm).

State	25%-ile	Median	Mean	75%-ile
East (^{o}lon/day)	0.88	1.14	1.17	1.52
West (^{o}lon/day)	0.87	1.10	1.03	1.21
East (km/day)	81.6	105.1	108.6	140.7
West (km/day)	80.3	101.4	95.3	111.5

Table 10.2. Summaries of mean + 2 standard deviations of distance moved (in km/day) for the 60 individuals by state. These quantities should be interpreted as upper values of daily movement distances estimated by the models.

State	25%-ile	Median	Mean	75%-ile
East (km/day)	180.7	244.6	250.0	314.3
West (km/day)	176.3	204.6	205.1	224.5
Resident (km/day)	57.6	73.2	74.2	82.4

Comparing the results in **Table 10.2** to estimates derived from empirical studies of SBT physiology is informative and allows the model predictions to be compared against independent data. Fitzgibbon *et al.* (2007) estimated swim speeds of captive SBT before and after feeding based on energetics experiments. Using both pre- and post-feeding estimates provides a range of 0.71 to 2.6 body lengths per second. The juveniles in our dataset are between 2 and 5 years old, i.e. an approximate range of 80 to 120 cm in length. This leads to estimates of daily distances (km) moved based on results in Fitzgibbon *et al.* (2007) of:

- 80cm individual (~2 yrs old): 48 and 180 km/day
- 100cm individual (~3 yrs old): 60 and 225 km/day
- 120cm individual (~5 yrs old): 73 and 269 km/day

The lower estimates from these calculations fit in well with the summary of mean + 2 SDs for the resident state (**Table 10.2**). The summaries of mean + 2 SDs for the migration states (**Table 10.2**) are similar to the upper estimates from the calculations based on Fitzgibbon *et al.* (2007).

There was no evidence of a relationship between movement rate and age in the estimates from the HMM models. For each age class (n=3 for age 1, n=26 for age 2, n=25 for age 3, n=6 for age 4), the range of mean distance moved is similar to that for all ages combined. The same is true for estimates of standard deviation.

Estimates of transition probabilities are not easy to interpret, but it is again informative to consider the variability between individuals and the average levels (over all individuals) of transition probabilities between the states. **Table 10.3** shows there is a much higher probability of remaining in a given state than of switching. This is consistent with what we see in longitudinal plots – there are periods of weeks or months when the longitude stays at roughly the same value and then periods when longitude changes quite rapidly as the animal moves east or west. There is remarkable consistency between individuals, as evident in the relatively narrow inter-quartile range.

Table 10.3. Summaries of transition probabilities estimated for the 48 three-state models. The first set are for transitions between different states, the second set are probabilities of remaining in the same state. 'East' and 'West' refer to the two migrating states.

State (from, to)	25%-ile	Median	Mean	75%-ile
Resident to East	0.018	0.032	0.037	0.050
Resident to West	0.027	0.038	0.045	0.056
East to Resident	0.079	0.110	0.137	0.178
West to Resident	0.111	0.136	0.159	0.189
Stay in Resident	0.89	0.93	0.92	0.95
Stay in East	0.82	0.89	0.86	0.92
Stay in West	0.81	0.86	0.84	0.89

Estimates of daily movement rates:

Based on the analysis above we can provide the following answers to the questions originally posed.

How far do juvenile SBT move in a day when they're migrating?

> On average, juvenile SBT move about 100 km per day (based on 1^{o} longitude, which is about 100 km at 37^{o}S) but potentially up to 200 km per day when migrating.

How far do they move on average when they're resident?

> When they're resident they move relatively little longitudinally, but they may move up to about 70km per day.

10.3.2. Summaries of most probable behaviour state

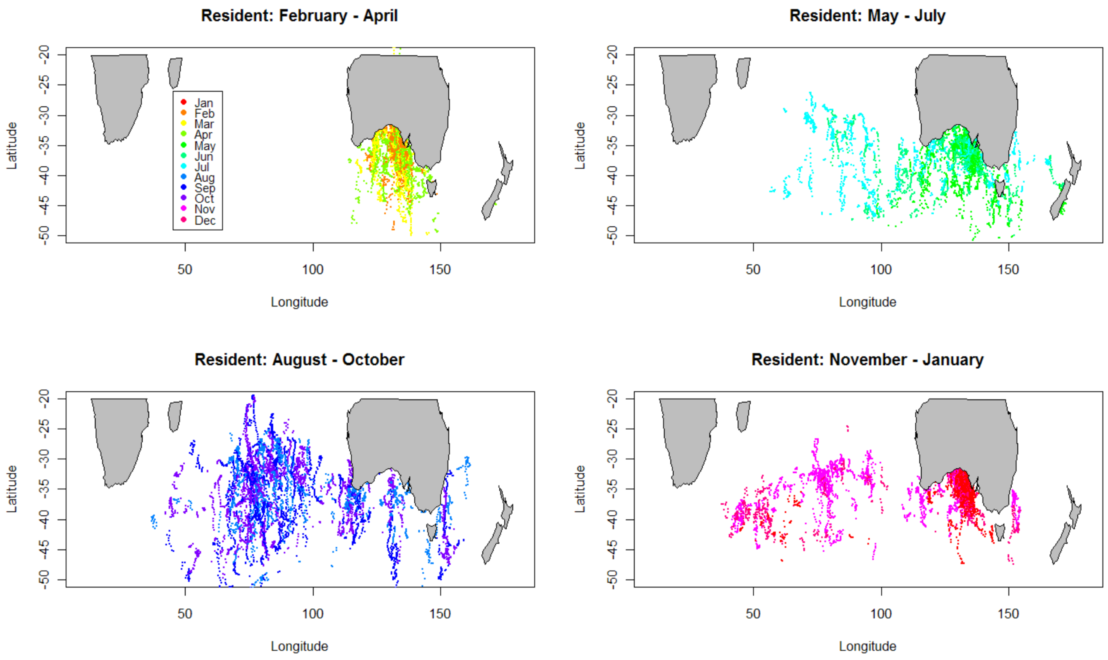
Where are juveniles in the resident state?

Are there specific "migration" paths?

When are most juveniles migrating out of the GAB and back into the GAB?

The output from the HMMs provides a sequence of “most probable states” (MPS) based on the state with maximum probability at each time-step. This essentially classifies each location along a track as relating to the resident, migrating east, or migrating west state. One great advantage of obtaining this via HMMs is that it is done within a consistent statistical framework. Maps of locations showing when and where juveniles are in each of the states (i.e. where MPS=resident, etc.) can easily be constructed. The MPS can also be summarised by counting, for each day in the year, how many observations, or what proportion, there were in each of the 3 states. This shows when the main migrations occur.

Figure 10.5 shows locations where the MPS is resident. Data for all years are shown grouped together by sets of 3 months. The first panel is for February to April because these are the 3 months when all the resident locations (for tags in the migration modelling subset) are resident off southern Australia; there are some locations in the Indian Ocean and Tasman Sea where the MPS is migrating (east or west), but none that are resident. Between May and July many individuals are still resident off southern Australia, but some individuals have moved and are resident in the eastern Indian Ocean. By July, some are resident in the central Indian Ocean and as far across as 60^{o}E. Other individuals are resident in the Tasman Sea during these months. In August to October residency in the Indian Ocean is at a peak and occurs throughout the region as far as 35^{o}E (south-east of South Africa), and some individuals are also resident in the Tasman Sea. Although the panel for August to October in **Figure 10.5** does not show much structure, we will explore this in more detail in **Section 11** (Habitat modelling). Finally, by November to January many juveniles have returned to the GAB, but there is still some residency in the Indian Ocean, particularly in the waters south-east of South Africa, at a longitude of about 80^{o}E, off Western Australia and in the Tasman Sea. As noted in **Section 8**, there have been some changes in movement to the Tasman Sea between the late 1990s and mid 2000s; this is explored in more detail in **Section 11**.


Resident: February - April

Resident: May - July

Resident: August - October

Resident: November - January

Figure 10.5. Locations where the most probable state is "resident" for all years and grouped by month as indicated in the titles above each panel. Within each panel, colours represent months; the legend is in the first panel.

The main migration out of the GAB occurs over the period May to August, with the furthest longitudes west being reached in August (**Figure 10.6**). Locations east of Tasmania in the "Migrating West" panel of **Figure 10.6** are mostly individuals that move briefly into the Tasman Sea (usually in May) and back (i.e. west) to waters off southern Australia again in June. The return migration from the Indian Ocean east to the GAB occurs mainly in October to January. Locations east of Tasmania in the "Migrating East" panel of **Figure 10.6** are mostly individuals that remained in waters off southern Australia over winter and moved briefly into the Tasman Sea before returning to the GAB, or individuals that were already in the Tasman Sea and did east-west movements within that area. There does not appear to be a specific or narrow "migration path" in either direction, though we have noted (**Section 7**) that latitudes are estimated with significantly less precision than longitudes.

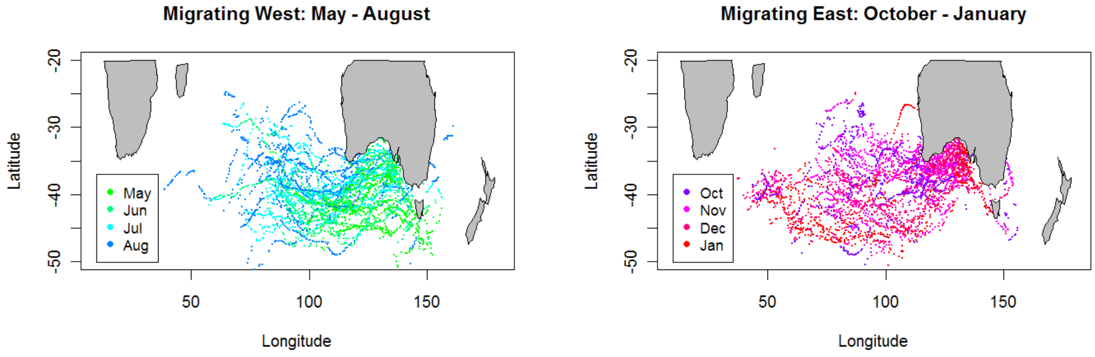


Figure 10.6. Locations where the most probable state is: (left) "migrating west" in May to August, or (right) "migrating east" in October to January, for all years. Within each panel, colours represent months as indicated in the legends.

Summaries of MPS, over all years and individuals, illustrate the main times of migration and residency (**Table 10.4 and Figure 10.7**). Several clear patterns emerge:

- highest levels of residency occur in January through to May (primarily in southern Australia[17], SA);
- highest levels of westward migration (represented primarily by migration from SA to the IO[18]) in the months of June to September, but starting to increase as early as April/May;
- highest levels of eastward migration (represented primarily by migration from the IO to SA) in November to January;
- at all times of year, there is at least an average of 50% residency for all SBT in the dataset – i.e. times during which the individuals do not move long distances (in a longitudinal direction).

The pictures change slightly when done by year (or e.g. 1998-2000 and 2004-2006) but there are no strong signals of difference, and differences are most likely a function of the large individual variability in timing of departure from and return to SA.

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[17] The terminology 'southern Australia' (SA), is used in preference to GAB because it includes the whole of the area south of Australia, between 115 and 145°E

[18] There is no visible difference if observations with longitudes > 145°E (i.e., fish that migrated to the Tasman) are excluded

Table 10.4. Percentages of observations (lat, lon pairs) in the three states estimated from HMMs, for locations west of 145°E (i.e. excluding the Tasman Sea). The final two columns gives the split of those in the resident state into the two regions: southern Australia (SA; 115-145°E) and the Indian Ocean (IO; <115°E). Note: results are almost identical when calculated as the means of monthly percentages by individual.

	Percentage observations in each state			Of those in Resident state, percentage in SA and IO	
Month	Migrating West	Migrating East	Resident (all areas)	Resident in SA	Resident in Indian Ocean
January	7	22	71	96	4
February	5	11	84	100	0
March	6	9	85	100	0
April	11	14	75	100	0
May	24	10	66	98	2
June	32	4	64	77	23
July	33	7	60	53	47
August	32	6	62	28	72
September	23	14	63	18	82
October	12	24	64	12	88
November	12	31	57	31	69
December	6	40	54	73	27

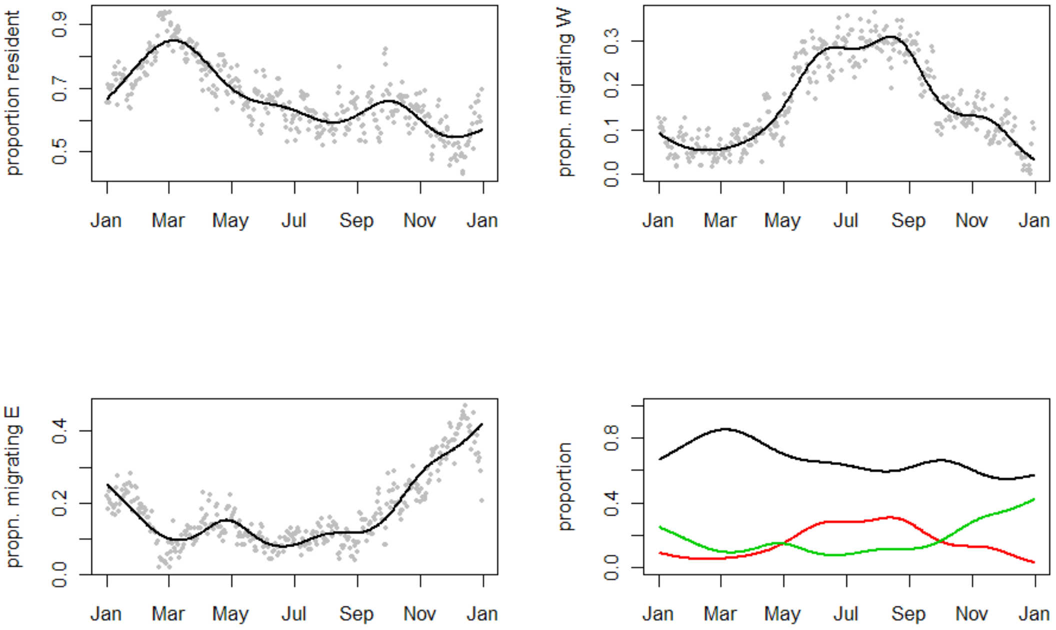

Figure 10.7. Proportions of observations in each state (resident, migrating west, and migrating east) on each day of the year, summarised over all years and all individuals, with lines showing smoothers fitted through the points. Note the different scales. The final panel shows the three smooths together: black=resident; red=migrating west (W); green=migrating east (E).

When we look separately at the tags that went to the Tasman (11 out of the 60 and note that they are all from the period 1998-2000), it is useful to distinguish between being resident in SA (taken to be between 115 and 145^{o}E) and resident in the Tasman (taken to be east of 145^{o}E) (**Figure 10.8**). This figure should be interpreted with some caution given the small number of tags involved. Since latitude is NOT taken into account in the analysis, the "bump" during Jun-Sep showing higher residency in SA outside of the main summer months (Dec-Mar) may well mean that individuals are south of the GAB "proper".

Departure from SA to the Tasman happened in April-May (migrating East, 9 of the 11), with a relatively high residency in the Tasman from June to November, even December (**Figure 10.8**). Over that time, two individuals moved between the two areas, returning a second time to the Tasman Sea in November (hence the third peak in eastward migration). The second peak in migrating East (August) is primarily due to 2 individuals making their first migrations at that time, but it also includes individuals already in the Tasman sea, but migrating further East. In this sense, the figure does not just reflect the timing of "crossing the line" at 145^{o}E. Generally, the return to SA for summer happened in early January. However, this represents one tag that came back from the Tasman to SA in January, and another which went to the Tasman and came back to SA in the same month (Jan 1999; **Figure 10.9**). The same figure shows that two of the individuals that went to the Tasman also went to the Indian Ocean – either in the same winter, or the following winter.

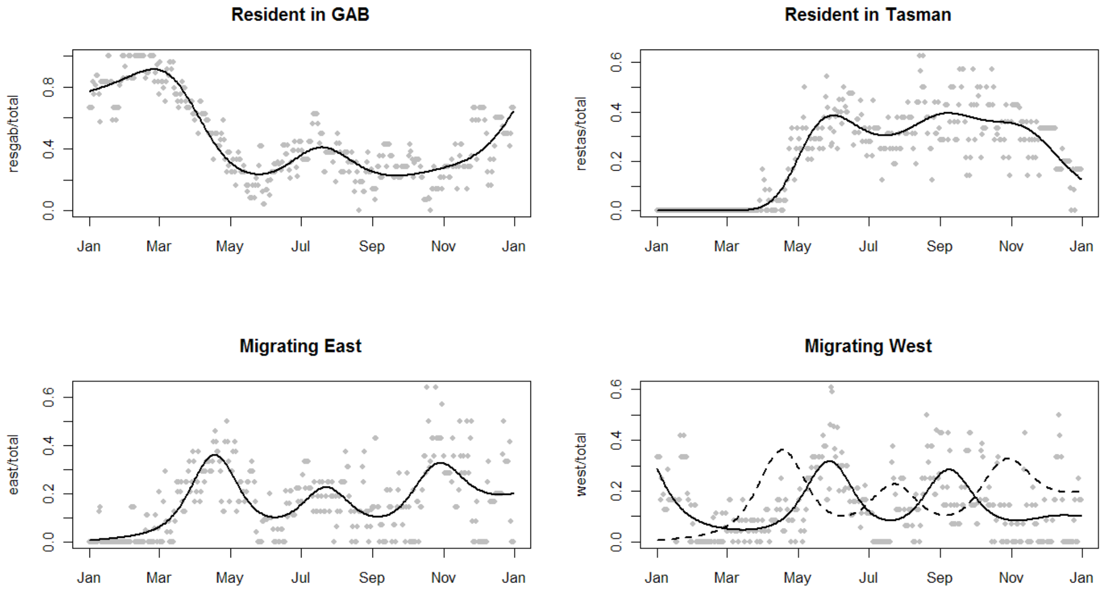

Figure 10.8. Proportions of observations in each state (resident in southern Australia – labelled as GAB * will CORRECT for final report *), resident in the Tasman, migrating west, and migrating east) on each day of the year, summarised over all years and using only those tags that went to the Tasman (east of 145^{o}E) at some point along its track. Lines show smoothers fitted through the points. Note the different scales. The final panel shows the smooth for migrating west (solid line) and repeats the smooth for migrating east (dashed line).

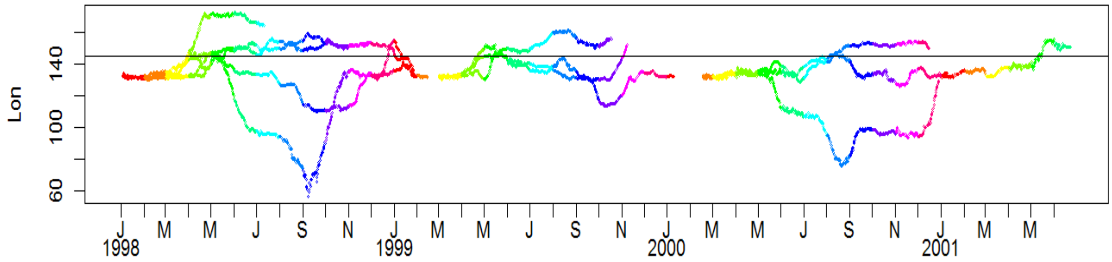

Figure 10.9. Longitude plots over time for tags that went east of 145°E, colour-coded by month (x-axis).

Estimates of most probable behaviour state:

Based on the analysis above we can provide the following answers to the questions originally posed.

Where are juveniles in the resident state?

> In summer they are primarily, and in February to March almost exclusively, resident in the GAB and off southern Australia. In winter some individuals

remain in waters off southern Australia, but most are resident throughout their range in the Indian Ocean (as far as south-east off South Africa) and in the Tasman Sea.

Are there specific "migration" paths?

There is no evidence of particular or narrow migration paths; juveniles seem to migrate throughout the latitudinal band of about 30 to 45°S, though we note that estimates of latitude are relatively uncertain compared to estimates of longitude.

When are most juveniles migrating out of the GAB and back into the GAB?

Most of the migration out of the GAB occurs in June to August, but it starts in about May and continues as late as September. Most migration back to the GAB occurs in November and December, but it starts in October and continues as late as January.

10.3.3 Periods spent in each of the states

How long are "resident" periods in the GAB in summer?

How long do they stay in a "migratory state", and is it the same for leaving and returning to the GAB?

The sequences of most probable state (MPS) can also be used to calculate the number of consecutive days an individual spends in each state. We refer to these as "run-lengths". At times, the model can switch quite rapidly between states and this can lead to high counts of very short run-lengths (1 or 2 days). Although this is quite possible, we also argue that when SBT are in the GAB, they may be moving relatively large distances, but they may not obviously (i.e. by looking at the sequence of longitudes) be in a "migrating out of the GAB" mode (see e.g. **Figure 10.10**). In order to focus on what one might call the 'main migration' periods, it is informative to also consider run-length summaries where we assume that all observations in the GAB area (128-145°E) are in the resident state. We choose the GAB area a little more conservatively than the southern Australia area (SA = 115-145°E) to avoid incorrectly re-classifying too many migratory states.

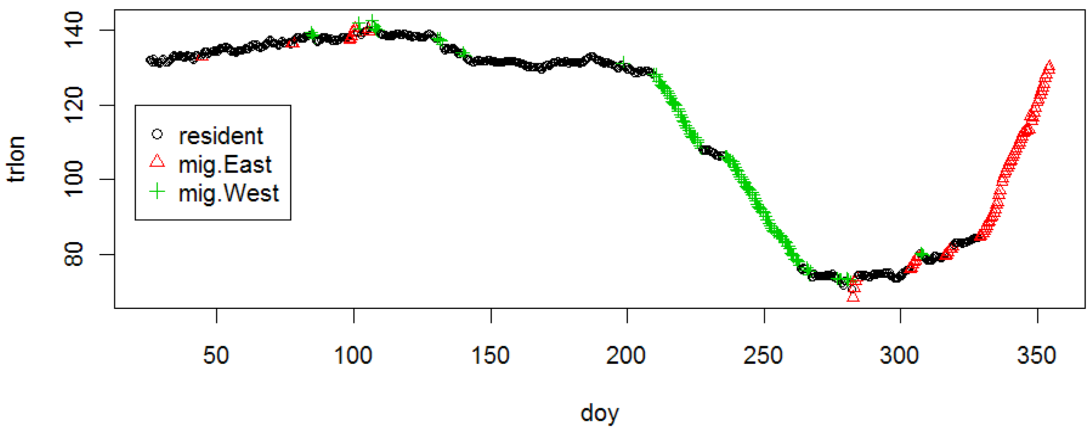

Figure 10.10. Example of longitudes over time with associated most probable state (MPS). The individual moved large enough longitudinal distances e.g. around day 100 for the MPS to be migratory, but one could argue that it is essentially still resident in the GAB, and only starts the main migration west around day 205.

The summaries of run-lengths (**Figure 10.11 a,b**) again show the seasonal patterns that were evident in **Figures 10.7 and 10.8**, but show more clearly the large variability in the number of days individuals might spend in one state or another. Irrespective of how the run-lengths are calculated, the resident state has the longest runs (note the vertical scales are different in the 4 panels), and the longest resident periods occur in January and February (in the GAB). Although the longest runs for migrating east occur in January, MOST individuals return in October to December (**Figure 10.12**), so it is only a few that return to the GAB later than was previously thought. The mean migrating west periods are only about 5 days during May to August – the time when most migration west occurs. This is slightly lower than the mean migrating east periods during October to December - the time when most migration east occurs. It reflects what is evident from plots of longitude colour-coded by state (e.g. like **Figure 10.10**), that many individuals switch more between migration and residency on the trip west to the Indian Ocean than on the trip east, back to the GAB.

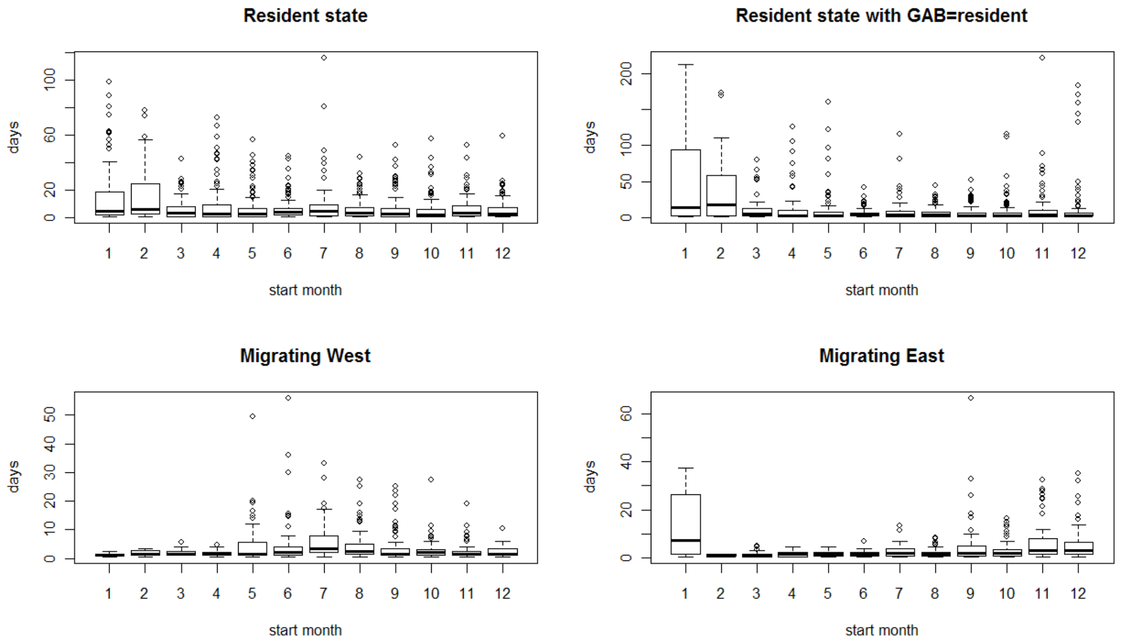

Figure 10.11a. Summaries of run-length in days by state and by the month in which the "run" started. The top row compares run-lengths for the resident state as estimated by the HMMs (left) and under the assumption that any observation within the GAB area (128-145°E) is a resident state (right). The second row shows run-lengths for the two migratory states for the case where observations in the GAB area are assumed to be resident. The boxes show the quartiles; the bold horizontal lines represent the medians.

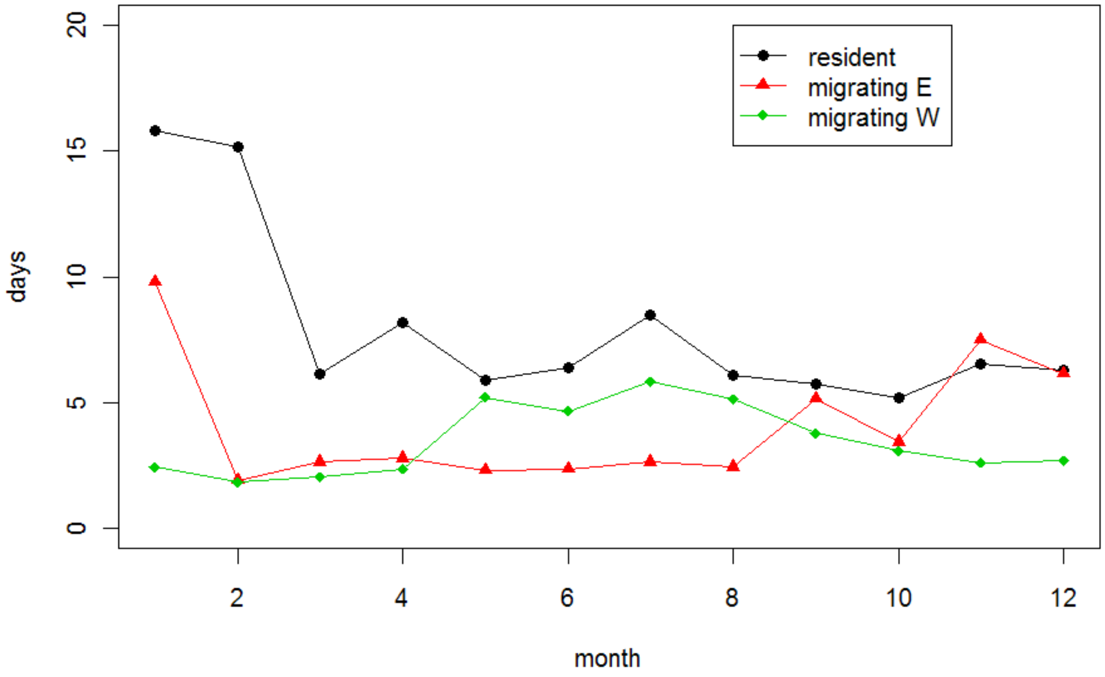

Figure 10.11b. Mean run lengths by month for the three states. For the resident state, it includes residency in all areas, not just southern Australia.

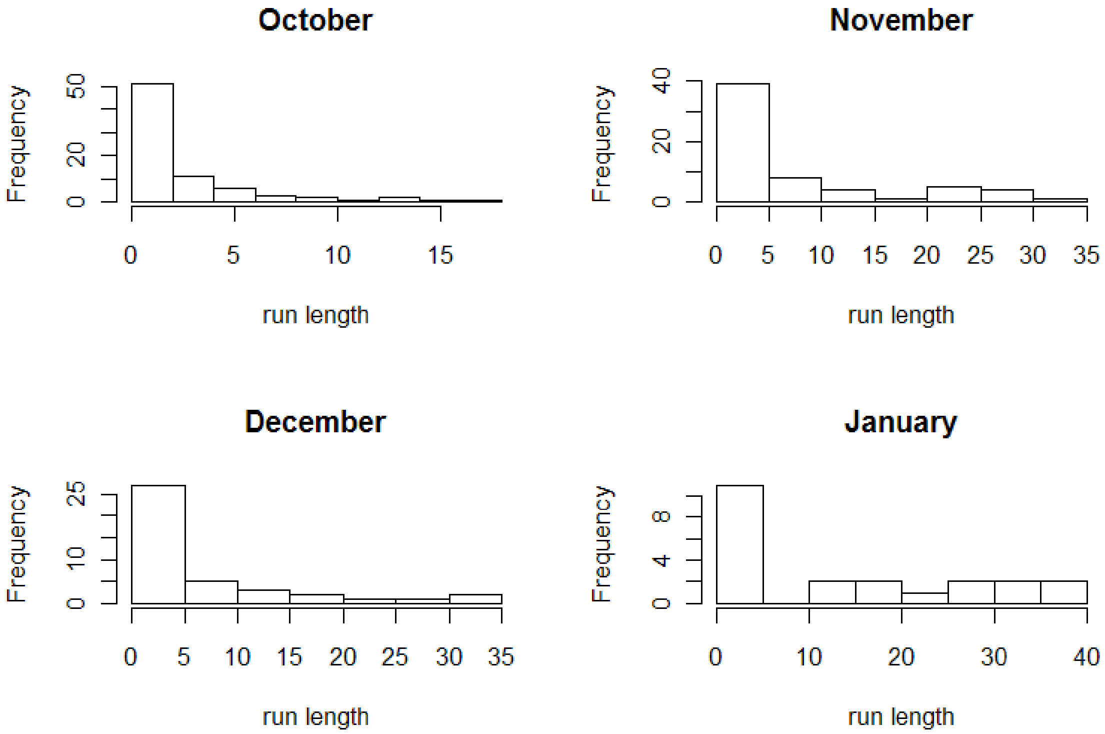

Figure 10.12. Frequency distributions of run-lengths for migrating east (back to the GAB) in October to January. Note the scales are different on both axes. Most individuals (highest frequencies) start migrating east in October to December, but the longest mean and median run-lengths are in January.

It is interesting to contrast run-lengths in the resident state in southern Australia in summer with those in the Indian Ocean in winter, as well as southern Australia in winter (some individuals stayed east of 115°E over winter, hence remained in the southern Australia area). The mean run-length, of those over 5 days in length, is about 25 days in summer in southern Australia compared with only 15 in May to July, both in the Indian Ocean and in southern Australia (**Table 10.5a**). Note this is without any changes to the estimated MPS sequence (i.e., no changes to the states estimated in the HMMs). In late winter/early spring, however, the mean run-length, of those over 5 days, drops to about 10 in southern Australia; it remains at about 15 for the IO. The longest run-lengths overall (mean, median and 75th percentile) are still in southern Australia in summer. If, however, we assume that all observations in the GAB area are in the resident state, in order to get a sense of the overall 'stay' in the GAB (**Table 10.5b**), then the run-lengths in the GAB are substantially longer in summer (Dec-Feb); the median run-length is 49 days and the mean run-length is 77 days.

Table 10.5. Summaries of run-lengths greater than 5 days, for resident state in southern Australia and the Indian Ocean. Note the maximum can be larger than the length of the period (e.g. 99 > 90 = number days in Jan+Feb+Mar) because only the start of the run needs to be within the identified period.

(a) States as estimated in the HMMs

State, Area, Period	25%-ile	Median	Mean	75%-ile	Max
Resident, SA, Dec-Feb	10	18	25	31	99
Resident, IO, May-Jul	6	10	15	18	116
Resident, SA, May-Jul	7	9	15	16	81
Resident, IO, Aug-Oct	8	11	15	21	53
Resident, SA, Aug-Oct	7	8	10	10	42

(b). As in (a), but assuming all observations in the GAB area (128-145^{o}E) are in the resident state.

State, Area, Period	25%-ile	Median	Mean	75%-ile	Max
Resident, SA, Dec-Feb	21	49	77	130	213
Resident, SA, May-Jul	8	11	20	26	97
Resident, SA, Aug-Oct	7	9	18	12	116

It is important to emphasise once again that the states reflect larger movements in longitudinal directions when in migratory mode than in resident mode, but are NOT assumed to reflect anything about whether individuals are feeding more, less or at similar levels in the different states.

Periods spent in each state:

Based on the analysis above we can provide the following answers to the questions originally posed.

How long are periods in the "resident" state in summer and in winter?

> The longest periods of being in the resident state occur in summer in the GAB. The mean period is 25 days (if we ignore periods of less than 5 days). Twenty five percent of the resident periods are longer than a month. Note these figures are not the same as the length of time individuals are in the GAB (see **Section 10.2.4**). In winter the mean resident period is only 15 days.

How long do they stay in a "migratory state", and is it the same for leaving and returning to the GAB?

The mean period in the migratory state is relatively low even during the main months of migration. It is only about 5 days for migrating west in May to August, and about 7 days for migrating east in September to December, but 10 days in January. The maximum period can be as much as a month or even two. There is a slight tendency for longer periods when returning to the GAB than when leaving the GAB.

10.3.4. Departure and arrival dates

How much variability is there in the timing of departure from and arrival back in the GAB between individual SBT?

Do they take as much time migrating out of the GAB as migrating back to the GAB?

We defined the departure dates from the GAB to be the date of crossing 128°E and moving into the IO, or crossing 145°E and moving into the Tasman Sea. Departures from the GAB and from the IO back to the GAB are summarised in **Figure 10.13**. The dates can be seen in plots of the longitudes colour-coded by the MPS, plotted against day of year (doy) as in **Figure 10.10**, for example. The dates can also be determined from summaries of the cumulative sum of number of days in each given state; points where the cumulative sum switches from constant to steeply increasing signals a switch to periods of exclusively, or primarily, being in that state. The individual variability – and possibly interannual variability – in arrival and departure times are clear from the spread in the histograms (**Figure 10.13**). In this set there are only two tags that contribute data to more than one year (e.g., have two departures from the GAB); the data so far suggest more variability between individuals than between years. Nonetheless, the pattern of cyclic movement between the GAB in summer and other areas (Indian Ocean in particular) in winter is clear. The sample size for departure dates from the GAB to the Tasman Sea is only 14 (compared to more than 40 for the other sets of dates). Apart from the small sample size, migration to and from the Tasman Sea is much less clear, so we have not attempted to summarise return dates from the Tasman Sea in more detail than already given in **Section 10.3.2**.

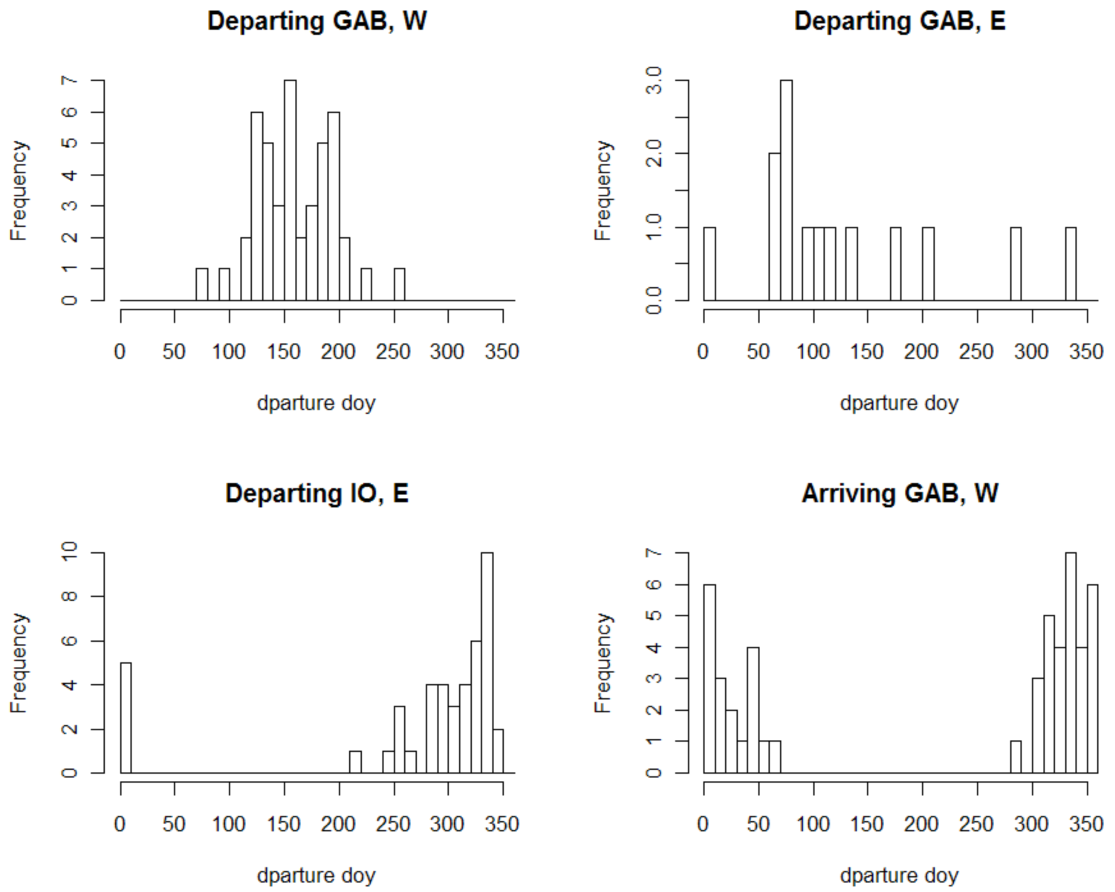

Figure 10.13. Histograms of the (a) departure dates ("doy" = day-of-year) from GAB moving west into the IO for winter, n=44, (b) the GAB moving east to the Tasman Sea, n=14, (c) departure dates from the IO moving east, back to the GAB for summer, n=45 and (d) arrival times in the GAB from the IO, n=48. The departure/arrival boundary for the GAB is taken to be 128^{o}E. Note that 'doy' values equate to the following dates: 100=10 Apr, 150=30 May, 200=19 Jul, 250=7 Sep, 300=27 Oct, 350=16 Dec.

This information then also allows calculation of the duration of the trip from departing the GAB to reaching the furthest west longitude, the duration of the trip from the furthest west longitude to arriving in the GAB, and the duration of the stay in the IO (at the furthest longitude west). These trip durations can include periods in resident and in migratory state, so they are different from the periods within a state considered in **Section 10.3.3**. Some individuals take longer to get to their furthest point west and then only spend a short time there; others go there quite quickly and stay there longer. In general, the return migration is shorter with fewer occurrences of the resident state than the migration out of the GAB. This may be because return trips to the GAB are targeting a more specific location, whereas outward migrations might be more influenced by local conditions and productivity encountered en route

We have also calculated the duration of stays in the GAB (128-145°E) but this quantity is slightly problematic for two reasons. First, many of the tags were released in the GAB and it is obviously unknown how long an individual had already been in the GAB when released with a tag. Second, many of the tags were recaptured in the GAB and it is then unknown how much longer an individual would have stayed. The distribution for GAB stays shown in **Figure 10.14** should be interpreted with caution given these issues. There are only 6 tags for which we have an arrival into and departure from the GAB and for these tags the durations are 40, 95, 100, 145, 155 and 170 days.

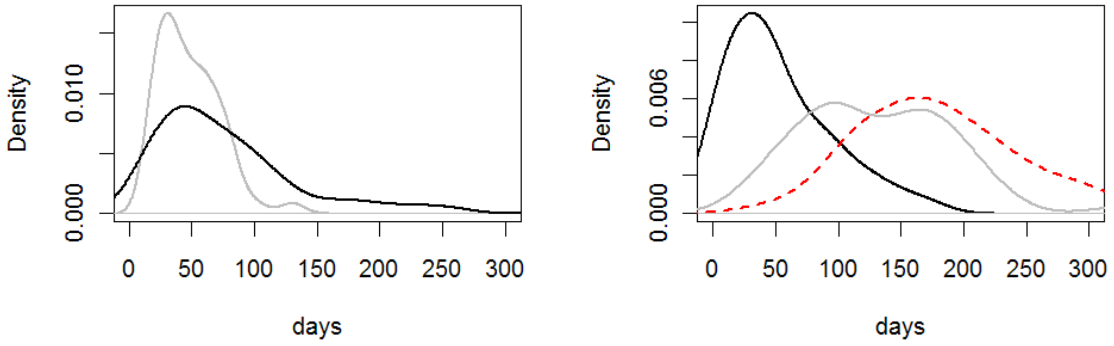

Figure 10.14. Density plots of the duration of: (a) black = migration out of the GAB (W of 128°E) to the most westerly longitude and grey = migration back from the most westerly longitude to the GAB (crossing the 128°E longitude); and (b) black = days in the IO at the most westerly longitude, grey = days in the GAB (128-145°E), and red dashed = days between departing from the GAB and arriving back in the GAB. See text for detail.

There is a weak relationship between the duration of the trip from the GAB to the most westerly longitude and the most westerly longitude (**Figure 10.15**): generally trip length is longer the further west an individual goes. It is not, however, necessarily the case that the further west an individual goes the longer – or shorter – it will stay at that longitude / in that region. Although the sample size is relatively small (a subset[19] of 39 from the full set of 60), the stays are generally longest around 70-80°E and 110-115°E, and possibly around 40°E. We comment further on these area in **Section 11**, Habitat modelling.

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[19] Individuals that make a one-way trip out of or back to the GAB cannot be used for the calculation of "stay in the IO", though their relevant departure or arrival dates can be used.

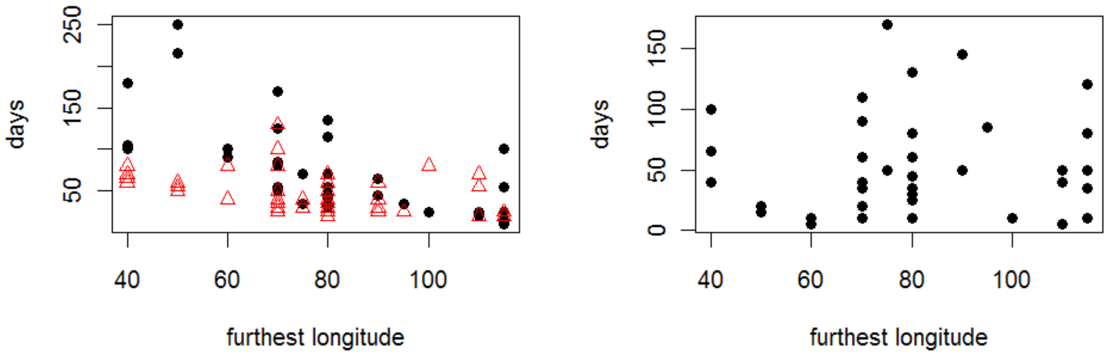

Figure 10.15. Left panel: duration of trips from the GAB to the furthest longitude in the IO (black dots) and from that longitude back to the GAB (128°E) (red triangles) shown as a function of the furthest longitude west. Right panel: duration of stay at the furthest longitude. NOTE that the lowest values (e.g. 40°E) are furthest away from the GAB (at 128°E)

Departure and arrival dates:

Based on the analysis above we can provide the following answers to the questions originally posed.

How much variability is there in the timing of departure from and arrival back in the GAB between individuals?

> There is a period of about 100 days, from mid-April to mid-July when most departures (to areas west of 128^{o}E) occur. There is a similar period from about the start of November to the end of January when most arrivals back to the GAB (east of 128^{o}E) occur.

Do they take as much time migrating out of as migrating back to the GAB?

> There is some evidence that individuals take longer on their westward migration into the IO because they switch between migrating and being resident, than on their eastward migration back to the GAB when the tend to stay in the migrating state, heading "straight back" to the GAB.

10.3.5 Tag-based covariates by behavioural state

Are there differences in the sea surface temperature between the different states?

Do SBT exhibit differences in depth distribution when migrating compared to being resident?

The electronic tags gather data on internal (body cavity) temperature, external (water) temperature and depth. These covariates are not subject to the issue of uncertainty in geolocation, and are therefore informative to consider in the context of movement dynamics. Most of the data for the 60 tags in the migration-modelling set occur in the two periods 1998-2000 and 2004-2006. We therefore focus on these two periods for summaries of on-board measured temperature as it relates to the most probable state (MPS) estimated by the HMMs. Only 10 of the 60 tags considered in this analysis spent any time in the Tasman Sea, and this only occurred in the early period; we therefore focus on the subset of data with estimated longitudes west of 145^{o}E. Also, 8 tags from the recent period showed some signs of drift in the external temperature sensor (see **Section 6.5.3**). These 8 tags were excluded from the temperature summaries.

The summaries presented here are based on the night and day summaries (**Section 6.5.5**) calculated for each individual along its track (excluding any time in the tuna farms), in which the average, minimum and maximum values of external temperature, depth, sea surface temperature (SST) were calculated for each day and night. Here we focus on differences by state rather than day-night differences.

The mean SSTs in all states and in most months are higher in the recent than in the early period (**Figure 10.16**). This is not surprising and reflects the general warming that has occurred in the southern Indian Ocean and the waters to the south of Australia, including the GAB (see **Section 3, Box 2**). The final panel in **Figure 10.16** shows that individuals are generally in cooler water when in migratory states than in the resident state, particularly during the main months of migration (i.e. May-Aug for migrating west and Sep-Feb for migrating east). Even if we just look at resident and migratory states in the Indian Ocean (i.e. longitude < 115^{o}E), the picture is similar. Recall these are the temperatures recorded when individuals were in the top 5m of the water column. **Figures 10.17** and **10.18** considered together also show that individuals are in deeper, cooler waters during the main months of migration. Depth is obviously also a function of location; bathymetry limits the depth distribution. It is therefore not surprising that the depth distribution is shallower during the summer months (Jan-March) when SBT are resident in the GAB, particularly when they are on the shelf, as we know from the surface fishery and aerial survey. There are also differences in the depth distributions by day and night (**Section 6.5.5** and **6.5.6**). **Figure 10.18** is for day and night combined; a figure like this for day only, shows an even stronger pattern of individuals being deeper while migrating, during the main months of migration, than when resident.

The proportion of time spent at the surface (i.e., in the top 10m) does not show any patterns when calculated by state, but there is a clear difference by night and day which varies seasonally, as noted in **Section 6.5.6**.

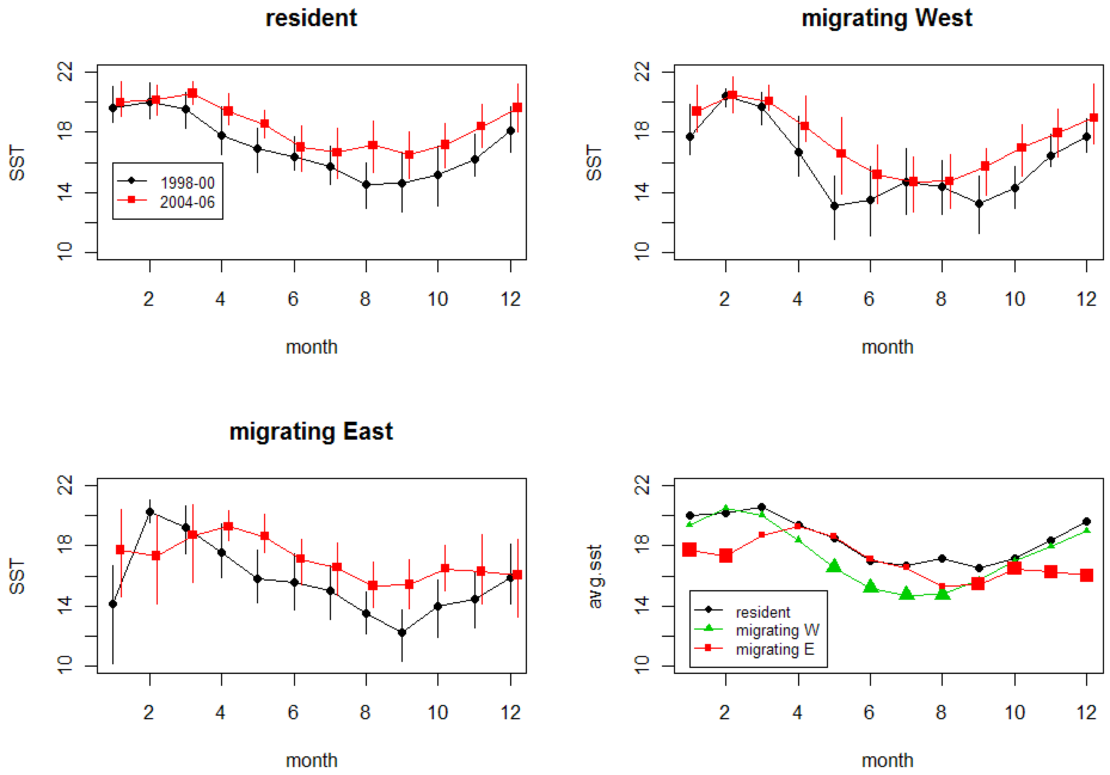

Figure 10.16. Summaries of on-board SST (external temperature in the upper 5m of the water column) by state and month, for the early (1998-2000) and recent (2004-2006) periods. Points are means of average SST over all relevant years. Vertical lines are between the 75th percentile of the maximum SSTs and the 25th percentile of the minimum SSTs. The final panel compares the mean average SST in the 3 states for 2004-2006. The larger symbols identify the main months of migration in the relevant direction, i.e. May-Aug for migrating west, and Sept-Feb for migrating east.

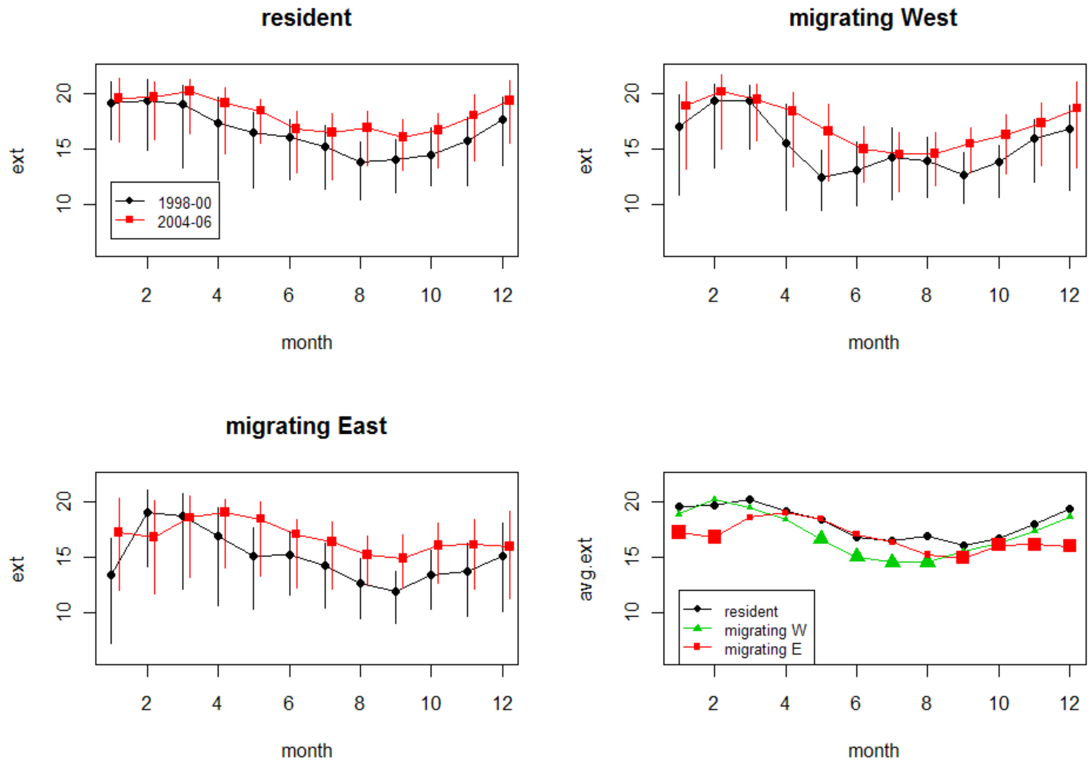

Figure 10.17. As **Figure 10.16** but for on-board external temperature (i.e. at depth).

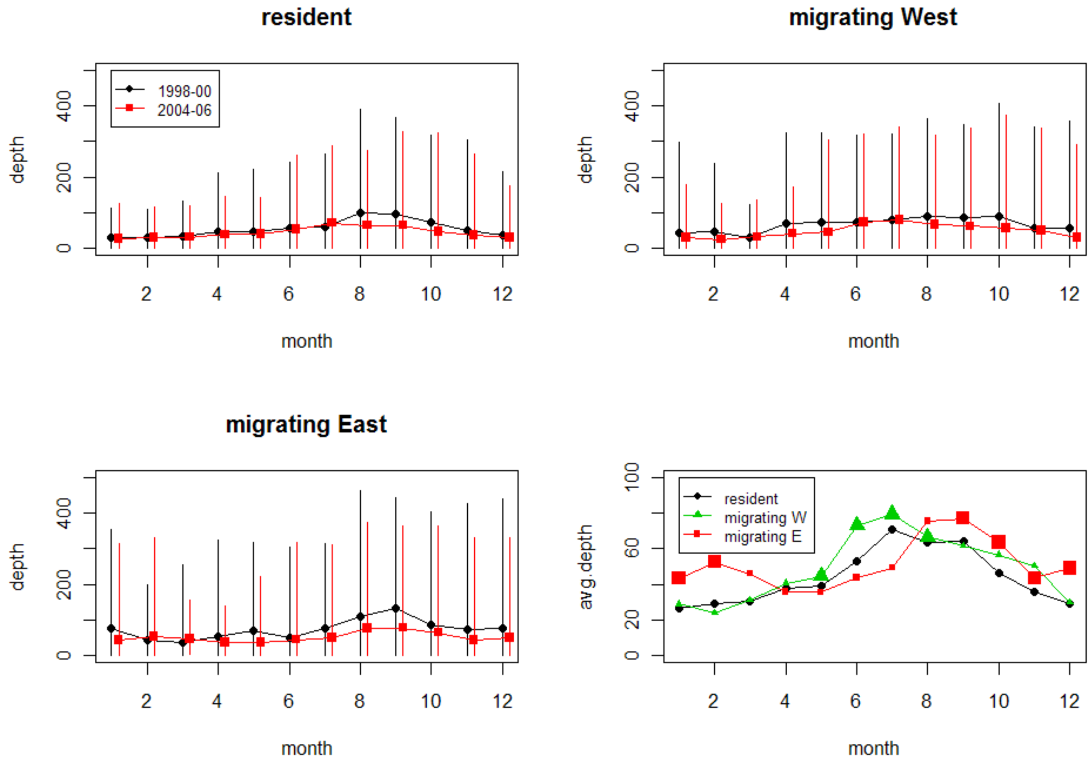

Figure 10.18. As **Figure 10.16** but for average depth (in m). Note direction of depth scale (so a larger number means deeper).

Tag-based covariates by behavioural state:

Based on the analysis above we can provide the following answers to the questions originally posed.

Are there differences in the sea surface temperature between the different states?

> During the main months of migration (west in May-Aug, east in Oct-Jan) the mean SST is generally lower for the migratory state than the resident state (in the same month).

Do they exhibit differences in depth distribution when migrating compared to being resident?

> During the main months of migration (west in May-Aug, east in Oct-Jan) the mean depth is generally deeper for the migratory state than the resident state (in the same month). The effect is strongest during the day. This also means that average temperatures experienced by SBT are slightly cooler when in the migratory state than in the resident state.

10.2.6 Summer residency and catches

Are there juveniles that do not visit the GAB in summer?

Is there likely to be a large proportion of juvenile SBT resident in waters off South Africa in summer?

In a report on Taiwanese catches in the Indian Ocean, Gunn and Farley (2000) confirmed that in the summer months (Nov-Feb of 1998) catches off South Africa were primarily of 2-3 year old SBT. These catches were being taken at the same time as juveniles of the same ages were being caught by the Australian surface fishery in the GAB. This suggested that a proportion of the juvenile population is not in the GAB in summer, and that some individuals may never visit the GAB. This raised concerns with regard to two data sources used to assess stock status.

First, if a proportion of the juveniles remain off South Africa rather than in the GAB at the time of the aerial survey, they would not be included in an index of relative abundance based on the aerial survey. If this is the case, but the proportion of juveniles off South Africa is constant (or approximately constant) over time, the fact that they are not included would not be a problem because the aerial survey is used as an index of <u>relative</u> abundance. The index can still be interpreted as being proportional to the total juvenile abundance. If, however, the proportion is not approximately constant, and if in addition, the proportion off South Africa is substantial compared to the proportion in the GAB, then problems with the interpretation of the aerial survey index would arise. The question of whether there is a substantial proportion of the juvenile population resident off South Africa in summer and whether that proportion is highly variable or not, has therefore been highly relevant. Now that the aerial survey is part of the CCSBT operating model and potentially of the management procedure (Anon. 2010), the questions are even more relevant.

Second, if a proportion of the juveniles is off South Africa and never visits the GAB, then this has implications for the interpretation of conventional tag returns (in mark-recapture analyses, particularly of returns at ages 2-4) given that juveniles are only tagged in southern Australian waters (see **Section 9**). Therefore, from the point of mark-recapture programs for estimating mortality rates and abundance, the question of a resident juvenile population off South Africa is highly relevant.

What is the evidence from this study? First, the movement data from this study suggest that individuals that are off South Africa in late spring or early summer may start their return journey back to the GAB as late as January. Therefore, individuals that escape capture in fisheries operating in Nov-Dec may still end up back in the GAB towards the end of the same summer.

Second, movement data from this study suggest that the vast majority of individuals tagged in the GAB, off WA and in the Indian Ocean return to the GAB (or WA) each summer after tagging and before recapture. Only one individual[20] briefly returned to the GAB in the first summer after tagging (then aged 2, going on 3), and then remained in the Indian Ocean and waters off South Africa for the subsequent two summers (then aged 3 going on 4, and 4 going on 5; **Figure 7.13** in **Section 7**), and winters. This is one tag out of 39 (1.3%) if we just count those deployed for 1 year or

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[20] Unfortunately, this individual is not included in the migration and habitat modelling datasets because we only have longitude estimates (the TrackIt software failed to converge, so there is no estimated track).

more, or one out of 79 (2.6%) if we just count those deployed for 18 months or more. This clearly shows that there are some juvenile SBT (of age 3 and older) that spend their summers off South Africa, but it also suggests that the proportion of individuals that stop migrating to the GAB as young as 3 or 4 is very small.

Monthly catches in the area south and south-east of South Africa (**Figure 10.19)** since 1968 show that the fishery off South Africa has primarily been a winter fishery, with peak catches in June or July. Only in the very early years of the fishery (1969-1971) were there monthly catches in summer greater than 1000t. There was an increase in summer catches between 1997 and 2001, but the maximum monthly catch in that period was only about 300t. Catches in 2008 and 2009 summer months did not exceed 100t. This is in contrast with catches of the order of 5000t taken in the past by the surface fishery in the GAB in summer. This again suggests that it is unlikely that there is a substantial proportion of the juvenile population off South Africa in the summer months. As noted above there may be some juveniles that remain off South Africa.

In addition to the catches being very small, the proportion of age 2-4 SBT taken off South Africa in the late summer has been small in recent years. For example, in January to May, 2004 to 2006, the proportions of juvenile SBT in catches (grid squares 40°S, 20-65°E) were: 1.4% age 2, 9% age 3 and 9% age 4. This is a total of less than 20% of an already small catch of about 50 tonnes (annual average) of which most is taken in May.

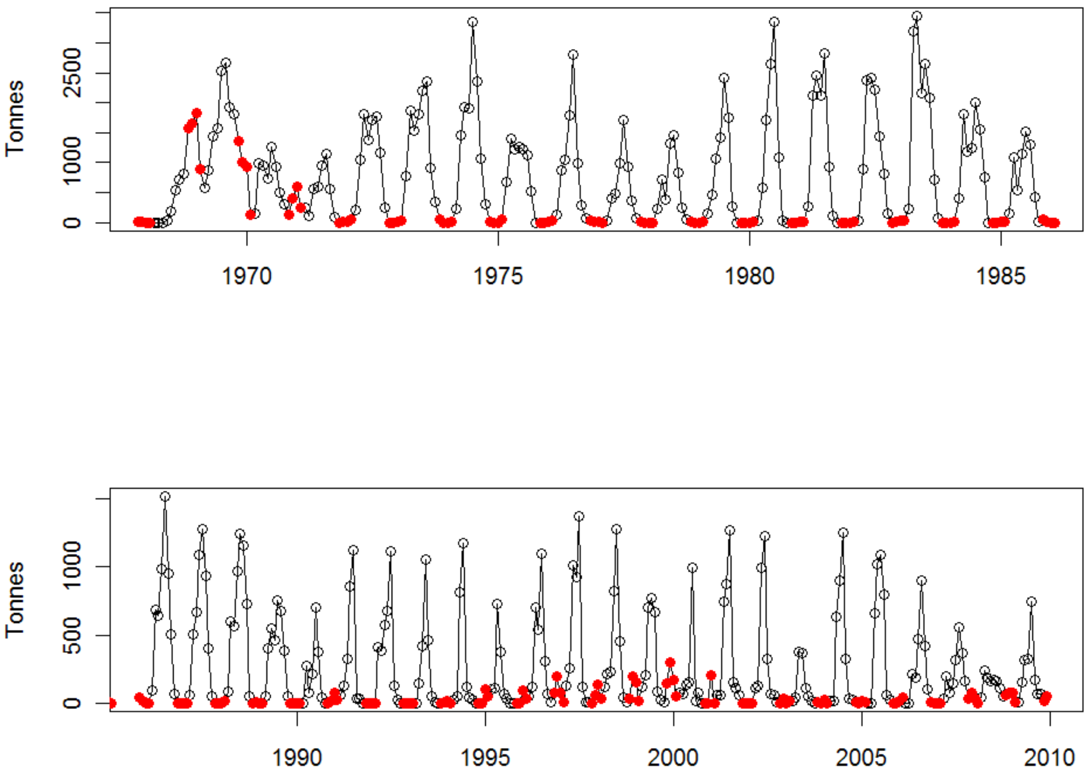

Figure 10.19. Monthly reported catches in tonnes in the area south and south-east of South Africa (20-55°E, 35-45°S) for 1968 to 1985 (top) and 1986 to 2009 (bottom). The summer months, November to February, are indicated by red solid dots. Note the difference in scales.

The question, however, remains: are there any juveniles that spend their summers off South Africa and never visit southern Australia or the GAB? Although we released some archival tags off South Africa (see **Section 6**), we have not yet received any returns from these releases, so the answer to the question could still be "yes". If it is, the relatively low catches in the summer months off South Africa, compared to the magnitude of surface fishery catches in the GAB suggest that the proportion is unlikely to be substantial.

The return of a tag released off South Africa would only answer the question if that individual made no visits to the waters off southern Australia. That would be proof that there is some unknown number of individuals that never visit the GAB. Ideally this individual would have been tagged at age 1 or 2; if tagged at age 3, it could have been in the GAB at age 2 and the answer would be less conclusive.

Tagging alone cannot answer this question, but an approach that can directly answer this question, and provide substantial additional information on, for example, the proportion of individuals that visit the GAB each summer, is based on otolith microchemistry. Results from a pilot study are very promising (N. Clear pers.comm.[21]), and we plan to pursue this approach further.

The implications of the findings in this section are discussed in **Section 12 (**Management Implications).

Summer Residency:

Based on the analysis above we can provide the following answers to the questions originally posed.

Are there juveniles (age 2-4) that never visit the GAB in summer?

> The answer to this question is still unknown and could still be "yes". One individual paid a very brief visit to the GAB in its first summer after tagging (age 2) and then migrated to the Indian Ocean and waters off South Africa where it remained for the subsequent two winters and summers.

Is there likely to be a large proportion of juvenile (age 2-4) SBT resident in waters off South Africa in summer?

> All the evidence before us suggests it is unlikely that there is a large proportion of juvenile SBT resident in waters off South Africa in summer. Catches, and the proportions of age 2-4 SBT in those catches, have been very low in that area compared to catches in the GAB in the same months. Also, all but one of the tags in our dataset returned to the GAB in each subsequent summer during its deployment.

10.4. Summary

In this section, our aim was to develop a seasonal migration model for juvenile SBT. We fitted Hidden Markov Models (HMMs) to the tracks of 60 tags. Although this approach is not perfect from the point of view of uncertainty estimation, results are

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[21] A working paper by N. Clear and co-authors was submitted to the CCSBT Scientific Committee meeting in July 2011. This paper cannot be cited yet because of the CCSBT rules of procedure; the paper is currently deemed confidential. However, it should be available for citing in the Final report of this project, following the CCSBT Commission meeting in the first week of October 2011.

highly consistent with what is visually clear in the data (e.g. in terms of ‘categorising’ migratory and resident states), and results are consistent between individuals (e.g. in terms of parameter estimates). We therefore have confidence that our conclusions are robust. Results have enabled us to identify, in a consistent statistical framework, the probability of the individual being in a resident (undirected, slow movement) or migratory (directed, fast movement) state. This has highlighted both the patterns and the variability amongst individuals in movement dynamics. It has enabled us to quantify the periods of time spent in the resident state in summer and in winter, and the time spent migrating, either out of the GAB or back into the GAB. We have been able to quantify the main departure times from, and arrival times to, areas of high residency, as well as, the variability in those times. These results provide us with a substantially clearer picture of juvenile SBT migration.

In **Section 11** we integrate the HMM results from this section with oceanographic covariates to develop habitat preferences for juvenile SBT across their range.

11 Habitat preferences of juvenile SBT across their range

Key findings

- In summer
    - Habitat preference maps, described by a combination of SST and *chl a*, show that in most years, the GAB is the most preferred summer location in the southern oceans.
    - There is a high preference habitat band across the Indian Ocean (IO), although extension of this habitat all the way to South Africa has been reduced in recent years.
    - The Tasman Sea contained high preference habitat in the early analysis period (1998-2000), but this has become reduced in recent period (2004-2006).
- In winter
    - The highest preferences are in the central IO, but there is also an area of high preference in the GAB in both periods.
    - In the Tasman Sea, the band of high preference is almost entirely absent in the recent period, and there is no connecting band of high preference between the GAB and the Tasman Sea.
- Changes in habitat preferences of SBT between the early and recent period may partly explain apparent distribution shifts.
- Fewer SBT appear to migrate to the Tasman Sea and South African side of the Indian Ocean in the recent period, and environmental conditions may explain this pattern.

11.1 Introduction

Juvenile southern bluefin tuna (SBT) range widely between the major juvenile summer grounds in the Great Australia Bight (GAB) and wintering areas in the southern ocean (**see Section 10)**. The extent of these movements and the behaviours of SBT in different regions may be related to environmental conditions, as has been demonstrated for this species at other life stages (e.g. Patterson *et al.* 2009; Bestley *et* *al.* 2010; Fujioka *et al.* 2010; Fujioka *et al.* in press). Ocean conditions may directly influence distribution and behaviour, may act indirectly through influences on prey, or through a combination of the two. In the absence of information on prey distribution, only the influence of environmental conditions alone can be determined, but we note the exact mechanism may remain elusive.

In this section we explore the relationship between environmental covariates and SBT behaviour states. We have already noted that the work in this and the previous section (Migration modelling; **Section 10**) are closely linked and relate to Objectives 5 and 6 of the project. These two objectives were revised in the course of the project (see **Section 5** for more detail) and reworded as follows:

Revised objective 5: Integrate the position, temperature and depth data provided by the tags with oceanographic data to develop a seasonal model of residence times and habitat use for regions with consistent temporal patterns across the years.

Revised objective 6: Evaluate the implication from the seasonal habit model for the interpretation of future catch and effort data and monitoring strategies.

The focus of the analyses in this section was to relate some of the observed patterns and changes in movement dynamics to environmental conditions. These movement-environment relationships are important in order to attribute changes in catch rates of SBT to either changes in total abundance, or to changes in distribution (and hence local abundance).

11.2 Methods: Habitat preference analysis

The daily location of SBT was determined by analysis of the archival tag data (**Section 7**). The resulting tracks provide estimates of the ocean regions that are used by SBT during feeding and migration phases of their life cycle. One of the key features of electronic tag data, including estimated tracks, is that the data are autocorrelated (Patterson *et al.*, 2009). The set of locations is a time-series with each location depending, at least to some extent, on the location 12 hours, or a day, ago. This is not just a feature of animal movement itself, but also a feature of the Trackit method for estimating the locations on the track (see **Section 7**). Furthermore, the environmental "seascape" through which SBT are moving is also autocorrelated in both space and time. For example, sea surface temperature (SST) in the Indian Ocean increases from south to north such that contours of equal SST run east to west; and seasonal changes in temperature are also such that SST at a given location is autocorrelated in time. This means the locations on a track are not random points, and environmental covariates are not random quantities either. Therefore, analyses which do not account for this complex correlation between habitat and movement may draw spurious inferences regarding the relationship between habitat and movement (Forester *et al*. 2009).

A second issue that arises with analyses of animal tracks and environmental covariates relates to the questions of interest. For example, if we are only interested in the environmental conditions where SBT are found, then it is sufficient to consider just the conditions associated with the fish locations along their tracks. For this exercise, any on-board covariates as measured by the tag sensors (such as water temperature) can be used directly. However, an understanding of animal movement is likely to be enhanced by an understanding of where animals did *not* go (and, possibly, why they did not go there) – i.e. habitat choice (Matthiopoulos 2003; Aarts *et al*. 2008). In this case, examination of both the environmental conditions "on track" and "off track" is important. Various approaches have been used to undertake this type of analysis, including random background sampling, such as in species distribution modelling (e.g. Elith and Leathwick 2009; Robinson *et al*. 2011).

In terrestrial situations, species distribution and hence habitat choice predictions have been generated with presence-absence data (e.g. Elith *et al.* 2006; Elith and Leathwick 2009). For example, a survey over a gridded area determines whether, say a particular plant, is present or absent in each cell. Additional information such as soil type, typography, etc., is also collected. The presence-absence data can then be analysed with relation to large numbers of covariates using a variety of statistical approaches (e.g. Araújo and New 2006; Elith and Leathwick 2009). Unfortunately, this approach is not suitable for analysis of animal track data because of the autocorrelated and "repeated measure" elements (i.e. one individual contributing multiple data points) nature of the data (Patterson *et al*. 2008).

In **Section 7** we noted that, in theory, the whole sequence of modelling – track estimation, movement/behaviour and preference in relation to environmental covariates – should ideally take place in a single, enormous model. This would allow for the correct propagation of errors through all stages, and would give quantitative estimates of the uncertainty in conclusions. However, such an approach is technically extremely complicated and, most importantly, makes it much harder to run exploratory analyses and check diagnostics. In this report our aim has been to establish what the patterns of movement behaviour and relationships with environmental covariates are, and to see whether our conclusions are ‘qualitatively’ sound. We have already discussed the first two steps in the modelling sequence (track estimation in **Section 7** and movement/behaviour in **Section 10**).

We take a relatively simple approach to the third step of estimating so-called “habitat preferences” and comment further on the issue of autocorrelation when using this approach below. First we consider an example that only looks at the preference in terms of a single environmental covariate. The steps to calculating preferences are as follows:

1. identify the spatial area of interest (latitude and longitude ranges);
2. identify the time-period of interest;
3. find the overall frequency distribution of the covariate in the ocean in the time-period and spatial area (i.e. all locations in the spatial area), then
4. find the overall frequency distribution of the covariate at locations on the SBT tracks in the time-period and spatial area, and
5. scale both frequency distributions to sum to 1 and calculate the ratio of the ‘SBT’ scaled frequency distribution to the ‘ocean’ scaled frequency distribution; this is referred to as the preference curve.

The covariate frequency distributions can be described as histograms with counts of how many times a covariate (e.g. SST) was in each of the chosen histogram ‘bins’, e.g. in the intervals [10-11°C], [11-12°C] and so on. The density distributions can sometimes be noisy at the edges, away from the mean, when the counts are very small. This can then lead to spikes in the preference curves. When this happens, the solution is to group together bins at the edges of the distribution to increase the counts in those bins, such that the bin interval is larger at the edges of the frequency distribution than at the centre.

The preference curve makes intuitive sense by noting that if SBT have no particular ‘preference’ for particular environmental conditions and are randomly distributed in space, the SBT frequency distribution of the covariate would be almost identical to the frequency distribution of the covariate as seen over the whole ocean region. The resulting preference curve would be close to 1 at all values of the covariate, and thus, not show any real preference. If, on the other hand, SBT ‘prefer’ certain conditions, the preference curve will be greater than 1 at preferred covariate values, and less than 1 at less preferable covariate values (see e.g. **Figure 11.2** below).

A similar approach can be applied to combinations of more than one environmental variable. For example, for pairs of variables (e.g. SST and chlorophyll *a* (*chl a*)), the frequency distributions and the result would be 2-dimensional surfaces (see **Figure 11.5**). For the purpose of visualization, preference levels are binned; and the highest level on the scale represents the lower value of the final interval. The bivariate analyses can be thought of in terms of interactions between covariates. In theory, more than two variables could be considered, but interpretation and representation of results become rather difficult and cumbersome. We therefore only consider single covariates or 2-covariate interactions in the analyses presented here.

A preference curve or surface can also be converted into a spatial map (by latitude, longitude). This is done by relating the value of a covariate at a given location to its ‘preference’ value and plotting the preference values, colour coded for example, on a map (e.g. **Figure 11.4**).

As noted earlier, the data used in calculating the preferences are autocorrelated when based on archival tag tracks. This means that although there may be a large number of ‘points’ involved, the effective sample size (in the statistical sense of the term) is almost certainly smaller, and potentially much smaller. This can lead to the preference curves or surfaces being noisy. It is in fact preferable to fit a statistical model, such as a Generalized Additive Model (GAM), to the noisy preference data (Wood 2006). Within the GAM we use a tensor product smooth to model the counts associated with the SBT frequency distribution, as a function of the two covariates, and with an offset term to reflect the ocean density distribution (essentially the quantity we divide by when forming the unsmoothed preference values). The error distribution of the data was assumed to be the Tweedie distribution in order to deal with non-integer counts

The autocorrelation in the count data (input into the GAM) was dealt with by using an effective sample size, rather than actual sample size, when choosing the smoothing parameter of the GAM. The effective sample size, i.e. the sample size of a hypothetical uncorrelated dataset that would provide the same information content, is estimated via the dispersion parameter in a separate modelling step.

Fitting a GAM has the advantage of resulting in a smoother preference curve which may make more sense from a behavioural point of view (for example unimodal, or possibly bimodal, preference curves instead of highly multimodal ones), provided the covariate is actually meaningful. It also provides the ability to check the goodness of fit and the predictive capability of the model via model diagnostics such as residual plots, etc.

In some cases we found that the GAMs had difficulties fitting the data at the extremes of the range, particularly when there were noisy “spikes” at low counts. This sometimes leads to peaks of high preference at the edge, and away from the main “dome” of high preference (e.g. **Figure 11.11**). As noted above, this can be resolved by combining bins in the covariate frequency distribution. The analysis outlined above can be performed using all locations on each track within the chosen area and time period. It is also possible, and potentially informative, to do the analyses only where SBT are in the Resident state, or only where SBT are in one, or either, of the Migratory states as estimated from the HMMs (**Section 10)**. In this case, the counts are the sums of the relevant state probabilities estimated by the HMMs. It is preferable to use the state probabilities (which can be any value between 0 and 1) rather than the “most probable state” which is only 1 if the particular state has the maximum probability and 0 otherwise.

11.2.1 Uncertainty in location estimates

Given that we are interested in relating SBT movement and residency to oceanographic conditions, we need to know at which location to “measure” the relevant covariate. If we were only interested in SST (or temperature at any other depth), we could choose to use temperature measured on-board the tag when the fish was at the surface (as determined by the depth sensor), but no other oceanographic covariate is measured by the tag sensors. Also, the fish’s location needs to be specified (both longitude and latitude) in order to extract other covariates from remote sensing data. Ideally, the uncertainty in fish location should be taken into account; however, doing this more complex analysis is continuing work in progress and was never intended as part of this project.

When calculating the density distribution of covariates relating to SBT, only the point estimates of locations are used to extract the oceanographic covariates[22]. Some fish locations (latitudes in particular) are, however, quite obviously impossible or highly unlikely based on inspection of tracks. First, all locations that are estimated on land are excluded from subsequent analysis. Second, all latitudes with oceanographic SST (satellite-based) values outside the range of plausible values for juvenile SBT, as measured by the average external temperature when the fish is in the top 5 m of the water column (referred to as 'on-board SST'), are removed from the dataset. More detail is given in **Appendix 7**.

We also commented on the fact that latitudes have higher standard deviations around the spring and autumn equinoxes (22/23 September and 21/22 March), and may also be biased given the lack of contrast in the light curves at sunrise and sunset (see **Section 7**). We therefore did sensitivity analyses for each of the preference surfaces by repeating the analysis but with data points within 14 days either side of the equinox removed (i.e. data between 8 March and 5 April, and between 8 September and 6 October). Results are given in **Appendix 7**, and in all cases the removal of the data had no effect, or only very limited effect, on the preference surfaces and preference maps.

In addition to uncertainty in location, oceanographic products from which we extract the covariates are also subject to a range of errors. For example, on satellite measured variables, cloud cover may lead to biased or missing data, while chlorophyll *a* measurements are rated to within 50% of their true values (e.g. Gregg and Casey 2010). Some data are interpolated or averaged over several individual satellite passes to produce more coherent datasets (e.g. Hobday *et al.* 2011). Since the main focus is on broad-scale rather than fine-scale patterns, we consider that errors in fish location and environmental covariates should not be critical. We also perform some sensitivity analyses by the grid-based HMM tracks to minimise the chance of spurious results.

Finally, the data in the migration modelling subset (**Section 10)**, i.e. for which Hidden Markov Models (HMMs) were fitted, do not provide even coverage over time. Most of the archival tag data cover the periods 1998-2000 and 2004-2006 (**Section 6**). The

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[22] In fact, the point estimates of the best environmental variables, particularly remote-sensed variables, are typically at a spatial scale of between 4 – 27 km (0.1 to 0.25 degree), and a temporal scale of daily to weekly.

habitat modelling therefore focuses on these two periods, as illustration of general patterns.

11.2.2. Environmental covariates

There are a number of environmental covariates that can potentially be used to construct preference curves of where juvenile SBT spend time. We first consider how variables may be related to SBT distribution and movement, as well as how influential these variables might be in restricting SBT distribution and hence suitability as a measure of potential SBT habitat (**Table 11.1**).

Table 11.1. List of potential environmental covariates that may relate to SBT distribution and movement

Pathway	Environmental variable	Used in final analysis
I. Most influential or with existing evidence	Sea surface temperature (SST) Chlorophyll a (*chl a*) Productivity	Y Y Later period only (2004-2006)
II. Less influential	Mixed layer depth (MLD) Bathymetry Wind	N Limited N
III. Least influential, or without evidence to date	Frontal density Eddies (e.g. eddy kinetic energy, EKE) or sea surface height (SSH)	N N

It is likely that juvenile SBT preferences are strongly driven by areas and features where (i) the temperature range is ideal (or acceptable) from a physiological point of view and (ii) where there is sufficient prey to feed on (Fujioka *et al.*, in press). Direct measures and estimates of SST from a range of oceanographic products are available, and represent the upper few meters of the water column. Estimates of SBT prey abundance are not available. Instead we have to consider proxies such as measures of phytoplankton density, using satellite-based chlorophyll measurements. Chlorophyll *a* (*chl a*) is likely to be a proxy for tuna prey density in two ways. First, *chl a* information may reflect the presence of prey species that are of interest to SBT (Fujioka *et al.*, in press). Second, as for temperature, satellite measures of *chl a* represent only surface conditions (upper 10-15 meters). Suitability of a location, from a fish's point of view, will be a function of the whole water column (e.g. Hobday and Hartmann 2006) (even down to 500m or more[23]). In addition to *chl a*, which is a measure of standing phytoplankton biomass, a measure of water column productivity (a measure of production of phytoplankton, biomass and turnover) can be calculated using algorithms based on light penetration, water temperature, and *chl a* measurements. While potentially more useful, this data product is only available from 2004 onward for the region of interest. We do consider productivity for some of analyses presented here, but due to its limited temporal coverage, we could not use it for comparisons between the 1998-2000 and 2004-2006 periods.

The first set of covariates listed in **Table 11.1** are likely to be the most useful measures of potential SBT habitat compared to the other covariates. The level of productivity at a given location in the ocean is strongly driven by the amount of mixing and depth of the mixed layer. The second set of variables include mixed layer depth which is available as a derived oceanographic product, based on vertical structure of the ocean, and has been shown elsewhere to influence bigeye, yellowfin, and northern bluefin tuna distribution (e.g. Cayre and Marsac 1993; Itoh *et al*. 2003; Schaefer and Fuller 2003). Characteristics of the mixed layer depth also determine local productivity and *chl a* standing stock, foraging volume, and temperature at depth. Finally, the third set of covariates are those that reflect meso-scale ocean features and potentially habitat suitability for prey. Eddies and fronts for example concentrate prey and form feeding areas for larger predators (e.g. Royer *et al.* 2004). These last covariates are arguably the least direct in terms of physical impact on SBT, but may be more direct in terms of understanding prey distribution.

Bathymetry and persistent oceanographic features can also play a role in the aggregation of prey and hence SBT distribution (Hobday and Campbell 2009; Hobday *et al.* 2011). We did not create preference curves explicitly for bathymetry, because we considered it unlikely that the depth of the ocean floor would influence SBT preference directly. Indirect effects of bottom topography are perhaps more likely to be influential via prevailing currents and wind, or with regard to the steepness of the continental shelf. These combined features may lead to the retention of prey that might influence SBT habitat preference. Therefore, we secondarily consider

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[23] The deepest depth on a tag is at 1286m, and 5% of depths are greater than 500m. See **Section 6** for more detail.

bathymetry in relation to some of the mapped preference curves (see e.g. **Figure 11.14** and **Figure 11.19**).

During the exploratory phase we considered all the single-covariates in **Table 11.1** and attempted to construct preference curves. SST was the only covariate that consistently gave plausible preference curves, i.e. which were relatively noise free and not highly multi-modal. Preference curves for *chl a* and productivity were promising, but not as clear as for SST. The other covariates considered on their own, tended to produce very noisy preference curves which seemed to identify multiple modes of preferred values (not just one or two modes, and not at a consistent set of covariate values). This suggested that either the covariate was not a suitable measure, not a sufficiently strongly related proxy, varied over the spatial range considered, or was interacting with another covariate and hence not meaningful on its own.

In the second phase of analyses we therefore primarily considered interactions between SST and *chl a*, and between SST and productivity for available periods.

11.3 Results of preference analyses

We consider resident and migratory behaviour in relation to SST and *chl a* in the two periods 1998-2000 and 2004-2006 in the following subsections:

11.3.1 Residency in summer off southern Australia

11.3.2 Residency in winter and spring in the Indian Ocean

11.3.3 Migration East to the Tasman Sea in autumn

11.3.4 Migration West into the Indian Ocean in winter

11.3.5 Migration East to southern Australia in spring/summer

In **Section 10**, we considered migration patterns by month. Here months are grouped together to make analyses and interpretation easier. Grouping months provides larger datasets and greater spatial coverage than does analysis based on single months. The percentage of observations in behavioural modes estimated from the HMM in **Section 10** (repeated here in **Table 11.2**) provides guidance for sensible groupings of months. Data were grouped in relation to several questions of interest with respect to southern Australia (SA) (includes Western Australia and the GAB, as defined in **Section 10**) and the Indian Ocean. Habitat preference associated with resident behaviour in SA is investigated by grouping data from January to May (months 1-5) together. Residency in the Indian Ocean is investigated by grouping data from August to November (months 8-11) together, since they have the highest percentages of residency. Similarly, for habitat preference associated with migration West, we consider May to September (months 6-8) and for migration East, we consider October to January (months 10-1).

Table 11.2. Percentages of observations (lat-lon pairs) in the three states estimated from HMMs for locations west of 145°E (i.e. excluding the Tasman Sea). The first three columns show the percentages of observations in each state (from the “most probable state” estimated in the HMMs). The last two columns show the percentage of observations in the Resident state that are in southern Australia (SA) or the Indian Ocean. Bold entries for a given state (column) indicate months that were grouped together for exploring habitat preferences associated with that state.

Month	Migration West	Migration East	Resident (all areas)	Resident in southern Australia (SA)	Resident in Indian Ocean
January	7	**22**	71	**96**	4
February	5	11	84	**100**	0
March	6	9	85	**100**	0
April	11	14	75	**100**	0
May	24	10	66	**98**	2
June	**32**	4	64	77	23
July	**33**	7	60	53	47
August	**32**	6	62	28	**72**
September	23	14	63	18	**82**
October	12	**24**	64	12	**88**
November	12	**31**	57	31	**69**
December	6	**40**	54	73	27

11.3.1 Residency in summer off southern Australia

In this first sub-section we consider an example in some detail based on data in years 2004-2006 to illustrate the process of developing a habitat preference curve, preference surface and preference map. In subsequent sections we present only the main results. We use residency in summer off southern Australia, referred to as “summer in SA” in short, as the example. The area and time definitions are:

Summer in SA 00’s: Area: 110-145E, 45-25S Time: January to May, 2004-2006

The average environmental conditions in southern Australia in summer, in terms of SST and *chl a*, are shown in **Figure 11.1** Note that the north-south gradient in *chl a* does not exactly follow SST contours although there is some correspondence between these two variables. Following the method described in **Section 11.1**, we construct density distributions of SST in the ocean (all locations within the defined area and times) and SST for SBT (all locations where SBT where present in the area and times, weighted by the probability of being in the resident state), and derive the preference curve as the ratio between the two density distributions (**Figure 11.2**). Notice how the distribution for SBT is much narrower than that in the ocean; the preference curve reflects this as values greater than 1 between SST of ~ 16 to 21^{o}C.

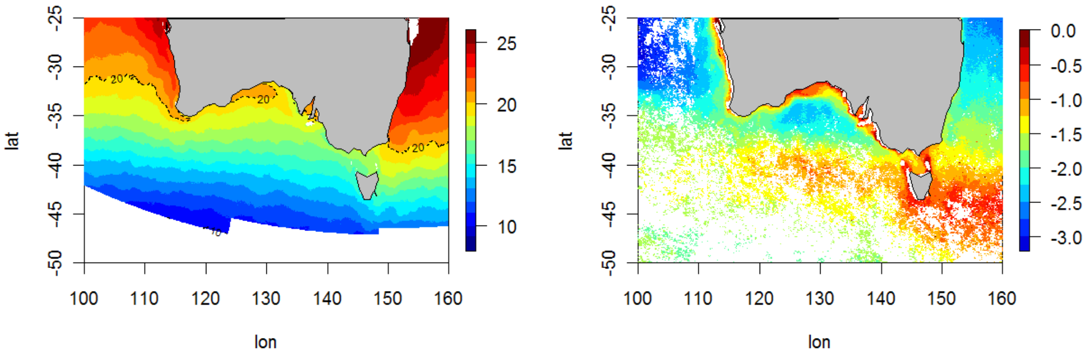


Figure 11.1. Maps of average SST (left panel) and average *chl a* (on a log scale; right panel) in Jan-May, 2004-2006.

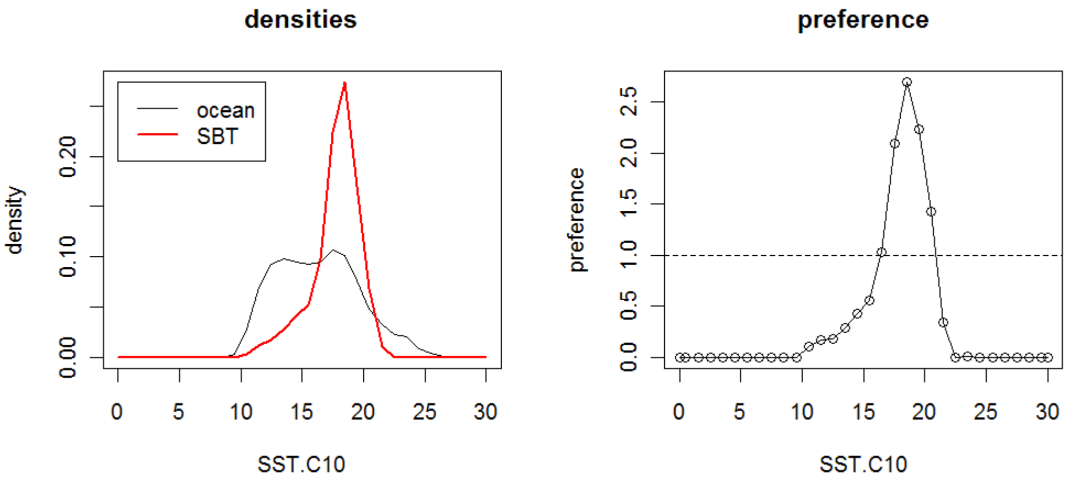


Figure 11.2. Density distributions of SST (product 103) for ocean conditions and for SBT in summer in southern Australia (110-145°E, Jan-May, 2004-06; left panel), and the resulting preference curve (right panel); values above 1.0 indicate preferred areas.

A similar figure can be constructed for just *chl a* (**Figure 11.3**). The density distribution for SBT is strongly peaked and this is again reflected in the preference curve with levels above 1 for *chl a* between ~ 0.05 and 0.17 (mg C m^{-3}). The next step is to construct preference maps by taking, for example, SST at each location within the area and finding the coinciding preference value, and colour-coding these values on a map. **Figure 11.4** shows preference maps based on the SST preference curve (left panel) and on the *chl a* preference curve (right panel). South of Australia there is not much difference between the two maps, but the maps differ quite substantially off the west coast of Australia. Before considering the implications of the preference curves for the area further west into the Indian Ocean, we construct a preference surface for the combination (or "interaction") of SST and *chl a*.

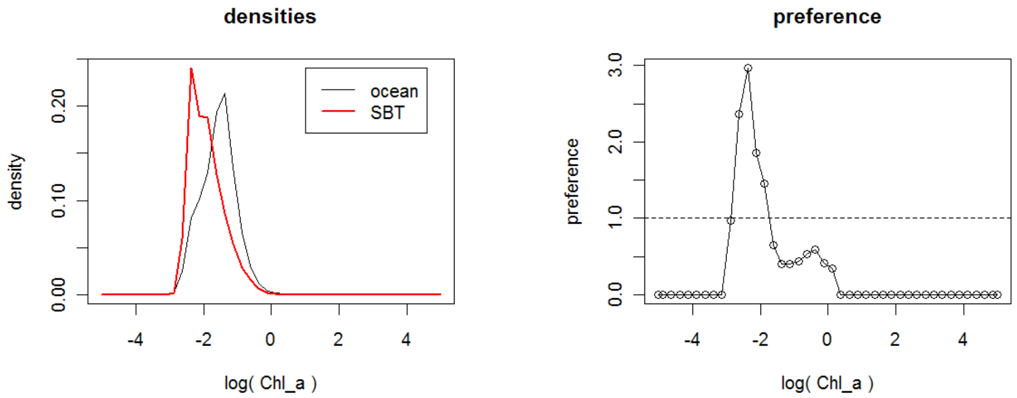


Figure 11.3. Density distributions of log(*chl a*) for ocean conditions and SBT in summer in southern Australia (110-145°E, Jan-May, 2004-06; left panel), and the resulting preference curve (right panel); values above 1.0 indicate preferred areas.

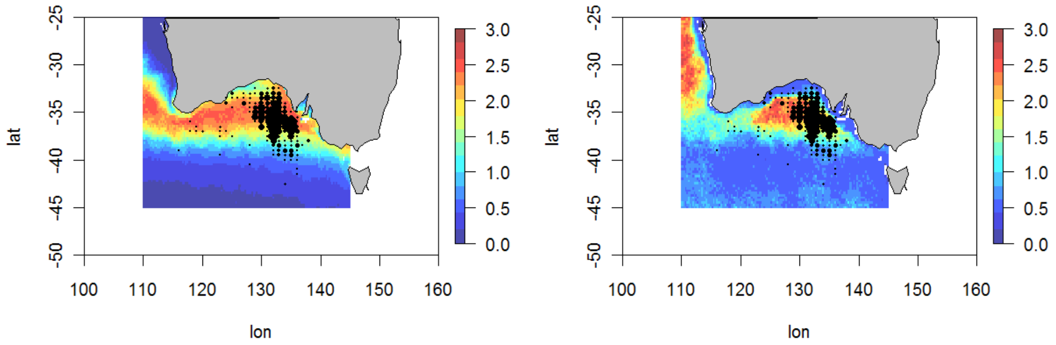


Figure 11.4. Preference maps for SBT in the resident state in summer in southern Australia, based on single covariates SST (left panel) and log(*chl a*) (right panel) and only plotted over the spatial region used in constructing the preference curve. The black dots show relative levels of residency of SBT in the same period, Jan-May 2004-2006. Values above 1.0 indicate preferred areas.

The 2-dimensional density distributions and preference surface for combinations of SST and *chl a* are shown in **Figure 11.5**. The density distributions are reasonably clear – for example the ridge of high density in (orange and red) in the ocean – but the preference map is somewhat noisier. It is therefore informative to fit a smooth surface through the noisy preference values. **Figure 11.6** shows a comparison of the noisy and the smoothed preference surfaces. The latter more clearly shows the preferred combinations of SST and *chl a*. The resulting (geographic) maps are usually very similar whether the smoothed or unsmoothed preference surface is used.

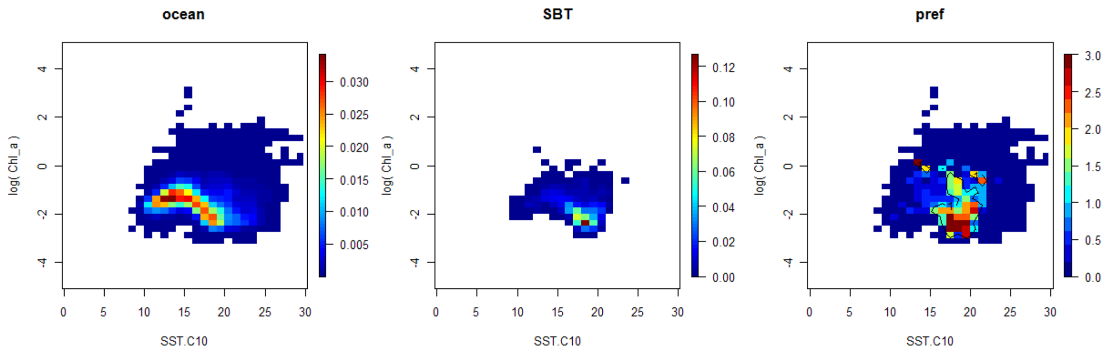


Figure 11.5. Bivariate density distributions of SST and log(*chl a*) for ocean conditions (left panel) and SBT in the resident state (central panel) in summer off southern Australia (110-145ºE, Jan-May, 2004-06), and the resulting preference surface (right panel). White areas imply no observations of those combinations in the ocean, or for SBT during the relevant moths and in the relevant area. The preference scale has been truncated at 3 for clarity, i.e. higher values are shown at same colour as 3.

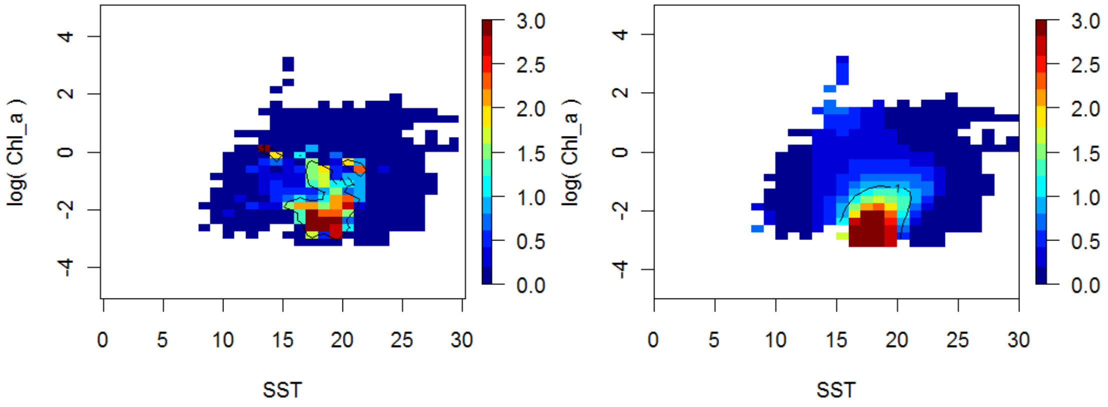


Figure 11.6. Bivariate preference surface for SBT in the resident state, in terms of SST and log(*chl a*) in summer in southern Australia (110-145ºE, Jan-May, 2004-06) unsmoothed (left panel; identical to right panel in **Figure 11.5**) and smoothed (right panel; see text for detail).

Finally, we construct a preference map (**Figure 11.7**, left panel) based on the bivariate preference surface; in this case the unsmoothed version. If we compare the contours where preference values are equal to 1 from the three approaches of i) SST only, ii) *chl a* only and iii) combinations of SST and *chl a* (**Figure 11.7**, right panel) there appears to be little difference. Arguably, the contour based on SST and *chl a* combined, is not very different from that based just on SST in the area south of Australia, but it is quite different off the east coast of WA. When we project the two preference curves and surface over a wider geographic area, an interesting picture emerges (**Figure 11.8 a,b,c**).

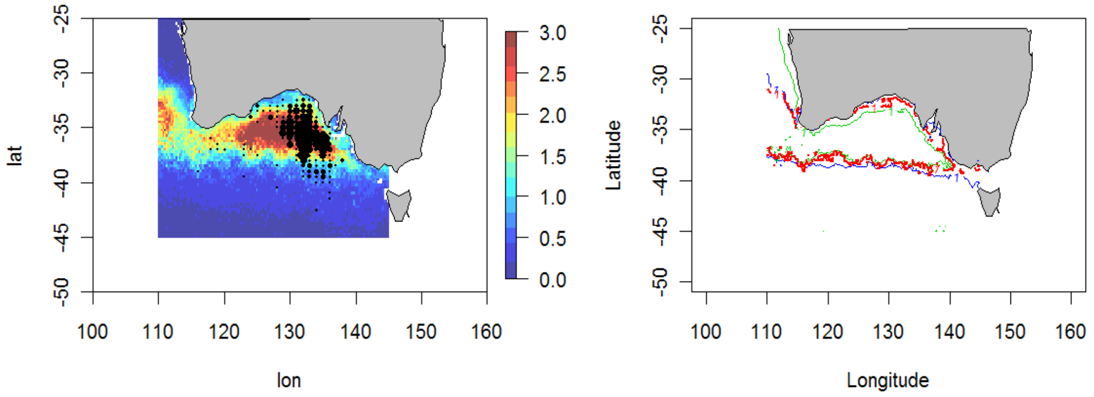
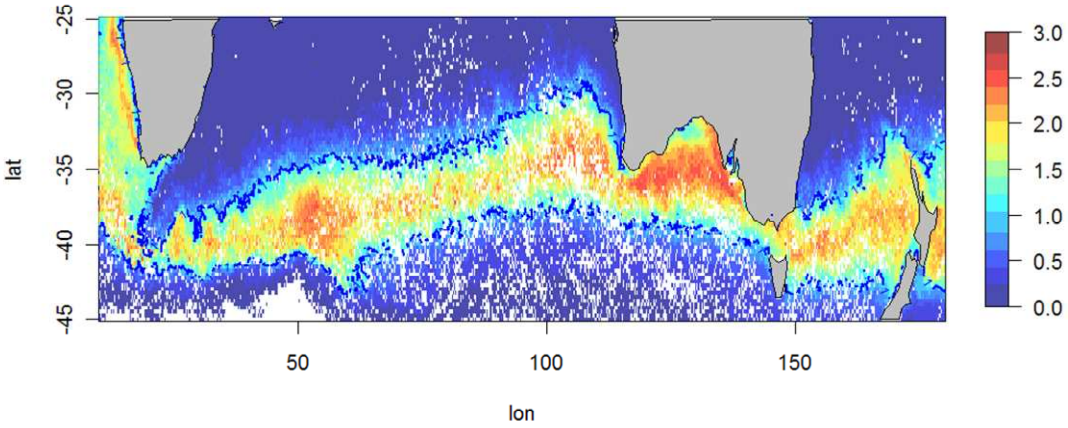
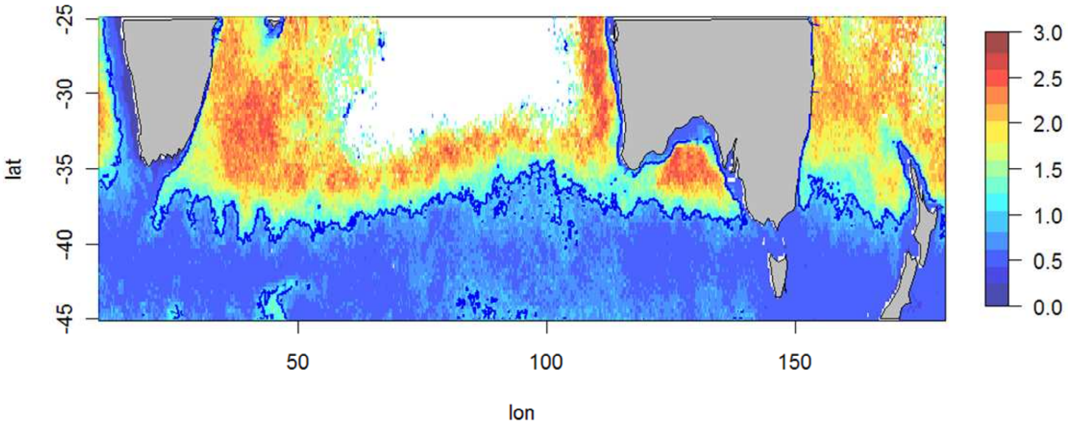


Figure 11.7. Preference map for SBT in the resident state in southern Australia, based on the bivariate preference of SST and log(*chl a*) combinations (left panel) and only plotted over the spatial region used in constructing the preference curve. The black dots show relative levels of residency of SBT in the same period. Contours of preference=1 are shown in the right panel for SST only (blue), log(*chl a*) only (green) and both covariates (red) (right panel).

a) SST preference curve



b) *chl a* preference curve



c) SST and *chl a* preference surface

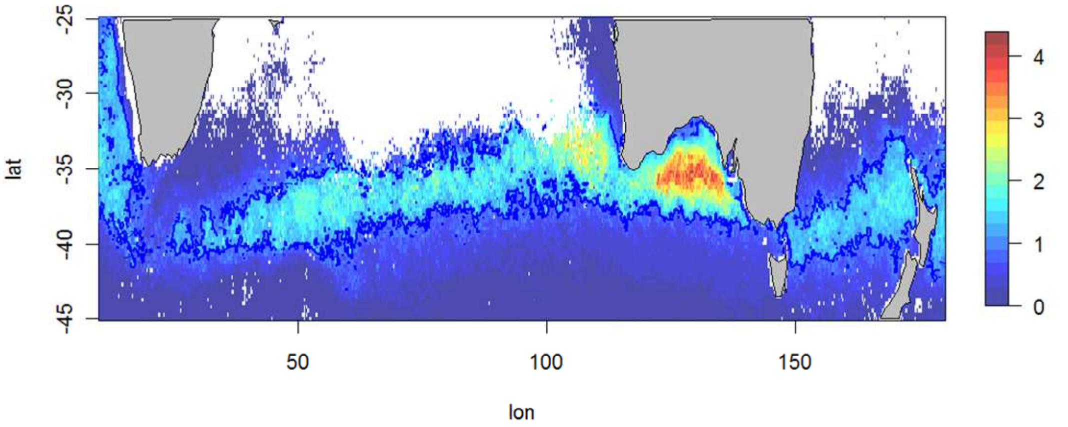


Figure 11.8. Preference maps for SBT in the resident state, based on preferences in summer in southern Australia (110-145°E, Jan-May, 2004-06) (a) just SST, (b) just *chl a* and (c) combinations of SST and log(*chl a*), projected over oceanographic conditions in the whole of the Indian Ocean. A contour at preference =1 is shown in blue. White areas reflect missing oceanographic data or covariate values outside those of the preference curve.

Over the period January and May, between 66% and 85% of the juvenile SBT are in the resident state, and of those in the resident state, between 96% and 100% are resident off southern Australia (**Table 11.2** above). It is interesting how **Figure 11.8** also strongly suggests that there are few other areas, if any, that have similar conditions in terms of combinations of SST and *chl a* as the waters off southern Australia. There were, in fact, some catches taken in the same period (January to May) off the south-west coast of WA where the map shows a hint of high preference. In the 5°x5° grid squares with western corners of 100°E, 30°S and 35°S, about 180t was reported (to CCSBT) in 2004 and about 290t in 2005 (publicly available catch data from CCSBT at www.ccsbt.org). Japanese longliners took 98% of this catch and based on their size and age frequency data, 6% were aged 2, 12% aged 3 and 11% aged 4 (publicly available size frequency data from CCSBT at www.ccsbt.org).

There are a few observations of SBT outside the area off southern Australia in the resident state during the same period. The locations are shown in **Figure 11.9**, and although most (~75%) lie within the preference contour of 1, some (~25%) lie outside. There are many possible reasons for this, such as errors in latitude, errors in the state classification, or inadequacy of the proxies and/or the model to deliver a perfect "prediction" of residency outside the area used for the preference surface.

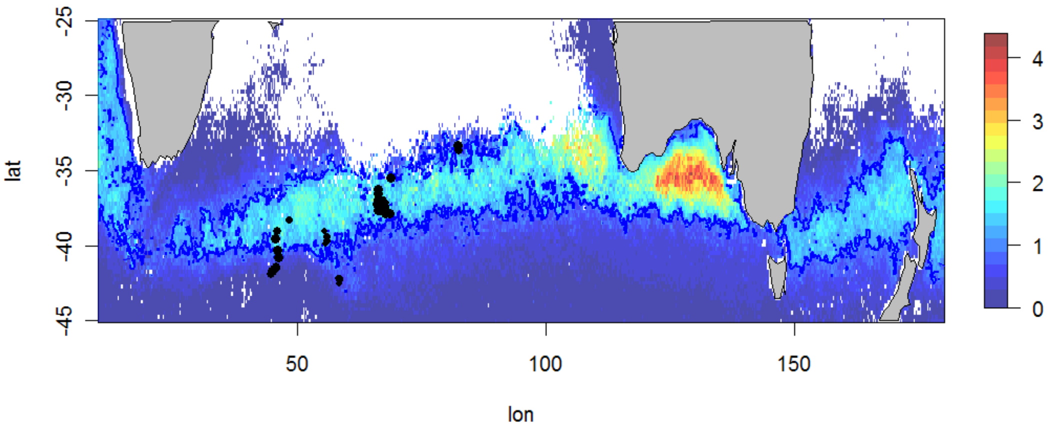


Figure 11.9. Preference map for SBT in the resident state as in Figure 11.8.c, with points (black dots) showing locations where SBT were in the resident state outside southern Australia, but in the same period (Jan-May, 2004-06). (Points do not show up when plotted as relative residency).

Residency in summer in SA: Comparison with the period 1998-2000

In order to assess temporal changes in preference distributions, we next compare results for 2004-2006 with those from the earlier period, 1998-2000; the area definition and months are identical, and we again consider preference surfaces for SBT in the resident state.

Summer in SA 90's: Area: 110-145E, 45-25S Time: January to May, 1998-2000

The preference surface, and smoothed version, in terms of SST and *chl a*, are shown in **Figure 11.10a**, and a comparison of the implied maps just for the area used to derive the preference curves are shown in **Figure 11.10b**. There is a striking difference between the two maps: in the recent period, the highest preference region lies slightly offshore in the GAB, but in the earlier period (1998-00) it lies close inshore. A repeat of the analysis for 2004-06 with just individuals of age 3 and older did not change this result. A closer look at individual years (**Figure 11.11**), however, shows that:

a) the pattern in 1998 dominates the overall result for the early period (it contributes ~3000 data points from SBT locations compared to 1999 and 2000 which each contribute ~ 1300 data points from SBT locations);

b) the pattern in 2006 dominates the overall result for the recent period (it contributes ~ 3300 data points from SBT locations compared to 2800 (in 2005) and 1600 (in 2004)

c) year-by-year preference maps can be substantially different from the pattern obtained when the SST and *chl a* data are combined across years.

The differences that are apparent in **Figure 11.11**, particularly off the south-west coast of Australia, hints at possible changes in conditions from year to year that may affect movement of SBT from WA to the GAB or to the Indian Ocean. This is discussed further in **Section 11.4**.

The projected map, for the larger area, is shown in **Figure 11.12**; there are a few differences between this map and that for 2004-06 (**Figure 11.8c**). The regions in the Indian Ocean, off the west coast of southern Africa and the Tasman Sea that have preference values of around 1.6-1.8 (light blue) in 2004-06, have preferences around 2.8 or 3.0 (yellow to orange) in 1998-2000. Differences between the maps result from differences between the preference surfaces (based on just the area off SA). These in turn are different because of differences in both the ocean conditions (**Figure 11.13)** and the SBT covariate distributions.

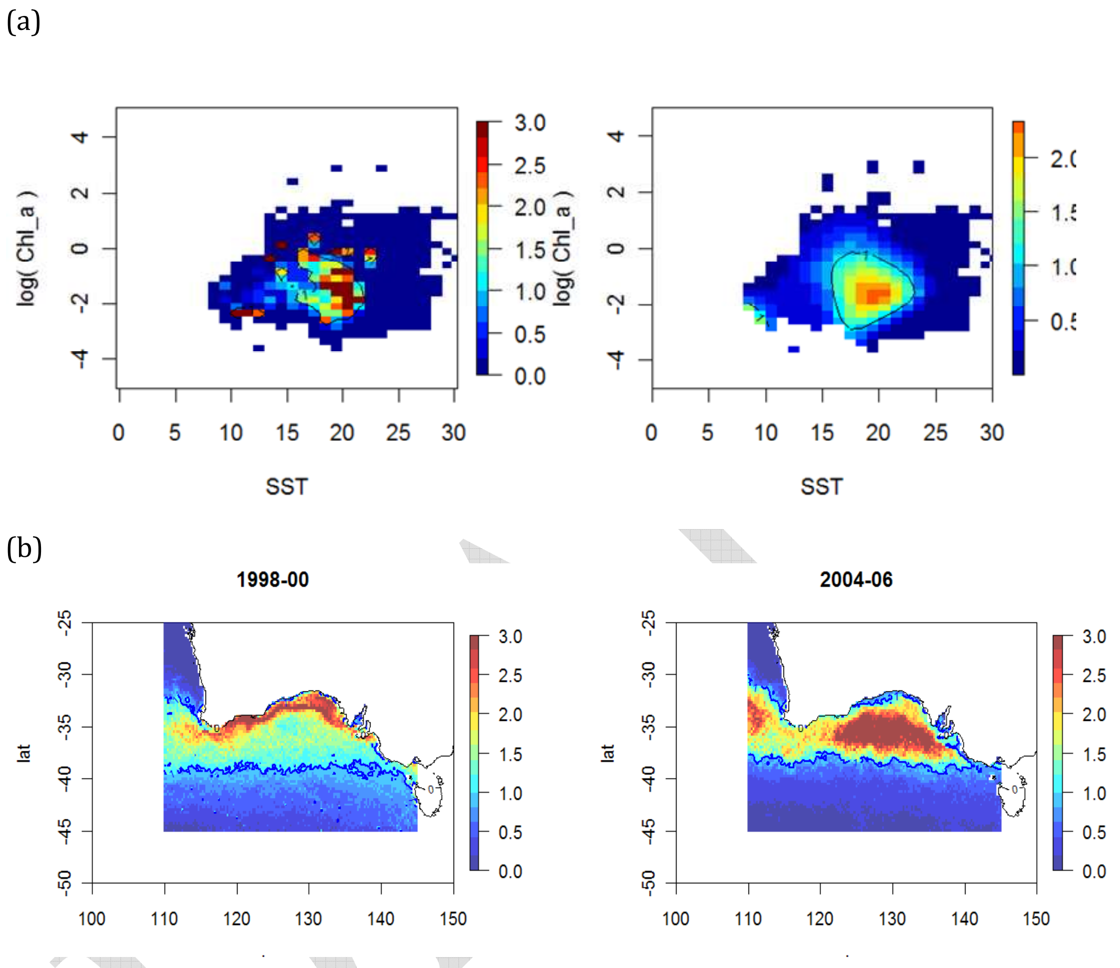


Figure 11.10. a) Unsmoothed (left panel) and Smoothed (right panel) bivariate preference surface for SBT in the resident state, in terms of SST and log(*chl a*) in summer in southern Australia (110-145°E, Jan-May, 1998-00). b) Preference maps just for the southern Australia area in 2004-06 (left panel) and 1998-00 (right panel).

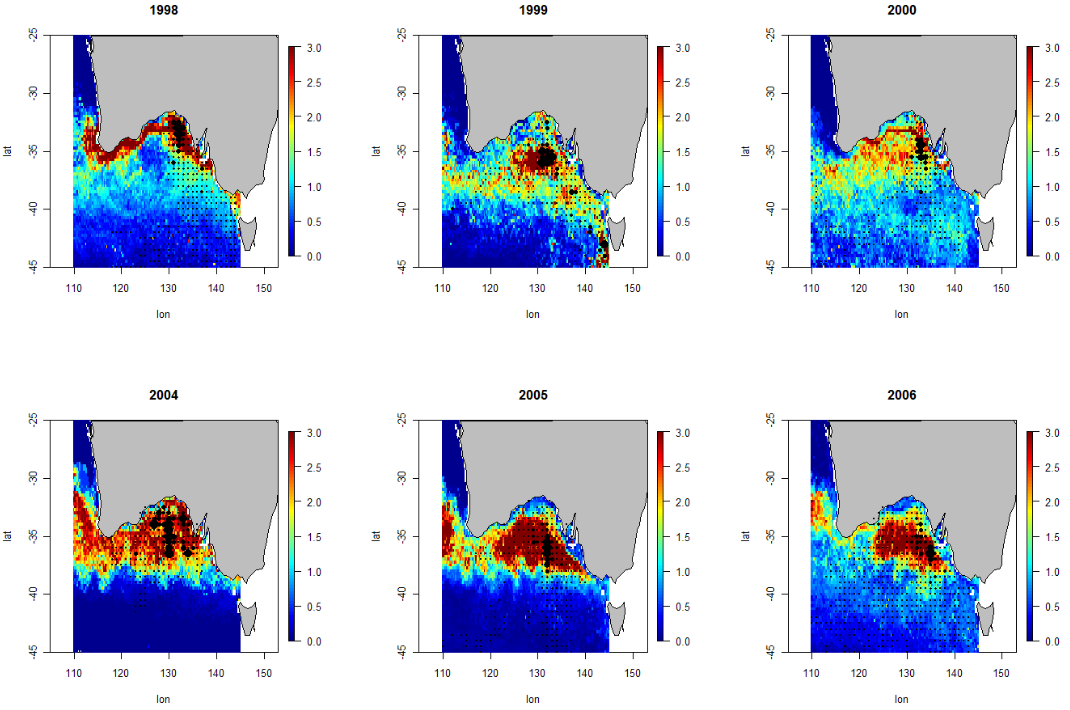


Figure 11.11. Preference maps by year, based on separate preference surfaces for each year for the early (1998-2000) and recent (2004-2006) periods in southern Australia. The area is as in Figure 11.10, for months 1-5 and SBT in the resident state.

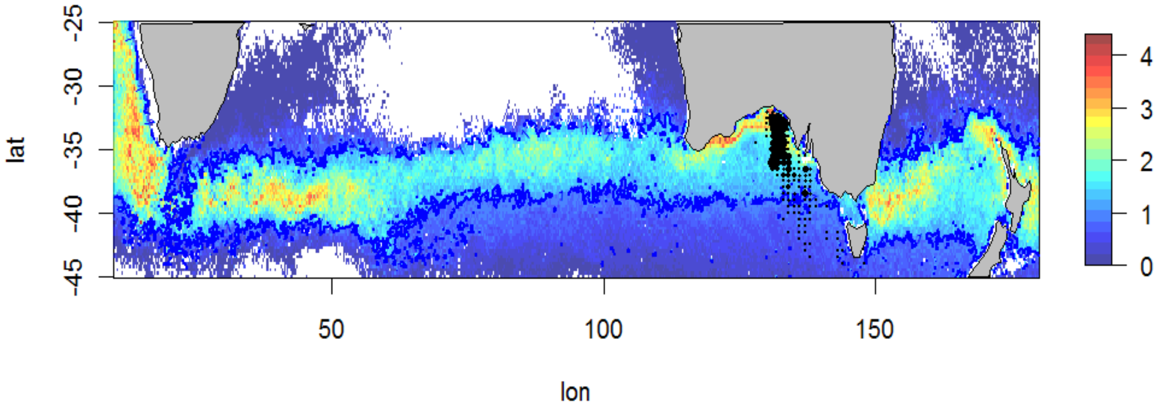


Figure 11.12. Preference map for SBT in the resident state, based on preferences in summer in southern Australia in the 90's (110-145°E, Jan-May, 1998-00) for combinations of SST and log(*chl a*), projected over oceanographic conditions in the whole of the Indian Ocean. A contour at preference =1 is shown in blue. White areas reflect missing oceanographic data or covariate values outside those of the preference curve. Black dots are proportional to the sums of resident state probabilities in 2°lon x 1° lat grid squares.

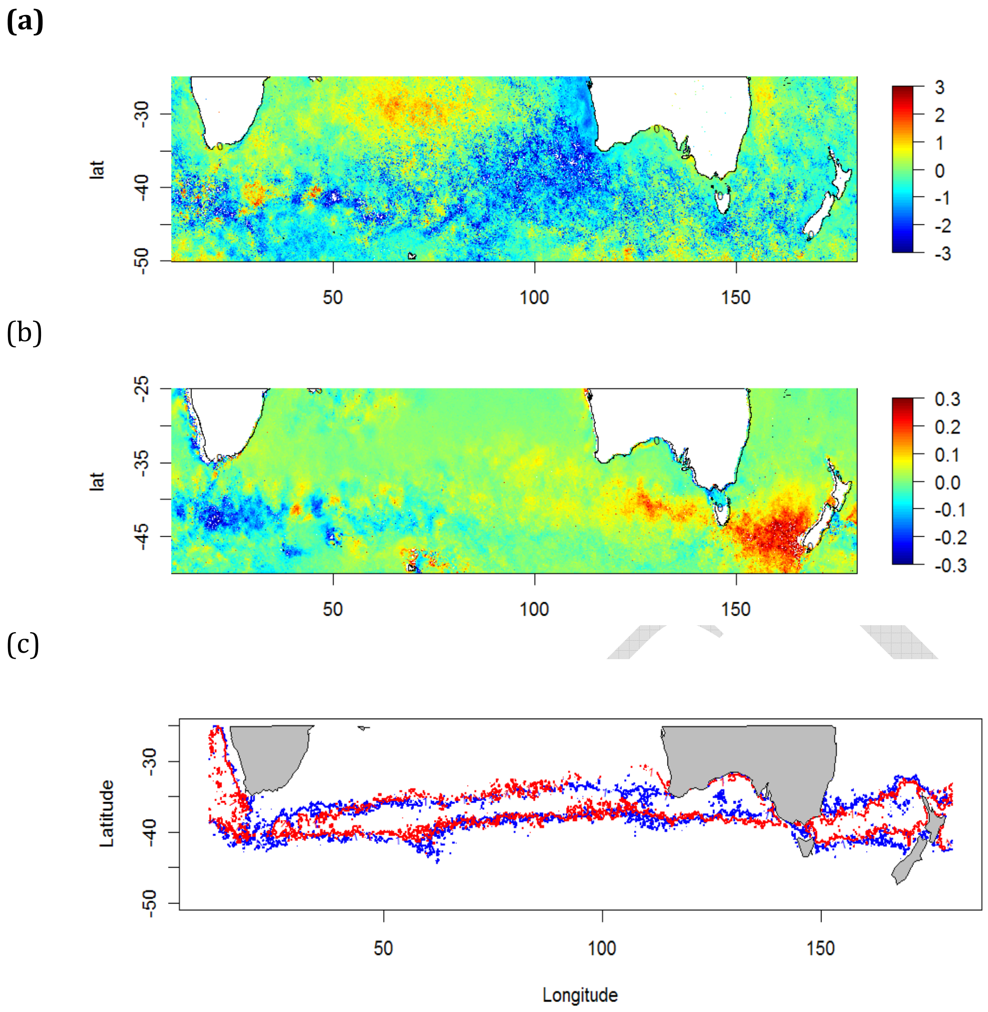


Figure 11.13. Differences between (a) average SST in Jan-May 2004-06 and the same months in 1998-2000; (b) average *chl a* for the same periods. Positive values mean 2004-06 values were greater, and vice versa. Panel (c): contours at preference=1 for 1998-00 (blue) and 2004-06 (red).

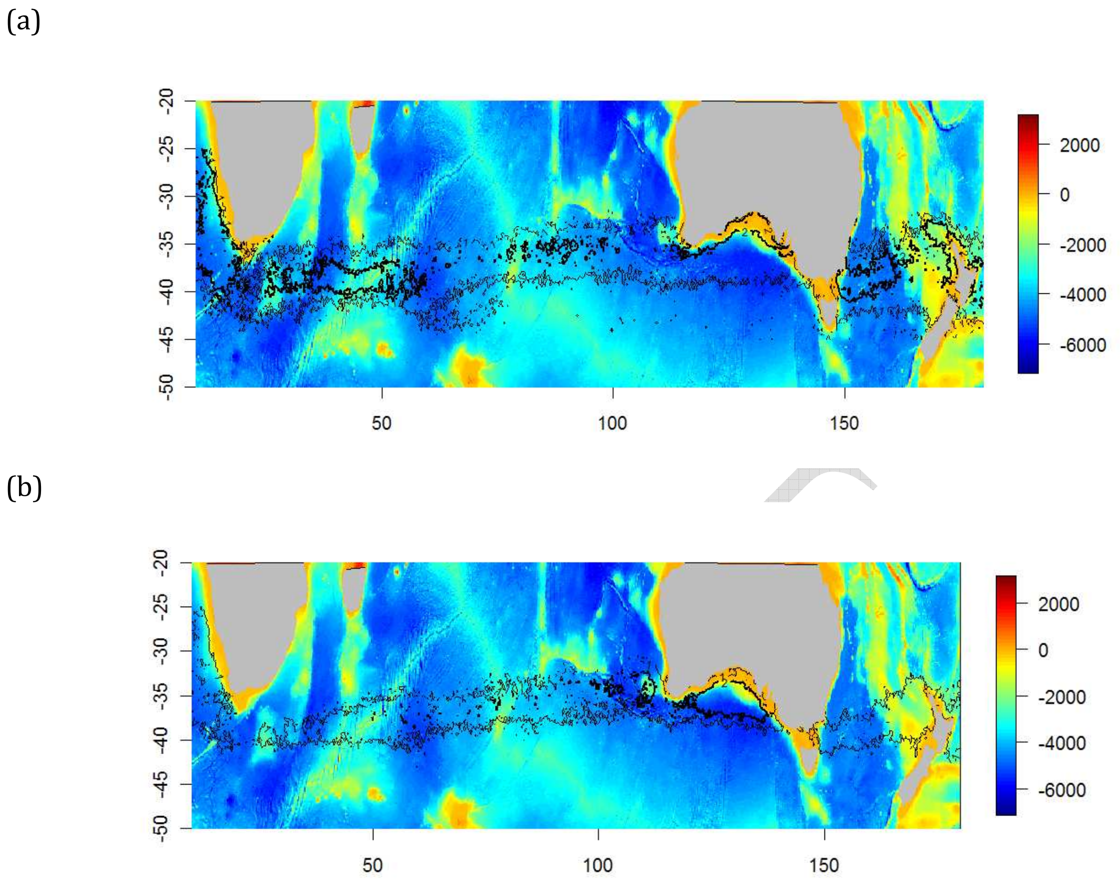


Figure 11.14. Preference contours at values of 1 (thin black line) and 2 (thick black line) for (a) 1998-00 and (b) 2004-06 plotted over bathymetry of the region, based on preferences of SBT resident in southern Australia in January to May.

If we plot the difference between average SST in Jan-May 2004-06 compared to 1998-2000 at each grid point, and do the same for average *chl a*, some patterns emerge (**Figure 11.13 a,b)**. For example, the area off South Africa where the 2004-06 period had lower preference than in 1998-00, shows up as having lower *chl a* levels. At the same time, however, the area in the southern Tasman Sea where 2004-06 also had lower preference than in 1998-00 has higher *chl a* levels. It is not obvious why this should be the case, but we note that the relationship between SST and *chl a* is not linear and it is unlikely that SBT have a “linear” response to *chl a* levels. For other species, a habitat preference for an intermediate value of *chl a*, possibly related to water clarity for feeding has been shown (Brill *et al.* 2002). Other than these two differences, and the difference in location of the highest preference area, the contours at preference=1 are quite similar for the two periods (**Figure 11.13 c**).

Preference contours (at values of 1 and 2) shown on a map of the bathymetry (**Figure 11.14**) does not highlight any additional patterns associated with features. It is in fact more informative to refer to **Box 3.2, Figure 3**, which shows the circumpolar fronts in the Indian Ocean; the high preference area in the Indian Ocean appears to be associated with the South Subtropical, the Agulhas and the North Subtropical Fronts (also see Bestley *et al*. 2008).

Sensitivity analyses with data from 14 days either side of the March equinox removed, showed only very minor differences between the preference surfaces and no discernable effect on the preference maps (**Appendix 7**).

Summary: Residency in summer – early versus late period

Preference surfaces in terms of combinations of SST and *chl a* lead to more informative maps of preference than each covariate on its own.

The preference ranges in 2004-2006 are 15-21^{o}C for SST and between 0.05 and 0.37 mg C m^{-3} for *chl a*. It is similar in 1998-2000, but includes some combinations of higher SST (up to 23^{o}C) and higher *chl a* (up to 1 mg C m^{-3}).

The highest preferences are in the GAB in both periods, but in 2004-06 it is further offshore than in 1998-00.

The earlier period is dominated by data from 1998 and there is interannual variability during both periods; the annual patterns hint at differences which may sometimes affect movement of fish off WA into the GAB or the Indian Ocean (see Discussion).

Preference maps projected over the broader area reveal a band of high preference across the Indian Ocean. In the recent period, this habitat is ‘fragmented’ around South Africa, whereas it is more continuous in the early period (**Figures 11.8c** and **11.12**)

In the Tasman Sea, the band of high preference is narrower, and a high preference region off the coast of NSW is less prominent in the recent period than it was in the early period (**Figures 11.8c** and **11.12**; see Discussion).

11.3.2 Residency in winter and spring in the Indian Ocean

By May/June juvenile SBT typically start leaving the waters off southern Australia (departure from the GAB typically begins around March) and migrate east into the Indian Ocean (IO). In June and July the furthest westerly locations in the resident state are around 80°E. Some SBT spend the next several months switching between being resident in the IO and migrating further west towards South Africa, but others may only migrate as far as, say 90°E and remain resident there until they return to the GAB in late spring, early summer. In the next set of figures we consider the preference surface for SBT in the resident state in the IO during August to November. We first look at the period 2004-2006; the area and time definitions are:

Winter in IO 00's: Area: 40-115°E, 45-25°S Time: August to November, 2004-2006

By October and November, there are high levels of residency throughout the southern IO, but it remains concentrated in certain areas associated with physical features (**Figure 11.15**). What does the preference surface in terms of SST and *chl a* look like for this area and time?

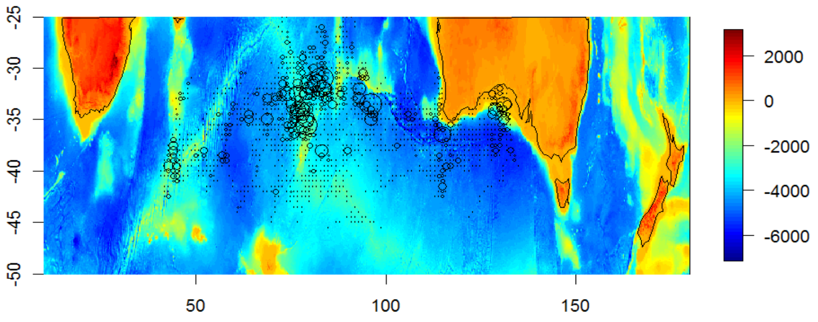


Figure 11.15. Areas of residency in October and November, 2004-2006 plotted over a map of bathymetry. Circles are proportional to the sum of the probabilities of resident state (from HMMs) in each (2°lon x 1°lat) grid square, and relative to the maximum in any grid square.

The unsmoothed and smoothed preference surfaces shows high preference in the temperature range between about 11 and 20°C, and *chl a* levels below about 0.35 mg C m^{-3} (log(*chl a*) < ~ -1) (**Figure 11.16a).**

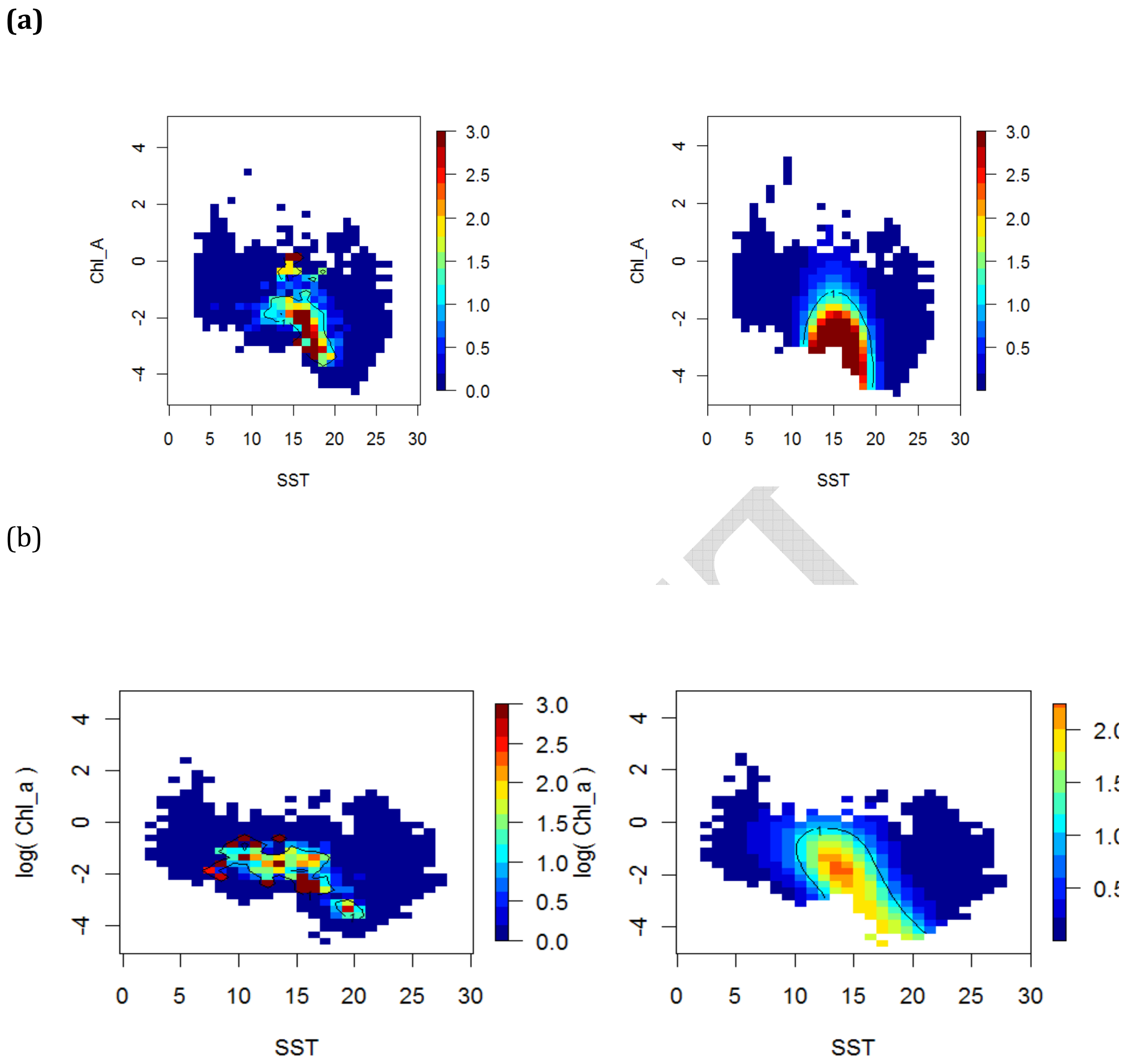


Figure 11.16. Unsmoothed (left panel) and smoothed (right panel) bivariate preference surface, for SBT in the resident state, in terms of SST and log(*chl a*) in winter in the Indian Ocean (40-115^{o}E, August-November) for (a) 2004-06 and (b) 1998-00.

Figure 11.17a shows a map of preference levels projected over the larger area (10-180^{o}E) based on the smoothed preference surface for 2004-2006. There is, in fact, not much difference between maps based on the smoothed or unsmoothed preference surfaces. Compared to the “preferred conditions” during residency off southern Australia in summer, residency in the Indian Ocean in August to November is associated with a cooler temperature range between 11 and 20^{o}C. The *chl a* levels are similar, but include lower values than the preference surface for southern Australia in summer. This is at least the case in 2004-2006. Note that although only data in the IO were used to estimate the preference surface, the projected map shows a high preference region off southern Australia where some SBT remained resident (or returned early).

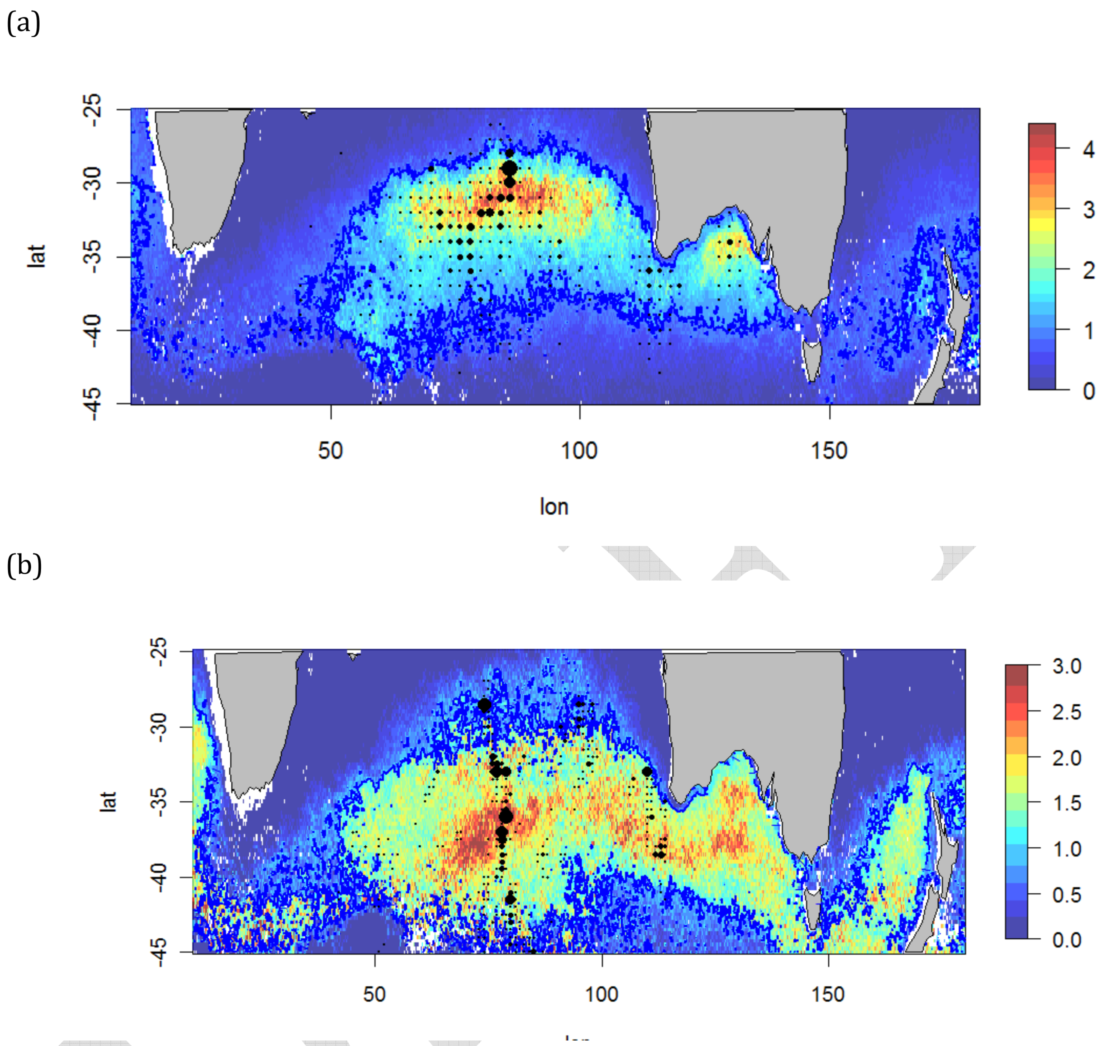


Figure 11.17. Preference map for SBT in the resident state, based on preferences in winter in the IO (40-115°E, August-November) for combinations of SST and log(*chl a*), projected over oceanographic conditions in the whole of the Indian Ocean and in (**a**) 2004-06 and (**b**) 1998-00. A contour at preference =1 is shown in blue. White areas reflect missing oceanographic data or covariate values outside those of the preference curve. Black dots show relative levels of residency in each (2°lon x 1°lat) grid square.

It is interesting that the high preference region (preferences above, say, 1.25) in **Figure 11.17a** essentially stops at about 50°E. The region to the south and south-east of South Africa has fewer grid squares with preferences above 1. Although some catches are taken in the region ~ 40°S, between 30 and 45°E, the highest monthly mean catches in that region (3 5°x5° grid squares) were taken between May and July in 2004-2006 (~ 180tonnes). In the other months, catches in that region are between 0 and 5 tonnes (publicly available data from CCSBT at www.ccsbt.org). In this case too, a preference map based on SST alone has a continuing band of high preference linking the Indian Ocean to the Atlantic Ocean, suggesting the combination of SST and *chl a* is important in defining SBT preferences.

Winter/spring in the IO: Comparison with the period 1998-2000

We compare results for 2004-2006 with those from the earlier period, 1998-2000; the area definition and months are identical, and we again consider preference surfaces for SBT in the resident state.

Winter in IO 90's: Area: 40–115°E, 45-25°S Time: August to November, 1998-2000

The preference surface, and smoothed version, in terms of SST and *chl a*, are shown in **Figure 11.16b** and the projected map in **Figure 11.17b**. The shape of the smoothed preference surface is quite a bit different for that in 2004-06. The maps too have some striking differences. The earlier period has a much larger area of high preference around Tasmania and into the Tasman Sea than the more recent period. The earlier period also shows a somewhat larger area of high preference off South Africa, though it is rather broken up. Between 1998 and 2000, the highest mean monthly catches in the region ~ 40°S, between 30 and 45°E were taken over a longer period, March to July (~ 160 tonnes). Within the central IO, the highest preference area in the earlier period lies slightly further south than in the recent period. The longitudes at which juvenile SBT have high probabilities of being resident are much more limited and concentrated in 1998-2000 than in 2004-2006. The analysis for 1998-2000 involves 20 individuals and 4517 data points, whereas that for 2004-2006 involves 32 individuals and 8265 data points. Part of the difference could simply be due to the larger number of individuals, but it could also relate to the changes in movement behaviour we identified in **Section 8**.

Plots of the differences between the density distributions and preference surfaces for the two periods highlight where the main differences lie (**Figure 11.18**); there are differences both in the density distributions of the ocean and SBT which implies differences in the preference surfaces.

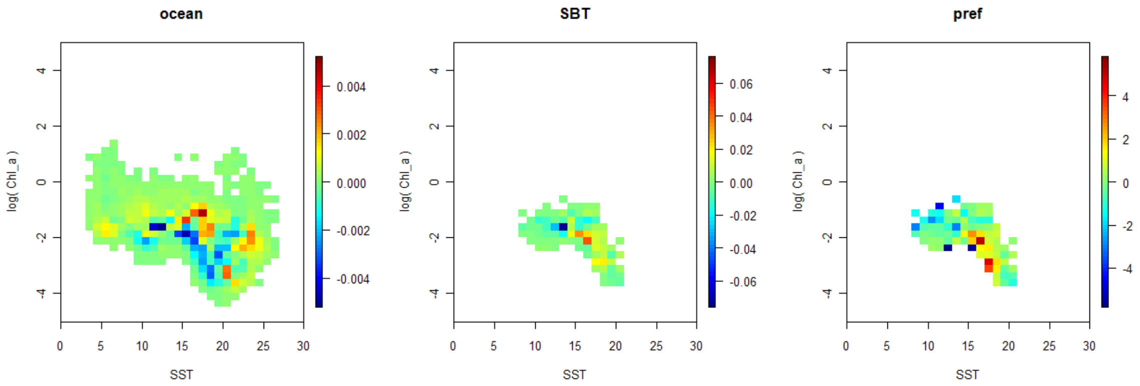


Figure 11.18. Differences between the 2004-06 and the 1998-2000 density distributions in terms of SST and log(*chl a*) for ocean conditions (left panel) and SBT (central panel), and for the preference surfaces (right panel). Green pixels imply identical or very similar values; warm colours mean higher density or preference in 2004-06 than 1998-2000; cool colours mean lower density or preference in 2004-06 than 1998-2000.

We note that although the average age in the 1998-2000 set is just over 3 years, and that in the 2004-2006 set about 2.5 years, a preference curve and map based just on age 3 and older SBT in 2004-2006 still show most of these differences.

Sensitivity analyses with data 14 days either side of the September equinox removed showed only very minor differences between the preference surfaces and no discernable effect on the preference maps (**Appendix 7**).

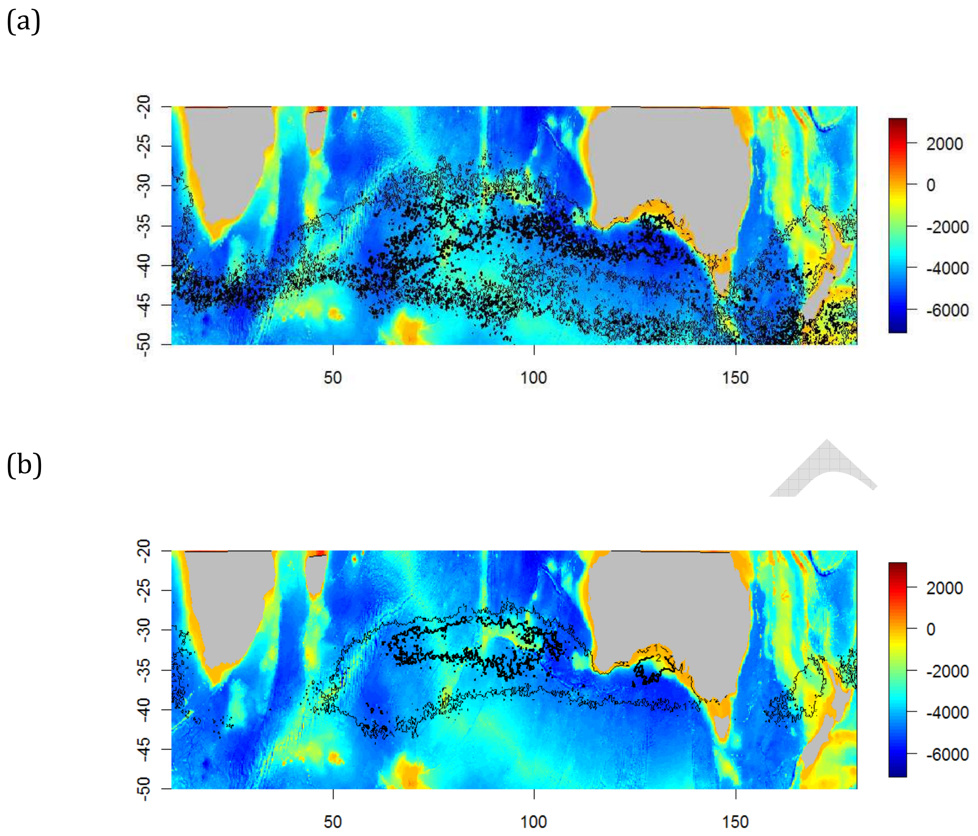


Figure 11.19. Preference contours at values of 1 (thin black line) and 2 (thick black line) for (a) 1998-00 and (b) 2004-06 plotted over bathymetry of the region, based on preferences of SBT resident in the IO in August to November.

Preference contours (at values of 1 and 2) shown on a map of the bathymetry (**Figure 11.19**) should again be viewed in the context of the map of circumpolar fronts (**Box 3.2, Figure 3**). In addition to the South Subtropical, the Agulhas and the North Subtropical Fronts, the high preference area for residency in winter/spring in the Indian Ocean appears to also be associated with the Subantarctic front, particularly in 1998-2000.

Summary: Winter/spring residency in the Indian Ocean

The preference ranges in 2004-2006 are 11-20°C for SST and between 0.02 and 0.35 mg C m^{-3} for *chl a*. The SST range is similar in 1998-2000, but the surface includes higher values of *chl a* (up to 1 mg C m^{-3}). The shape of the habitat preference surface is somewhat different.

The highest preferences are in the central IO in both periods, but there is also an area of high preference in the GAB in both periods

In the recent period, the high preference area essentially stops at 50^{o}E, with only very slight indications of preferences (values ≈ 1) running in a band south of South Africa and up the west coast of South Africa.

In the earlier period, there is more of an indication of a (potentially) connecting band of high preferences south of South Africa and potentially linking with a high preference band off the west coast of South Africa.

In the Tasman Sea, the band of high preference is almost entirely absent in the recent period, and there is no connecting band of high preference between the GAB and the Tasman Sea.

In the earlier period there is a connecting band of high preference between the GAB and Tasman Sea and a high preference area off the west coast of New Zealand (also see **Section 11.3.3**).

11.3.3 Migration east to the Tasman Sea in autumn

The observation that a substantially smaller proportion of archival tags showed migration into the Tasman Sea since 2000 compared to the 1990s was discussed in **Section 8**. Here we consider whether there is any evidence or signal from environmental covariates to suggest why this may have occurred.

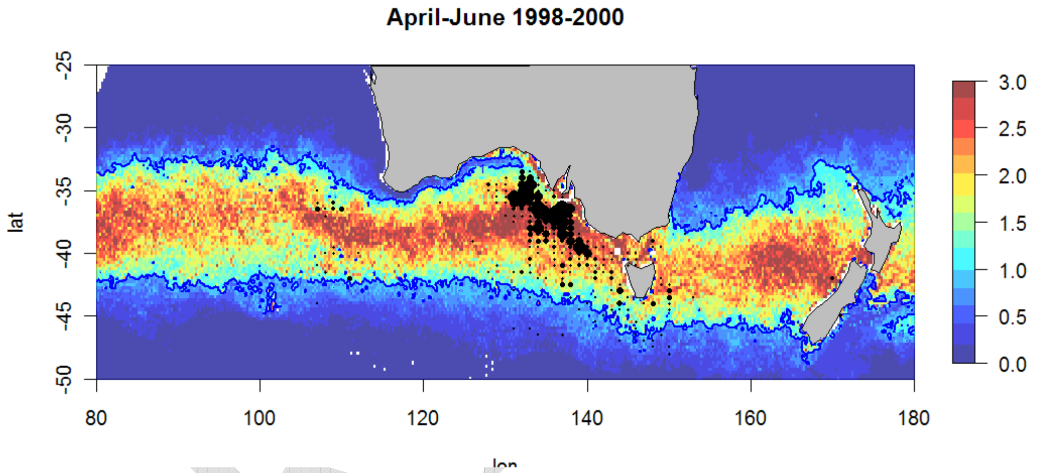
In the late 1990s, the first migration to the Tasman Sea, after summer in the GAB, was primarily in the second quarter, particularly April and May. Regarding the area to consider, it is potentially informative to include some waters in the eastern Indian Ocean. The time and area definitions for this sub-section are:

Autumn to Tasman, 90’s: Area: 80–180^{o}E, 45-25^{o}S Time: April to June, 1998-2000
Autumn to Tasman, 00’s: Area: 80–180^{o}E, 45-25^{o}S Time: April to June, 2004-2006

In contrast to earlier sub-sections, we begin with direct comparisons between the two periods as it is not obvious whether any differences between the two periods would be reflected by preferences relating to the resident and/or migration states. At the end of this sub-section we comment on additional sensitivity analyses.

Maps (**Figure 11.20**) of the preference surface for SBT in resident state and in terms of SST and *chl a* combined show marked differences between the two periods. In 1998-2000 there is a band of high preference values that extends along the west and south coasts of Tasmania and into the Tasman Sea; the contour at preference = 1 lies well offshore and south of Tasmania. In 2004-06 there is no such connecting band of high preference values; the contour at preference = 1 runs into Tasmania's north-west coast, and resumes off the south-east coast. The differences are even clearer when we just focus on the area around Tasmania (**Figure 11.21**).

(a)



(b)

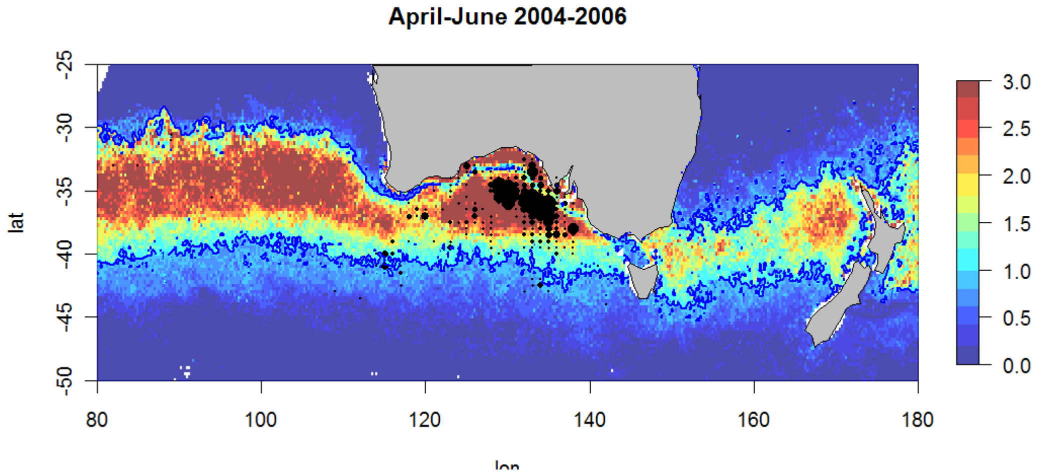


Figure 11.20. Preference maps for SBT in the resident state in April-June over the area 80-180°E, for combinations of SST and log(*chl a*) in (a) 1998-2000 and (b) 2004-2006. A contour at preference =1 is shown in blue. Black dots show relative levels of residency in each (2°lon x 1°lat) grid square.

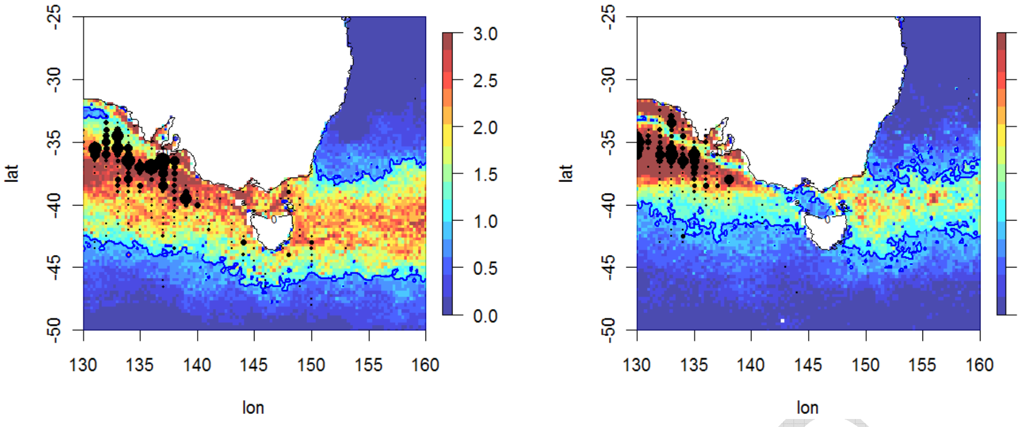


Figure 11.21. Identical to **Figure 11.20**, but zoomed in on the area around Tasmania; left panel is for 1998-00; right panel for 2004-2006.

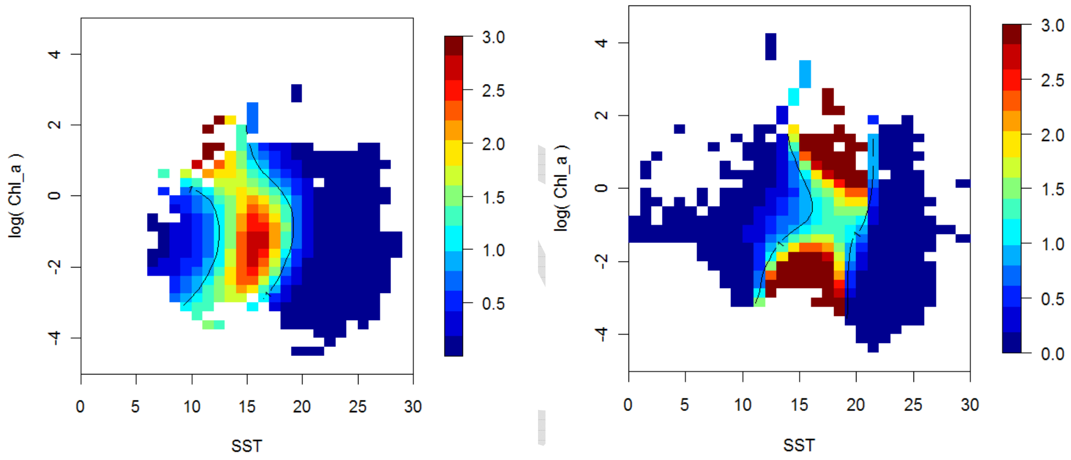


Figure 11.22. Smoothed bivariate preference surface, for SBT in the resident state in terms of SST and log(*chl a*) in the area 80-180°E in April to June of 1998-00 (left panel) and 2004-2006 (right panel).

The differences between the smoothed preference surfaces for the two periods (**Figure 11.22)** may be a large part of the differences between the maps. One way of checking whether this is the case, is to use the preference surface from the 1998-00 period and project that onto a map of SST and *chl a* conditions in the 2004-06 period. The result (**Figure 11.23**) still shows a much lower preference region off the west coast of Tasmania compared to that in the left panel of **Figure11.21**; the gap is arguably less extreme, but it is still evident. This suggests that it is not just the difference in the preference surface that is causing the difference in the preference maps.

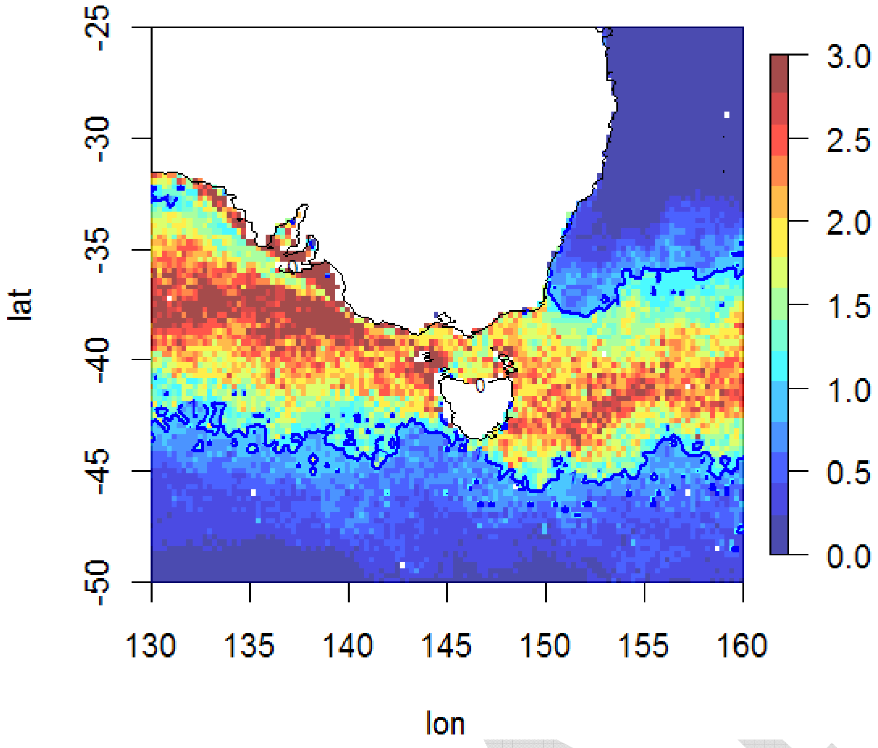


Figure 11.23. Preference map for SBT from combinations of SST and log(*chl a*) in April-June 2004-2006, but based on the preference surface from April-June 1998-00.

If we plot the difference between the average SST values in (April-June) 2004-06 and those in 1998-00 at each grid point, and do the same for *chl a*, some patterns emerge (**Figure 11.24**). The area off south-west Tasmania was cooler in April-June 2004-06 than in the same months in 1998-00, by up to 2°C; this can be seen in light and dark blue area south-west of Tasmania. At the same time, the *chl a* levels were higher (by about 0.1 mg C m^{-3}) just offshore, and further offshore it was slightly higher or slightly lower, so on average not substantially different.

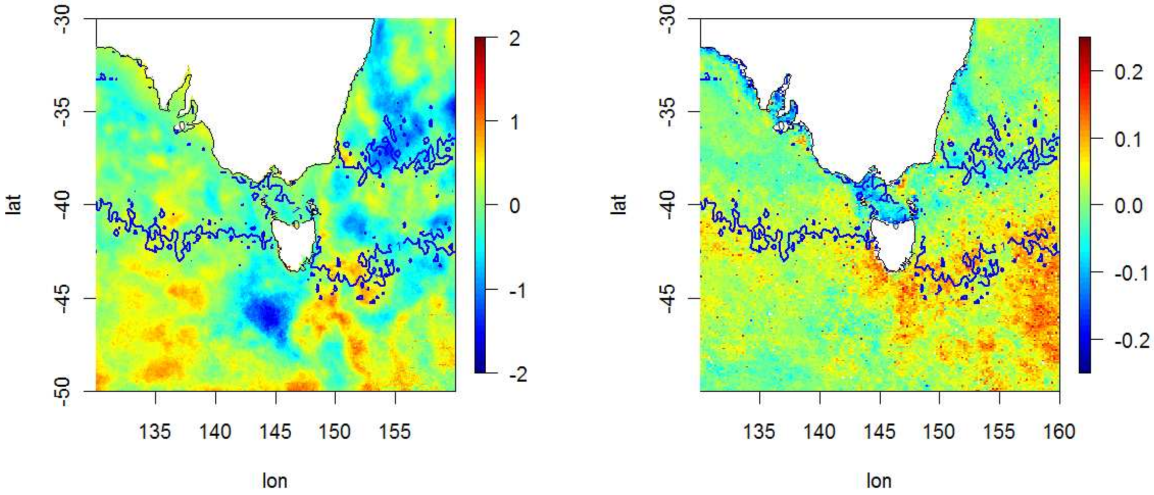


Figure 11.24. Maps of the difference between SST in the two periods (April-June 2004-06) and (April-June 1998-00) (left panel) and similar for *chl a* (right panel). The dark blue contour is where preference=1 for the 2004-06 period (i.e. identical to that in the right panel of **Figure 11.21**).

Sensitivity analyses

A substantial amount of sensitivity analyses were also conducted to explore the strength of the pattern between the early and late period. The absence of high preference values (a gap) off south-west Tasmania in 2004-06 is clearest (**Table 11.3**) when the combination of SST and *chl a* are used in the construction of the preference surface and when the preference surface from the same period (rather than that from 1998-00) is used. It is evident irrespective of whether the preference surface is based on all states, or whether it is based on weightings by the probabilities of the resident state, or the “migrating East” state. Furthermore, this pattern seems to persist into the third quarter (Jul-Sep; not shown in Table).

Table 11.3. Summary of comparisons between 1998-00 and 2004-06 preference maps, with particular reference to whether there is a "gap" of preference values < 1 off the west coast of Tasmania in 2004-06. The first column indicates which state probability weightings were used; the second whether two different preference surfaces were used (one for each period), or whether the 1998-00 preference surface was projected onto SST and *chl a* conditions for 2004-06. Results are then given for preference curves based only on SST, only on *chl a* or on combinations of the two.

ASSUMPTIONS		**RESULTS**		
State weighting	**One or two preferences**	**Preference based on SST only**	**Preference based on *chl a* only**	**Preference based on both SST and *chl a***
Resident state	Two different preferences	Slight gap	Gap NW of Tas and lower preferences	Gap and lower pref
	Project with 1998-00 preference	No gap	No gap	Gap but less than with changing preferences
Migrating East state	Two different preferences	No gap, but lower preference	Gap NW of Tas and lower preferences	Gap and lower pref
	Project with 1998-00 preference	No gap	No gap	Gap but less than with changing preferences
All states (no weighting)	Two different preferences	Slight gap/ lower & narrower preference region	Clear gap W of Tas	Gap and lower preferences
	Project with 1998-00 preference	No gap but lower pref	No gap	Gap but less than with changing preferences

All the analyses presented so far were based on location estimates from Trackit. In **Section 7** we presented some results for an alternative method, the grid-based HMM method, and noted that although the longitudes are, for the most part, very similar, there can be some large differences between latitude estimates. One way of checking the sensitivity of results to different latitudes is to use the alternative set of tracks in the same analysis. The grid-based HMM tracks are only available for a set of tags from the 2000s, so only results for 2004-06 have been obtained. Also, we only consider a version based on all states (no weighting) because the resident/migration-state HMMs have not been applied to the grid-based HMM tracks. The result is again very similar (**Figure 11.25**) with a clear gap in high preference values off Tasmania, irrespective of which set of tracks are used in calculating the preference surface.

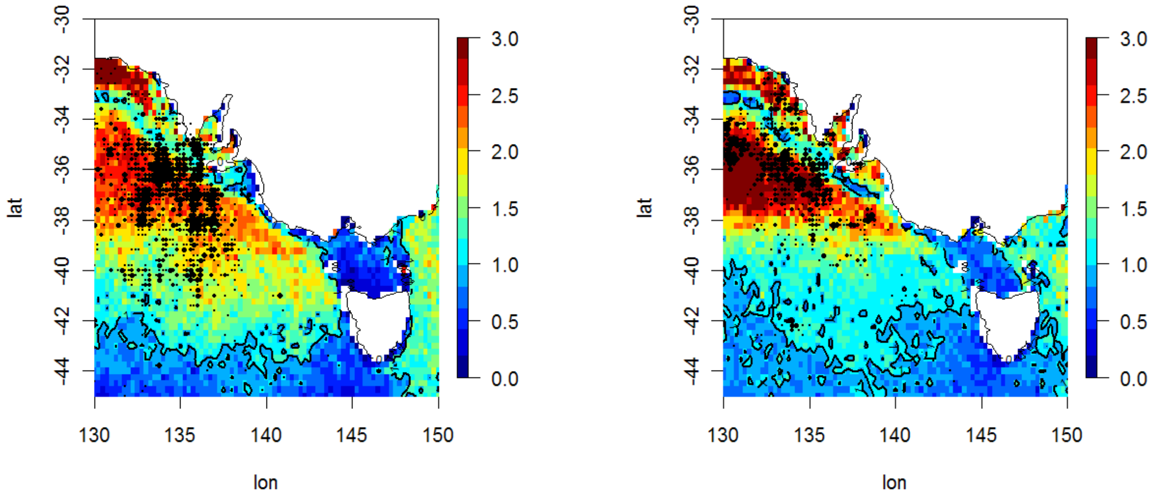


Figure 11.25. Preference maps for April-June 2004-06, over the area 80-180°E for combinations of SST and log(*chl a*). All states were included (i.e. no weighting). The preference surfaces underlying the maps were based on locations estimated by the grid-based HMM method (left panel) and Trackit (right panel). A contour at preference =1 is shown in black. Black dots show relative counts of observations in each (2°lon x 1°lat) grid square.

Finally, the 1998-00 subset of tags in these analyses are mostly from 3-year olds (mean age 3.1), whereas the 2004-06 subset covers a wider range from 2- to 5- year olds (mean age 2.5). We know that individuals change their behaviour as they grow larger (see e.g. Gunn and Young, 1999). It is therefore worth exploring whether the pattern could be due to this difference in age, and the most direct comparison is between results for just 3-year-olds in the two periods (**Figure 11.26**). The gap in high preference values off Tasmania again appears in 2004-06, but it is interesting to note that it is somewhat less extreme than that in **Figure 11.21** (right panel) which is based on all ages. The reason is clear when we look at a similar map just for 2-year-olds in 2004-06 (**Figure 11.27**); 2-year-olds are much more strongly associated with inshore waters, and the gap in high preference values off Tasmania is even larger.

In addition, sensitivity analyses with data 14 days either side of the March equinox removed showed only very minor differences between the preference surfaces and no discernable effect on the preference maps (**Appendix 7**). In this case there were very few data points removed, just at the start of April.

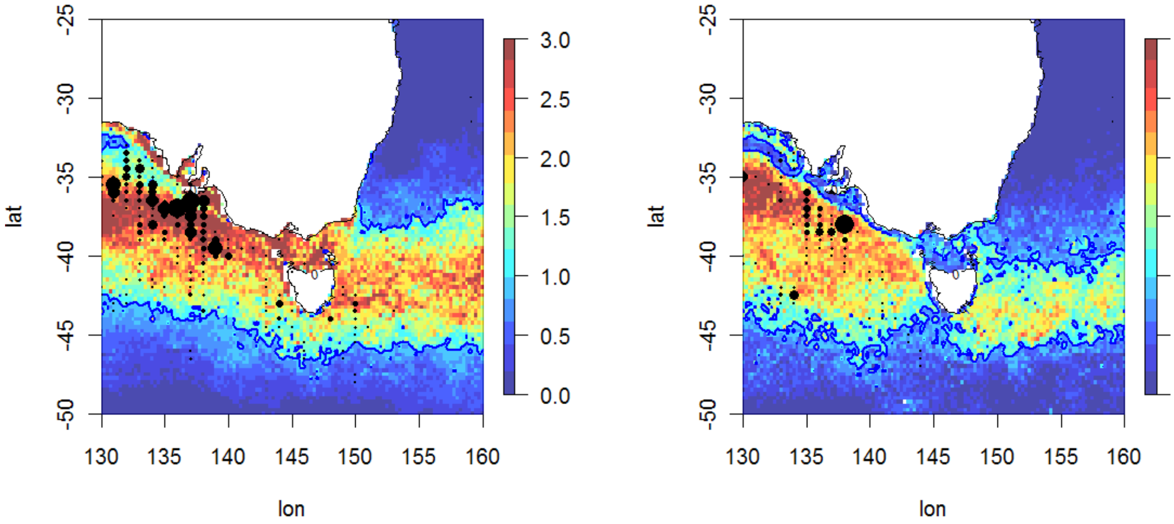


Figure 11.26. Preference maps for age 3 SBT in the resident state, April-June over the area 80-180°E and for combinations of SST and log(*chl a*) in 1998-00 (left panel) and 2004-06 (right panel). A contour at preference =1 is shown in black. Black dots show relative counts of observations in each (2°lon x 1°lat) grid square.

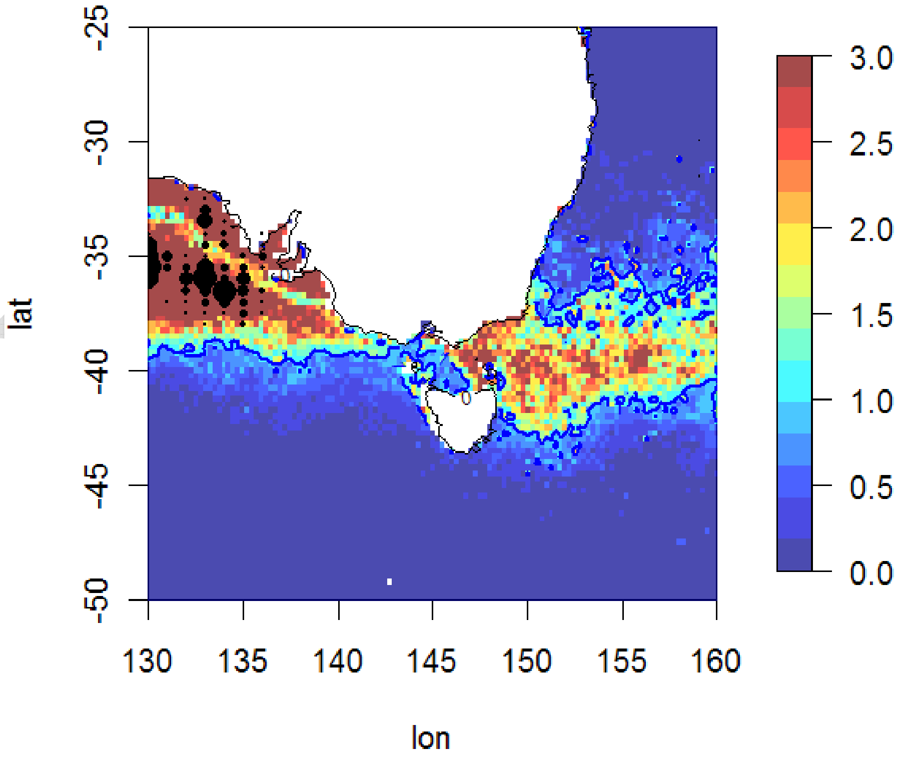


Figure 11.27. Preference map for age 2 SBT in the resident state, April-June over the area 80-180°E and for combinations of SST and log(*chl a*) in 2004-06. A contour at preference =1 is shown in black. Black dots show relative counts of observations in each (2°lon x 1°lat) grid square.

Summary: Migration east to the Tasman Sea in autumn

The preference ranges in 1998-2000 are 10-18^{o}C for SST and a wide range of between 0.05 and 2.5 mg C m^{-3}, or even higher for *chl a*. In 2004-06, the SST range includes some higher SST (up to 20^{o}C) and high *chl a* values (up to 5 mg C m^{-3}).

The shapes of the surfaces are somewhat different, though related; both have two peaks, though they are in somewhat different positions within the covariate-space.

There is a strong pattern of a high preference band in April to June along the west coast of Tasmania and into the Tasman Sea in the early period, but an absence of such a ‘connecting’ band between the GAB and the Tasman Sea in the recent period.

This pattern persists over a large range of sensitivity analyses using different assumptions (e.g. different location estimates, different HMM state weightings).

11.3.4 Migration west into the Indian Ocean in winter

The main months of migration from southern Australian into the Indian Ocean (IO) are June to August. For the analyses in this sub-section, the area and time definitions are:

Migrating West to IO:	Area: 40 – 115^{o}E, 45-25^{o}S	Time: June to August, 1998-2000
Migrating West to IO:	Area: 40 – 115^{o}E, 45-25^{o}S	Time: June to August, 2004-2006

The area within the GAB and off WA (between 115°E and 145°E) was not included, in order to avoid conditions in that region dominating the preference surface and potentially obscuring the pattern for the Indian Ocean. We have already seen that SBT are generally in cooler waters when in the migration state than in resident state (**Section 10**). This is also evident in the preference surface for SBT migrating west in June to August (**Figure 11.28**). The temperature range of the preference surface is between about 8 and 17^{o}C (compared to ranges closer to 15-20^{o}C when in resident mode). The *chl a* range is wider than seen before, particularly in the smoothed preference surface.

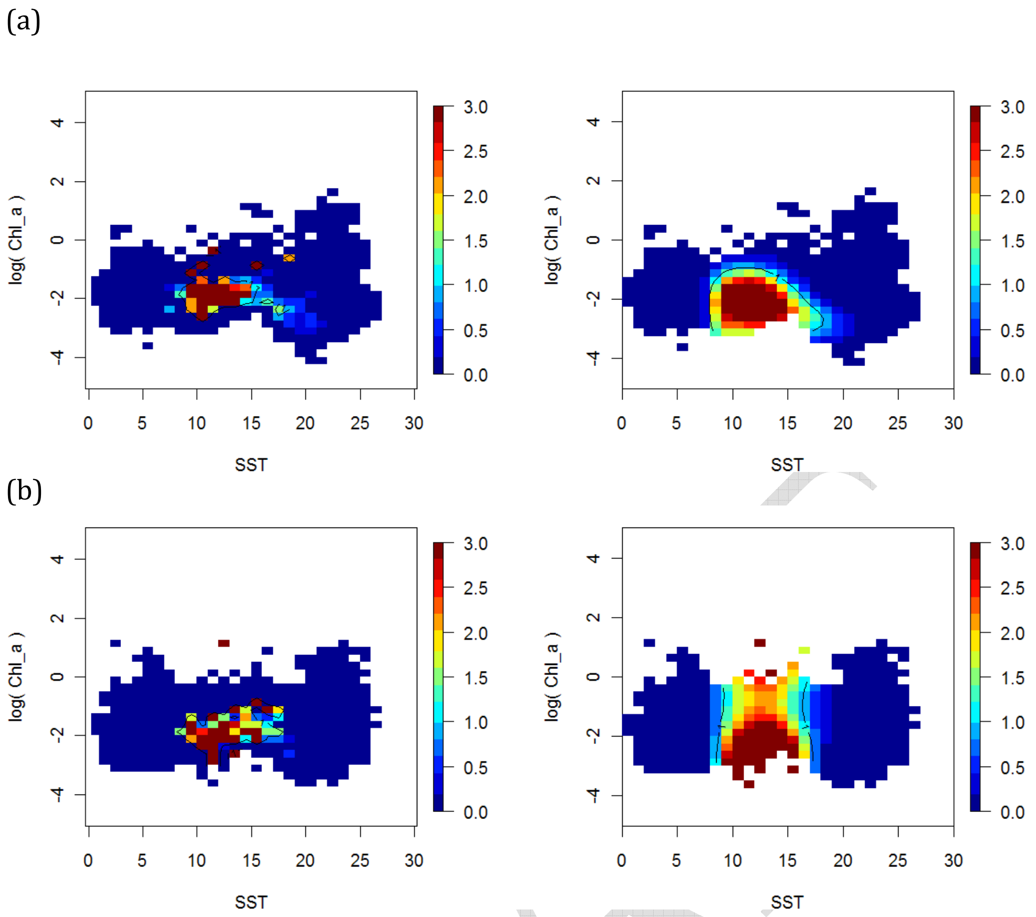
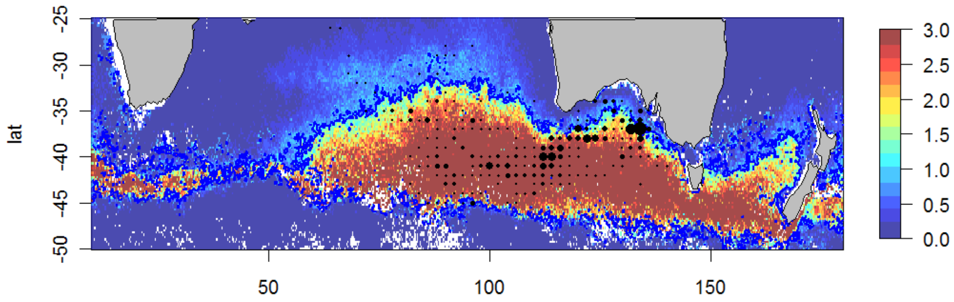


Figure 11.28. Unsmoothed (left panels) and smoothed (right panels) bivariate preference surface, for SBT in migrating West state, in terms of SST and log(*chl a*) in winter in the IO (40-115^{o}E) and for (a) 2004-06, and (b) 1998-00.

(a)



(b)

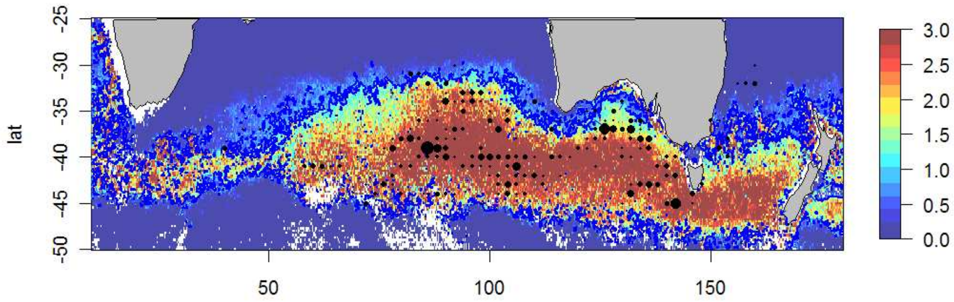


Figure 11.29. Preference map for SBT migrating west, June to August, for combinations of SST and log(*chl a*) in (a) 2004-06 and (b) 1998-00. A contour at preference =1 is shown in blue. Black dots show relative counts of observations in each (2°lon x 1°lat) grid square.

The preference maps are very similar between the two periods. The highest preference values lie towards the southern edge of the contoured region. It is interesting to note that the high preference region “disintegrates” somewhat around 50°E in 2004-06. This is due to a change in the estimated preference surface; the band remains intact if the 1998-00 preference surface is used to project a map with the 2004-06 oceanographic conditions. It is also interesting to note that in this case the continuous band of high preference around Tasmania and into the Tasman Sea is present in both the early and recent periods.

The period of June to August considered in this analysis does not include an equinox or dates within 14 days either side of an equinox, so sensitivity analyses regarding this aspect are not applicable.

Summary: Migration west into the Indian Ocean in winter

The preference ranges in both periods are quite similar; about 8-17^{o}C for SST and between 0.05 and 1 mg C m^{-3}, or slightly higher for *chl a*. The shapes of the surfaces are slightly different.

The preference maps for the two periods are very similar; a high preference band extends from the waters south of southern Australia across the Indian Ocean. The highest preferences lie towards the southern edge of the contour at preference=1.

There is a slight difference in the area off South Africa; the high preference region is more broken up in the recent than the early period.

During June to August, a band of high preference is present off Tasmania and into the Tasman Sea in both the early and recent period.

11.2.5 Migration east to southern Australia in spring/summer

The main months of migration from the Indian Ocean back to the GAB and southern Australia are October to January. For the analyses in this sub-section, the area and time definitions are:

Migrating East from IO: Area: 40-115^{o}E, 45-25^{o}S Time: October to January, 1998-2000
Migrating East from IO: Area: 40-115^{o}E, 45-25^{o}S Time: October to January, 2004-2006

The reason for excluding the southern Australian area (between 115^{o}E and 145^{o}E) is again to prevent conditions in this region from dominating the preference surface. The preference range for SST (8-17^{o}C) is again cooler than for the resident state, particularly in the early period (**Figure 11.30**). The *chl a* range is again quite wide and not that different from levels when SBT are migrating West.

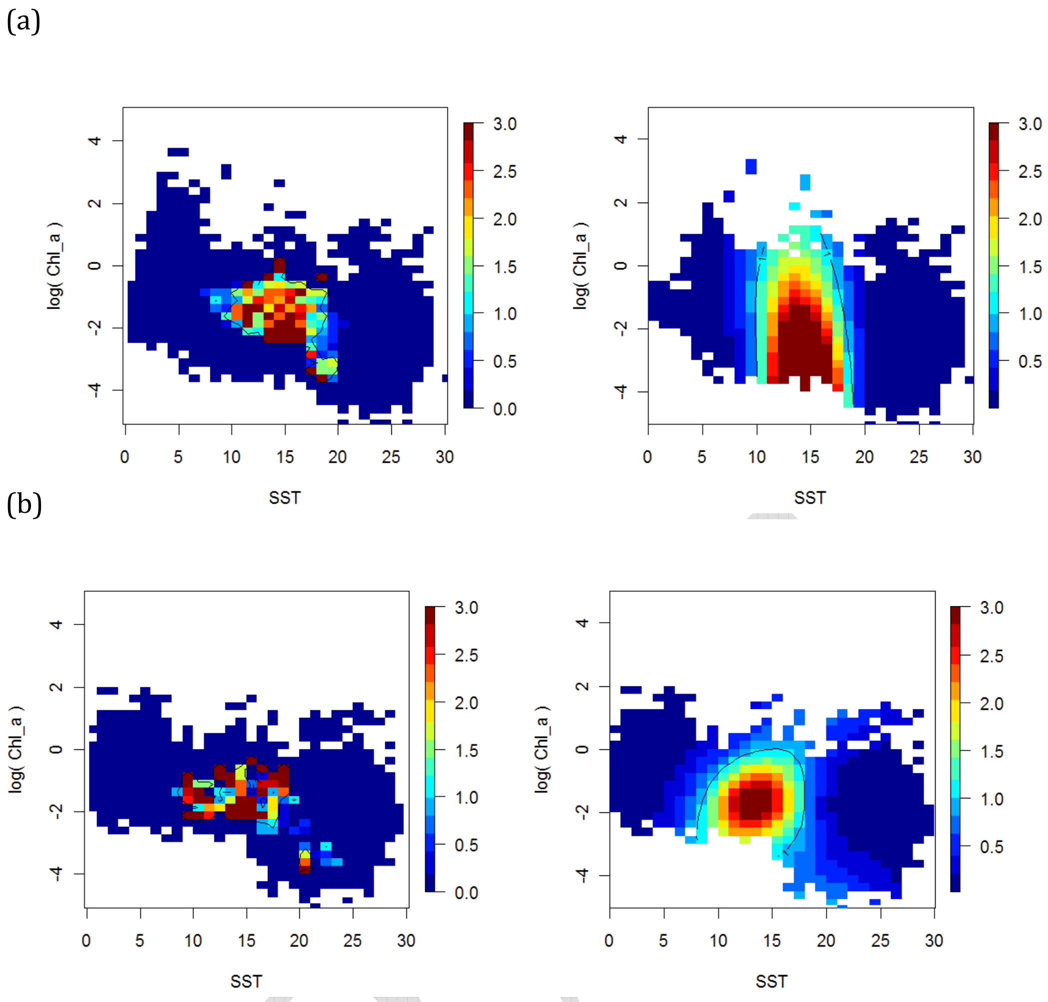


Figure 11.30. Unsmoothed (left panels) and smoothed (right panels) bivariate preference surface, for SBT in migrating East state, in terms of SST and log(*chl a*) in spring and summer in the IO (40-115^{o}E) and for (a) 2004-06, and (b) 1998-00.

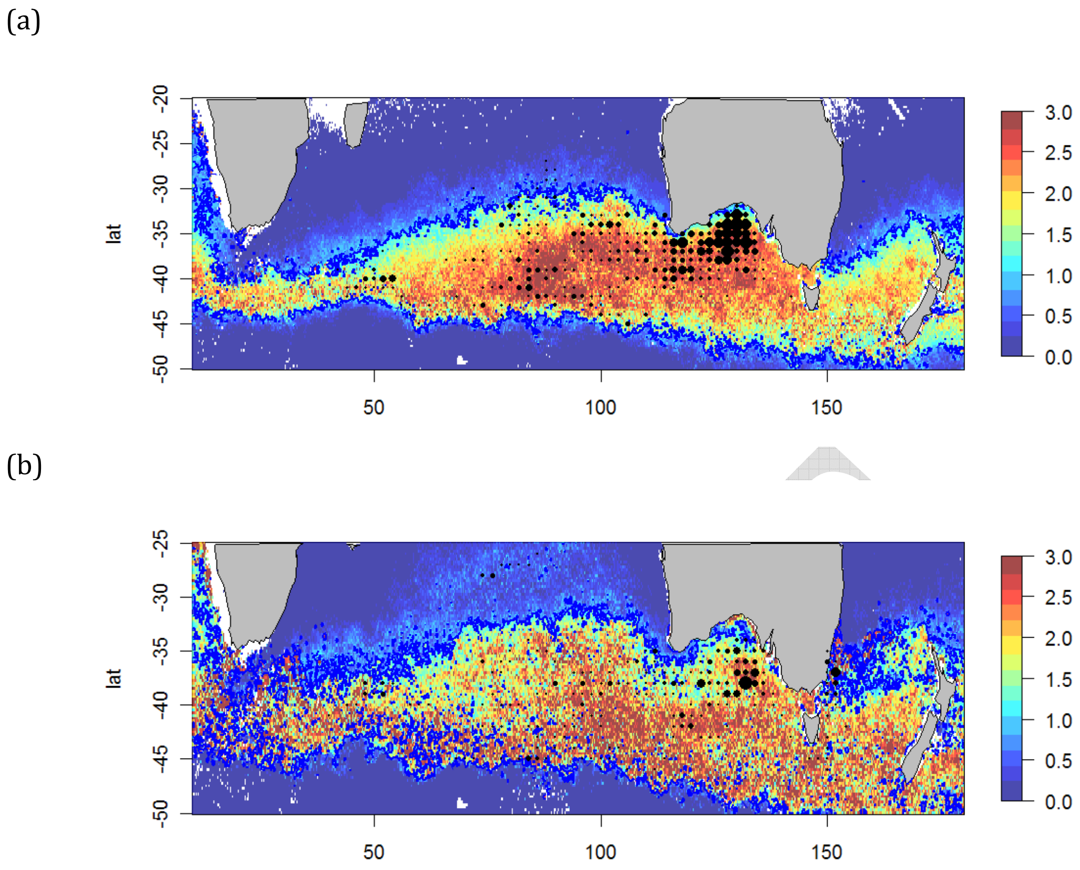


Figure 11.31. Preference map for SBT migrating east, October to January, for combinations of SST and log(*chl a*) in (a,) 2004-06 and (b) 1998-00. A contour at preference =1 is shown in blue. Black dots show relative counts of observations in each (2°lon x 1°lat) grid square.

Preference maps for the whole region show a similar band of high preference values across the Indian Ocean as far as South Africa and into the Tasman Sea, including to the east of New Zealand. The map (and preference surface) for the 1998-00 period is very noisy, and we note that this analysis only has 21 tags, whereas the 2004-06 period has 33 tags.

Sensitivity analyses with data from 14 days either side of the September equinox removed showed only very minor differences between the preference surfaces and no discernable effect on the preference maps (**Appendix 7**). In this case few data points are removed, just at the start of October.

Summary: Migration east to southern Australia spring/summer

The preference ranges in both periods are relatively similar; about 8-17°C for SST and between 0.05 and 1 mg C m^{-3}, or slightly higher for *chl a*. The shapes of the surfaces are slightly different.

The preference maps for the two periods are very similar, though the map for the early period is very noisy; a high preference band extends from the waters south of southern Australia across the Indian Ocean.

There is a hint of low preference off the south and south-west cost of WA in the early period, compared to the more recent period.

There is a slight difference in the area off South Africa; the high preference region is more fragmented in the early than the recent period. This is the opposite from what we saw for migration west into the Indian Ocean in winter.

During October to January, a band of high preference is present off Tasmania and into the Tasman Sea in both the early and recent period.

11.4 Discussion

The maps of high preference areas for juvenile SBT in a range of months and in either resident or migratory state (as estimated from the HMMs in **Section 10**) have revealed patterns that provide possible reasons for the apparent changes in juvenile SBT movement noted in **Section 8**. These patterns are based on historical analysis and, without direct experimental manipulation (which is impossible for this species given its geographic range), support weak inference only (sensu Platt 1964). Here we revisit some key questions from **Section 10**, and discuss them in the light of the preference maps developed in this section.

11.4.1 The Tasman Sea Question

The "Tasman Sea Question" raised in **Section 10** was: why did a much smaller proportion of SBT migrate to the Tasman Sea in autumn in the 2000s compared to the 1990s? The results presented here - comparisons between April to June 1998-00 and the same months in 2004-06 - suggest that there were changes in environmental conditions. Waters off the south-west of Tasmania were cooler in the recent period, and *chl a* levels were higher just offshore of the west coast of Tasmania, but further offshore levels were, on average similar.

In addition, there appears to have been changes in the SBT preference surface between the two periods. It is not obvious how to interpret this, particularly since we are working with SST and *chl a,* which are environmental proxies rather than direct measures of SBT prey fields. In addition, these proxies represent surface conditions, whereas SBT "habitat" in fact spans a much greater range of the water column (Hobday and Hartmann 2006). The temperature preferences identified in this project are within the wide range SBT are known to occupy given their ability to thermoregulate (Gunn and Young 1999, Bestley *et al.* 2009; Fujioka *et al.* 2011). In other words, any observed changes with regard to SST in the preference surface is likely to be more driven by its interaction with *chl a*, as a proxy for prey via food-webs, than directly by impacts due to temperature change. Changes with regard to *chl a* in the preference surface (see e.g. **Figure 11.23**) are much harder to interpret. This requires a closer examination of changes in the pelagic ecosystems in the region off western Tasmania. Such studies were completed on the east coast of Tasmania in the 1990s, and related water mass properties to prey composition and availability for yellowfin tuna (Young *et al.* 1996; Young *et al*. 2001), but to date there has been little work on the ecosystem structure west of Tasmania.

It is unsurprising that habitat preference changes with SBT age, but we note that for the juvenile age classes tagged in this study, age alone does not explain the reduction in migration to the Tasman Sea in the more recent period. Given that the 1998-00 period consists primarily of 3-year-olds, the only direct comparison possible is with just the subset of 3-year-olds in 2004-06. In this comparison there is again no 'gap' in the early period, but a 'gap' of high preference values in 2004-06.

There is one more factor which could have played a role in the reduction in the observed migration to the Tasman Sea. The CCSBT operating model (Anon. 2010) estimates the abundance of the year 2000 to 2002 cohorts as being very low and certainly well below the average in the period prior to that. Individuals from these cohorts form part of our dataset (for example, the 2002 cohort would have been age 2 in 2004, 3 in 2005 and 4 in 2006). It could be that the lower cohort size resulted in a smaller spatial distribution. Dell and Hobday (2008) reported that as population sizes of SBT declined over a 40 year period, SBT tended to form mixed age-class schools, and older fish returned to the GAB for more years, perhaps because they were schooling with more abundant younger fish with a higher return frequency to the GAB. In the light of results presented here, it is plausible that changes in the relative abundance of different age classes could have been a factor, but it is not the full explanation.

We should, however, explore the converse question: whether the reduced migration to the Tasman Sea actually drove or determined the low recruitment estimated in the CCSBT operating model and inferred from stock status indicators. The evidence for low recruitment comes from four primary data sources, as noted in Anon. (2005):

1. acoustic survey in southern Western Australia
2. size frequency (commercial fisheries)
3. commercial aerial spotting (SAPUE) in the GAB[24], and
4. conventional tagging data

Of these four sources, it is only the commercial size frequency data from the Tasman Sea that can potentially be affected by reduced migration of cohorts of juveniles from the GAB. The acoustic survey and commercial aerial spotting take place during summer in Western Australia and the GAB, respectively, prior to migration to the Tasman Sea, so they should be unaffected. Although returns from the tagging data show reduced returns from the Tasman Sea (as already noted in **Section 8**), very low recruitment in years 2000 and 2001 are consistent with high fishing mortality estimates on these year classes in subsequent years (i.e., at ages 3 and 4 in years 2003 to 2005). These high fishing mortality estimates were obtained using a non-spatial analysis of the tag-recapture data, and was confirmed in the spatial analyses done as part of this project (**Section 9**). We conclude that three of the data sources support the interpretation of low recruitments in 2000 to 2002, but that there is also evidence of reduced migration of juvenile SBT to the Tasman Sea in the 2000s compared to the late 1990s.

It seems likely that there was a change in environmental conditions which may have caused, or at least contributed to, the reduced migration of juvenile SBT to the Tasman Sea in the 2000s compared to the late 1990s. It would be interesting to explore further the conditions in 2007 onward, noting that small SBT have re-appeared in the New Zealand size frequency data (Anon. 2010). We also acknowledge that there are catches (under quota) of larger SBT in the Tasman Sea in New Zealand and Australian longline fisheries (Hobday *et al*. 2010).

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[24] Not the scientific aerial survey because it was suspended during the relevant years.

11.4.2 The South Africa Question

The "South Africa Question" was: why did a smaller proportion of SBT seem to migrate to the waters off South Africa (west of 55°E) in the 2000s compared to the 1990s? In **Section 8** we considered this question which arose around 2007, based on the returns we had at the time. The pattern (of a smaller proportion of SBT going further west than 55°E) is no longer as clear, and is not statistically significant if releases in the GAB, WA and the Indian Ocean are considered. Nonetheless, results presented here hint at the possibility that, in some years, environmental conditions (combinations of SST and *chl a*) may not be as conducive to SBT migrating as far west as in other years. There are hints of the high preference region being truncated at around 50°W, or fragmenting more in the figures associated with residency in the GAB (**Figures 11.9, 11.12**; Jan-May), residency in the IO (**Figure 11.17**; Aug-Nov) and migrating West into the IO (**Figure 11.29**; Jun-Aug). Most of the tracks that do reach and extend west of 55°W do so in the months of September to December. This question must be considered in future analyses and as additional archival tags are returned.

11.4.3 The Western Australia Question

The "WA Question" was: what happened to the fish tagged off WA as age 1 in the 2000s? The problem is described in detail in **Section 9**, but in short, returns of conventional tags from these fish (the 2000 to 2003 cohorts) were proportionally much smaller than, for example, the same cohorts tagged in the GAB, or returns from the same cohorts when tagged at older ages. Polacheck and Eveson (2007) considered this question in detail, and note that there are three possible reasons for the lack of returns from smaller tagged fish are: (1) high tagging mortality of small fish, (2) incomplete mixing and (3) high natural mortality rates on smaller/younger fish. They conclude that high tagging mortality seems unlikely given lack of evidence (e.g. from acoustic tagging), and noting that it would require a substantial increase in natural mortality between the 1990s and the 2000s to explain the reduction in returns). Regarding mixing, Polacheck and Eveson (2007) comment that if the reason is incomplete mixing, then it is not just a matter of these juveniles not going to the GAB (and hence not being caught in the surface fishery), but also not going to the areas where the longline fisheries operate.

Although we have not investigated this issue in any detail, we do note that there appear to be different patterns in terms of preference maps in the area off southern Australia, and particularly the region off the south-west ‘corner’ of WA. For example, **Figure 11.11** shows interannual differences which are very likely to relate to the strength of the Leeuwin Current in summer. The Leeuwin Current index (based on sea level at the coast), was particularly weak in 1998, above average in 1999 and particularly strong in 2000. In the recent period (2004-2006) the Leeuwin Current was about the same strength in each year, and slightly weak (a little below average). With regard to the period in question, i.e. when the conventional tags were released on 1-year-olds (2001-2004), the Leeuwin Current index is slightly above average in 2001and slightly below average in 2002-2004. We conclude that the question about the movement of 1-year-old SBT from WA remains unanswered and requires additional archival tagging of age-1 fish on the west coast of Australia before they move into southern Australia, or other approaches such as acoustic tagging and monitoring (e.g. Hobday *et al.* 2009) and otolith microchemistry (Clear *et al*. CCSBT report). For example, preliminary analysis from acoustic tracking shows that the proportion of age-1 SBT that move to the Western Australia south coast in summer varies between years, as does the residency on the south coast (Fujioka *et al*. 2010). The proportion of fish that do not move to the south coast, and instead move directly to the Indian Ocean, is unknown.

12 Implications for SBT management

Key findings

Results from this project have implications for management of SBT that pertain to: use of CPUE as a stock indicator, analysis of mark-recapture data, abundance surveys (GAB aerial survey), development of a spatial operating model, and spatial management options.

- CPUE: use as a stock status indicator
  - High variability in migration paths and timing among individuals and years mean that low spatial (and temporal) coverage of effort remains a serious problem for obtaining a reliable index of abundance from catch and effort data. Low coverage and operational changes in fleets – two major concerns with CPUE – cannot be addressed by including environmental covariates, or doing "habitat standardisation" dealing with catchability by depth.
  - A spatial model and spatially explicit CPUE indices are likely to provide a more reliable interpretation of trends in CPUE time series.
- Mark-recapture analyses: use in determining population parameters
  - Using electronic tag data along with conventional tag data in a spatial model should provide unbiased estimates of mortality rates, in contrast with a non-spatial model (which is likely to give biased estimates when tags are not released in all areas).
  - Simulation results show the number of electronic tags required in combination with conventional tags is not prohibitively expensive and should be considered in future..
- Aerial survey index of juvenile abundance: use as a recruitment index
  - Results confirm the timing of the aerial survey (Jan-Mar) is ideal given most juveniles arrive in the survey area by the start of the survey and remain until the survey has ended.
  - The proportion of time that juveniles spend at the surface in the GAB declines over the months of the survey. Further analyses are needed to establish if this is consistent across years and/or related to covariates used in standardisation, to ensure robustness of the index.
- Spatial operating model: underpinning management procedure
  - There is strong evidence from results that a spatial operating model for SBT would be preferable to a non-spatial model, both from the point of view of mark-recapture programs and the interpretation of CPUE. One major advantage of a spatial operating model for SBT would be the ability to directly evaluate the value of spatially explicit management.

12.1 Introduction

The final objective of the project is to: "Evaluate implications of the spatial dynamics of juvenile SBT for the management of the SBT resource (e.g. the potential consequences and benefits of either ignoring or using spatially explicit management actions)".

There is an important distinction to be made between spatially explicit assessment or operating models and spatially explicit management. There are also different interpretations of the term "spatial management". Here spatial management is defined as managing catch or effort in a spatially explicit manner, such as setting separate total allowable catch (TAC) or effort (TAE) for pre-defined spatial regions. Other types of spatial management, are used for SBT and other species, such as operational measures to limit by-catch in a fishery which does not target SBT (e.g. Hobday and Hartmann 2006; Hobday *et al.* 2010), but these management options are not the focus here.

Spatially explicitly management as defined above requires spatial information in order to be meaningful. It therefore requires a spatial operating model[25], and a management procedure (OM and MP; see Acronyms for more detailed definitions) which produces spatially explicit catch recommendations. On the other hand, a spatial OM does NOT imply that management should be spatially explicit; an MP which produces a global catch recommendation can be associated with, and be evaluated by, a spatial model.

It is useful to have an understanding of how the various data sources, such as CPUE or (conventional) tagging data can inform an assessment or operating model. In **Box 12.1** we illustrate this to highlight the need for a range of, ideally fishery-independent, data sources to inform a population dynamics model which includes all age classes. In the next two sections we discuss implications of the results of this project for a spatial operating model in the context of CPUE (**Section 12.2**) and mark-recapture studies (**Section 12.3**). In **Section 12.4** we consider implications for the aerial survey of juvenile abundance, which is currently an important input both to the OM and the candidate MPs. Implications, and the possible need, for spatially explicit

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[25] We use the terms operating model (OM) and management procedure (MP) because these are the tools used within the CCSBT to provide management advice (see Acronyms for definitions). We also refer just to "catch" because that is the current management measure used by the CCSBT, though in a more general context spatial management can be via input (e.g. effort) or output (e.g. catch) control, or a combination of the two.

management are discussed in **Section 12.5**. In the final section (**Section 12.6**) we summarise conclusions and consider ways forward.

BOX 12.1. What data are used in the operating model and how does each data source contribute?

The diagram below shows three components – groups of different age classes – of the SBT population. Given that SBT are a long-lived species (up to 40 years), it is desirable to have data on a wide range of age classes. Fisheries data on total catches and size (and, or age) frequencies provide information on all the harvested age classes. The size/age data are indirect in the sense that they reflect the size frequency of catch, but not necessarily that of the underlying population, as they are dependant on the fisheries 'selectivity' (the gear being used, areas fished, size of fish being sought, etc.).

The fisheries independent surveys provide information on juveniles. In particular, the acoustic survey off WA aims to obtain an index of age 1 SBT abundance; the aerial survey represents the combination of ages 2-4.

Conventional tagging programs for SBT were conducted in the 1990s and 2000s (see **Section 9**). In theory such programs can provide information on a large number of age classes, depending on (a) how many tags are deployed and at which ages and (b) how high harvest rates are and the extent to which recaptured tags are returned. Although usually considered to be in the category of "fisheries independent" data, there is some fisheries dependency through the reporting of recaptured tags. It is for this reason that alternative tag types (e.g. PIT or gene-tags) are being explored for use in mark-recapture studies (Basson *et al.*, 2008).

A fisheries independent estimate of spawning biomass (SSB) should become available from the 'Close kin' project (Bravington *et al.*, 2010) during the course of this year (2011).

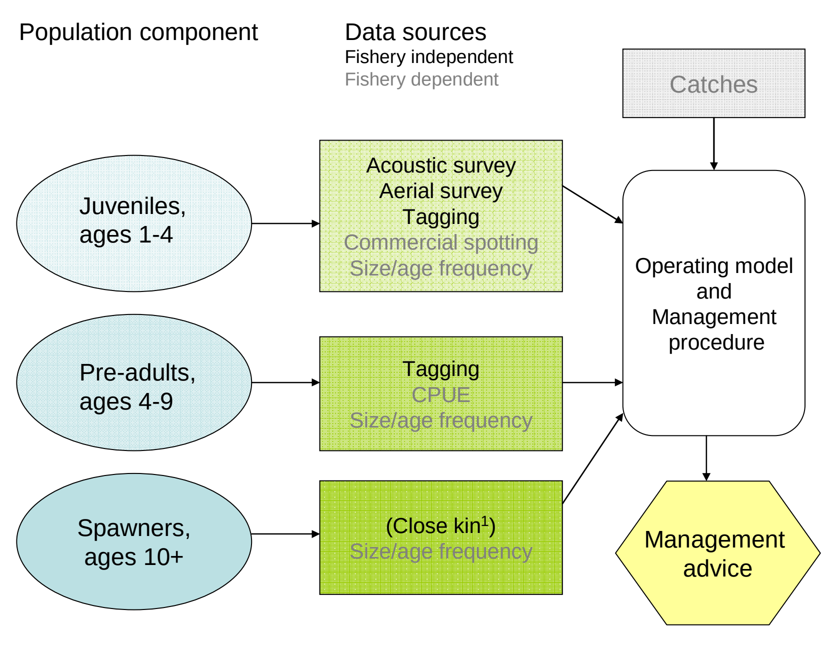

Figure Box 12.1.1 Diagram of groups of age classes in the SBT population, actual or potential data sources for use in the operating model and management procedure. Catches, used with tagging data and size/age frequency data provide information on all age classes, provided the catch data are reliable.

[1] The close kin project is still underway; it aims to provide a fishery independent estimate of spawning stock biomass (SSB).

BOX 12.1. – continued

All the data sources can be (and most currently are) integrated within the CCSBT operating model to provide estimates of historic and current stock status with associated uncertainty, both in terms of parameter estimates and alternative scenarios, e.g. for historic catches (e.g. Anon. 2010). The current candidate management procedures are based on CPUE and the aerial survey, but in future additional or alternative data sources could be used.

In a spatially explicit operating model, the catches and size/age frequency data would be aggregated by the defined areas in the model, rather than over all areas. The tagging data would be analysed spatially similar to that presented in **Section 9**. Ideally, separate CPUE indices would be constructed for each relevant area in the model (though a hybrid model that uses a single index could be devised). The acoustic and aerial surveys are already 'spatial' since they occur in one particular area (and time) of juvenile distribution. Given no evidence of more than one spawning area for SBT, the Close Kin estimate can also be incorporated as an overall estimate.

There will, however, be the need for an additional data source not shown in the diagram, namely electronic tagging data for estimating movement rates between areas.

12.2 Implications for catch, effort and CPUE

Longline catch and effort data, from the Japanese fleet (including data from the Japanese joint venture operations), are used within the CCSBT assessment process to derive a standardised catch per unit effort (CPUE) series. This is used as an index of total abundance in the CCSBT operating model (OM) and the candidate MPs. The CPUE index is based on catches of ages 4 to 9 only.

When relating results from this project to the interpretation of CPUE, it is important to note that the data available from these archival tags are primarily for age 2-4 individuals[26]. Any extrapolation from these results to SBT of age 5 and older should be done with great caution, because we know that as SBT grow, their behaviour changes (**Box 3.1)**. They are better able to thermoregulate (e.g. Fujioka *et al.*, 2011) and can therefore use habitats that younger, smaller individuals may avoid, as has been shown for other bluefin species (e.g. Kitagawa *et al.*, 2000; Teo *et al.*, 2007).

12.2.1 Spatial distribution of juvenile SBT

The archival tag data have highlighted that SBT migration and distribution can change over time (**Section 8**), but also that the reasons for such changes are unclear (**Section 11**). The data have also highlighted that although there are strong cyclic patterns in the movement behaviour, there is also substantial variability between individuals (**Section 10**). This means that the timing of migration is variable, and the duration of stay in the

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[26] The subset of tags used in the migration and habitat preference sections (10 and 11) include data for individuals at age 1 (4 tags), age 2 (28 tags), age 3 (49 tags), age 4 (25 tags) and age 5 (5 tags).

GAB is also variable. Migration occurs over several months and covers broad areas of the ocean. There appear to be some "preferred" areas, or longitudes, in the Indian Ocean where juveniles may remain for some time, but again, arrival times and departure times from these areas are variable. Of those tags from our data set of long enough deployment, all but one returned to the GAB each summer and there was little evidence of site-fidelity for the Indian Ocean, or the Tasman Sea. Some individuals did not even migrate in winter, but remained in the waters off South Australia. What does all of this imply for the interpretation of catches and nominal CPUE?

In short, it implies that the low spatial (and temporal) coverage of effort is potentially a serious problem for getting a reliable index of abundance from catch and effort data. Operational changes that lead to substantial and sudden changes in the spatial distribution of the fleet, as documented in Itoh (2010) for example, is also potentially a serious problem. The potential changes in movement dynamics from year to year, and the variability between individuals, mean that the number of fish in any particular grid square and month can vary considerably between years. When there is full spatial (and also ideally temporal) coverage of the longline fleet then this should not be a major problem. However, the spatial and temporal coverage has declined substantially since the early 1970s (**Figure 10.1**). A CPUE index based on a small number of grid-squares (compared to the overall distribution of SBT) could be very sensitive to random variations in SBT movement dynamics, and may be both biased and "noisy". Low spatial coverage has been a concern for some time (see **Section 3: Background**, and **Section 4: Need**), and no amount of statistics or modelling of the existing data can remove the uncertainties associated with unfished areas[27].

One could argue that if a change in the population is large enough, then this should be detected by a CPUE index, even if it is based on low spatial coverage. This may well be the case, but it is likely to only become evident after several years when the signal becomes apparent through the noise, and it may still not be proportional to the change in actual abundance (e.g. Hampton *et al.,* 2005; Polacheck 2006).

One option to consider is whether a spatial model would improve the situation. For example, in a spatial model with a CPUE index for each area defined within the

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[27] In the CCSBT this issue has been dealt with in a range of ways, using a range of different assumptions in an attempt to "bracket" the CPUE series, i.e. estimate both an upper and a lower series, and using a range of different CPUE series in the OM (Anon. 2010c).

model, an increase in one area but a decrease in another may be correctly interpreted as a change in distribution rather than a change in abundance. A spatial model could also, potentially, cope better with changes in the distribution of the longline fleets than a non-spatial model. Although a spatial model may well be preferable, auxiliary data (e.g. from archival tags, or a combination of archival and conventional tags) would be required to estimate movement rates between the areas. And, if such data are available from a mark-recapture program, particularly one which avoids the issue of reporting rates (by using genetic tagging for example) then it is questionable whether a CPUE-based index would still be required.

12.2.2 CPUE Standardisation

Two concerns about the interpretation and standardisation of CPUE have been noted several times in this report. First, low spatial coverage creates serious difficulties for dealing with areas where there was no fishing. Second, changes in fleet behaviour - where the fleets fish, how many vessels are involved, how they search and communicate information about fishing grounds (Itoh 2010, Anon. 2010) – create serious difficulties for standardisation (Hampton *et al.* 2005; Polacheck 2006). Such changes have occurred, and there is no reason to assume no further changes will occur in future. Furthermore, it is notoriously difficult to standardise for such changes because it is not obvious what the relevant covariates should be (e.g. Bigelow *et al.* 2002; Bigelow *et al.* 2007; Itoh 2010).

These two issues – spatial coverage and changes in fleet dynamics – are sufficiently serious and problematic that investment of efforts to develop alternative standardisation approaches for longline catch-effort data should be seriously questioned before it is embarked upon. The potential benefit from such work should be weighed up against alternatives, particularly fishery-independent approaches. We discuss these alternatives further in **Section 12.6**.

Returning to implications of results, the section on Habitat preferences (**Section 11**) is of particular relevance. We first discuss implications for incorporating environmental covariates into standardisation using classic general linear models (GLMs). We then discuss implications in the context of so-called “habitat standardisation”.

Standardisation by GLM – accounting for environmental effects

Exploratory analyses using a wide range of single covariates to estimate preference curves for SBT residency or migration (**Section 11**), only revealed strong patterns with sea surface temperature (SST) and, to a lesser extent, with chlorophyll *a* (*chl a*). The combination of SST and chl *a* seemed to be particularly informative regarding juvenile SBT distribution. Both covariates are still, however, only proxies for the actual determinants of SBT habitat preference and distribution. Nonetheless, temperature is clearly meaningful in the context of SBT having physiological limits, albeit rather broad limits, of temperature. Chlorophyll *a* was apparently a useful proxy, and given its indirect relationship to prey abundance via the food web it is therefore likely to bear some relation to SBT distribution (see **Section 11**). What do these discoveries imply for CPUE standardisation using techniques such as generalised linear models (GLM)? Should SST or other environmental covariates be included in standardisation?

Before including environmental covariates, it is important to ask whether that covariate is likely to affect catchability (e.g. whether fish are easier to catch because they are feeding more actively) or availability (i.e. there are more fish in the area; see **Box 12.2** below). If the covariate affects catchability then it should be included in the standardisation, but if it affects availability (or distribution) then it should not be included. Unfortunately, determining whether a covariate affects catchability or availability is not straightforward, particularly for longline fishing (e.g. Bigelow *et al.*, 2007). In our experience, the question is usually not asked; instead, covariates are included in analyses and diagnostics are used to decide which covariates the GLM should retain. This approach should exclude covariates that bear no relation to catch and is likely to correctly retain covariates which relate to catchability; however, it is also likely to incorrectly retain covariates which relate to availability and we note that statistical approaches alone cannot resolve this.

Results from **Section 11** relate directly to distribution and therefore availability of primarily age 2-4 SBT in relation to environmental covariates. The focus is primarily on horizontal, i.e. two-dimensional, movement. The third dimension – depth distribution of SBT – is clearly of particular relevance when it comes to questions of CPUE (Bigelow *et al.*, 2007). Results from this project do not cast light on the specific question of catchability i.e. feeding behaviour of SBT. Recall that the "resident" and "migratory" states used in the Hidden Markov Models (**Section 10**) were based on distances moved and not whether SBT are feeding more or less (but see Bestley *et al.* 2008).

To explore the issue of catchability in relation to environmental covariates would require a substantially more complex set of analyses of SBT feeding behaviour. This could, in theory, be attempted with the archival tag dataset, noting however the very small sample size of ages 4 and older in the dataset. For example, Bestley *et al.* (2008) conducted a study on feeding ecology based on similar data for 19 SBT. They found significant fish-to-fish variability in the patterns of feeding success, and noted that this may explain why a population-level parameterization failed to reveal any significant pattern. In the light of this, we conclude that although further studies of SBT feeding ecology would be valuable for improving our understanding, they would not be worthwhile just for the sake of CPUE standardisation.

It is also important to note that the inclusion of environmental covariates can only sensibly be considered for use with shot-by-shot data. Although the shot-by-shot data are now regularly analysed (e.g. Itoh and Takahashi 2010), the only catch-effort data available to all member scientists within the CCSBT are the spatially and temporally aggregated data (5^ox5^o grid-square x month).

One additional comment is worth making. In **Section 6** we noted that there are differences in depth distribution between night and day, particularly when juveniles are on the winter grounds. This suggests that time of setting and hauling should possibly taken into account when standardising CPUE, unless there is extreme uniformity within the fleet and consistency in practice over time. Again, this can only sensibly be considered for use with shot-by-shot data. The observation about day-night depth differences is by no means new for this or other similar species, but it does suggest that there may be covariates other than environmental ones that should again be explored for their potential relevance in CPUE standardisation.

BOX 12.2. CPUE standardisation – availability or catchability?

Catch per unit effort (CPUE) is assumed to be proportional to population abundance, or density, because we assume that:

Catch = (Catchability) x (Effort) x (Number of fish)
and CPUE = C/E = q.N

Standardisation is needed however, because catchability (q) is not necessarily the same in all areas or all months, and usually depends on how the gear is designed and set, as well as a range of other factors. Before including environmental covariates in a standardisation, we should ask whether particular covariates are likely to affect catchability (e.g. whether fish are feeding more actively) or availability (i.e. there are more fish in the area). The importance of this is easily illustrated.

Example 1: Catchability is affected by a covariate

Take two small areas A and B, with the same number of fish and the same effort, but assume that catchability in B is twice what it is in A because of some environmental covariate (say, sea surface temperature):

	A	**B**
N=Number of Fish	10,000	10,000
E=Effort	1000	1000
q=Catchability	0.0001	0.0002
This will imply:		
qEN=Catch	1000	2000
Nominal CPUE	1	2

Comparing the CPUEs, we would **incorrectly** infer that the number of fish in area B is twice what it is in area A. To get the correct inference, i.e. that there is the same number of fish in each area, we need to multiply the CPUE in area B by the ratio of the catchabilities:

standardised CPUE(area B) = 2 x 0.0001 / 0.0002 = 1.

Thus, we **should** standardise for the effect of the environmental covariate if catchability is affected.

Example 2: Availability is affected by a covariate

Now assume that the environmental covariate affects the distribution of fish, so that there are twice as many fish in area B as in area A, but the catchability is not affected:

	A	**B**
N=Number of Fish	10,000	20,000
E=Effort	1000	1000
q=Catchability	0.0001	0.0001
This will imply:		
qEN=Catch	1000	2000
Nominal CPUE	1	2

Now we would **correctly** infer from the CPUEs that the number of fish in area B is twice what it is in area A. If we were to "correct" the CPUE as we did in example 1, we would make the wrong inference. Thus, we **should not** standardise for the effect of the environmental covariate if availability is affected.

Unfortunately, it is usually very difficult to determine whether catchability or availability, or both to various extents, are affected by any particular environmental covariate.

"Habitat" standardisation of CPUE

In what follows, the term "habitat standardisation" refers to the model introduced by Hinton and Nakano (1996) for incorporating habitat information into the standardization process of longline catch-effort data, which stratifies catchability by depth. At the time it was introduced, the method offered an approach to directly account for changes in fishing patterns that had occurred in the Japanese longline fishery in the Atlantic, namely an increase in fishing depth (Goodyear *et al.* 2003). Since then, attempts have been made to develop models for tunas and billfish which standardise catch-effort data accounting for how fish behaviour affects catchability. These usually incorporate 'habitat' information such as preferred temperature and ⁄ or depth ranges obtained from electronic tags (Bigelow *et al,* 2002; Kleiber *et al.* 2003; Campbell and Young 2010).

Although habitat standardization for longline CPUE offers a potentially useful alternative to the statistical procedures used in the past, Goodyear *et al.*. (2003) argued that most of the assumptions of habitat standardization methodology were untested, and provided outlines of research required to ensure the methods for habitat standardisation produce robust estimates of CPUE.

There are at least two components to the problem of "habitat standardisation": a model describing the actual probability distribution that a fish will take a bait it encounters (the fish model), and the actual distribution of the hooks on deployed gear (the gear model), both now and in the past (Goodyear *et al.,* 2003). The same paper notes that if factors such as bait type or bait movement prove to be important, then these factors must also be integrated into both the fish and gear models.

In the case of SBT, it is not obvious that "habitat standardisation" would deal any better with the two major issues of concern – operational fleet changes (unrelated to depth of fishing) and spatial coverage – than a classic GLM standardisation. Regarding fish behaviour, Bestley *et al.* (2009) note that the behavioural flexibility shown by SBT throughout their range of habitats has implications for their catchability. Bestley *et al.* (2009) conclude that their results indicate the application of habitat standardisation would not be straightforward for a species like SBT, whose complex behavioural patterns would not be easily represented using temporal or spatial strata. This is because, within a season, vertical distribution can vary significantly among habitats, and spatial habitat boundaries in a dynamic ocean can vary both seasonally and interannually.

We now have a much larger dataset on which we could base a detailed analysis of juvenile SBT feeding behaviour, stratified by depth, time of year, and covering a reasonably long time-period. But, could results from age 2-4 SBT reliably be extrapolated to older fish which form the majority of the longline catch? It seems unlikely given the behavioural changes juveniles undergo as they grow, and direct data from fish of ages 5 and older would be required to build a reliable ‘fish model’.

Regarding gear models, Goodyear *et al.* (2003) note that the weakest link of the habitat-standardization may lie in the inadequacy of assuming a catenary curve (e.g. **Figure 12.1**) for the gear model and calculating the depth of the hook (and catch) from the order of the branch line on the mainline. It now seems imperative to use time-depth recorders (TDRs) and hook-timers to inform the gear model, and interactions between fish and gear. Campbell and Young (2010, FRDC Project 2005/004) provides a good example of the range of fieldwork, types of data and analyses required to develop a reliable data-driven model of the fish–gear interactions. Their study found that, in the Australian East Coast longline fishery, the catenary equation was a good predictor of overall mean sink depth, but not a good predictor for any single hook (Campbell and Young, 2010). Specific fieldwork studies would have to be conducted on commercial longline vessels fishing for SBT in the various regions where the fleets operate to build a reliable ‘gear model’.

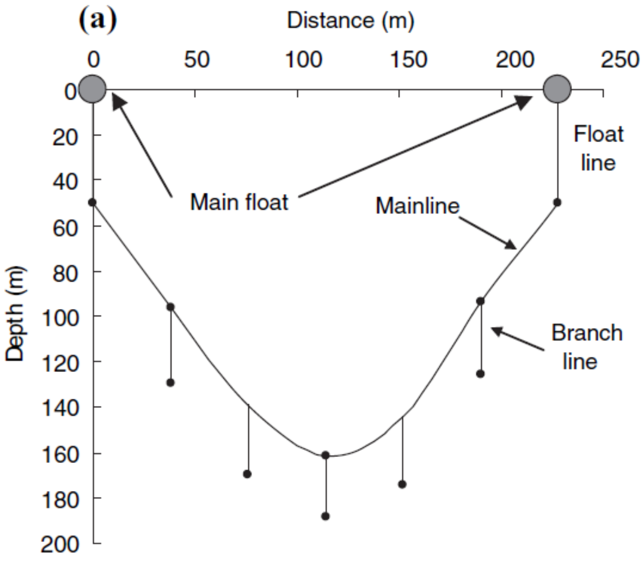


Figure 12.1. Example configuration of a tuna longline (source: Shiode *et al.* 2005)

In summary, it would take a large amount of research, including gear-related fieldwork, to develop a reliable and well-informed habitat standardisation model for SBT. Even if this is possible for the future, it is unlikely to be applicable retrospectively to historic data, given the long time-period involved (the current CPUE series starts in 1969), the known changes that have taken place in the fleets and the unknown changes that SBT behaviour may have undergone. It is unlikely that a habitat standardisation model dealing with catchability by depth would be able to resolve the main issues of concern regarding CPUE as a reliable index of abundance, namely spatial and temporal coverage, and operational fleet changes driven by economic and/or management factors. Regardless of whether electronic tag data are used directly in CPUE standardisation, these data are still vital in order for us to continue to improve our understanding of SBT feeding behaviour and vertical distribution, and continue to monitor changes in horizontal distribution.

Dealing with areas and periods with no fishing effort

There is another interpretation of the words “habitat standardisation”, namely standardisation which takes account of the spatial (horizontal) habitat occupied by SBT. The current CPUE standardisation process estimates several time series based on different assumptions about catch rates in areas and periods where there was no fishing effort in recent years, compared to the early years of the fishery. The relevance of this is clear when we note that the CPUE index in each year is the sum of estimated SBT densities in each of several areas and months, weighted by the size of each area (Itoh and Takahashi 2010). If there was effort in a particular area/month in the early part of the CPUE series (e.g. the 1970s), but then no effort in the recent period, the weighted sum would be smaller simply due to no effort rather than due to a lower density. The areas and periods included in the analyses can be reduced up to some point, but this is not ideal since it reduces the available data on which to base the estimated densities, leading to increased variance and year-to-year variability. One potential use of results from the habitat preference analyses (**Section 11**) could be to inform how to deal with areas and periods with no fishing effort. In this particular interpretation it is not so much the depth distribution that is the focus, but rather the horizontal distribution. The simplest use would be to assume that the preference analyses informs us about availability of SBT in a given area and period.

Preference analyses can potentially provide a predictive model of likely distribution of SBT throughout its range as a function of environmental covariates and time of year, or a prior for likely distribution which can be incorporated into CPUE standardisation with the particular view of dealing with grid cells with zero effort. Unfortunately, the preference surfaces available from this project cannot be used directly for the purpose because our datasets are dominated by 2-4 year olds, whereas the longline CPUE index is currently based on ages 4-9. More tags from this project may still be recaptured, and we hope that they will be returned (tags will be processed and data uploaded to the database even after the formal end of this project) because they would provide invaluable information on behaviour of older SBT. Some information is available from pop-up tags deployed on older, larger fish (age 10+) (Patterson *et al.* 2008), but more data, particularly on ages 4-9, are required.

Irrespective of the future returns of tags deployed under this project, more analyses would in any case be required to evaluate the predictive power of any particular ‘habitat preference’ model. The details of exactly how to construct the overall standardisation using such an approach would need to be explored; for example, is stratification sufficient for dealing with “space” or is a full spatial model with movement dynamics required, and if so, what are the appropriate time and spatial scales required?

If this approach is to be pursued in a serious way, we consider it important to obtain direct data (from electronic tags) of age 5 and older SBT, over as wide a region and time (at least within the period of April to September) as possible. This would also provide information on the question of site fidelity of older fish in relation to potential spatial depletion (see **Section 12.6** below). We also note that long-term deployments of electronic tags on spawning-age fish would provide a direct estimate of how age affects time spent on spawning grounds, which is an important parameter of the close-kin genetic estimate of abundance (Bravington *et al.* 2007) Given the interannual variability and changes we have observed in our dataset, we would also recommend that data from multiple years be collected. Clearly, a proper design study should be conducted before deploying large numbers of electronic tags. As already noted, regardless of whether electronic tag data are used directly in CPUE standardisation, these data are still vital in order for us to continue to improve our understanding of, and monitor changes in, SBT behaviour, and to inform a spatially explicit models in future. Deployment of electronic tags should therefore be undertaken with these multiple purposes in mind (see **Sections 12.3** and **12.6**).

12.3 Implications for mark-recapture models

In this section we consider implications of results generated in this project for using mark-recapture (‘conventional tagging’) studies for assessing the SBT stock (i.e., for estimating mortality rates and abundance). We focus on whether a spatial framework is necessary, and if so, whether there is a need to incorporate archival tag data into the model (as developed in **Section 9**). Mark-recapture studies remain a potentially powerful approach to assessment, provided some of the difficulties encountered in the past (e.g. reporting rate issues with the 2001-2007 SRP tagging program) can be overcome (see **Section 12.6**).

We remind the reader that mark-recapture programs can provide estimates of mortality rates (natural and fishing) and also, when used with reliable catch-at-age data, estimates of cohort size. A mark-recapture model can, therefore, be used as a stand-alone assessment method, or it can be integrated with other data sources (e.g. size frequency data, CPUE index, aerial survey index of juvenile abundance) as has been done for the 1990s tagging data in the current CCSBT operating model (and see **Box 12.1** above). The discussion that follows is in terms of a stand-alone mark-recapture model, but it is equally applicable to integrated models.

While our main focus here is on SBT, we start by considering more broadly when a spatial model is required for stock assessment purposes. **Figure 12.2** presents a flow chart to aid in determining whether a spatial model is required, and if so, whether archival tag data are likely to be needed to get reliable estimates of the movement parameters (and thereby reliable estimates of the area-specific fishing mortality and abundance estimates). It is important to note that even when spatial (i.e. area-specific) estimates are not of interest, a spatial model is still required to get unbiased estimates if tagged and untagged fish do not mix fully across the species’ range (most likely to be a problem for wide-ranging species like tuna). Spatial models require estimates of fish movement. The most common, and perhaps the only viable, way to get estimates of movement is through tagging of animals. Traditionally, conventional tags have been the main source of information on movement, but archival (electronic) tags are much more informative in this regard. In fact, when conventional tags are only released in a limited range of the species' distribution, then archival tags are necessary to estimate movement rates if a spatial model is being used—necessary to get estimates of all the model parameters in some cases, but still necessary to get reliable (precise) estimates in other cases. This was shown using simulations (see **Appendix 6**), and was also apparent in our application of a spatial tag model to SBT data in **Section 9** (where unrealistic movement estimates were obtained when archival tag data were not included). Note that while electronic tags are highly informative about movement, the sample sizes are usually too small for estimating mortality rates and abundance – thus, conventional tags are generally still required.

Working through the flowchart in **Figure 12.2**, the following observations can be made:

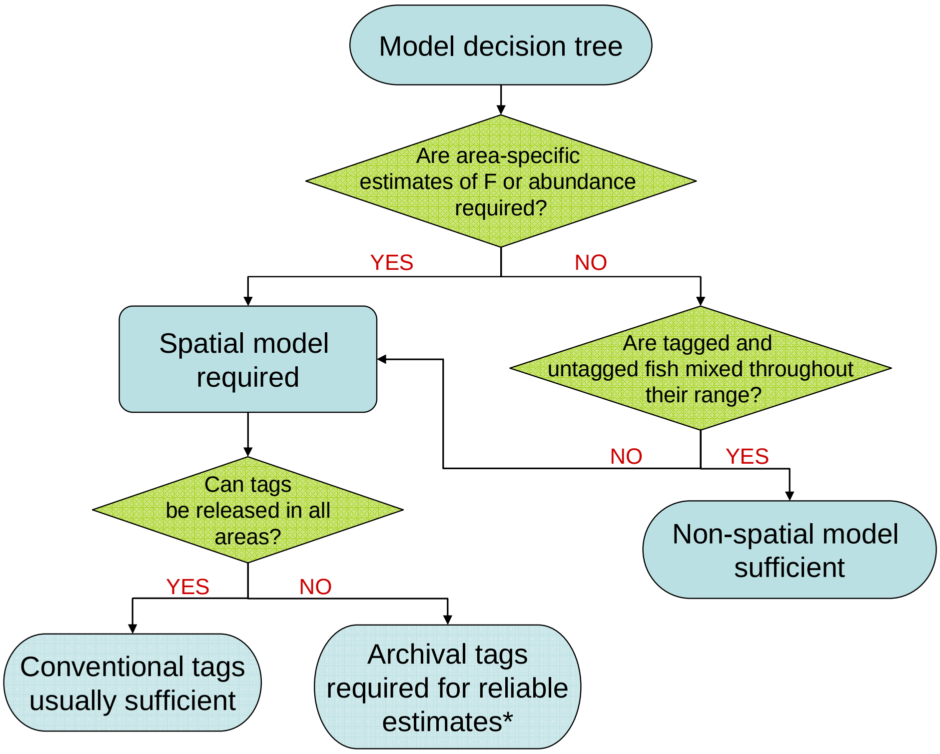
- For SBT, the first decision in the flow chart (whether or not area-specific estimates are required/desired) needs consideration. Current management is not area-specific (a global TAC is set), and the operating model is not spatially structured (see **Section 12.5**). However, this may change in future, especially given the significant changes in spatial dynamics of the Japanese longline fleet in recent years (as a result of reduced quotas; Itoh 2010), and also apparent changes in spatial dynamics of juvenile SBT between the 1990s and 2000s (see **Section 8**).
- Another consideration is that if the catch data are not accurate (biased), then it may be better to focus on harvest rates (F) for management, and in that case having spatial estimates may be more informative.
- If it is decided that area-specific estimates are not required (i.e., overall F and total abundance are sufficient), then we need to evaluate the degree of mixing of juvenile SBT to determine if a spatial model is required. If mixing is not achieved, then the estimates from a non-spatial model will be biased.
- The movement data collected here suggest reasonably good mixing of juveniles throughout their range (see **Section 9**); however, most archival returns are from GAB or WA releases, so it is still difficult to fully evaluate the extent of mixing. For instance, the existences of a "resident" portion of the juvenile SBT stock off South Africa that never venture to the GAB seems unlikely considering all evidence available (see **Section 10.2.6**). However because we have not had any

recaptures of fish tagged off South Africa, the question remains partially unanswered.

- In **Section 9** we compared overall fishing mortality (F), natural mortality (M) and abundance estimates for SBT derived from the spatial model with archival tags (i.e., average/total estimates across all regions) with estimates obtained from a non-spatial tagging model. The F estimates from the spatial and non-spatial models were fairly similar in the 1990s, but in the 2000s, the F estimates from the spatial model were substantially smaller. Also in the 2000s, the total age-1 abundance estimates from the spatial model were larger across all cohorts. In both decades, the spatial model gave a considerably smaller estimate of M at age 2+.
- Although there are a number of issues/caveats with interpreting the SBT results due to large uncertainties in some of the data inputs (such as the catch data and reporting rates – see **Section 9**), they demonstrate that the differences in the estimates for SBT using a spatial versus non-spatial model can be large enough that they might influence management decisions. How much of an influence will depend in part on the management strategy being employed (e.g., the MP that is adopted). We note that the current set of candidate MPs (Anon. 2010) use CPUE and the aerial survey indices as inputs rather than estimates of F.
- If a spatial model for SBT is adopted in future, it will be important to design an appropriate release strategy for archival tags. Given that movement patterns of juvenile SBT have changed in past (not just recent changes, but also disappearance of juveniles from NSW waters in 1980s) and may continue to change in future, the release should be designed so that changes could be detected and reliable estimates of movement rates between regions could be obtained.
- The number of archival tags that would need to be released for beneficial input to a spatial model depends on several factors, such as future fishing mortality, natural mortality and reporting rates (all of which govern the number of returns). However, based on the values used in our simulations (**Appendix 6**), which were chosen to be within a realistic current range for SBT, the numbers need not be prohibitively large and relatively small increases can have a large

impact. For example, increasing the number of archival tag releases from 25 to 50 tags per year and age-class (ages 1-3 for SBT) reduced the coefficients of variation in the fishing mortality estimates by 10-20%. If, say, fishing mortality rates for juvenile SBT were to decline substantially in future, then the number of releases required would be greater, but could be evaluated using a similarly designed simulation study.

Conclusions arising from, and related to, this section are considered in **Section 12.6**.



*In some cases, required for estimation of all parameters to be possible.

Figure 12.2. Flow chart to guide whether a spatial model is required, and if so, whether archival tag data are required.

12.4 Implications for the aerial survey index of juvenile abundance

A summer aerial survey in the GAB has been conducted since 1993 (suspended in 2001-2004 for logistical reasons – see Cowling *et al.* 2003) with the goal of providing a fisheries-independent estimate of relative abundance of juvenile SBT (2-4 year olds) (Eveson *et al.* 2010). Since the aerial survey was suspended at the time this project was proposed, there were no explicit objectives relating to the aerial survey. Nonetheless, some results from this project are relevant to the aerial survey.

The aerial survey consists of a set of survey transect lines flown by aircraft in January through March. Trained spotters record sightings of surface schools (size and location of school, size of fish in the school, and related information). The data are analysed to produce a standardized time series of relative juvenile abundance. This index has now been incorporated into the CCSBT operating model and the candidate management procedures being developed (Anon. 2010).

The timing of the aerial survey was initially informed by the timing of the surface fishery in the GAB, and early archival tag returns from the mid 1990s provided some independent confirmation of the main periods of residency of SBT in the GAB. The more recent and much larger archival tag dataset available from this project allowed us to verify this understanding and check whether changes may have occurred over time. This could not be determined as part of the Cowling *et al.* (2003) FRDC project. The migration modelling in **Section 10** showed that from January to May juveniles are primarily resident in the GAB and off the southern Australian coast (between 115 and 145^{o}E), and in February and March they are almost exclusively resident there. Migration out of the GAB starts in May, but mainly occurs in June to August; whereas migration back to the GAB occurs mainly in November and December but continues as late as January. These results confirm that the timing of the aerial survey (Jan-Mar) is ideal given most juveniles (at least those that migrate to the GAB, which we discuss below) will have arrived by the start of the survey, or if not then definitely before the survey has ended, and essentially all individuals will remain in the survey area until the survey has ended. These results were similar between the two time periods for which we have the most archival tag data (1998-2000 and 2004-2006).

Catches of mostly age 2-3 SBT by Taiwanese longline vessels in the western Indian Ocean off South Africa in the summer have been reported (see Gunn and Farley 2000). Although the maximum monthly tonnage of these summer catches has been less than ~300t since the mid-1970s, it still raises the concern that some juveniles are not found in the GAB in summer. If in fact a proportion of the juvenile (age 2-4) population is found outside of the GAB (off South Africa, or elsewhere) at the time of the aerial survey, it would not be included in the index of relative abundance derived from the survey. If this is the case, but the proportion of juveniles outside of the GAB is (approximately) constant every year, the fact that they are not included would not be a problem because the aerial survey is used as an index of *relative* abundance. The index can still be interpreted as being proportional to the total juvenile abundance. If, however, the proportion outside the GAB is substantial and variable, then problems would arise with interpretation of the aerial survey index. Thus, the question of whether there is a substantial proportion of the juvenile population outside the GAB in summer, and whether that proportion varies significantly between years, is important, especially now that the aerial survey is part of the CCSBT operating model and potentially of the management procedure (Anon. 2010).

The archival tag data collected to date suggest that the proportion of age 2-4 fish in the GAB during the months of Jan-Mar is very high (close to one) every year. All but one of the returns from tags deployed as part of this project, and one of the returns from previously deployed tags, migrated to the GAB in each subsequent summer after release. Both of these individuals were present in the GAB during at least one summer (we cannot know what they did prior to tagging), and the summers they spent outside the GAB were spent in the western Indian Ocean and waters off South Africa. Although we released some archival tags off South Africa (see **Section 6**), we have not yet received any returns from these releases, so it is still possible that some juveniles spend their summers off South Africa and never visit the GAB. However, even if this were true, the proportion that does so is unlikely to be substantial given the relatively low catches in the summer months off South Africa compared to the magnitude of surface fishery catches in the GAB. Thus, all the evidence before us suggests it is unlikely that there is a large proportion of juvenile SBT resident in waters off South Africa in summer (and we have no evidence of juveniles resident elsewhere during the summer).

The proportion of time that juveniles spend at the surface during the day in summer in the GAB also has implications for the aerial survey, since schools can only be spotted when they are near the surface. As shown in **Figure 6.15** of **Section 6**, the proportion of time spent at the surface during the day in the GAB averages ~ 45% in January, 40% in February and 35% in March. As long as the proportion of time at the surface each month is consistent over years, then the fact that the proportion differs by month will not be an issue for interpretation of the aerial survey index of abundance, again, because it is a *relative* index. However, if the proportion by month is not approximately the same across years, AND it is not related to one of the environmental covariates being included in the aerial survey model[28], then it could be an issue. Although the proportion of time spent at the surface each month does vary between years (e.g., ranging from an average of 31% in January of 2004 to 56% in January of 2001), the large amount of variability and small numbers of tags involved in the calculation for each year make it difficult to be conclusive.

12.5 Implications for spatially explicit management

As background to this discussion we note that the current CCSBT management system sets a global (total) TAC for all fleets. This total is then allocated to members and non-members (http://www.ccsbt.org/site/total_allowable_catch.php). The CCSBT does not allocate any TAC to specific spatial areas. The question is, should the TAC also be 'allocated' to specific areas?

In some cases spatial management is required to conserve genetic stocks because the rate of exchange between genetic stocks is so low that one undepleted stock would not help replenish another heavily depleted one (e.g. as for Pacific salmon in North America; Young 1999). There is only one known spawning ground for SBT, and no evidence of separate genetic[29] stocks (**Box 3.1;** Grewe *et al.* 1997), so there is no need for spatial management from this point of view. However, preservation of genetic stocks is not the only reason for considering spatial management. There are two other reasons for considering spatial management for a broadly distributed, highly mobile species: segregation by age and persistent spatial sub-structure that is not reflected on genetic time-scales.

Segregation by age occurs at the juvenile stage (ages 2-4) when SBT form surface schools in the GAB in summer. Catches by the Australian surface fishery in summer are therefore concentrated on a narrow age range. Under the current CCSBT management system a proportion of the global TAC is allocated to Australia, and the majority of the Australian allocation is currently taken by the surface fishery in the GAB. Although the size of the allocation is not based on the estimated age structure

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[28] If the proportion of time at the surface is related to one of the environmental covariates being included in the aerial survey model (say, for example, it increases as SST increases), then the index will get "standardised" to a common level of that covariate, and hence to a (roughly) common proportion of time at the surface.

[29] Genetic stocks: where the rate of migration of animals is low enough to induce genetic differentiation, i.e. over hundreds of generations. For marine fish, genetic stocks are often too coarsely separated to be appropriate for management, in that long-term 'local' over-depletion is quite possible within just one sub-region of a single genetic stock.

of the population, it can to some extent – by accident rather than design – be considered as 'spatial management'.

In comparison, there appears to be less age segregation in areas where the longline fleets operate, and they take a broader size (and age) range (Sakai *et al*. 2010; Anon. 2010b). There is a separate TAC allocation for the Indonesian fishery, which primarily catches spawning-size SBT, but other longline fleets also take spawning-size fish; further comments on spawning grounds are made below.

The second reason for spatial management, spatial sub-structure, essentially relates to avoiding local depletion. The potential advantages of spatially explicit management are most clear in the case of sessile organisms with pelagic larvae. Overharvesting of a single mussel bed may lead to growth overfishing of that bed, and to lower yields than if the same total catch was taken from several beds, but it is unlikely to lead to recruitment overfishing of the entire stock.

In the case of SBT, the lack of evidence for separate genetic stocks does not preclude the existence of persistent spatial sub-structure: for example, juveniles that spend summers in the GAB and juveniles that spend summers off South Africa, or sub-adults that spend winters in the Indian Ocean and sub-adults that spend winters in the Tasman Sea. It is again interesting to recall that historically (beginning in the 1950s), there was a large surface fishery for juvenile SBT off the east coast of New South Wales (NSW), but by the mid-1980s this fishery had collapsed (Caton 1991) and the juvenile population in this region has not supported a direct fishery since. One possible reason (see **Section 8**) is that juveniles ceased to go to NSW in response to the population decline, but schooled with juveniles that remained in the GAB (one could call this a form of 'range contraction', e.g. Dell and Hobday 2008). Another possible reason is because the NSW juvenile population was a group of individuals that persistently went to NSW, and that this group was depleted (local depletion of a persistent spatial sub-structure). If it was a separate, persistent sub-structure of the global stock, spatially explicit management could potentially have prevented this fishery disappearance.

First consider the possible spatial sub-structure of juveniles, i.e. juveniles in the GAB and juveniles off South Africa in summer. There is no evidence from this project to suggest that a large proportion of juveniles remain off South Africa in summer

(January-March) (see **Section 10**). If evidence did become available however, and a sizeable juvenile SBT fishery developed, then the need for spatial management of that fishery would need to be considered. The reason lies in the fact that our dataset shows very high fidelity of juveniles to the GAB in summer (**Section 10**). If there is a large proportion of juvenile SBT off South Africa, they are also likely to exhibit strong site-fidelity in summer (otherwise we should have seen many of our tags spending some summers off South Africa). In this case, the strong site-fidelity would imply persistent spatial sub-structure, at least during summer, and hence a risk of location depletion if management is not spatially explicit.

Regarding possible spatial sub-structure of ‘Tasman Sea SBT’ and ‘Indian Ocean SBT’ in winter, our dataset indicates much weaker winter, than summer, site fidelity for age 2-4 SBT. We do not, however, know the levels of site fidelity of older individuals taken by the longline fleets (ages 5+), particularly ages 5-9. Gunn et al., 2006 and Patterson et. al., 2008 found that all pop-up satellite tagged large SBT (156-200cm; ~age 10 and older, tagged in the western Tasman Sea) that seemed to be migrating towards the spawning grounds, did so late in the spawning season and would only have reached the grounds towards the end of the spawning period. They hypothesise that there might be more spatial structure in than previously thought, but further data are required to further investigate this hypothesis.

Although spatial structuring is unknown, we have observed is a change in migration between the 1990s and the 2000s (**Sections 8** and **11**): fewer age 2-4 SBT have been migrating to the Tasman Sea between about 2001 and 2006 than prior to 2001. Evidence of this change also exists in the New Zealand size frequency data (Anon. 2010b). The year-classes involved were from low recruitments (**Section 11**), so there could have been some aspect of ‘range contraction’, but there also appear to have been environmental changes that could have contributed to this change in movement behaviour (**Section 11**).

The need for spatially explicit management of sub-adult SBT in the Indian Ocean and Tasman Sea, two main regions for longline catches, is still unclear because we do not have data on winter site fidelity of the relevant age classes. In the absence of this knowledge, the precautionary approach would in fact be to ensure that not all the longline catch is taken in one single area, in case there is persistent spatial sub-structure. Such a measure would be aimed at preventing local depletion. Under the current management system, the majority of longline catches could come from one area, though it may of course not happen in practice.

A major advantage of a spatial operating model is the ability to evaluate the need for spatially explicit management under different assumptions about population structure, and under different options for spatial management. For example, one option for spatial management of the longline catch is to define TACs by area (allocations to members can, of course, be retained within that). But, it may be difficult to set appropriate spatial TACs for a highly mobile species such as SBT that may be highly variable in distribution from one winter to the next. A better option may be to use a ‘hybrid’ measure where an overall TAC for all areas is set, but where there are additional management measures to ensure that harvest rates (Fs) in each area are unlikely to lead to local depletion. These different options can be directly compared by evaluation within a spatial operating model and management procedure framework.

A final comment is worth making here. One superficially attractive option for ‘spatial management’ is to limit catches on the spawning grounds, or even impose spawning ground closures. This is only effective if the *overall* harvest rate on spawners is sustainable, i.e. catches in the rest of the year and in other areas did not increase to make up for the loss of catches on the spawning grounds (Shepherd 1993). The size frequency distributions of several fleets (Sakai *et.al*. 2010; Anon. 2010b) show that spawning-size SBT are caught off the spawning grounds, so the overall harvest rate is not just a function of catches on the spawning grounds during the spawning period.

12.6 Conclusions and future directions

Results from this project indicate that a spatial operating model for SBT would be preferable in order to provide unbiased estimates of mortality rates from mark-recapture data, and to improve the likelihood of correctly interpreting trends (rather than responding to noise) in CPUE.

Following a detailed consideration of alternative approaches to CPUE standardisation (**Section 12.2**) it is clear that one of the major issues – operational changes in fleet fishing practices – is likely to remain, because it is almost impossible to standardise for. The second major concern – low spatial coverage of fishing effort across the range – could possibly be addressed through a ‘habitat preference’ approach, but the approach has not yet been proven, and the data for the relevant age classes are not yet available. Embarking on such a program of work would require substantial electronic tag data from age 5 and older SBT, and detailed analyses to evaluate the predictive power of models.

We have been critical of continuing to use longline CPUE as a key data source in the operating model and management procedures. Davies *et al*. (2008) and Basson and Davies (2008) also outlined reasons for using CPUE with caution, and suggested alternative approaches. Recall that the CPUE index provides information on age 4-9 SBT, and there is no fisheries independent data source for this age group (see **Box 12.1** above). As an alternative, or in addition to, CPUE we suggest considering a return to mark-recapture approaches, both for use in the operating model (‘assessment’) and for use in a future management procedure. This approach can contribute fisheries independent data to the juvenile component, as evident from the past (**Section 9**). The extent to which it can contribute to the sub-adult (ages 4-9) component is currently less clear. In the past, it has only been possible to estimate harvest rates up to age 5 with acceptable standard errors (**Section 9**). Although estimates have been obtained up to age 7, low numbers of returns from these older age classes mean they have high standard errors. Part of the reason for low returns from the older age classes may be a lack of reporting of recaptures from longline fleets. The reporting rate problems encountered in the 2000s mark-recapture program (see **Section 9** and references therein) can, in our view, be overcome by using alternative tagging techniques, such as gene-tagging[30] (Davies *et al*. 2008). It is, therefore, still possible that a well designed mark-recapture program could in future provide fisheries-independent information on the sub-adult component of the stock. The combination of an aerial survey, mark-recapture program and close kin estimate of spawning biomass, would then provide a fishery independent data source for each of the three components of the population.

Results in **Section 9** strongly indicate the need for also deploying electronic tags in order to analyse results in a spatial model, and obtain unbiased estimates of mortality rates. We emphasise that the cost of an electronic tagging program need not be

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[30] This should not be confused with the Close Kin project which uses genetic techniques to identify parent-offspring pairs. The gene tagging we refer to means taking genetic samples from juveniles and releasing them (tagging); taking genetic samples from the catch and analysing them to find matches with the ‘tagged’ fish; the matches are the recaptures.

prohibitive: tag deployment costs, which dominate the total program costs, are similar to those for conventional tags, and although electronic tags are much more expensive than conventional tags, far fewer are needed. The tools developed in **Section 9** and **Appendix 6** can be used to determine appropriate levels and temporal design of an electronic tag deployment program as part of a mark-recapture program. It is important to note that any deployment of electronic tags (archival tags in particular) as part of a mark-recapture program will provide substantial information on other aspects of SBT behaviour, as illustrated by this project: for example, changes in migration patterns, changes in spatial or vertical distribution (including surfacing behaviour) or changes with regard to environmental conditions. It will also provide opportunities for exploring the use of such data in conjunction with CPUE analyses.

Developing a spatial model is possible, as we show in **Section 9**, but extending it to include all age classes will not be a straightforward or quick task. Decisions within the relevant CCSBT forums (Stock Assessment Group, Scientific Committee for example) about how to deal with the historic data, how to structure the model, how to collect information on movement rates of older (age 5+) SBT would need to be made, and model development and testing completed. A program for ongoing data collection to inform the spatial model would need to be designed. The development is likely to take a minimum of 3-5 years.

Results to date do not, in our view, indicate a strong need for spatially explicit management. This is partly because the current CCSBT management system of TACs allocated to members (and hence fishing fleets) already indirectly implies a separate TAC for juvenile SBT, i.e. when ages 2-4 in surface schools are essentially segregated from other age classes. It is also because there is currently little evidence to suggest that a large proportion of juveniles have persistent summer residency off South Africa. A definitive answer to the question whether some juvenile SBT never visit the GAB (see **Box 3.1**) is likely to be cost effectively answered by otolith microchemistry whereby ocean area usage can be determined from analysis of fish captured in commercial fisheries. This approach does not just provide information on the current or recent ocean area usage, but for archived otoliths from adult SBT, it can provide information on ocean area usage in the past.

The need for spatially explicit management for winter longline fisheries in order to avoid local depletion is unclear, because the level of winter site-fidelity of age 5 and older SBT (taken by the fisheries) is still unknown. Addressing this substantial knowledge gap with electronic tagging is a highly feasible undertaking. In the absence of this knowledge, and in the light past experience of the disappearance of the NSW fishery in the mid-1980s (**Section 12.5**), the precautionary approach would be to ensure that not all the longline catch is taken in one single area, in case there is persistent spatial sub-structure. Under the current management system, the majority of longline catches could, in theory, come from one area. It may be difficult to set appropriate spatial TACs, since the distribution of SBT may be highly variable from one winter to the next. It may, however, be possible to maintain the current process for dealing with the global TAC (i.e. allocation by member), but to apply additional management measures to ensure that harvest rates (Fs) in each area are unlikely to lead to local depletion. A major advantage of a spatial model would be the ability to evaluate the need for, and quantify the risks of not having, spatially explicitly management. It is therefore, at the very least, worth the CCSBT considering the development of a spatial operating model for SBT.

13 Benefits

The beneficiaries of this research, as identified in the project proposal, are the management agencies responsible for the stewardship of the resource, at both a domestic (Australian Fisheries Management Authority (AFMA)) and international (Department of Agriculture, Fisheries and Forestry (DAFF); Commission for the Conservation of Southern Bluefin Tuna (CCSBT)) level. The fishery also benefits through reduced uncertainty regarding the impacts of SBT movements and residency on the assessment processes.

Adoption of the research outputs, informed by regular reports to the CCSBT and pending CCSBT endorsement, will be through: modification of the operating model used by the CCSBT Scientific Committee and member scientists; modification to CPUE standardisation processes where relevant; and formation of a firm basis for the development of future mark-recapture programs for SBT. Uptake of results has been delayed by the CCSBT's recent focus on developing a management procedure for SBT.

Results have increased our confidence in the recruitment index based on the aerial survey in the GAB by confirming that the timing and duration are ideal, that the majority of juvenile SBT return to the GAB each summer, and that there is no evidence for a large proportion of juvenile SBT remaining off South Africa over summer. This is of benefit to all stakeholders and management bodies, including the CCSBT.

Investigation of stock structure was also required as part of EPBC Act conditions for the operation of the domestic SBT fishery, and we support the understanding that there is a major summer area occupied by juvenile SBT in the GAB.

14 Further Development

Presentation of results to CCSBT meetings and distribution to CCSBT members will be important in dissemination of results to the international SBT management community. Discussions about these results with domestic SBT fishing companies as part of the next science workshop at Port Lincoln will be important. Publication of the results, now underway, will inform the international science community about the importance of spatial dynamics in assessment of resource status.

15 Planned outcomes

The planned outcomes in the application were to generate an understanding of juvenile southern bluefin tuna spatial structure that would support continued responsible management of the species. The extension of SBT assessment methods to include spatial components is a significant scientific achievement, and of major interest to the international community. A publication on this spatial model has been submitted for publication (Appendix 6).

Adoption of the research outputs, informed by regular reports to the CCSBT, will be through modification of the operating model used by the CCSBT Scientific Committee and member scientists, modification to CPUE standardisation processes where relevant, and by forming a firm basis for the development of future mark-recapture programs for SBT.

We initially suggested that methodologies developed as part of this project, such as CPUE standardization through habitat characterization, will have important benefits when applied to other tuna and large pelagic fisheries. The analyses suggested that CPUE standardization was not likely to be as useful for SBT as first anticipated, and so may not be appropriate for consideration in future assessments. The methodologies used to model migration and habitat preference may, however, be extended to other tuna and large pelagic species.

The understanding of the migration and residency patterns for juvenile SBT will also allow informed discussion on the utility of spatial management instruments, such as a spatial TAC, by national (e.g. AFMA) and international (i.e. CCSBT) management agencies.

Finally, the methods for including archival tag data into assessment models will also be of great international interest, given the resources devoted to electronic tagging projects around the world. The publication outputs from this project will inform improved use of these data by many scientists and managers, and demonstrate that Australian fisheries management is world-leading.

16 Conclusion

Despite a general understanding that juvenile SBT move between the GAB in summer and the Indian Ocean or Tasman Sea in winter (**Section 4**), a number of uncertainties remained prior to this project. The schematic in **Figure 16.1** illustrates the new information gained through this project that is relevant to the spatial dynamics of this wide ranging species.

International collaboration between SBT fishing nations was critical to achieving the objectives of this project (**Section 6)**. Tag deployment, particularly fish handling and surgery, requires training, and the training we provided to partners allowed successful deployment opportunities. Technologies to support tagging from a range of vessels were developed, and as a result a total of 568 tags were released in all five desired areas. To date, 13% of releases (n = 74) have been recovered. Combined with earlier tag programs, a total of up to 122 tags were available for use in analyses. Quality controlled data were archived in a database, facilitating analysis. Two tags recorded over 4 years of data, 75% of tags covered at least 6 months, and 41% covered at least one year. Preliminary analyses shows SBT are deeper during the day, spend less time at the surface during daylight, particularly during winter, and maintain a body temperature that is up to 5°C warmer than the surrounding waters.

Two different approaches for estimating the daily position of each SBT (latitude and longitude) from the light and depth data recorded by the archival tags gave broadly consistent results (**Section 7**). These location estimates were subsequently used in three areas of analyses: 1) a spatial model for analysis of mark-recapture data, (2) the development of a seasonal migration model and (3) estimating habitat preference. Clear signals of cyclic seasonal movement are apparent from the estimated tracks. All SBT in our dataset spent each summer (or part of summer) in waters south of Australia (the GAB and waters south of WA), except one SBT tagged in the Indian Ocean in winter that visited the GAB in the summer following tagging, but spent two subsequent summers in waters off South Africa. The majority of SBT migrated from southern Australia to the Indian Ocean for winter, a much lesser percentage to the Tasman Sea and, somewhat surprisingly, several individuals overwintered in southern Australia. Juvenile SBT move in a broad area between 30-50^{o}S in the Indian Ocean;

there does not appear to be specific, or narrowly defined, migration routes (**Section 7, 8 and 10**).

Two large conventional tagging programs were conducted by the CCSBT in the 1990s and the 2000s to estimate mortality and abundance. For logistic reasons, juvenile SBT can only cost-effectively be tagged off southern Australia in summer. In such a situation, an analysis that ignores spatial structure can lead to biased estimates of mortality rates and abundance; however, estimating movement rates (as needed in a spatial model) can be difficult with conventional tag data alone. Thus, methods of incorporating archival tag data into a spatial mark-recapture model were developed. Application of these methods to simulated data showed that including data from even a modest number of archival tags can substantially improve the precision of movement and fishing mortality estimates, particularly when fish are only tagged in some areas (**Section 9)**. Application of the methods to SBT conventional and archival tag data from the 1990s and 2000s showed that estimates of movement probabilities were unrealistic without archival tag data (e.g. for the 1990s almost no fish were estimated to return to the GAB for summer); realistic estimates were obtained when archival tag data were included. For the 2000s, cohort size estimates were consistently higher and natural mortality and fishing mortality estimates were consistently lower from the spatial model compared to estimates obtained from a non-spatial model.

The periods of time spent in the resident state in summer and in winter, and the time spent migrating, either out of the GAB or back into the GAB, varied between individuals (**Section 10)**. Methods developed enabled us to quantify the main departure times from, and arrival times to, areas of high residency, as well as the variability in those times. These results have confirmed that the aerial survey timing and duration are well matched to the arrival and departure times of SBT. In addition, all the available evidence suggests it is unlikely that there is a large proportion of juvenile SBT resident in waters off South Africa in summer. This substantially increases our confidence in the aerial survey as an index of juvenile SBT abundance. However, the archival tag data to date cannot answer the question whether there are juveniles (age 2-4) that never visit the GAB in any summer; the answer could still be “yes”. A return from a tag released off South Africa (of which we have none to date) may answer the question, but a definitive answer is most likely, and most cost effectively, obtained by otolith microchemistry.

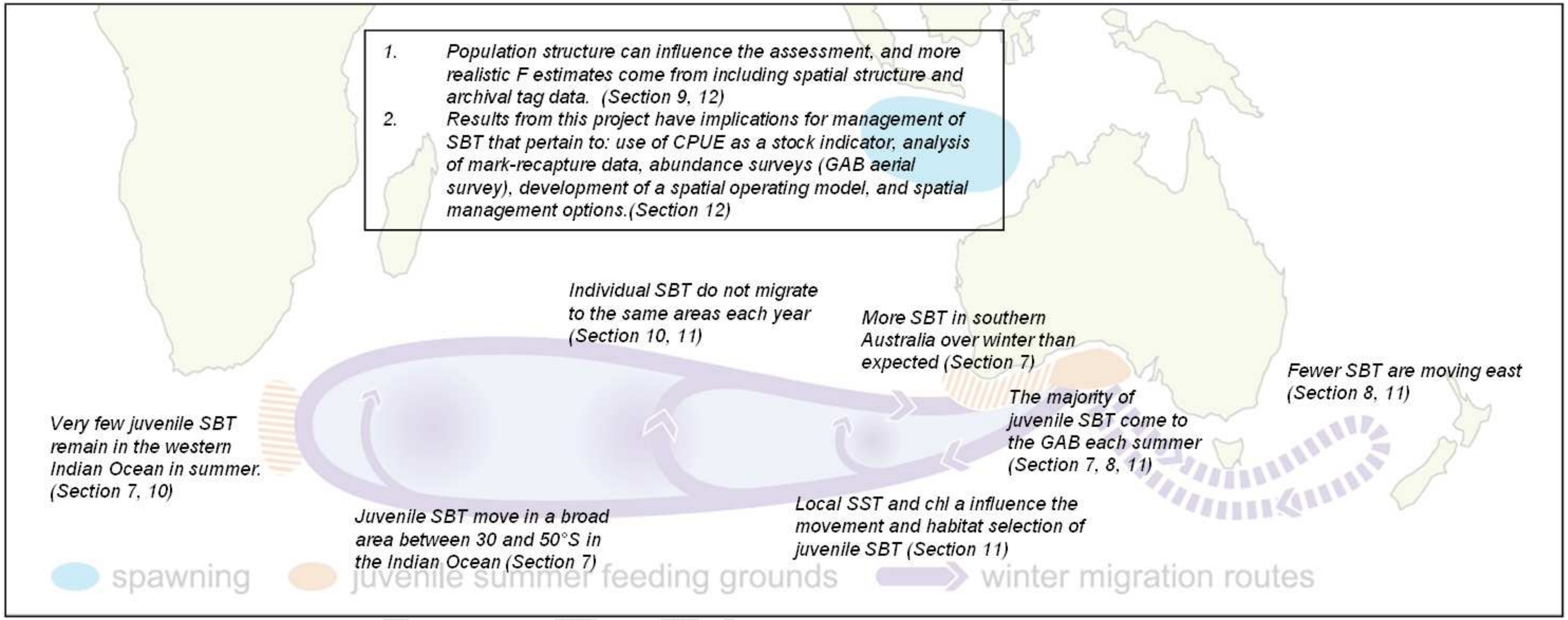
Habitat preference was determined by considering combinations of (i.e. interaction between) sea surface temperature and chlorophyll *a* (**Section 11)**. Preference maps show that in most years the GAB is the only summer location of high preference in southern Australia. In some years the area off NSW, where a surface fishery used to operate until the early 1980s, also shows up as an area of high preference. Preference maps for the late 1990s show a linking band of high preference around Tasmania and into the Tasman Sea in April to June; this linking band is almost absent in recent years. This could be a contributing factor to the observation that far fewer juvenile SBT have been migrating to the Tasman Sea in winter since 2001.

Habitat preference analyses could potentially assist in the standardization of CPUE indices for use in the CCSBT stock assessment process, particularly dealing with areas and regions with no fishing effort (**Section 12)**. However, habitat preference for the age classes in the longline catches will have to be developed and variation in preference and environmental conditions over time will have to be considered before this is possible. Other approaches to CPUE standardisation, such as developing models for estimating catchability by depth, will require substantial additional data collection (e.g. on sub-adult SBT behaviour) and analyses, and we doubt the value of embarking on such an exercise, given that it would not resolve the major concerns of (1) operational changes in longline fleet behaviour and (2) lack of spatial and temporal coverage. This is not to say we doubt the value of collecting more data on sub-adult behaviour, which is lacking for SBT, just that we discourage doing so solely for the purpose of CPUE standardisation.

Spatial structure of a population can influence stock status assessments, and results from this project suggest that a spatial operating model for SBT would be preferable to a non-spatial model, both from the point of view of mark-recapture data analyses and the interpretation of CPUE indices (**Section 12)**. Developing a spatial model should be possible, but will not be a straightforward or quick task. Decisions about a range of modelling issues would need to be made within the relevant CCSBT forums. A program for ongoing data collection to inform a spatial model would need to be designed. We also suggest a return to mark-recapture approaches, both for use in the (ideally, spatially explicit) operating model and for use in a future management procedure (**Section 12)**. The problems encountered in the 2000s mark-recapture program can, in our view, be overcome by using alternative tagging techniques, such as gene-tagging.

Regarding spatially explicit management, there is a strong case for a separate TAC on age 2-4 juveniles in the GAB during summer because of their segregation by age and their strong summer site fidelity (**Section 12**). By accident – rather than design – this is the case since Australia has a separate ‘member country’ allocation, and currently most of this is taken by the surface fishery operating in summer in the GAB. There is currently no evidence of a large proportion of juvenile SBT off South Africa in summer, but if this situation changes and if a sizeable fishery did develop, then the need for spatial management of that component should be considered. This is because there is a strong possibility that juveniles off South Africa would show similar high levels of summer site fidelity as juveniles in the GAB do. The need for spatial management of the winter longline component (i.e. ‘Tasman SBT’ and ‘Indian Ocean SBT’) to avoid localised depletion is less clear because winter site-fidelity of age 5 and older SBT is unknown. Another advantage of a spatial model would be the ability to evaluate the need for spatially explicit management.

Overall, we have assembled the most comprehensive picture yet of the cyclical seasonal migration and global movements of juvenile SBT which will support future spatial assessment (and management where appropriate), as well as process understanding for this species. Remaining issues for the spatial dynamics of juvenile SBT include fish movements and residency along the western Australian coastline, prior to southern Australia. Acoustic tagging is providing evidence of local residency during the summer along the coast of Western Australia, consistent with the results based on archival tags from this project, but the fraction of age-1 fish that do not move to southern Australia in the summer months is unknown. A combination of acoustic and archival tagging on the west coast of Australia could address this question. Archival tagging of juvenile SBT off South Africa could also be a focus in future programs, as we accept that the power to detect summer residency from fishes in the western Indian Ocean is weak in this project, although catch data and the movement of most fish suggest that summer residency by a large fraction of the juvenile population is unlikely. Another promising approach is that of otolith microchemistry; a pilot project is currently nearing completion and will inform future research decisions. For sub-adult fish (age 5-9) comprising the bulk of the longline catches, the implications of movement and stock structure on the assessment of the resource remains speculative at this time, and will require additional tag-based data collection and analyses. This important component of the population currently has no fishery independent data source to inform the stock assessment/operating model.



1. Population structure can influence the assessment, and more realistic F estimates come from including spatial structure and archival tag data. (Section 9, 12)
2. Results from this project have implications for management of SBT that pertain to: use of CPUE as a stock indicator, analysis of mark-recapture data, abundance surveys (GAB aerial survey), development of a spatial operating model, and spatial management options.(Section 12)

Very few juvenile SBT remain in the western Indian Ocean in summer. (Section 7, 10)

Juvenile SBT move in a broad area between 30 and 50°S in the Indian Ocean (Section 7)

Individual SBT do not migrate to the same areas each year (Section 10, 11)

More SBT in southern Australia over winter than expected (Section 7)

The majority of juvenile SBT come to the GAB each summer (Section 7, 8, 11)

Local SST and chl a influence the movement and habitat selection of juvenile SBT (Section 11)

Fewer SBT are moving east (Section 8, 11)

Figure 16.1. New insight into the movement and habitat use of juvenile (age 2-5) southern bluefin tuna throughout their range has resulted from this project. Juvenile SBT can occupy a broad area of the southern Indian Ocean, with several higher use areas. Fewer juveniles move to the Tasman Sea (dashed line). Some SBT are found in southern Western Australia in summer and winter.

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18 Appendix 1: Intellectual property

Some of the archival tag data analysed in this project was collected under other projects and the IP remains with those projects. The tag database at CSIRO that houses the tag data has been further developed and modified to handle a range of tag types and species. The overall concept of the tag database is described in Hartog *et al.* (2009).

A number of methods related to geolocation and applied to tag data in this project were also developed under external project funding arrangements, including the day/night filter, time varying depth attenuation correction, the twilight likelihood and grid-based HMM methods. The IP for these methods remains with the original developers and projects.

Environmental data from remote-sensed products used in the analyses is publicly available and so should not be considered IP from this project.

19 Appendix 2: Staff engaged on the project

CSIRO staff

Marinelle Basson – project PI, analysis

Alistair Hobday – tag training, tag deployment, analysis (original Co-PI)

Paige Eveson – analysis

Toby Patterson – analysis

Tom Polacheck – analysis, project liaison (original Co-PI)

John Gunn – project liaison (original Co-PI)

Thor Carter – tag deployment, tag training

Naomi Clear – tag training

Grant West – liaison, rewards, and database

Matt Lansdell – liaison, rewards, and database

Clive Stanley – liaison, rewards, and database

Scott Cooper – database design

Jason Hartog – database, tag quality control, analysis

New Zealand collaborators led by Talbot Murray

Taiwan collaborators led by Eric Chang

20 Appendix 3: Communication of progress and results

CCSBT REPORTS (reverse chronology)

Basson, M., Eveson, P., Hobday, A. and Lansdell, M. 2010. Update on the global spatial dynamics archival tagging project – 2010. CCSBT-ESC/1009/Info3.

Basson, M., Eveson, P., Hobday, A. and West, G. 2009. Update on the global spatial dynamics archival tagging project – 2009. CCSBT-ESC/0909/38.

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CONFERENCE PRESENTATIONS

Basson, M., Bravington, M.V., and Hartog, J. A likelihood for light-based geolocation. Fourth International Science Symposium on Biologging. 14-18 March 2011. Hobart, Tasmania.

Eveson, P. Basson, M., and Hobday, A. Are archival tags useful for fisheries management? Incorporating archival tag data in a tag-based assessment model. Fourth International Science Symposium on Biologging. 14-18 March 2011. Hobart, Tasmania.

21 Appendix 4: Archival Tag Surgery Training Program

Version – April 2005

Dr Alistair Hobday – CSIRO Marine Research Introduction

Why use Archival Tags

- What are they
- What they can tell us
- Why the information is important

Preparation of tags

- Initialization (turned on at CSIRO, 5 year memory…)
- Recording tag numbers
- Sterilization/cleaning of equipment

Selecting a fish

- Landing technique
- Dehooking
- Killer attributes (in water observations, gill bleeders, eye bleeders, deck skidding)
- Transferring to the tagging area (get length)
- Position in the cradle
- Calming a fish
- To flush or not to flush the gills (if have people to spare…)

Surgery

- Incision
    - Position and depth
- Insertion of tag, position of light stalk

- Stitching, help in holding the stitch (20 practice stitches)
- Expected time for surgery (~3 minutes)

Aborting a surgery

- Too long
- Fresh bleeding

Releasing a fish

- Lifting, headfirst

Post-release checks

- Tag check
- Preparation for next fish

Troubleshooting

- Liaison with crew and captain
- Getting assistance

Training elements

- Talk
  - Why this archival tag study (powerpoint)
  - Videos, pictures,
- Demonstration
  - Kit preparation
  - Fish handling
  - Incision (foam and water balloons)
  - Stitching (practice on back of a chair)
- Quiz (on theory) and then practical test – must complete in <2 minutes
- Certificates presented

22 Appendix 5: SBT Tagging Procedure for Archival Tags

EQUIPMENT FOR TAGGING

- Sharp knife (9 cm blade)
- Absorbable sutures
- Needle holder for suturing incision (see Note 2)
- Antibiotic and disposable syringes (see Note 3)
- Archival tag
- Betadine antiseptic solution to wash knife and needle holder between use
- Data sheets

CRITERIA FOR TAGGING

- Choose SBT that are agreed size and whose condition is judged suitable for tagging
  - SBT must not be bleeding from gills or mouth when landed and after having the hook removed
  - Fish must be in good condition and not visibly damaged

LANDING SBT FOR TAGGING

Have tagging equipment and work area prepared ahead of time. Have one tag in Betadine ready to use and with its number recorded on the data sheet.

SBT that are suitable for tagging should lifted aboard with all care taken to avoid them contacting the side of the vessel.

Once aboard work quickly

Wear disposable surgical gloves and keep your hands and the fish wet.

Hold the fish close to your chest when carrying it

Use a tagging mattress – always place fish on wet smooth surfaces to avoid body damage. Use clear restraining strap on tail of fish.

Remove hook and check for damage

Cover the fish's eyes with flap of tagging mattress or a damp cloth

Measure fork length of the fish

Roll fish to expose ventral surface for tagging

IMPLANT ARCHIVAL TAG

Locate a point along the middle of the ventral surface between the pelvic and anal fins far enough forward that the end of the stalk will not hit the anal fin.

Use the knife to cut through the skin, fat and muscle but leave the peritoneum intact. Make a small slit about 4 cm long

Use your finger to break through the peritoneum.

Inject antibiotic directly into the body cavity.

Gently insert the archival tag so that it lies lengthwise inside the body cavity and push it forward so that the stalk is near the front of the incision.

Close slit with one stitch, tie off suture, and cut thread about 5 mm above the knot. Note that if the fish is in good condition but there is concern about it being out of the water too long, it is possible to release it without putting in a suture.

RELEASE TAGGED SBT

Release the fish head-first into the water as quickly and gently as possible without scraping it along the deck.

Record the details of the release on the data sheet: fork length, date/time, position etc

Note 1: It is best to use the tags in numerical order to avoid any confusion over tag numbers. By having the next tag number to be used already entered on the data sheet it saves time trying to read the small writing especially under difficult light situations.

Note 2: Ethicon Coated Vicryl absorbable sutures, 27 inch (70 cm), needle has taper XLH. Product code J-583G. Sutures come in boxes of 12 (about $150 per box), we can stitch 2-3 fish per suture.

Note 3: Give the fish a dose of the broad spectrum antibiotic, amoxycillin, use either 'Betamox' or 'Moxylan' which comes in 100 mL bottles, 2 mL for a 40 kg fish is recommended. The antibiotic is injected with a disposable syringe (one for each fish) without any needle. Antibiotic is injected directly into the body cavity.

REMEMBER: If in doubt, don't release the tagged fish
(Even the most experienced taggers abort releases)

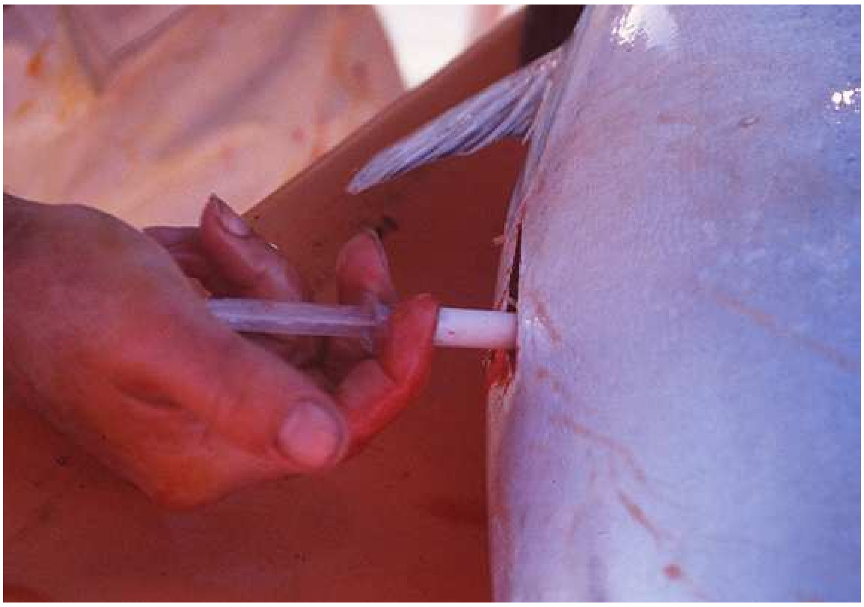
Don't Release a SBT:

1) If bleeding from the gills or eyes
2) If any internal bleeding from the gut cavity
3) If time out of the water exceeds 4 minutes from landing to release
4) If the fish has been dropped on the deck or slid out of the tagging mattress
5) If the incision is too far forward, too far back or too deep, or leads to bleeding

Basic equipment for implanting archival tags in southern bluefin tuna.

Locating the point for the incision and cutting through the body wall, note this photo was prior to wearing gloves.

Before inserting the archival tag the body cavity is flushed with antibiotic using a disposable syringe with the needle removed.



Inserting the head of the archival tag through the incision.

Error! Objects cannot be created from editing field codes.

SBT with archival tag implanted and suturing being completed. Eyes are covered and fish is kept wet. Note orientation of archival tag antenna.

Error! Objects cannot be created from editing field codes.

Archival tag implanted and entry point sutured.

23 Appendix 6: Using electronic tag data to improve parameter estimates in a tag-based spatial fisheries assessment model

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Abstract

Despite the increased deployment of archival (data-logging) tags on commercially exploited fish species over the past decade, the use of archival tag data in fisheries management has been uncommon. One reason is the lack of analytical methods for including these data in stock assessment models. We show how archival tag data can be incorporated into a spatially-explicit tag-based assessment model for estimating natural mortality, fishing mortality, abundance and movement. Archival tags provide important information on fish movement not available from conventional tags that facilitates separation of mortality from movement. Using simulations, we evaluate the benefit of including archival tag data in the model using two model formulations: one with a very general spatial structure and one with movement and fishery dynamics based on juvenile southern bluefin tuna. Our results show that including archival tag data can lead to significant improvements in precision of movement and fishing mortality estimates, particularly when tagging is not feasible in some regions and time periods. Furthermore, there are situations for which archival tag data are necessary in order for all parameters to be estimable.

Introduction

The deployment of archival (data-logging) tags on commercially exploited fish species has become increasingly common over the past decade, with particular focus on the wide-ranging and valuable tuna species. Important information has been gained on the spatio-temporal behaviour of individuals and populations, including distributional range, migration patterns, depth distribution and diving behaviour (see Sibert and Nielsen 2001; Nielsen et al. 2009). However, the use of information from archival tags to inform fishery management—which is often stated as the primary goal of the research—has been relatively uncommon. In the few examples we know of the data have been used in an indirect or auxiliary capacity; for example temperature data from pop-up satellite archival tags (PSATs) have been used in a habitat preference model for a bycatch species (southern bluefin tuna) to help set management boundaries that minimize this bycatch (Hobday and Hartmann 2006; Hobday et al. 2010). Similarly, electronic tag data have been proposed for habitat-based catch-per-unit-effort standardization (e.g., Bigelow et al. 2002), although concerns about this approach exist (Maunder et al. 2006).

We are unaware of any cases where archival tag data have been used as direct input to spatially explicit stock assessment or management models. Reasons for this include: (i) the accuracy and precision of light-based position estimates from archival tags can be poor (Welch and Eveson 1999; Musyl et al. 2001; Teo et al. 2004); (ii) archival tags are much more expensive than conventional tags, so the latter are often considered sufficient for assessment purposes; (iii) electronic tagging experiments are often not designed with regard to the needs of assessment models, and, (iv) there is a lack of established analytical methods for including data from archival tags in spatial assessment models. With regard to the first reason, many management applications only require knowing the broad-scale location of animals (e.g., spawning grounds versus feeding grounds; management areas), which can often be determined with the current levels of position accuracy and precision. For instance, boundaries of stock management areas have been queried and proposed based on data from electronic tags (e.g., Block et al. 2005). Also, advances in geolocation methods are improving the accuracy of position estimates derived from current tag data (Teo et al. 2004, Ekstrom 2004, Nielsen and Sibert 2007; Sumner et al. 2009), and novel tag sensors will lead to further improvements in future (e.g. magnetic field sensors [http://www.desertstar.com/Products_product.aspx?intProductID=7]). In terms of the expense of archival tags compared to conventional tags, we show that having only a small amount of archival tag data can be very informative when spatial assessment models, which require estimates of movement, are being employed. With regard to the last point, fishery assessment models that allow for spatial structure, such as MULTIFAN-CL (Fournier et al. 1998), CASAL (Bull et al. 2005) and SS3 (Methot 2011), rely mostly on conventional tag release-recapture data for estimating fish movement; none accommodate electronic tagging data. Spatial applications of these models have been relatively uncommon (exceptions include assessments done on skipjack tuna (Langley and Hampton 2008), broadbill swordfish in the Western and Central Pacific (Davies et al. 2008), and Patagonian toothfish around Macquarie Island (Fay 2011)), because they have been considered unnecessary, too complex, and/or the conventional tagging data have been insufficient for estimating movement (e.g., albacore in the south Pacific; Hoyle et al. 2008). However, electronic tagging studies are revealing a diversity of movement patterns that support the need for spatial structure in the models for some species, whilst also making available the data necessary for estimating movement parameters. Recognition of the usefulness of archival tags for assessment purposes will lead to improved collaboration between modellers and biologists in designing tagging experiments.

With the demand for spatial assessment models increasing and electronic tag data accumulating for a greater number of exploited populations, methods for incorporating these data into assessment models (by which we mean any model for estimating harvest rates and/or abundance) are progressing. For example, Miller and Andersen (2008) have developed a finite-state (also referred to as discrete-space) continuous-time Markov model for estimating migration and mortality rates using data from one or more of archival tags, PSATs and conventional tags. The model is applied in a situation with two regions (states). Although the authors suggest it could be extended to more regions, the convergence problems they encountered with just two regions when sufficient tags were not released in both regions would presumably become worse with more regions. In a second example, Kurota et al. (2008) include data from archival tags and PSATs in their model to estimate movement and mortality rates for Atlantic bluefin tuna (*Thunnus thynnus*); however, they only retain release and recapture data from these tags. Thus, the only advantage they realise over using conventional tag data is that movement can be estimated from the PSATs without being confounded with fishing mortality and tag reporting rates This advantage does not apply for archival tags, which still require the fish to be caught and the tag returned.

Here we present a method that integrates archival tag data into a discrete-space, discrete-time model previously developed by Eveson et al. (2009). The spatial model in Eveson et al. (2009) is a likelihood-based model with a likelihood component for conventional tag-recovery data and one for corresponding catch data. It is referred to as the spatial Brownie-Petersen model since it is a spatial extension of the Brownie-Petersen model developed in Polacheck et al. (2006a). The tag-recovery (Brownie) component contains information for estimating mortality rates and movement probabilities, and the catch (Petersen) component enables estimation of abundance. We show how archival tag data can be included directly in the model through an additional likelihood component. Archival tags provide the same information on recapture rates, and hence mortality rates, as conventional tags, but because sample sizes for archival tags are so much lower, their direct value in this regard is expected to be minimal. The real potential of archival tags is that they provide important information about the location and movement of tagged fish between the time of release and recapture that cannot be obtained from conventional tags. This is important because the model has difficulty separating mortality from movement with conventional tagging data alone.

Using simulations, we examine the effect that including archival tag data in the spatial Brownie-Petersen model has on the parameter estimates, and also consider the trade-off between releasing more archival versus conventional tags. In practice, tagging in some regions and time periods will not be feasible because it is too expensive or logistically difficult, and we expect information from archival tags to be particularly valuable in such situations. Thus, we conducted our simulations under two tag release designs: full (tagging in all regions and time periods) and reduced (tagging limited to certain regions and time periods). In addition, we considered two different model formulations. First, we used the model as presented in Eveson et al. (2009), which has a very general structure with no restrictions on movement between regions or on when and where fishing occurs (referred to subsequently as the general spatial model). Second, to show how the model can be formulated for a specific situation and how the effect of including archival tag data can vary, we used a version of the model that has movement and fishery dynamics resembling those of juvenile southern bluefin tuna (SBT, *Thunnus maccoyii*) (referred to subsequently as the SBT spatial model).

Methods

General spatial model

The general spatial model is presented for a multiyear tagging experiment in which fish from a particular cohort are tagged (some with conventional tags and some with archival tags) in K discrete regions in I consecutive years, at ages 1 to I (note that year and age are interchangeable terms for a single cohort). Fish from the cohort are caught in a fishery operating in all regions over J years starting in the year of tagging (i.e., at ages 1 to J, $J \geq I$). Estimates of the numbers of fish from the cohort caught in each region and year are assumed to be available. Rewards for reporting archival tags that are recaptured in the catches are assumed to be high enough that all recaptured archival tags will be reported. Rewards for conventional tags are much lower, so only a proportion of the conventional tags that are recaptured are assumed to be reported. A number of methods exist for estimating reporting rates (Pollock et al., 2001). We assume that unbiased estimates of reporting rates for the conventional tags are available and treat them as known in the model. This is for the sake of simplicity, but uncertainty can be incorporated through either an additional likelihood component if the data used to estimate reporting rates are independent of the data from the primary experiment (e.g., planted tag experiments; see Polacheck et al. 2006a); or, modifications to the existing likelihoods if observer data are used (e.g., Eveson et al. 2007). The model is presented for a single cohort of fish to simplify notation, but it can naturally be extended to multiple cohorts (see Eveson et al. 2009).

The usual assumptions for tag-recapture models, as outlined by Brownie et al. (1985) and summarized clearly by Pollock et al. (1991), are required (e.g., complete mixing of tagged and untagged fish in each region; homogeneous survival and recapture probabilities within each region and year). For the Petersen (catch) component of the model, the estimated numbers of fish caught in each year and region (derived from a sample of the total catches) are assumed to be unbiased and independent. Additional assumptions relating to the spatial structure of the model are: for conventional tags, regions of fish at release and recapture are correctly determined; for archival tags, regions of fish at all time periods between release and recapture are correctly determined.[31] In addition, to separate mortality from movement, it is necessary to model the timing of movement in relation to the mortality processes. We assume that during a given year, fish stay within the same region, where they may be caught or die naturally. Exactly at the end of each year, fish move between regions according to a Markov chain model; i.e., fish movement at the end of the current year does not depend on its movement at the end of previous years. Furthermore, we assume that fish movement is independent of the movement of other fish. If long-term schooling behaviour is common in the species being modelled, this assumption would be violated. The parameter estimates derived from the model should still be unbiased, but the model-based standard error estimates would be too small.

Because the likelihood components for the conventional tag data and catch data were previously described (Eveson et al. 2009), we review them only briefly here. For the conventional tag data, the numbers of tag returns by year and region

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[31] In practice, tracks estimated from archival tags often stop before the fish is caught and the tag recovered due to reasons such as light sensor or battery failure. The model can be modified to accommodate such tags by treating each one the same as any archival tag up until the track stops, then treating it as a conventional tag that was released in the last recorded region/time period (and recaptured in the region/time period where the fish was caught).

corresponding to releases in a given year and region are modelled as multinomial. The probability of a tag being returned from a given region and year is the function of year- and region-specific survival, capture and movement probabilities and reporting rates. The likelihood is then just the product of multinomial densities over all release years and regions.

For the catch data, the numbers of fish caught in each year and region are modelled as independent Gaussian, with expected values that are the function of year- and region-specific survival, capture and movement probabilities and region-specific abundance at the beginning of the tagging experiment (i.e., at age 1 for the experimental design assumed here). The standard deviation of the catch in each year and region is assumed known, and for convenience, is parameterized in terms of coefficient of variation (CV) (i.e., standard deviation relative to the mean). The likelihood for the catch data is then just the product of Gaussian densities over all years and regions of catches.

We now focus on the new likelihood component for the archival tag data. For each archival tag return, the data needed for the likelihood is the region that the fish was in during each year (or time period, as defined in the model) between release and recapture. It is conceptually simpler to calculate the probability that a fish will be in a given region during a given time period for an archival tag compared to a conventional tag, because all intermediate transitions between release and recapture are known. Thus, under the assumption that fish move between regions at the end of each time period, the probability of a fish released in region r_1 in time period t being recaptured in region r_2 in time period t+3 after having made transitions from r_1 to r_3 to r_1 to r_2 is just Pr(survive r_1 in time period t)*Pr(move from r_1 to r_3)*Pr(survive r_3 in time period t+1)*Pr(move from r_3 to r_1)* Pr(survive r_1 in time period t+2)*Pr(move from r_1 to r_2)*Pr(caught in r_2 in time period t+3). For a conventional tag, all possible intermediate transitions need to be accounted for.

While conceptually simple, the notation for the archival tag likelihood is cumbersome. Define tagging group (i,k) to be the $N\text{arc}_i^k$ fish tagged with archival tags in year i in region k. Let $R\text{arc}_i^k$ be the number of archival tags returned from tagging group (i,k) over the course of the experiment (i.e., in years i to J) in any region. Consider an individual fish, h, from tagging group (i,k) that was recaptured in year y_h ($y_h \le J$) and was in region $r_j(h)$ during each year j at liberty ($j = i,\ldots,y_h$); note that $r_i(h) = k$ by definition. We denote the probability of fish h having this particular history by $p_i^k\left(h\right)$, where

$$p_i^k\left(h\right) = \left(\prod_{j=i}^{y_h-1} S_j^{r_j(h)} \pi_j^{r_j(h),\, r_{j+1}(h)} \right) u_{y_h}^{r_{y_h}(h)}. \qquad (1)$$

S_j^k is the probability that a fish alive at the beginning of year j in region k survives the year; u_j^k is the probability that a fish alive at the beginning of year j is caught during year j in region k; and $\pi_j^{k,k'}$ is the probability that a fish moves from region k to region k' at the end of year j. These are the same survival, capture and movement probabilities required for the conventional tag and catch likelihoods. We assume that the reward for reporting a recaptured archival tag is high enough that non-reporting is negligible; however, if not, then a reporting rate parameter (assumed to be estimable from other sources) can be multiplied to Eq. 1.

We can further express the survival and capture probabilities in terms of natural mortality and fishing mortality, as follows:

$$S_j^k = \exp\left(-\left(F_j^k + M_j^k\right)\right) \tag{2}$$

and

$$u_j^k = \frac{F_j^k}{F_j^k + M_j^k}\left(1 - S_j^k\right) \tag{3}$$

where M_j^k and F_j^k are the instantaneous rates of natural mortality and fishing mortality, respectively, for fish in year j and region k. This assumes that, within each region, fishing and natural mortality occur continuously at constant intensities throughout each year.

The likelihood for all fish in archival tagging group (i,k) is just the product of the individual probabilities in Eq. 1 over all $R\mathrm{arc}_i^k$ recaptured fish from the group, times the probability of $N\mathrm{arc}_i^k - R\mathrm{arc}_i^k$ fish not being recaptured. Mathematically, the log-likelihood can be expressed as

$$\log L\mathrm{arc}_i^k = \sum_{h=1}^{R\mathrm{arc}_i^k} \log p_i^k(h) + \left(N\mathrm{arc}_i^k - R\mathrm{arc}_i^k\right)\log\left(1 - \sum_{h=1}^{R\mathrm{arc}_i^k} p_i^k(h)\right). \tag{4}$$

Summing over the log-likelihoods for all tagging groups gives the log-likelihood for the archival tag data:

$$\log L_{\mathrm{arc}} = \sum_{i=1}^{I}\sum_{k=1}^{K} \log L\mathrm{arc}_i^k \,. \tag{5}$$

The overall log-likelihood for the model is the sum of the log-likelihood components for the conventional tag data, the catch data and the archival tag data. The reporting rates for the conventional tags are assumed to be known, as are the CVs of the catch data. Polacheck et al. (2006a) found that the catch CVs could not be estimated reliably even in a non-spatial Brownie-Petersen framework, but that the model results were fairly robust to the values assumed. Thus, the parameters estimated by maximizing the overall likelihood are M_j^k, F_j^k, P_1^k (which denotes age 1 abundance in region *k*), and $\pi_j^{k,k'}$ for all *j* and *k*, with the following exceptions. When a cohort is tagged over I consecutive years (ages), only $I-1$ natural mortality rate parameters per region can be estimated; this is a well-known feature of non-spatial Brownie models. As such, we impose the constraint that $M_j^k = M_{I-1}^k$ for $I \le j \le J$, noting that other constraints (such as M being linear with age within each region) are possible. We also impose the obvious constraint that the movement probabilities for a given year and region sum to one; i.e., $\sum_{k'=1}^{K} \pi_j^{k,k'} = 1$.

Southern bluefin tuna (SBT) spatial model

While the general spatial model framework provides a good starting point for applications to real data, it will often need to be customized to suit the spatio-temporal dynamics of the population and fishery in question. Here we show how the model can be adapted to resemble the situation for juvenile SBT.

SBT are a long-lived (age 30+) and highly migratory species (Caton 1991). Large numbers of juveniles (ages 1-5) spend their austral summers in coastal waters south of Australia. At the end of summer, they migrate to deep oceanic waters from South Africa to New Zealand to spend their winters before many return to south Australian waters for the summer (Gunn and Block 2001). Tagging and catch by age data suggest that the proportion of the global stock of age 2-4 SBT found off south Australia during the summer months is relatively high, but decreases sharply after age 5 (Farley et al. 2007). Juvenile SBT are harvested primarily by Australian purse seiners operating off South Australia during the summer, and to a lesser extent by various Japanese, Korean and Taiwanese longline fleets operating throughout their oceanic range during the winter (these fleets catch mainly sub-adult and adult SBT).

Our spatial model for juvenile SBT consists of four regions: 1. Southern Australia (SA); 2. South Africa; 3. South-East Indian Ocean (SEIO); 4. Tasman Sea (Figure 1), and two seasons: 1. summer (Nov-Apr); 2. winter (May-Oct). The model assumes that fishing (and thus tag recapture) occurs only in summer in SA and only in winter in the remaining three regions. It also assumes that all fish migrate out of SA at the end of summer into one of the three longline regions, but only a fraction of the fish migrate from the longline regions to SA at the end of winter. To simplify the migration dynamics, the model does not allow for direct migration between the three longline regions. Thus, at the end of winter, a fish either remains within its current region or migrates back to SA.

The SBT model can be expressed in similar terms and notation to the general spatial model if we replace “year” with “time period” (not only in the model description but also in the assumptions), where odd time periods correspond to season 1 (summer) and even time periods to season 2 (winter). In this case, the *F* and *M* parameters represent rates of mortality per half-year, instead of annual rates. Furthermore, in season 2 and region 1 (i.e., j even and $k=1$), and in season 1 and regions 2-4 (i.e., j odd and $k=2,3,4$), $F_j^k=0$ so that $u_j^k=0$ and $S_j^k=\exp\left(-M_j^k\right)$.

The end-of-season movement dynamics can be described by the following transition matrices:

$$\Pi_j=\begin{bmatrix} 0 & \pi_j^{1,2} & \pi_j^{1,3} & \pi_j^{1,4} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{for } j \text{ odd (season 1),}$$

and

$$\Pi_j = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \pi_j^{2,1} & \pi_j^{2,2} & 0 & 0 \\ \pi_j^{3,1} & 0 & \pi_j^{3,3} & 0 \\ \pi_j^{4.1} & 0 & 0 & \pi_j^{4,4} \end{bmatrix} \quad \text{for } j \text{ even (season 2).}$$

Each row must sum to 1, so that $\pi_j^{1,4} = 1 - \pi_j^{1,2} - \pi_j^{1,3}$ for j odd, and $\pi_j^{k,k} = 1 - \pi_j^{k,1}$ for $k \in \{2,3,4\}$ and j even. The 1's on the diagonal of the season 1 matrix reflect the assumption that any fish in regions 2, 3 and 4 during season 1 remain in the same region at the end of the season. The 1 in the (1,1) position of the season 2 matrix is specified for completeness, but it is not used because the model assumes there are no fish in region 1 during season 2.

Tagging, both conventional and archival, is assumed to occur only in regions and seasons of fishing. Thus, the number of tag releases is zero in region 1 in season 2, and in regions 2 , 3 and 4 in season 1. Obviously recaptures can occur only in regions and periods of fishing, so an analogous statement applies for the recapture numbers.

The likelihood for each of the components can be formulated in the same way as for the general spatial model except with the above constraints on the *F*s, π s and release numbers. Also, when the number of recapture years is greater than the number of release years, some parameter reduction is necessary before the SBT spatial model is fully identifiable (see 'Model identifiability' sections of Methods and Results).

Model identifiability

For the general spatial model without archival tag data, Eveson et al. (2009) investigated a number of reduced parameterizations and tag release designs to see which ones led to the model being identifiable. Here we expand this investigation to include the SBT spatial model and, in particular, to see whether incorporating archival tag data can affect the results.

The parameterizations we considered for the general model are given in the left-hand column of Table 1. Recall that we are considering a single cohort of fish, so age and year are interchangeable; i.e., when a parameter is said to vary with age it could equally be said to vary with year. An equivalent set of parameterizations were considered for the SBT model (left-hand column of Table 2), with a few clarifications. When natural mortality is allowed to vary by age (denoted by M2), we assume it does not vary by season within an age-class (i.e., year). In mathematical notation, $M_j^k = 0.5m_{a(j)}^k$ where $m_{a(j)}^k$ is the instantaneous natural mortality rate per year in region *k* for fish of age $a(j) = \left\lfloor \frac{j+1}{2} \right\rfloor$. No such assumption is necessary when fishing mortality varies by age (F2), because fishing only occurs during one season in any given region. When the movement probabilities for a given season vary only by region and not between years (π1), the odd time periods (season 1) all have the same π parameters and likewise for the even time periods (season 2) (i.e., $\pi_j^{k,k'} = \pi_1^{k,k'}$ for odd j, and $\pi_j^{k,k'} = \pi_2^{k,k'}$ for even j).

For a given model and parameterization, we checked if the parameters were identifiable: a) with equal or more recapture years than release years; b) under full and reduced tag release designs (Table 3); and c) with or without archival tag data. The reduced design for the general spatial model was chosen based on simulation results in Eveson et al. (2009), which showed that such a design was viable for some model parameterizations (i.e., all parameters were identifiable). The reduced design for the SBT spatial model was chosen because it closely resembles the actual situation for tagging experiments conducted on juvenile SBT in the 1990s, for which approximately 99% of tagging occurred in SA in summer. Recall that large numbers of juveniles make return migrations to SA each summer so they are readily available there for tagging.

To determine parameter identifiability, we used the analytic-numeric approach described by Burnham et al. (1987) and applied by Kendall and Nichols (2002). Specifically, we generated non-stochastic (i.e., expected) conventional tag, archival tag and catch data (for the archival tag data, this meant generating the expected number of recaptured fish with each possible track history), and fitted the appropriate model to these data. We considered a parameter to be identifiable if the parameter value returned was within 0.0001 of the true value and the Hessian-derived coefficient of variation (CV) was a realistic value (we used 100% as a rule of thumb but in rare cases it could be larger[32]). We will refer to a particular model and parameterization as being identifiable if all parameters are identifiable. More formal analytic methods for determining parameter identifiability (e.g., based on rank of the information matrix) are more exact, but would need to be developed for the specific models at hand. The above method is much simpler and performed adequately for our purposes.

The parameter values used to generate the various data sets were the same as those used in our simulation runs for the general and SBT models (see the following two sections) when considering the {M2,F0,π1} parameterization (Table 1). Very similar values were used for other parameterizations. We would not expect the specific parameter values chosen to affect the identifiability results; however, as

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[32] In some cases, the likelihood surface is very flat and, therefore, the CV of some parameters can be very large even when they are estimable. How large depends on the sample sizes in the generated data, but CVs of over 100% were common for our sample sizes. When the model was clearly unidentifiable, the CVs of most parameters were huge (over 10,000%) or else not even attainable due to the Hessian matrix not being positive definite.

discussed in the Results section, we did find one exception in terms of the movement probabilities for the general spatial model.

In addition to knowing which parameterizations are feasible with and without archival tag data, we were interested in determining how much archival tag data can improve the precision of the parameter estimates in situations where the model is identifiable. We investigated this question through a series of Monte Carlo simulations using both the general model and the SBT model.

Simulations for general spatial model

Data were simulated under the general model framework for a tagging experiment involving a single cohort of fish with $K = 3$ regions, $I = 3$ release years and $J = 5$ recapture years. Two tag release designs were considered: full and reduced (Table 3). For each region and year of tagging, *x*% of the tags released were assumed to be archival tags and the value of *x* was varied from 0 to 50%.

With a full tag release design, the model allows for all parameters to vary by region and year, but the precision of some parameter estimates can be very poor with such a full parameterization. In practice it is beneficial to make the model as parsimonious as possible. The parameter constraints that are most appropriate will be case-specific. For our simulations, we used the parameterization denoted by {M2,F0,π1} (Table 1) because we found it to be identifiable under the reduced tagging design (see ‘Model identifiability’ section of Results). Thus, the total number of parameters to be estimated is 26: $I - 1 = 2$ M parameters, $J * K = 15$ F parameters, $K * (K - 1) = 6$ π parameters and $K = 3$ P_1 parameters.

The parameter values used to generate data for the full tagging design scenario are given in Table 4; the same values were used for the reduced tagging design (Table

5). The reporting rate for the conventional tag data was set at 1.0 and the CV of the catch data at 0.2, for all regions and years. For both tagging scenarios 1500 tags were released each year, but the distribution amongst regions differed. For the full tagging design, 500 tags were released in all three regions each year; for the reduced tagging design, 500 tags were released in all three regions in year 1 and then all 1500 tags were released only in region 1 in years 2 and 3. For each region and year of tagging, *x*% of the tag releases were archival. Because archival-tagged and conventional-tagged fish should experience the same fishing mortality, natural mortality, and movement, and because we are assuming 100% reporting rates for both (and no tag-induced mortality), the expected percent of tag returns that will be archival is the same as the percent of releases that are archival (i.e., *x*%).

For each tagging design scenario and level of *x*, we ran 500 simulations. Data were simulated using R (www.r-project.org) and optimization of the likelihood was performed using AD Model Builder (admb-project.org). The relative median bias (calculated as median minus true value, divided by true value) and coefficient of variation (CV; calculated as standard deviation divided by true value) of the 500 estimates for each parameter were calculated. Medians were used instead of means because some of the estimates, the fishing mortality estimates in particular, have right-skewed distributions and therefore the median tends to be less biased than the mean.

A question likely to be of interest to researchers as well as managers is how many conventional and archival tags need to be released to achieve a certain level of precision in the parameters of most interest. We extended our simulations to address this question using the reduced tagging design scenario as specified above. We varied the number of conventional tags released in each year and region of tagging from 100 to 500 (step size of 100) and archival tags from 0 to 100 (step size of 25). For each combination of tag numbers, we ran 250 simulations. We could then determine which combinations of archival and conventional tag releases achieved an equal level of precision for each parameter estimate, and also which combinations achieved a minimum level of precision across multiple parameters (for example, a minimum CV of 30% across all fishing mortality estimates). We will refer to these as ‘trade-off’ simulations.

Simulations for SBT spatial model

Data were simulated under the SBT model framework for a tagging experiment involving a single cohort of fish with $I = 6$ release periods (3 years) and $J = 10$ recapture periods (5 years); recall the SBT model has $K = 4$ regions. Two tag release designs were considered: full and reduced (Table 3). For each region and time period of tagging, *x*% of the tags released were assumed to be archival tags and the value of *x* was varied from 0 to 50.

We chose similar parameter constraints for the SBT model as for the general model, namely the parameterization denoted by {M2,F0,π1}. Under this parameterization, M does not vary with age, which we interpret the same as in the model identifiability section to mean it does not vary by season within an age-class. Thus, $M_j^k = 0.5m_1$ for $1 \le j \le 2$ and $M_j^k = 0.5m_2$ for $3 \le j \le 10$ where m_a is the instantaneous natural mortality rate per year for fish of age a (recalling that M can only vary by age/year up to the number of release years minus one). The total number of parameters to be estimated is 31: $I/2-1=2$ m parameters, $J/2=5$ F parameters for season 1, $J/2*(K-1)=15$ F parameters for season 2, $K-2=2$ free π

parameters for season 1, $K-1=3$ free π parameters for season 2, and $K=4$ P_1 parameters.

The parameter values used to generate data for the full tagging design scenario are given in Table 6; the same values were used for the reduced tagging design (Table 7). The reporting rate for the conventional tag data was set at 1.0 and the CV of the catch data at 0.2, for all regions and time periods of fishing. For both tagging scenarios 1500 tags were released each year, but the distribution amongst regions and seasons differed. For the full tagging design, 750 tags were released in region 1 in season 1 and 250 tags in regions 2-4 in season 2 each year; for the reduced tagging design, all 1500 tags were released in region 1 in season 1 each year. For each region and time period of tagging, *x*% of the tag releases were archival.

For each tagging design scenario and level of *x*, we ran 500 simulations. The relative median bias and CV (as defined for the general spatial model) of the 500 estimates for each parameter were calculated.

We again conducted trade-off simulations to address how many conventional versus archival tag releases are required to achieve equal levels of precision for the reduced tagging design scenario. We varied the number of conventional tags releases in each time period and region of tagging from 100 to 1000 (step size of 100) and archival tags from 0 to 150 (step size of 25), and for each combination of tag numbers we ran 250 simulations. The upper ranges for the tag numbers were extended compared to our trade-off simulations with the general spatial model because many parameters still had very high CVs with 500 conventional tags and 100 archival tags.

Results

Model identifiability results

For the general spatial model, we found that all parameterizations were identifiable when a full tagging design was used, even with fewer release years than recapture years, i.e. $I < J$. When the reduced tagging design was used, four of the parameterizations were not identifiable with $I < J$, but two of these became identifiable with $I = J$ (Table 1). It seems that there can be problems separating F from movement when movement is allowed to vary by year (i.e., parameterizations with π0) and there are more recapture years than release years; this holds true for the SBT spatial model as well (Table 2).

The inclusion of archival tag data in the general spatial model did not make any difference to the identifiability results when the parameter values used to generate the data were those specified in Table 4 (and Table 5). However, we found that if we replaced all values used for the movement parameters with 0.33, meaning an equal probability of a fish moving to any region (including staying in its current region), then archival tags could make a difference. Specifically, with equal movement probabilities, four parameterizations were no longer identifiable under a reduced tagging design if archival tag data were not included, but three of these became identifiable with the inclusion of archival tag data (Table 1). One such parameterization, {M2,F0,π1}, is the one used in our simulations with the general spatial model.

For the SBT spatial model, the inclusion of archival tag data had a much bigger influence on the identifiability results. In the case of $I < J$ and no archival tag data, there were three parameterizations for which all parameters were not identifiable even with a full tagging design; however, one of these, {M2,F1,π0}, became identifiable with archival tag data (Table 2). With the reduced tagging design, none of the parameterizations were identifiable without archival tag data, but three of these, including the one used in our simulations, {M2,F0,π1}, became identifiable when archival tag data were included. These findings were the same whether $I < J$ or $I = J$ (Table 2).

Simulations results for general spatial model

For the full tagging design scenario, the median estimates were very close to the true values for all parameters and all levels of archival tags (*x*), except for a small negative bias in the population size estimates. More specifically, the largest bias for the population size estimates was –4.1%, and all other parameter estimates were within 2.1% of their true values. A small negative bias in abundance has been observed with a non-spatial version of the model as well; the reason for this is explained in Appendix 6 of Polacheck et al. (2006b). In terms of precision, increasing *x* from 0 to 50 reduced the CVs of the movement probability estimates and the *F* estimates at ages 4 and 5 by several percent (Table 4). Even with no archival tags (*x*=0) the CVs are quite low—this is due to having fairly large numbers of releases and returns and good mixing/movement between regions, which is not likely to be the case in many applications. Thus, even though the improvements in precision from increasing *x* may be small in absolute terms, they are quite large in relative terms (e.g., with *x*=50 the movement probabilities have CVs that are roughly 35% smaller than with *x*=0).

For the reduced tagging design scenario, the median estimates were again very close to the true values for all parameters and levels of *x*. Two of the movement parameters showed very small biases (<5%) when no archival tags were included (*x*=0), but these disappeared for *x*>0. Increasing *x* led to significant reductions in the

CVs of both the movement probability estimates and many of the *F* estimates (Table 5). For instance, with no archival tag releases, the CVs of the *F* estimates for regions 2-3 and ages 2-5 were huge (58-126%), but with only 5% archival tag releases (which translates to an expected 5% of all tag recaptures), these CVs were dramatically reduced to 20-50%, and with 25% archival tags, they were reduced further to 14-30%. Note that it is the *F* estimates for regions and ages where tagging does not occur that were greatly improved by including archival tags.

Results from our trade-off simulations using the reduced tagging design show that the relative importance of conventional tags versus archival tags, in terms of parameter precision, depends on the parameter being estimated (Figure 2). For example, the CVs of the movement probabilities depend more on the number (and mostly just the presence) of archival tags, whereas the CVs of the natural mortality parameters depend mostly on the number of conventional tags. The fishing mortality parameters are influenced by both tag types, the relative influence depending on the specific age and region.

Results such as those in Figure 2 can help to determine the sample sizes required to meet a particular goal, and they can also aid in setting realistic goals. For example, the initial goal (prior to conducting simulations) may have been to determine tag numbers that will achieve a CV of at least 30% in all fishing mortality estimates. However, the simulation results suggest this is not a very realistic goal for this particular scenario because the CVs for the *F* estimates at ages beyond which tagging occurred (i.e., ages 4 and 5) are greater than 30% even with large numbers of archival and conventional tags. A revised goal based on these results may be to achieve a CV of 30% in the age 1-3 *F* estimates, or else the researcher may consider changing the design of the tagging experiment to also tag fish at ages 4 and 5. In case of the former, tag combinations that will achieve the revised goal are a minimum of 100 conventional plus 75 archival tag releases (in each region and period of tagging), or a minimum of 400 conventional plus 50 archival tag releases (ditto). Note that a CV of 30% could not be attained in several of the age 2 and 3 *F* estimates without the inclusion of archival tag data (Figure 2).

Simulation results for SBT spatial model

For the full tagging design scenario, there was no evidence of biases in any of the parameter estimates except for the population size parameters, which again showed very small negative biases (the greatest being –6.4%). In terms of CVs, increasing the percent of archival tags (*x*) led to small improvements in the *F* estimates, but most notably to improvements in the movement probability estimates (Table 6). Again, the CVs are quite small even without archival tag data so the important thing to note is the relative improvement compared to *x*=0; e.g., with *x*=5 the movement estimates improved by more than 20%, and with *x*=50 they improved by more than 60%.

For the reduced tagging design scenario, the median estimates were once again very close to their true values with the exception of the results with no archival tag releases (*x*=0). We showed previously that without any archival tag data, model parameterization {M2,F0,π1} is not identifiable under the reduced tagging design (Table 2). Allowing for any number of conventional tag releases in regions 2-4 in season 2 makes the model identifiable in theory, but the parameter estimates are very uncertain without reasonable release numbers. Thus, there is a very obvious benefit to including archival tag releases, as it makes the model viable without tagging in all regions (which may not be logistically possible). In terms of precision, increasing *x* again led to the greatest relative improvements in the movement parameter estimates

(Table 7), but also to significant improvements in the *F* estimates for regions 2-4 in season 2 (i.e., those regions and time periods for which tagging did not occur). A similar result was found with the general spatial framework when the tagging design was reduced, except that the relative improvements in the CVs were actually greater for the *F* estimates than the movement estimates.

Broad findings from our trade-off simulations with the SBT spatial model are similar to those with the general spatial model. For instance, the CVs of the movement probabilities were affected most by the number of archival tags, the natural mortality and population size parameters most by the number of conventional tags, and the fishing mortality parameters by both tag types (Figure 3). Again, we could use the results to determine which combinations of conventional and archival tag releases are needed to achieve a particular goal, as well as to evaluate whether the experimental design (e.g., number of release and recapture years, distribution of tag releases) is adequate. As one example, with the reduced tagging design used here, the population size estimates in regions 2-4 are highly uncertain (Figure 3). Although they improve significantly with increased conventional tags, their CVs remain very high even with the maximum tag numbers we considered due to lack of tagging in these regions (recall all tagging is in region 1). Thus, if region-specific population size estimates are of key interest, this particular tagging design is not likely sufficient.

Discussion

We have shown how archival tag data can be incorporated into a discrete space, discrete-time mark-recapture model for estimating parameters critical to fisheries management. One advantage of using a discrete-time model is that it naturally allows for parameters to differ between time periods. To do so with continuous-time models, such as that of Miller and Andersen (2008), is cumbersome because it requires the mortality and/or movement processes to be modelled using several sequential matrices with constant rates over shorter time periods. The interpretation of parameter estimates from continuous-time (or space) models for management purposes is also less clear, since mortality rates for discrete fishing seasons and regions are generally required for management. Also, if catch data are to be incorporated into the tagging model so that fish abundance can be estimated (as in the model presented here), then a discrete-time model makes sense because catch data generally only exist on discrete time scales. A disadvantage of most discrete-time models is that they assume animals move between regions instantaneously, usually at the beginning or end of time periods; our model assumes the latter. While this is not strictly required (e.g., Joe and Pollock 2001), it makes the mathematics much simpler and allows for easier separation of mortality parameters from movement parameters in the estimation phase. The assumption of instantaneous movement between regions can be reasonable for fish that exhibit seasonal migrations over relatively short time periods. Hestbeck (1995) investigated to what extent violations of the assumption of end-of-year movements can bias the parameter estimates in a capture-recapture setting. He found that biases in movement parameter estimates were variable and could be high in some situations, but that biases in survival and capture rate estimates, which are the parameters of key interest for management purposes, were consistently small.

Although we developed our model for implanted archival tags, it would be straightforward to modify it for PSATs. Similar to an archival tag, the data to be included in the likelihood for each PSAT is the region that the fish was in during each time period (as defined by the model) that it was at liberty. The difference between tag types is that a PSAT pops off the fish and transmits data via satellite (assuming successful transmission; Patterson et al. 2008), whereas an archival tag must be recovered from a captured fish. Thus, a PSAT provides the same information on movement as an archival tag up to the time it pops up, but not on mortality (except in cases where a PSAT popped up early due to the fish dying naturally or was recovered prior to its scheduled pop-up time due to the fish being caught).

Unlike simulated data, real data will not adhere exactly to the spatial and temporal structure of the model. In the case of our discrete time and space model, individual fish may not spend each time period entirely within one region. Even for a fish that transits between regions relatively close to the end of a time period, it may pass through one or more intermediate region on its way. The space and time definitions of the model can be chosen to minimize discrepancies between the model and the data to the greatest extent possible, but there needs to be a balance between model realism and simplicity/practicality. The right balance will depend on the goals of the research, and may also be influenced by the existing management framework.

Our simulations were intended to evaluate the potential value of including archival tag data in a tag-based assessment model. They do not address problems associated with fish having more complex spatial and temporal movement patterns than the model assumes – this is not a problem inherent to archival tag data, but to the model itself. In fact, archival tag data have the ability to reveal complexities and model discrepancies that may not be discernible with conventional tagging data alone.

Our simulations demonstrated that including archival tag data in the model can significantly improve the fishing mortality and movement parameter estimates in many situations. The results presented were for one particular set of parameter constraints for both the general and SBT spatial models (referred to as parameterization $\{M2,F0,\pi1\}$). We ran additional simulations using other parameterizations and found that, although the effect of including archival tag data on the precision of the parameter estimates was case-specific, there were some common traits: i) when the tagging design was full, the movement probabilities were the parameters most improved; ii) when the tagging design was reduced (i.e., no tagging in some regions and time periods), many of the fishing mortality estimates (particularly those in the regions and time periods where tagging did not occur) were also significantly improved, often by as much or more than the movement probabilities.

Not only does including archival tag data in the model improve parameter precision, but there are a number of situations for which archival tag data are necessary in order for all parameters to be estimable. This is particularly true if tags of either type are not released in all regions and time periods of the experiment. It is easy to imagine situations where it would be logistically difficult or impossible to tag fish in all regions of their distribution, such as high seas regions of tuna longline fisheries; in these cases, the use of archival tags could make an otherwise unviable tagging experiment possible.

Our findings differ somewhat from those of Miller and Andersen (2008), who used simulations to explore the behaviour of their discrete-space continuous-time model for estimating mortality and movement rates from conventional and archival tags. It is hard to compare results directly since the models and spatial designs being considered are quite different, but some basic differences are worth noting. Firstly, Miller and Andersen (2008) found problems with parameter estimation with low release numbers when tags were released in all areas, which we did not with our discrete-space model. Secondly, we found that the precision of many parameter estimates could be improved more by the use of archival tags than conventional tags, whereas Miller and Andersen (2008) found that for a given number of releases, archival tags and conventional tags performed very similarly.

Trade-off simulations such as those conducted in this paper can provide useful information with regard to experimental design, including what levels of precision can be achieved with different numbers of conventional and archival tags, how many release and recapture years are needed to achieve a particular goal, and what distribution of tag releases amongst regions and time periods is most suitable. Such information can better guide researchers starting up tagging programs, and can be used in discussion with fishery managers.

Archival tags are around 1000 times more expensive than conventional tags. However, tag deployment costs (e.g. staff salary, vessel charter) are generally the dominant cost component of a tagging program, and are similar regardless of tag type. Thus, releasing electronic tags should be considered in this context when planning tagging experiments. Nevertheless, the improvement in parameter precision from including archival tags in an assessment model may not be considered sufficient to offset the increased costs. This will depend on the value of the fishery and the implication of the parameter estimates on management measures such as total allowable catch. Of course, in situations that require archival tag data for parameter estimation to be possible, their value is infinitely greater than conventional tags. In any case, it is imperative to keep in mind the additional benefits that archival tag data can have for assessment models beyond their direct impact on parameter precision. For example, archival tag data can provide critical information for developing a model that has appropriate spatial and temporal structure for the situation at hand. In the case of juvenile SBT, archival tag data revealed the seasonal migratory patterns assumed in the SBT spatial model and helped determine appropriate delineations of regions. Also, in the case of broadbill swordfish in the southwest-central Pacific, structural changes regarding spatial disaggregation and movement were made to the assessment model based on new information from satellite archival tagging data (Davies et al. 2008).

In summary, the value of archival tags for learning about the biology and behaviour of fish is well documented. This paper demonstrates that archival tag data can also play an important role in fisheries management through direct input to spatial assessment models. The model used here was a tag-based assessment model, but the likelihood we developed for the archival tag data could equally be included in more traditional spatial stock assessment models (e.g., Fournier et al. 1998, Bull et al. 2005, Methot 2011).

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Table 1. Model identifiability results for the general spatial model using a range of parameterizations, numbers of release (I) and recapture (J) years, tag release designs (full or reduced, as defined in Table 3), and with or without archival tag data.

	$I = 3$, $J = 5$				$I = J = 3$			
	Full		Reduced		Full		Reduced	
Parameterization	No arch.	With arch.	No arch.	With arch.	No arch.	With arch.	No arch.	With arch.
M0, F0, π0	yes	yes	no	no	yes	yes	no	no
M2, F0, π0	yes	yes	no	no	yes	yes	yes*	yes*
M2, F1, π0	yes	yes	no	no	yes	yes	yes*	yes
M0, F0, π1	yes	yes	no	no	yes	yes	no	no
M2, F0, π1	yes	yes	yes*	yes	yes	yes	yes*	yes
M2, F1, π1	yes	yes	yes	yes	yes	yes	yes	yes

* Indicates situations where the model became unidentifiable when the values used for the movement probabilities were equal between all regions.

M0: *M* varies by region and age (up to age $I - 1$)

M2: *M* varies by age only (up to age $I - 1$)

F0: *F* varies by region and age

F1: *F* varies by region only

π0: movement probabilities vary by region and age

π1: movement probabilities vary by region only

Table 2. Model identifiability results for the SBT spatial model using a range of parameterizations, numbers of release (I) and recapture (J) time periods, tag release designs (full or reduced, as defined in Table 3), and with or without archival tag data. See Table 1 and 'Model identifiability' section of Methods for definitions of the different parameterizations.

	$I = 6,\ J = 10$				$I = J = 6$			
	Full		Reduced		Full		Reduced	
Parameter-ization	No arch.	With arch.	No arch.	With arch.	No arch.	With arch.	No arch.	With arch.
M0, F0, π0	no	no	no	no	yes	yes	no	no
M2, F0, π0	no[#]	no	no	no	yes	yes	no	no
M2, F1, π0	no^	yes	no	yes	yes	yes	no	yes
M0, F0, π1	yes	yes	no	no	yes	yes	no	no
M2, F0, π1	yes	yes	no	yes	yes	yes	no	yes
M2, F1, π1	yes	yes	no	yes	yes	yes	no	yes

[#] many parameters are estimable, but not Fs and πs for last year

^ all parameters are estimable except πs for last year

Table 3. Definition of the full and reduced tag release designs for the general and SBT spatial model formulations.

Tagging design	General model	SBT model
Full	Fish tagged in all regions each year	Fish tagged in region 1 in odd time periods (season 1) and in regions 2-4 in even time periods (season 2)
Reduced	Fish tagged in all regions in year 1 then only in region 1 in subsequent years	Fish tagged only in region 1 in odd time periods (season 1)

Table 4. Coefficient of variation (CV, %) of parameter estimates obtained from simulations using the general spatial model with parameterization {M2,F0,π1}. Results are for the full tagging design and different values of *x* (the percent of releases that were archival tags); 500 runs were conducted for each value of *x*.

	True value	Percent archival tag releases (*x*) 0	5	10	25	50
M_1	0.40	11.3	11.1	11.1	11.0	10.7
M_2	0.20	18.6	19.0	18.0	17.9	18.2
F_1^1	0.10	14.2	14.3	14.7	14.0	13.4
F_1^2	0.20	11.2	11.1	11.2	11.1	10.6
F_1^3	0.30	9.6	10.0	9.9	9.1	9.4
F_2^1	0.15	9.9	9.9	9.2	9.3	9.4
F_2^2	0.25	8.4	8.4	8.4	8.1	8.0
F_2^3	0.35	8.0	7.7	7.4	7.3	7.5
F_3^1	0.20	9.3	9.8	9.8	9.2	9.1
F_3^2	0.30	8.7	8.3	8.1	8.4	7.6
F_3^3	0.40	8.3	8.3	7.6	7.1	7.3
F_4^1	0.25	17.0	17.0	15.4	14.5	14.0
F_4^2	0.35	15.3	15.1	14.7	15.2	13.9
F_4^3	0.45	16.0	15.7	16.1	14.0	13.0
F_5^1	0.30	26.2	25.9	23.0	23.9	22.3
F_5^2	0.40	25.0	25.7	25.0	24.6	23.1
F_5^3	0.50	28.8	28.0	26.5	24.3	22.6
P_1^1	2.5e5	21.5	19.6	20.5	19.9	19.7
P_1^2	2.5e5	19.8	19.3	20.4	20.2	21.5
P_1^3	2.5e5	19.0	21.6	19.6	20.1	19.2
$\pi^{1,1}$	0.50	7.2	7.0	6.2	5.8	4.8
$\pi^{1,2}$	0.25	12.2	11.4	10.4	9.8	8.0
$\pi^{2,1}$	0.25	13.1	12.2	11.7	10.1	8.7
$\pi^{2,2}$	0.50	6.8	6.8	6.5	5.6	5.0
$\pi^{3,1}$	0.25	14.2	13.6	13.1	10.1	8.8
$\pi^{3,2}$	0.25	13.0	12.6	11.6	9.7	8.7

Table 5. Coefficient of variation (CV, %) of parameter estimates obtained from simulations using the general spatial model with parameterization {M2,F0,π1}. Results are for the reduced tagging design and different values of *x* (the percent of releases that were archival tags); 500 runs were conducted for each value of *x*.

	True	Percent archival tag releases (*x*)				
	value	0	5	10	25	50
M_1	0.40	12.2	11.0	11.4	11.1	11.1
M_2	0.20	20.7	20.1	20.0	20.5	20.5
F_1^1	0.10	14.3	13.8	14.5	14.2	13.8
F_1^2	0.20	10.9	11.3	11.0	10.9	10.8
F_1^3	0.30	9.6	10.0	9.9	9.5	9.5
F_2^1	0.15	6.8	6.7	6.7	6.7	6.7
F_2^2	0.25	69.8	21.5	17.7	14.4	13.7
F_2^3	0.35	57.7	20.3	17.3	14.2	13.5
F_3^1	0.20	6.7	6.6	6.4	6.6	6.2
F_3^2	0.30	99.0	26.7	18.8	15.0	13.5
F_3^3	0.40	80.9	25.5	19.6	15.2	12.9
F_4^1	0.25	14.4	13.6	14.2	14.1	12.7
F_4^2	0.35	109.6	31.2	22.9	18.9	16.5
F_4^3	0.45	92.6	29.9	24.0	17.3	15.0
F_5^1	0.30	24.2	24.2	24.2	23.3	23.0
F_5^2	0.40	126.4	49.7	32.0	29.6	26.5
F_5^3	0.50	117.3	41.2	37.0	30.3	26.7
P_1^1	2.5e5	20.5	20.7	20.2	19.7	20.8
P_1^2	2.5e5	19.7	19.2	20.4	19.2	20.0
P_1^3	2.5e5	20.0	19.1	19.5	20.0	20.8
$\pi^{1,1}$	0.50	8.2	7.5	6.8	5.6	3.9
$\pi^{1,2}$	0.25	37.8	18.5	14.2	9.7	6.8
$\pi^{2,1}$	0.25	24.7	19.0	17.4	14.0	10.8
$\pi^{2,2}$	0.50	25.7	12.9	11.1	8.5	6.6
$\pi^{3,1}$	0.25	25.0	20.1	17.9	14.8	11.7
$\pi^{3,2}$	0.25	40.5	22.9	19.3	15.1	11.9

Table 6. Coefficient of variation (CV, %) of parameter estimates obtained from simulations using the SBT spatial model with parameterization {M2,F0,π1}. Results are for the full tagging design and different values of *x* (the percent of releases that were archival tags); 500 runs were conducted for each value of *x*.

	True	Percent archival tag releases (*x*)				
	value	0	5	10	25	50
m_1	0.40	12.8	12.7	12.4	12.3	12.6
m_2	0.20	16.7	16.4	16.7	16.5	15.5
F_1^1	0.30	7.9	8.1	8.2	8.1	7.8
F_3^1	0.30	5.4	5.5	5.4	5.1	5.3
F_5^1	0.30	5.7	5.4	5.2	5.1	4.8
F_7^1	0.30	9.3	8.9	8.2	8.0	7.4
F_9^1	0.30	15.6	14.6	15.0	14.5	13.5
F_2^2	0.10	17.0	16.1	15.6	15.5	15.8
F_2^3	0.10	17.7	17.3	16.8	16.8	16.5
F_2^4	0.10	16.4	16.9	17.3	16.7	16.3
F_4^2	0.10	15.0	13.6	13.4	12.2	12.1
F_4^3	0.10	14.0	12.9	12.2	12.4	11.9
F_4^4	0.10	14.7	13.4	13.0	11.8	11.8
F_6^2	0.10	15.1	13.8	13.1	12.1	12.4
F_6^3	0.10	14.0	12.8	12.6	12.3	11.7
F_6^4	0.10	15.1	13.8	12.9	12.5	11.7
F_8^2	0.10	22.4	19.1	18.4	19.4	16.8
F_8^3	0.10	20.3	19.7	19.1	17.3	16.4
F_8^4	0.10	21.8	19.3	18.2	17.6	15.9
F_{10}^2	0.10	30.3	25.9	25.7	26.0	23.3
F_{10}^3	0.10	27.8	25.6	24.5	25.3	23.4
F_{10}^4	0.10	28.9	25.4	26.0	25.7	23.4
P_1^1	1.0e6	21.3	19.8	19.7	20.5	19.2
P_1^2	2.5e5	52.8	48.2	48.9	50.6	48.6
P_1^3	2.5e5	52.1	48.0	46.9	50.5	50.6
P_1^4	2.5e5	49.6	51.0	49.6	52.7	51.6
$\pi_1^{1,2}$	0.33	12.7	9.6	8.2	5.9	4.6
$\pi_1^{1,3}$	0.33	12.2	9.6	7.9	5.7	4.6
$\pi_2^{2,1}$	0.90	6.2	4.6	3.8	2.6	2.0
$\pi_2^{3,1}$	0.90	5.4	4.2	3.6	2.6	1.9
$\pi_2^{4,1}$	0.90	5.4	4.3	3.6	2.7	2.1

Table 7. Coefficient of variation (CV, %) of parameter estimates obtained from simulations using the SBT spatial model with parameterization {M2,F0,π1}. Results are for the reduced tagging design and different values of *x* (the percent of releases that were archival tags); 500 runs were conducted for each value of *x*.

	True	Percent archival tag releases (*x*)				
	value	0	5	10	25	50
m_1	0.40	–	9.9	10.0	9.4	10.2
m_2	0.20	–	17.7	17.5	17.0	18.8
F_1^1	0.30	–	5.8	5.7	5.4	5.7
F_3^1	0.30	–	4.5	4.5	4.5	4.5
F_5^1	0.30	–	4.6	4.5	4.5	4.8
F_7^1	0.30	–	9.7	9.5	9.3	10.0
F_9^1	0.30	–	18.9	18.0	17.8	19.4
F_2^2	0.10	–	24.7	21.9	19.5	19.5
F_2^3	0.10	–	23.6	20.5	18.9	18.5
F_2^4	0.10	–	23.3	21.0	19.3	19.5
F_4^2	0.10	–	20.6	17.8	14.6	12.9
F_4^3	0.10	–	21.4	16.5	14.1	13.4
F_4^4	0.10	–	19.3	16.3	14.4	12.7
F_6^2	0.10	–	21.6	17.4	14.6	13.2
F_6^3	0.10	–	21.4	16.8	14.5	13.4
F_6^4	0.10	–	19.5	17.2	15.3	13.3
F_8^2	0.10	–	25.1	22.8	20.2	19.5
F_8^3	0.10	–	26.9	22.9	19.6	20.4
F_8^4	0.10	–	25.0	22.7	19.9	19.8
F_{10}^2	0.10	–	34.3	30.0	28.2	30.2
F_{10}^3	0.10	–	35.6	31.6	27.7	32.0
F_{10}^4	0.10	–	31.2	33.3	28.2	32.8
P_1^1	1.0e6	–	19.3	19.7	19.3	20.4
P_1^2	2.5e5	–	56.0	51.5	50.4	52.1
P_1^3	2.5e5	–	50.7	51.0	51.7	50.4
P_1^4	2.5e5	–	54.4	51.6	54.6	54.2
$\pi_1^{1,2}$	0.33	–	13.7	10.0	6.0	4.1
$\pi_1^{1,3}$	0.33	–	13.1	9.0	6.0	4.2
$\pi_2^{2,1}$	0.90	–	6.0	4.7	3.0	2.2
$\pi_2^{3,1}$	0.90	–	5.3	4.4	3.2	2.3
$\pi_2^{4,1}$	0.90	–	5.5	4.5	3.2	2.3

Figure captions

Figure 1. Map showing the four regions defined for the SBT spatial model (SA = Southern Australia; SEIO = South-East Indian Ocean).

Figure 2. Coefficient of variation (CV, %) of the (a) fishing mortality, (b) natural mortality, (c) movement and (d) age 1 population size parameter estimates obtained from trade-off simulations using the general spatial model with parameterization {M2,F0,π1} and the reduced tagging design (250 runs were conducted for each combination of tag numbers).

Figure 3. Coefficient of variation (CV, %) of the (a) fishing mortality, (b) natural mortality, (c) movement and (d) age 1 population size parameter estimates obtained from trade-off simulations using the SBT spatial model with parameterization {M2,F0,π1}and the reduced tagging design (250 runs were conducted for each combination of tag numbers).

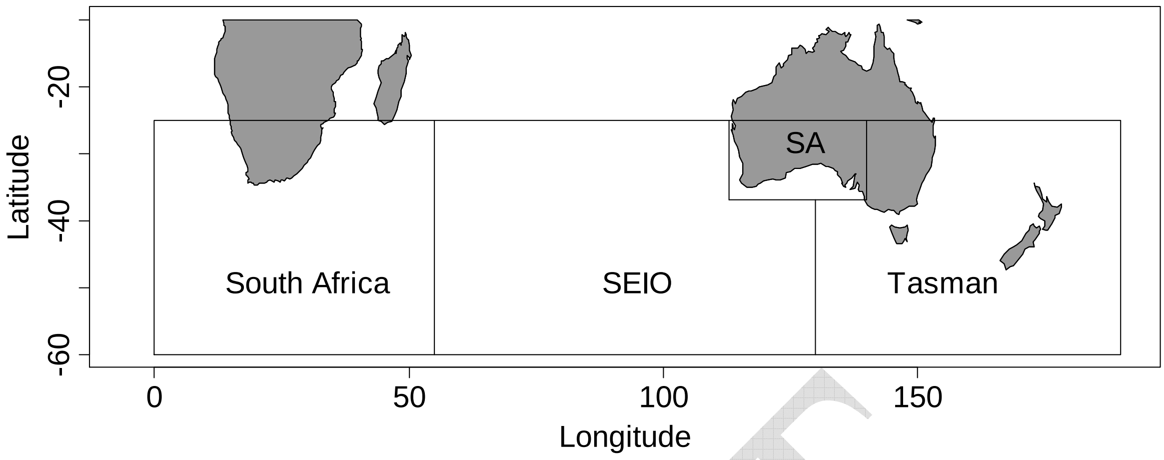
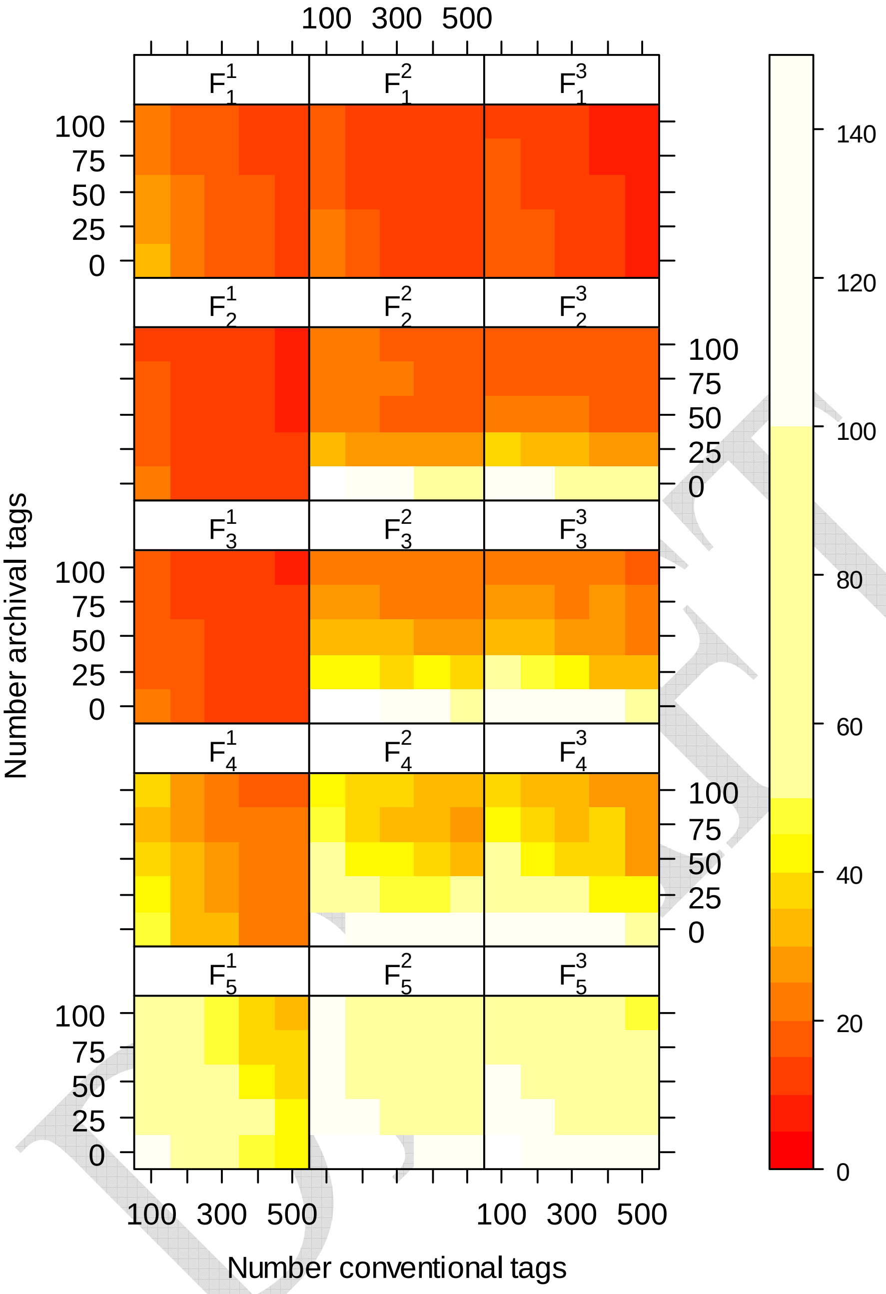


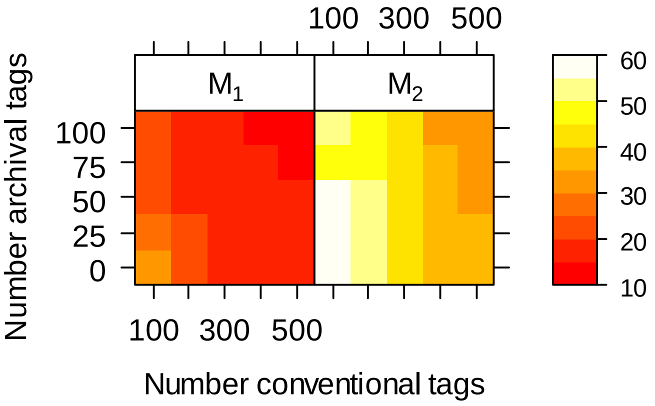
Figure 1. Map showing the four regions defined for the SBT spatial model (SA = Southern Australia; SEIO = South-East Indian Ocean).

(a)



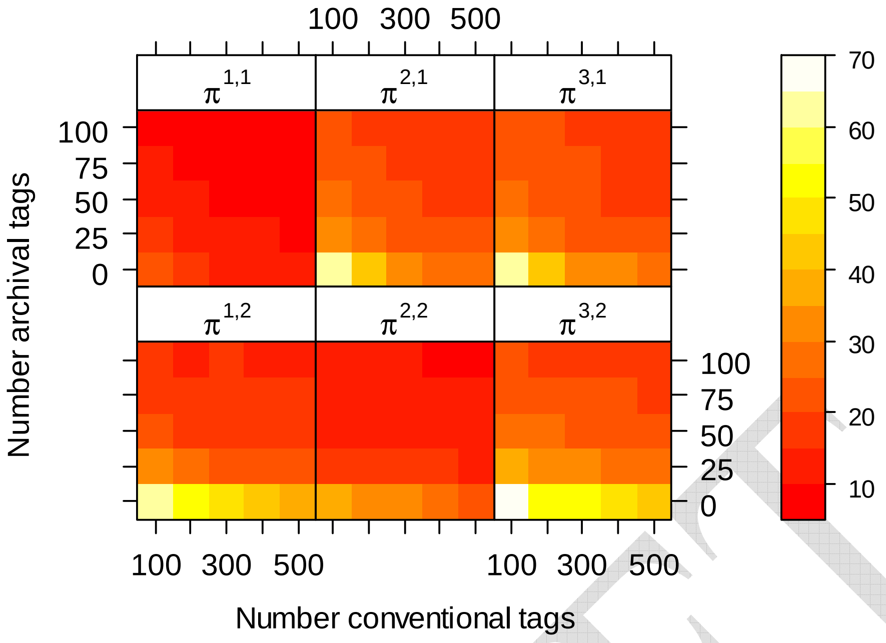
F_1^1
F_1^2
F_1^3
F_2^1
F_2^2
F_2^3
F_3^1
F_3^2
F_3^3
F_4^1
F_4^2
F_4^3
F_5^1
F_5^2
F_5^3
Number archival tags
100
75
50
25
0
Number conventional tags
100
300
500
140
120
100
80
60
40
20
0

(b)



M_1
M_2
Number archival tags
100
75
50
25
0
Number conventional tags
100
300
500
60
50
40
30
20
10

(c)



(d)

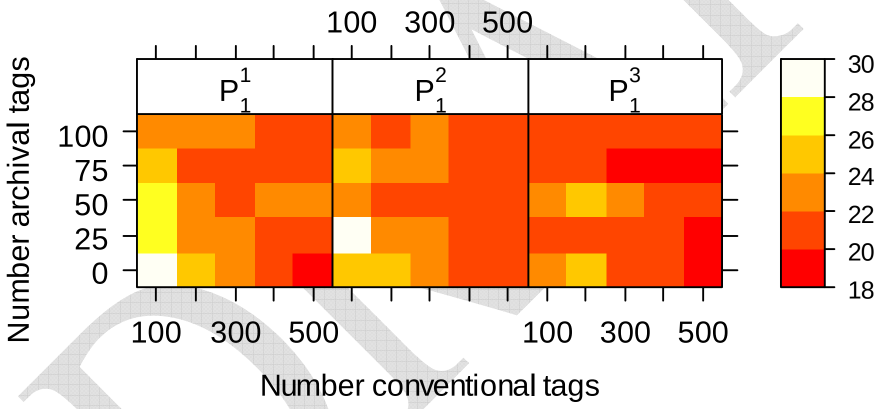
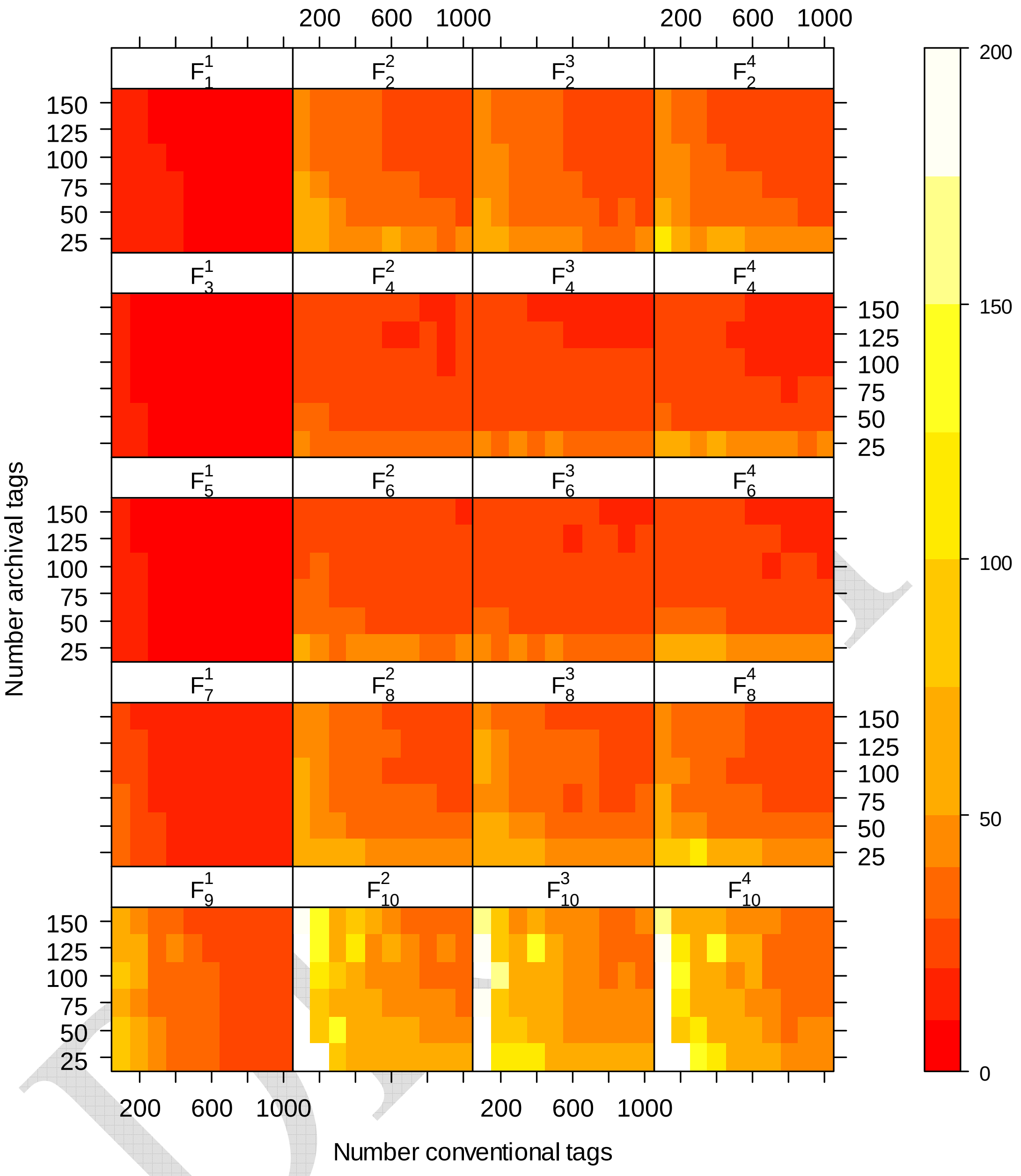


Figure 2. Coefficient of variation (CV, %) of the (a) fishing mortality, (b) natural mortality, (c) movement and (d) age 1 population size parameter estimates obtained from trade-off simulations using the general spatial model with parameterization {M2,F0,π1} and the reduced tagging design (250 runs were conducted for each combination of tag numbers).

(a)


F1 1
F2 2
F3 2
F4 2
F1 3
F2 4
F3 4
F4 4
F1 5
F2 6
F3 6
F4 6
F1 7
F2 8
F3 8
F4 8
F1 9
F2 10
F3 10
F4 10
Number archival tags
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125
100
75
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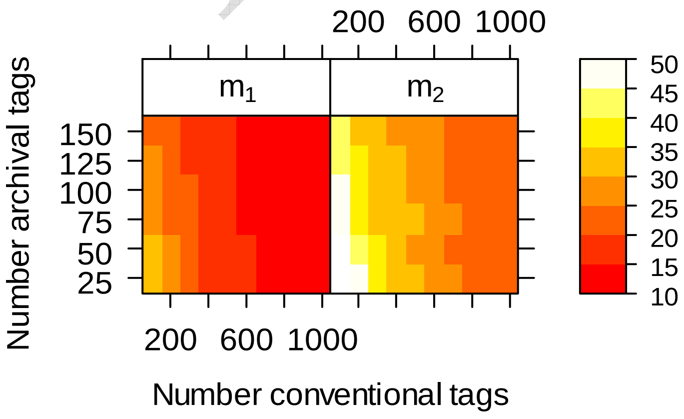
25
Number conventional tags
200
600
1000
200
150
100
50
0

(b)


m1
m2
Number archival tags
150
125
100
75
50
25
Number conventional tags
200
600
1000
50
45
40
35
30
25
20
15
10

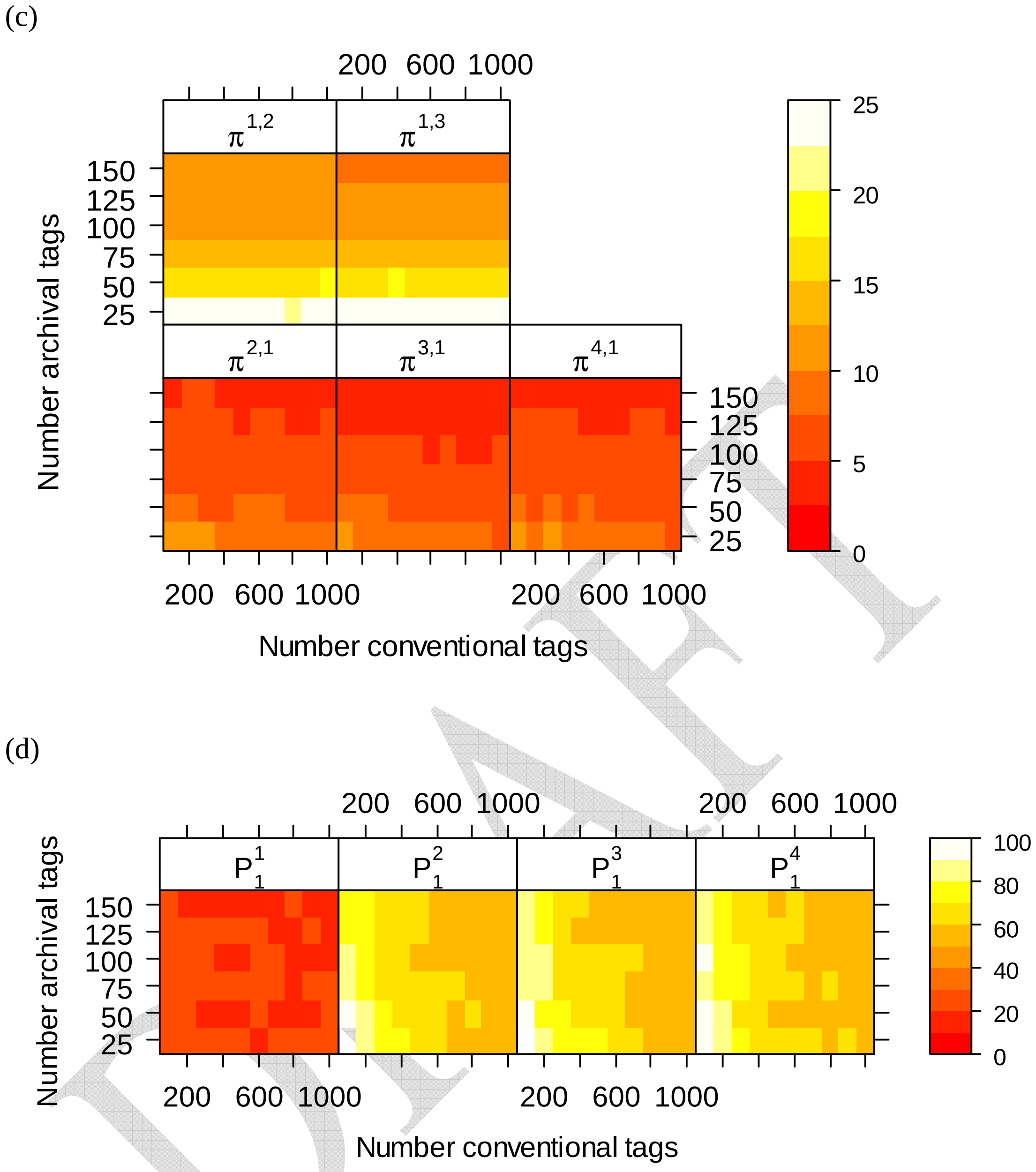


Figure 3. Coefficient of variation (CV, %) of the (a) fishing mortality, (b) natural mortality, (c) movement and (d) age 1 population size parameter estimates obtained from trade-off simulations using the SBT spatial model with parameterization {M2,F0,π1}and the reduced tagging design (250 runs were conducted for each combination of tag numbers).

24 Appendix 7: Implausible latitudes and equinox sensitivity analyses

A7.1. Implausible latitudes and the equinoxes

In **Section 11**: Habitat modelling we aim to relate movement behaviour to environmental covariates, so latitudes are required. Not all latitudes estimates in the dataset used for migration modelling (**Section 10**) are, however, plausible; recall that migration modelling only uses longitudes when fitting hidden Markov models (HMMs). There are three steps in the removal of data because of concerns about latitude estimates:

- implausible because the location is on land
- implausible because satellite SST suggests it is too cold or too hot at the estimated location, at the particular time
- possibly unreliable because it is near an equinox (21/22 March or 22/23 September)

Locations on land

The first set of locations that were removed from the dataset were those on land[33] (**Figure A7.1**). Although there are some not associated with an equinox, many are associated with the equinox in March when juvenile SBT are in the GAB. This step reduced the number of data points by 15%.

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[33] Locations on land were not removed from the dataset used in migration modelling, Section 10, because (a) only longitude was used and (b) extensive experience with light-based geolocation has shown that even when latitudes are poorly estimated, longitude estimates from different approaches are almost identical in the majority of cases. We therefore assume that estimated longitude is precise enough to be used for broad-scale (E-W) movement even when the latitude estimate is on land (due to N-S error).

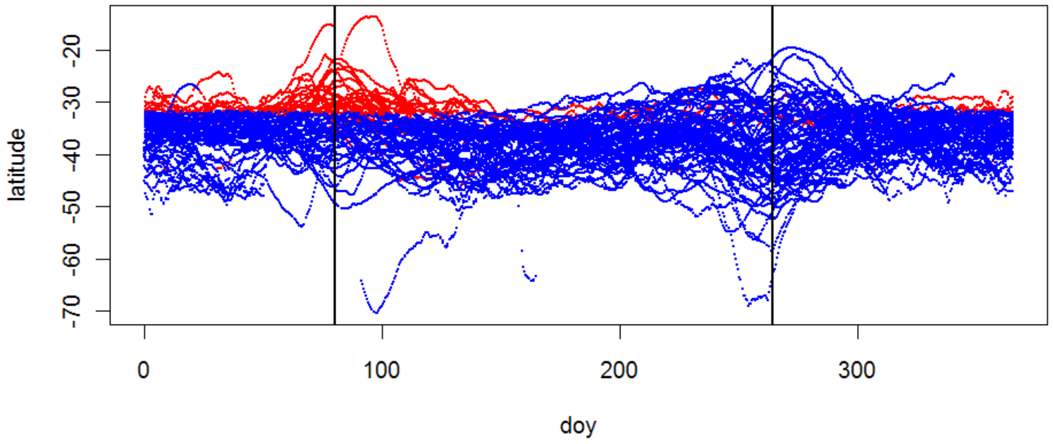


Figure A7.1. Latitudes plotted against day of year (doy). Blue points are locations in the ocean; locations on land (red points) are removed from the dataset. The solid black lines indicate the autumn and spring equinoxes.

Implausible satellite-based SST

We have already noted (**Section 7**) that we did not use SST as auxiliary data to improve latitude estimates because (a) the Trackit software failed when the SST-matching option was included and (b) software for incorporating SST into the Grid-based HMM model of geolocation is not yet available. Instead, our approach in this step is to remove latitudes where the ocean SST (satellite-based oceanographic product) is implausibly cold or hot in comparison to the temperatures range of 'on-board' average SST (calculated from external temperature at depths less than 5m recorded by the tag).

Ocean SST values were extracted for each location (or the closest available) and day (or closest available) with a view to comparing with on-board average SST. However, Hobday and Hartmann (2006) analysed 690 SST transmissions over 185 different days from tag deployments, and found that the SST reported by the tag was 0.76 ^{o}C (95% CI is between 0.49 and 1.03 ^{o}C) warmer than the satellite-based SST observation for the same position. We first explored this potential difference by comparing ocean and on-board SST just for the day of deployment when the location is known rather than estimated. This comparison showed that on-board SST in our dataset was on average 0.56 ^{o}C warmer than the ocean SST (the quartiles were -0.182

^{o}C and 0.812 ^{o}C). The percentiles of on-board average SST for the habitat-modelling dataset was:

Percentile	1%	5%	50%	95%	99%
Temperature (^{o}C)	10.7	12.4	17.8	21.2	23.1

Using the 5th percentiles together with the mean correction of 0.56 ^{o}C, latitudes were excluded if the ocean temperature extracted for that location and day was such that:

ocean temperature $< 12-0.56 = 11.44$ ^{o}C

or

ocean temperature $> 21+0.56 = 20.44$ ^{o}C

The points that were excluded are shown in **Figure A7.2**. This reduced the dataset by a further 5%. Within the set of retained locations there are still examples where there are large absolute differences (e.g. >2^{o}C) between the on-board SST and satellite SST. The intention here is not to exclude all those locations. They are retained because the latitude estimates lie within the plausible range of temperatures (for juvenile SBT).

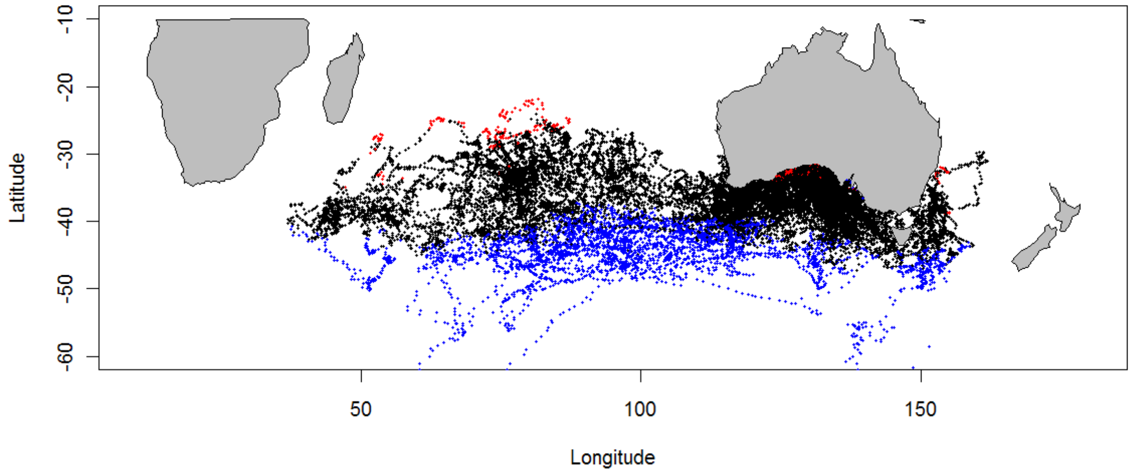


Figure A7.2. Locations with latitudes in ocean waters that were implausible cold (blue) or implausibly hot (red) were excluded from the dataset used in preference analysis (**Section 11**). The black points were included.

Latitudes associated with equinoxes

In the section on Geolocation and Track estimates (**Section 7**) we showed that latitudes are more uncertain around the equinoxes (21/22 March and 22/23 September) and potentially biased because of the lack of contrast in the light curves at dawn and dusk (the light curves are almost identical irrespective of latitude). We explored the sensitivity of our habitat modelling results (**Section 11**) to possibly erroneous latitude estimates near the equinoxes, by excluding data 14 days either side of the equinoxes (**Figure A7.3**). This implies leaving out data for the periods 9 March to 4 April and 9 September to 5 October. Exclusion of these periods implies a further 13% reduction to the dataset, but the impact on the preference analyses depends on which periods are being considered (see **Section A7.2**).

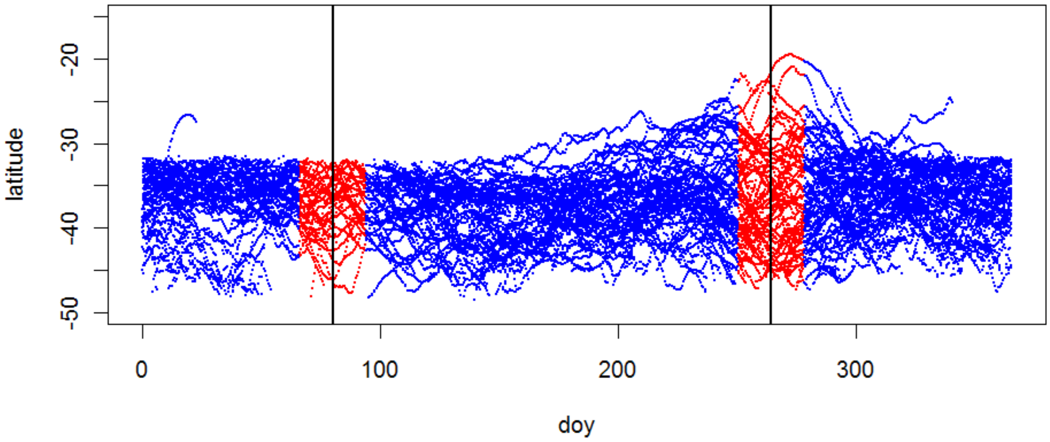


Figure A7.3. Latitude plotted against day of year (doy) with red points excluded from the dataset when conducting equinox sensitivity analyses. The vertical lines are at the March (doy=80) and September (doy=264) equinoxes

A7.2 Equinox sensitivity analyses

The analyses presented in **Section 11** excluded the locations on land and implausible locations as discussed above, but it included all data at or near the equinoxes. Here we present results for analyses with data around the equinoxes excluded as defined above.

A7.2.1 Residency in summer off southern Australia

Results here relate to **Section 11.3.1** in the main report. The period considered in this analysis was January to May which includes the March equinox. For the period 2004-2006, the reduced dataset had 13% fewer records than the full dataset. There were only very small differences in the preference surfaces between the full and reduced datasets (**Figure A7.4a**); the maximum differences were no larger than 1 and the overall difference is 0. This is clear from the third panel in **Figure A7.4a** - the overall colour is associated with a value of 0, and there are only very few combinations of SST and log(chl a) with differences around +1 or -1. There were no discernable differences between maps from the two preference surfaces.

Results are similar for the period 1998-2000 (12% reduction in the dataset), with an average difference of 0. The maximum and minimum differences between particular combinations are now larger as is evident from the different scale in the third panel of **Figure A7.4b**, but there are only about 3 combinations of SST and log (chl a) where the differences are this large. Again, the maps generated from the two different preference surfaces (i.e. with or without the equinox data) were essentially identical.

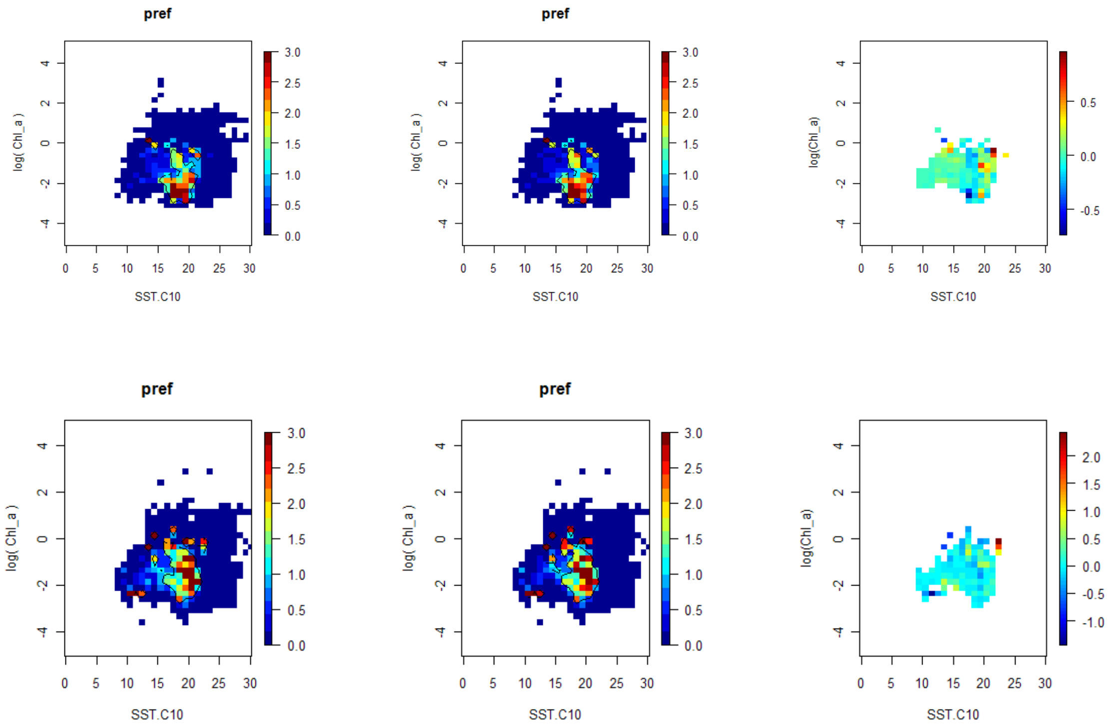
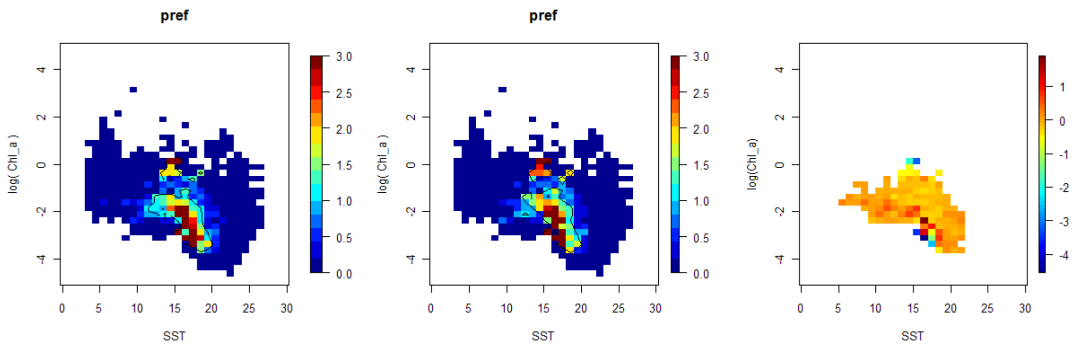


Figure A7.4. Preference surfaces for residency in summer off southern Australia in (a, top row) 2004-2006 and (b, bottom row) 1998-2000. Within each row the left panel is the preference surface for the full dataset, the central panel is for the dataset with equinox period excluded and the third panel is the difference between these two (note, the scale differs in the right-most panels).

A7.2.2 Residency in winter and spring in the Indian Ocean

Results here relate to **Section 11.3.2** in the main report. The period considered in this analysis was August to November which includes the September equinox. For the period 2004-2006, the reduced dataset had 22% fewer records than the full dataset. There were some large differences (up to +2 and down to -4), but only for a small number combinations of SST and log(chl a) (**Figure A7.5a**); the overall difference is again 0 (Note the scale is not the same as in **Figure A7.4**, so the colour light orange is associated with 0). Since the large differences were only present for a few combinations of covariate values, there were only very minor differences between maps from the two preference surfaces (**Figure A7.5b,c**).

For the period 1998-2000, the reduced dataset is 17% smaller than the full dataset. Results are very similar to those for the 2004-2006 period, and there are again only very minor differences between maps based on the two preference surfaces (**Figure A7.6**).



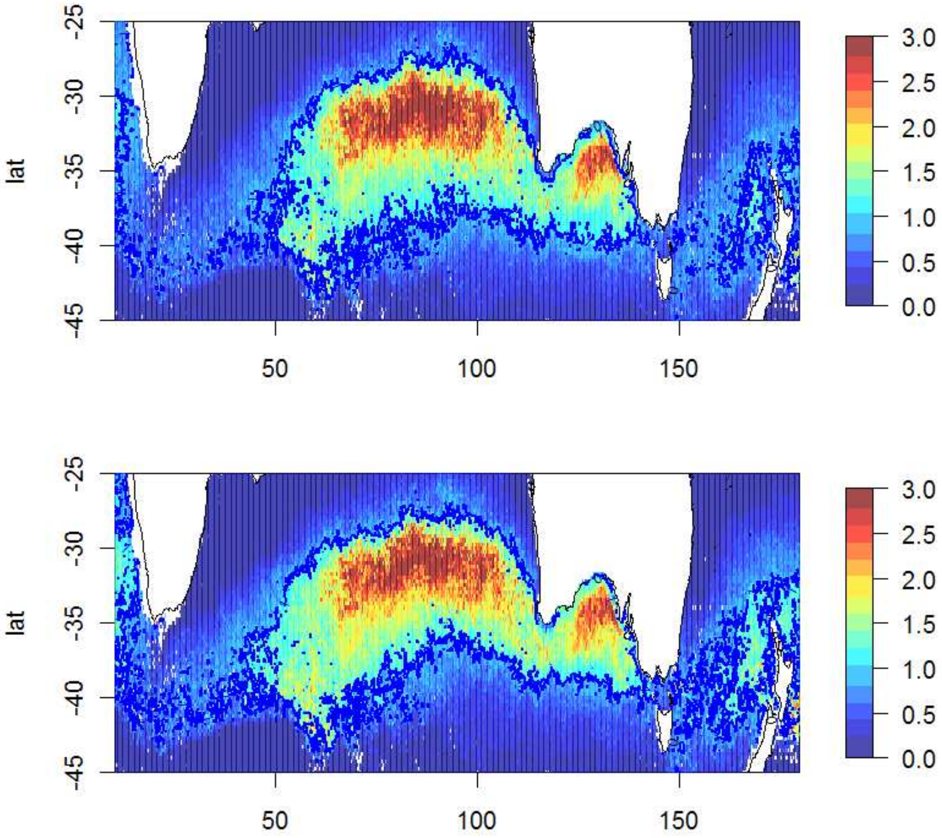
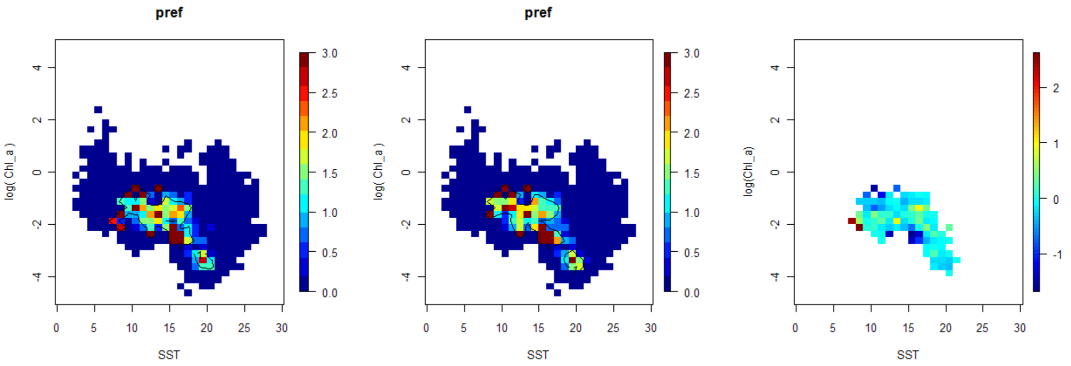


Figure A7.5 a,b,c. (a, top row) Preference surfaces for residency in winter and spring in the Indian Ocean in 2004-2006; within this row, the left panel is the preference surface for the full dataset, the central panel is for the dataset with equinox period excluded and the third panel is the difference between these two (note, 0 is light orange). (b, middle row) map based on the preference surface for the full dataset and (c, bottom row) map based on the preference surface for the dataset with the equinox period excluded.



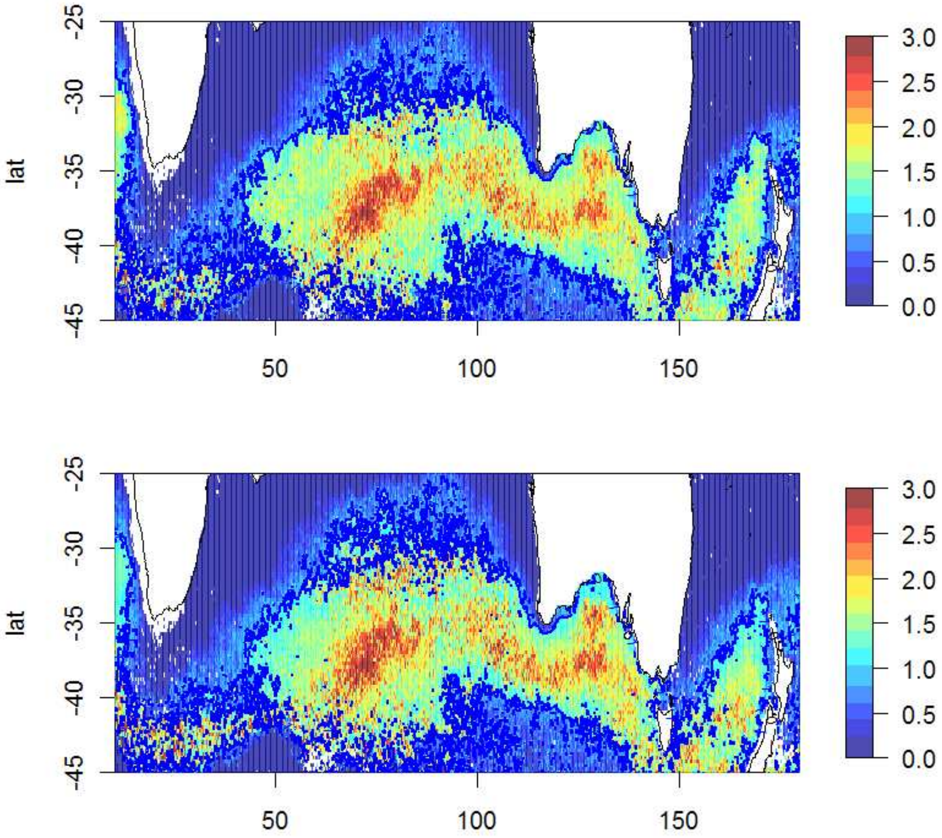


Figure A7.6 a,b,c. (a, top row) Preference surfaces for residency in winter and spring in the Indian Ocean in 1998-2000; within this row, the left panel is the preference surface for the full dataset, the central panel is for the dataset with equinox period excluded and the third panel is the difference between these two (note, 0 is light orange). (b, middle row) map based on the preference surface for the full dataset and (c, bottom row) map based on the preference surface for the dataset with the equinox period excluded.

A7.2.3 Migration East to the Tasman Sea in Autumn

Results here relate to **Section 11.3.3** in the main report. The period considered in this analysis was April to June which does not include an equinox *per se*, but includes the first few days in April (1st to 4th) that are in the 14 days after the March equinox. The reduced dataset for the period 2004-2006 is only 2% smaller than the full dataset, so we would expect hardly any difference. There were only very small differences (up to 0.8 and down to -0.2) and the overall difference is 0 (**Figure A7.7a**). Similarly, for 1998-2000, the reduction is less than 2%, differences are very small (up to 0.4 and down to -0.6) and the overall difference is again 0 (**Figure A7.7b**).

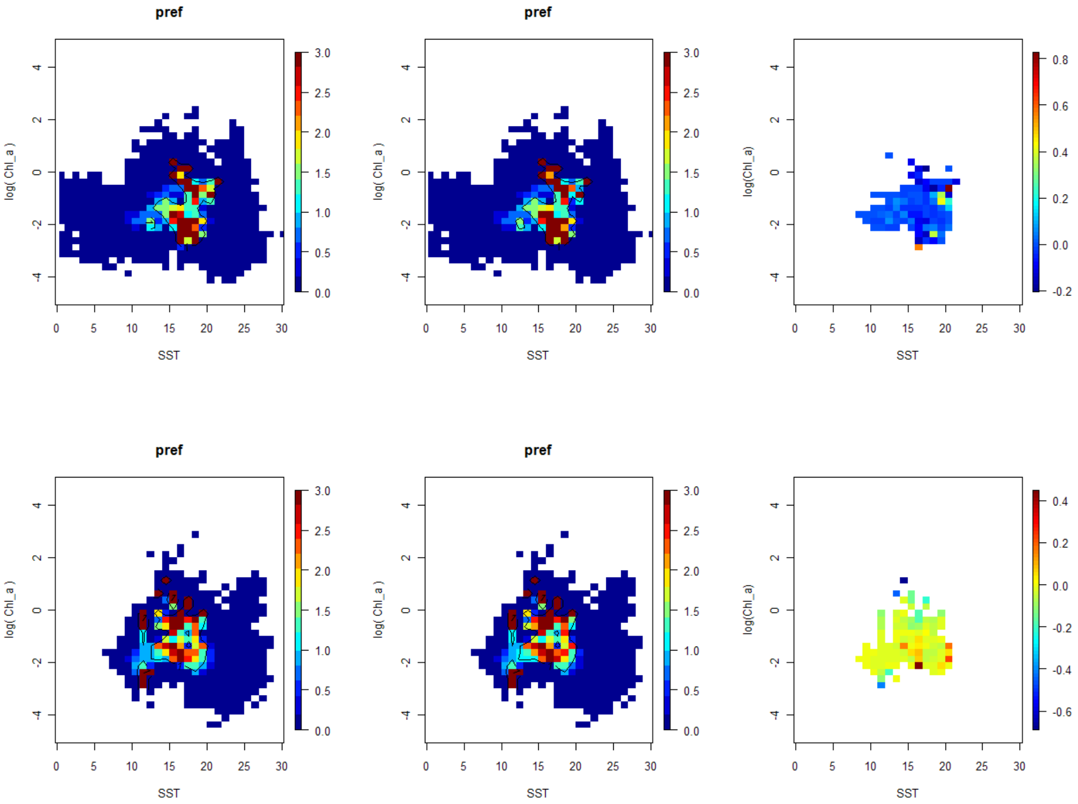


Figure A7.7. Preference surfaces for migrating east to the Tasman sea in autumn (a, top row) 2004-2006 and (b, bottom row) 1998-2000. Within each row the left panel is the preference surface for the full dataset, the central panel is for the dataset with equinox period excluded and the third panel is the difference between these two (note, the scale differs in the right-most panels).

A7.2.4 Migration to and from the Indian Ocean

Results here relate to **Section 11.3.4** and **11.3.5** in the main report. The period considered for migration west into the Indian Ocean was June to August. This period falls outside the equinox ‘exclusion’ periods, so sensitivity analysis is not applicable.

Migration East from the Indian Ocean back to the GAB was based on the period of October to January, thus including 5 days at the end of the September equinox ‘exclusion’ period. The reduced dataset for the period 2004-2006 is only 4% smaller than the full dataset, so we would expect hardly any difference. This is indeed the case (**Figure A7.8a**) with maximum differences between about 0.5 and -0.3, and an overall difference of 0. For the period 1998-2000 the reduced dataset is again only 4% smaller than the full dataset; differences are between about 0.01 and -0.10, and the overall difference is 0 (**Figure A7.8b**).

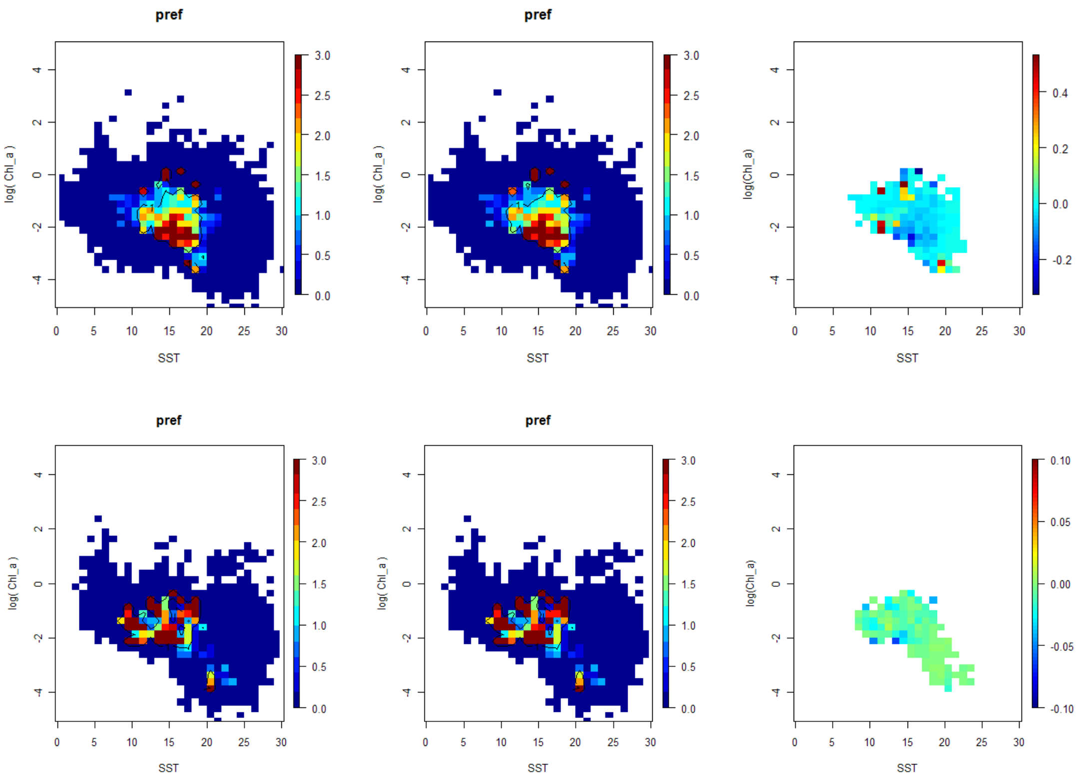


Figure A7.8. Preference surfaces for migrating east from the Indian Ocean to the GAB in spring/summer (a, top row) 2004-2006 and (b, bottom row) 1998-2000. Within each row the left panel is the preference surface for the full dataset, the central panel is for the dataset with equinox period excluded and the third panel is the difference between these two (note, the scale differs in the right-most panels).

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