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Southern bluefin tuna: spatial dynamics and potential impacts of noise associated with oil and gas exploration

Final Report GABRP Project 4.3

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GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

The Great Australian Bight Research Program is a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI, the University of Adelaide, and Flinders University. The Program aims to provide a whole-of-system understanding of the environmental, economic and social values of the region; providing an information source for all to use.

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Funding for this study was provided by the Great Australian Bight Research Program - a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI), the University of Adelaide and Flinders University. The program aims to provide a whole-of-system understanding of the environmental, economic and social values of the region; providing an information source for all to use. We are grateful for comments provided on earlier drafts of this report by the Great Australian Bight Research Program Management Committee, the Independent Science Panel and BP's Subject Matter Experts.

1. EXECUTIVE SUMMARY

1.1 Objectives

The objectives of this project were to:

1. Develop quantitative models of juvenile southern bluefin tuna (SBT) movement, feeding and surfacing behaviour and preferred habitats in the Great Australian Bight (GAB) based on historical archival tag data (1994–2011).
2. Estimate the extent to which movement and/or behaviour between the historic period and current exploratory period differ and, if so, in what way by comparison with data from contemporary electronic tag deployments.
3. Summarise historical oil and gas exploration activities that have occurred within the GAB from publically accessible records of exploration surveys.
4. Contribute data products, spatial dynamics methods for SBT, and interpretation for integrated analysis of other iconic and apex predators (Project 4.2) and broader integrative modelling of Theme 7.

1.2 Outputs and findings from this study

This project was designed to develop quantitative models of behaviour of SBT in the GAB ecosystem based on existing electronic tagging data from the period 1998 to 2011 (110 archival tag records each individually spanning <1 year and up to 3 years) from juvenile SBT and identify potential environmental/ecosystem factors that influence SBT behaviour in the GAB. Deployment of additional electronic tags during the project aimed at providing data on the behaviour of SBT during an exploratory phase of offshore oil and gas development by a number of companies in the GAB. The data derived from the contemporary tag deployments, combined with the behavioural models developed, would provide a basis for undertaking comparisons of movement, residency, feeding and surfacing behaviour of SBT in the GAB between the two periods.

In order to undertake such comparisons, the focus of the first part of the project was the characterisation of the behaviour of juvenile SBT behaviour within the GAB and investigation of the influence of environmental variability on individual behaviour. This involved:

1. Improvement of statistical methods for estimating the position of individual SBT from archival tag data using state-space modelling methods and incorporating ancillary sensor data, such as sea-surface temperature, and, where appropriate, bathymetry;
2. Refinement of understanding of the migrations of juvenile SBT and in particular the temporal components of migrations as well as potential drivers for migration;
3. Investigation of variability in the surfacing behaviour of juvenile SBT and relationships with environmental features within the GAB ecosystem;
4. Development of statistical methods to determine feeding signals, through examination of internal temperature records from tagged juvenile SBT, and development of models of feeding behaviour for juvenile SBT within the GAB;
5. Refinement of statistical models for the preferred habitats of juvenile SBT within the GAB and seasonal variability in their distribution within the GAB.

As a first step in examining the potential impacts of exploration associated with oil and gas on juvenile SBT whilst in the GAB, the study also collated and summarised the publically available

information on oil and gas exploration activities. This provided a profile of historical exploration for the region that could be discussed in light of the use of the GAB by juvenile SBT.

Unfortunately, we were not able to compare the migrations of juvenile SBT and their distribution and behavior within the GAB derived from historical tag deployments with that derived from contemporary deployments. This was a result of: i) a lack of sufficient contemporary archival tag returns within the lifetime of the project; and ii) an inability to source juvenile SBT of a size suitable for tagging with miniaturized PSATs. Because of this, the planned examination of the extent to which movement and/or behaviour between the historic period and current exploratory period differed was unable to be done within the timeframe of the project. The potential to undertake a comparison between the historical dataset and the contemporary dataset to determine the potential presence of broad-scale shifts in the behaviour of juvenile SBT in the future has not been lost. Deployment of an additional 125 electronic tags during the summer of 2014 in juvenile SBT in the GAB has facilitated ongoing collection of data from juvenile SBT beyond the timeframe of this project. As the tags deployed are returned over the coming years, they will add to the dataset generated by this study, providing a basis for future analysis.

Investigation of the movements of juvenile SBT showed that migrations of individual juvenile SBT were highly variable among individuals and often varied inter-annually within individuals. While winter foraging locations often varied within individuals from year to year, seasonal use of the GAB remained stable, highlighting the importance of the region as a summer-autumn habitat for juvenile SBT. The duration of migratory movements also varied, with movements from and back to the GAB occurring over periods as short as 61 days and as long as 481 days.

Intensive residence in the GAB by juvenile SBT was largely limited to the first 150 days of the calendar year. By the end of March, residency of individuals in the GAB began to decline and SBT migrated both west into the Indian Ocean and east toward the Tasman Sea. The departure date of fish from the GAB was highly variable, but began in February and extended into August, with the majority of fish having left the GAB by July. Returns to the GAB started to rise in November, peaking around December/January and continuing through to as late as March. The timing of the return to the GAB appeared to be more consistent across fish than the timing of their departure.

Areas of residence within the GAB were concentrated in three areas: the western GAB, the central GAB, and the upwelling region along the Bonney coastline to the east of the GAB. When compared with other areas of residence outside of the GAB, residency within the GAB appeared to occur during periods of higher surface temperatures and lower surface productivity. From December through to February, juvenile SBT were largely concentrated in inshore shelf waters or around the shelf break in the western and central GAB. During March through to May, there was an apparent shift in preference for areas in the eastern side of the GAB, with the northern, more coastal shelf waters of the GAB less frequented. During the austral winter months, the small proportion of tagged SBT remaining in the GAB were concentrated around the shelf break and continued to remain largely absent from the inshore regions of the shelf through September and October. As juvenile SBT returned to the GAB through November, occupancy of inshore areas of the GAB increased again.

While in the GAB, juvenile SBT were generally found at an average depth of less than 50 m (90% of all dawn, day, night and dusk time periods), and within an average temperature band of 16-23°C (96% of all time periods). The proportion of time juvenile SBT spent in surface waters (less than 20 m) while in the GAB varied both temporally and spatially with more time spent in surface waters during the day than at night. The time spent in surface waters during the day declined across the summer months and was associated with a deepening of the mixed layer depth and increased mixing of warm waters through the water column. Interestingly, the time spent in surface waters

during the day increased with the age of the individuals, but decreased at night. Time spent in surface waters increased as feeding activity increased, with most feeding events occurring during dawn periods when fish were at relatively shallow depths in the water column. The time spent by juvenile SBT at the surface across a 24 hour period demonstrated a crepuscular pattern, suggesting that the time spent at the surface is likely influenced by the diel vertical migration of their prey and the relationship of prey species with the deep scattering layer (DSL).

The models used to investigate feeding behaviour suggest a feeding strategy by juvenile SBT in the GAB based on smaller, frequent feeding events relative to that employed when on winter foraging grounds in the Indian Ocean and Tasman Sea, where feeding occurred less often and consisted of higher food intake and, presumably in association, larger prey. Temperatures associated with larger feeding events are consistent with juvenile SBT moving into cooler offshore waters over the winter period.

The timing of feeding events suggests that the ability of juvenile SBT to track their prey, as the depth of the DSL changes, is a trade-off between the availability of the DSL and the amount of light available, as SBT is considered to be a largely visual predator. Dawn and dusk periods are likely to provide enough light for identifying and pursuing prey, while also being dark enough that the DSL has ascended into those depths corresponding to isolumes[1] suitable for juvenile SBT.

These findings are consistent with what little is known of the diet of juvenile SBT. Small juveniles caught off the west coast of Western Australia have been recorded as having a diet of small pelagic crustaceans and small jack mackerel. Slightly older juveniles caught off southern Western Australia are known to feed on Australian sardines, blue mackerel and jack mackerel, with Australian sardines more abundant in the stomachs of fish in coastal regions and jack mackerel more abundant in the stomachs of fish closer to the shelf edge. Prey items in the stomachs of juveniles off South Australia were found to consist predominantly of Australian sardines and blue mackerel. Once outside of the GAB, SBT have been demonstrated to feed on a much higher diversity of prey.

It has been hypothesised that a decline in the lipid content of prey items, such as sardines, associated with seasonal declines in productivity may be the driver for juvenile SBT leaving the GAB (Ward et al. 2006). The GAB and, in particular, the eastern part of the GAB is an area of seasonal coastal upwelling driven by south-easterly winds primarily during the austral summer and autumn. Areas of upwelling are spatially variable and can range from relatively small and discrete features that may be active for only a few days at a time to widespread features extending out to the mid-shelf that persist beyond a few days. Sardines have been reported as having relatively high lipid content during the summer months, after which it decreases by more than half, suggesting potential linkages between the distribution of small scale, patchily distributed productivity events, the energetic benefits of prey items and the presence of juvenile SBT in the GAB.

Thermal regimes may provide additional drivers for the use of the GAB by juvenile SBT across the summer months, in particular. Previous growth studies have shown that a large proportion of the annual growth increment of SBT is achieved in the summer while in the GAB. The higher temperatures experienced in the summer months whilst in the GAB may infer physiological benefits. Whilst in the GAB, Juvenile SBT spend a large proportion of their days in surface waters whilst in the GAB which is thought to be a form of behavioural thermoregulation. This surface warming allows them to increase their body temperature, which in turn would be expected to increase digestion and

[1] The term ‘isolume’ is a common scientific term for lucid intensity. Within the ocean an isolume represents that part of the water column with an equal degree of brightness or consistent wavelength of light.

increase growth rates to a higher level than could be achieved in other coastal or oceanic environments.

1.3 Oil and gas exploration activities in the GAB in relation to juvenile southern bluefin tuna

Exploration for oil and gas in the greater area of the GAB using geophysical surveys has been occurring for more than five decades at variable levels. Peaks in exploration activity have occurred at relatively regular intervals, with the most recent associated with the release of lease areas in the offshore waters of the Bight Basin. Use of more complex, higher density 3D surveys has increased gradually since the turn of the century, with coarser 2D surveys decreasing.

There is no doubt that there has been overlap in the timing of seismic surveys and the occurrence of SBT in the GAB and that this temporal overlap within the GAB has been occurring for substantial amounts of time. Based on the distribution of SBT within the GAB established here, both the distribution of exploration activity and distribution of SBT in the GAB during the summer months has also overlapped, with 2007 the only year in which exploration activity did not occur during the summer months. Ascertaining direct measurements of overlap, however are largely impossible because of inherent errors in the light-based geolocation process used to estimate position. Although the improvements made to the process as part of this study has progressed our ability to better define the movements and areas of residency of juvenile SBT, it does not allow the pinpointing of an individual at an exact location at an exact time. Further, ascertaining any cause and effect relationships is impossible from observational data alone, particularly given the complexity of relationships between the environment of the GAB and juvenile SBT, as identified by this study. While some environmental parameters could be identified as influencing the behaviour of juvenile SBT, which ones, and the strength and direction of the relationships, varied temporally and across individuals. This made identifying clear relationships between behaviour with environmental parameters difficult, suggesting that the drivers for the behaviour of juvenile SBT are complex, and potentially interdependent and covarying in nature. This complexity limits any assessments of the potential impacts of overlapping oil and gas exploration activities on juvenile SBT based on simple overlays of distributional observations.

Determining the range of responses of a fish species to sound generated by anthropogenic activities requires well designed experiments that include adequate sample sizes and the necessary controls to account for potential compounding factors (e.g. the environment and other anthropogenic pressures placed on SBT both within and outside the GAB) to obtain reliable results. Such experiments are inherently complex, logistically difficult, and expensive. Such experiments should not only be able to detect and measure changes in behaviour, but also be able to attribute changes in behaviour to the factors that are driving them, factors that may be associated with exposure to sound, but also may be associated with other factors such as the physical environment or industrial activities such as fishing. Further, the many activities required for a successful experimental design, execution, and analysis require expertise from a range of disciplines including animal behaviour, experimental design and statistical analysis, hearing and auditory perception, sound generation and propagation in the ocean, ambient sound generated in the sea, and signal detection. Without due consideration of the requirements for adequately assessing the behavioural responses to sound generated by activities such as oil and gas exploration, assessing the impacts of these activities on marine animals will continue to be difficult and, as a result, largely either a qualitative or modelling exercise with inherent uncertainties.

1.4 Key knowledge gaps and recommendations

This study has substantially improved our knowledge of the behaviour of juvenile SBT and progressed quantitative approaches for assessing behaviour of juvenile SBT in relation to their environment. It has also highlighted the challenges to determining the range of responses of marine species to anthropogenic activities from observational data only. In light of the progress in understanding made by this study, some key knowledge gaps and associated areas for further work have been identified. These include the following:

- Many of the investigations conducted here would not be possible without the time series of observations provided by the historical archival tagging dataset collected. The study presented here highlights that in order to ascertain population-level responses to environmental variability, and pressures associated with human activity, long time series from animal populations are required. Extending the long-term monitoring of SBT though continued deployments of archival tags would allow for further definition of the movements and behavior of juvenile SBT, their relationships with the environment and assessment of the impacts of pressures from anthropogenic activities.
- The investigations conducted here explored variability in the behavior of juvenile SBT with a range of proximal factors, rather than direct observation of factors likely to directly influence SBT behavior, such as the distribution of prey species. This is largely because few data relating to factors directly influencing juvenile SBT behaviour exist, particularly at the spatial scale of the distribution of SBT and at scales that captures spatial and temporal variability in these factors. Incorporation of observations of the factors likely to directly influence SBT behavior, such as the distribution of prey species, would allow for the testing of a range of predator-prey, physiological, habitat related and migration hypotheses.
- The investigation of the feeding behavior of juvenile SBT presented here is a first step in quantifying temporal and spatial variability in foraging behavior, the drivers influencing foraging behavior, physiological processes associated with feeding and the productivity and energetics of feeding. Targeted collection of empirical data, particularly in relation to better defining the physiological signals of differing prey items, is required to better determine the links between the productivity and energetic benefits of prey and how these might be associated with the movements and habitat preferences of juvenile SBT. Further collection of observational data on the responses of digestion to environmental variability (e.g. water temperature) and what role the environment might have on use of the GAB over the summer months by juvenile SBT is required.
- There is no doubt that juvenile SBT, similarly to other marine animals in the pelagic environments of the GAB, are exposed to sound from a variety of sources, both natural and anthropogenic. Anthropogenic generation of sound in the GAB has a variety of sources and has been generated throughout the GAB for many decades. The future extent of acute sources of sound such as that associated with oil and gas exploration and production is largely unknown and will depend on many social and economic factors. In order to better understand of the impacts of oil and gas exploration activities on not only juvenile SBT, but also other marine predators, further work across a range of disciplines would be required. This would include (i) better understanding the processes involved in hearing in SBT, associated thresholds and , thereby providing a direct basis for testing behavioural responses and thresholds associated with sound (ii) extending monitoring of sound in the marine environment of the GAB to allow development of ocean soundscape models that capture the spatial and temporal variation inherent in the ocean environment and provide an overall baseline understanding of the sound sources and levels of sound generated in the GAB environment that juvenile SBT are exposed to and (iii) well designed experiments

that include adequate sample sizes and the necessary controls to account for potential compounding factors.

Keywords: southern bluefin tuna, *Thunnus maccoyii*, archival tags, spatial dynamics, surfacing behavior, feeding behavior, oil and gas exploration, Great Australian Bight.

2. INTRODUCTION

2.1 Overview

2.1.1 The southern bluefin tuna fishery

Amongst the tunas, southern bluefin tuna (SBT, *Thunnus maccoyii*) is a relatively long-lived (maximum age ~40 years), highly fecund and highly migratory species. Life history characteristics, including relatively slow growth, relatively late onset of maturity (maturity occurs at around 10 years), relatively low adult mortality and high longevity (see below), make it less resilient to overexploitation (Farley et al. 2014, 2015).

Industrial scale fishing of SBT commenced in the 1950s, involving Japanese longline vessels operating in the Indian Ocean and extending east into the Pacific, and Australian pole and line, purse seine and troll vessels operating in Australian coastal waters, predominantly on the southeast coast, but also in the Great Australian Bight (GAB; Caton 1991). Participation in the fishery has since expanded to include vessels from New Zealand, Indonesia, the Fishing Entity of Taiwan, the Republic of Korea, the European Union, South Africa and, to a limited extent, the Philippines (CCSBT 2016).

Very large catches by the longline and surface fisheries through the 1960s to late 1990s and associated overfishing resulted a very depleted stock by the late 1990s–early 2000s (CCSBT 2014; Hillary et al. 2014) The spawning biomass (an estimate of the reproductive potential of the population) was reduced to 3–8% of its original size and recruitment (young of the year entering the population) reached historical lows in the late 1990s and early 2000s (CCSBT 2014; Hillary et al. 2014). Revelations of large unreported catches and the depleted nature of the stock led to significant reductions in total catches (Polacheck and Davies 2008; Polacheck 2012) in 2005 and subsequent reductions in global catch limits, or Total Allowable Catch (TAC), in 2006 and 2009 (CCSBT 2006, 2009). The species is listed as “critically endangered” under the International Union for Conservation of Nature Red List of Threatened Species (Collette et al. 2011) and “conservation dependent” under the *Environment Protection and Biodiversity Conservation Act* 1999 (EPBC Act). The most recent stock assessment indicates that the catch reductions implemented in the first decade of the 2000’s have reduced fishing mortality (CCSBT 2014; Hillary et al. 2014) and recruitment monitoring from aerial surveys in the GAB demonstrate increases in the relative abundance of 2–4 year olds in the most recent years (Eveson and Farley 2016).

Within Australian waters, the fishery for SBT originally developed in southern Australian waters, has evolved over time and now is predominantly focused in two areas: a purse seine fishery that operates in the GAB during the austral summer months targeting surface schools of juveniles (Basson and Farley 2014) and a longline fishery that operates from New South Wales to Tasmania during the austral winter and spring months targeting sub-adult and adult SBT (Patterson and Stobutski 2016). The purse seine fishery, based in Port Lincoln, South Australia, is associated with inshore ranching operations where juveniles are grown out over a period of four to five months for the export market. This sector of the Australian fishery harvests about 98% of the national allocation of SBT in the GAB each summer and is of significant value to the regional economy (~$200M annually; Econsearch 2014).

2.1.2 The spatial dynamics of southern bluefin tuna

The GAB is particularly important for young SBT (1–4 years). Large numbers of juvenile SBT migrate into the warm, shelf waters of the GAB each summer to feed on abundant prey species, such as

sardines (*Sardinops sagax*; Caton 1991; Gunn and Young 1999; Ward et al. 2006). Juvenile SBT start to appear in the GAB around November/December and leave the GAB between March and May, spending the winter either in the Indian Ocean or Tasman Sea before returning to the GAB the following spring (Bestley et al. 2009; Basson et al. 2012). This cycle continues until fish are 4–5 years old, after which they disperse throughout southern temperate waters of the western Pacific, Indian and eastern Atlantic Oceans (Caton 1991). While in the GAB each summer, juvenile SBT aggregate into large surface schools (Eveson and Farley 2016) with individuals spending substantial time in the upper 100 m of the water column (Bestley et al. 2009). These surface schools are visible from light planes that are used by the Australian purse seine fishery to target schools (Figure 2.1). As fish move out of the GAB and into the Indian Ocean/Tasman Sea, they are targeted by recreational fisheries across southern Australian waters, and international longline fleets in the Pacific, Indian and Southern Oceans (Caton 1991; CCSBT 2016).

Figure 2.1. A purse seine vessel and associated vessel towing a cage of juvenile southern bluefin tuna as seen from a spotter plane in the Great Australian Bight (front). Surface schools, or “patches”, of juvenile SBT (dark areas) can be seen in the background. Photo: Jessica Farley (CSIRO).

2.1.3 Management of the southern bluefin tuna fishery

The international SBT fishery is managed by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT). The CCSBT sets global TACs for the fishery and determines national allocations. The Australian Government Department of Agriculture and Water Resources leads Australia’s

participation in the CCSBT. Domestic management of the fishery is the responsibility of the Australian Fisheries Management Authority.

A formal management procedure[2] (MP) was adopted by the CCSBT in 2011 as part of the Commission's agreed rebuilding plan for the stock. The MP consists of a scientifically tested rebuilding plan agreed and used by the CCSBT to recommend changes in the global TAC (Hillary et al. 2016) and is recognised as a central part of the rebuilding plan required by the EPBC Act listing. It has been used to set global catches in 2011, 2013 and 2016 (CCSBT 2016). The MP uses a recruitment index juvenile SBT (historically based on relative abundance derived from a fishery independent scientific aerial survey and in the future on absolute abundance determined via genetic techniques – see below) and a relative abundance index of the harvested component for the stock from standardised Japanese longline catch per unit effort (Itoh and Takahashi 2016) as the monitoring series.

2.1.4 Recruitment monitoring in the Great Australian Bight

Development of scientific aerial surveys for the estimation of the relative abundance of juvenile SBT in the GAB commenced in the early 1990s in response to increasing concern about the declining levels of recruitment and the lack of a fisheries independent means of monitoring the stock (Cowling et al. 2003; Eveson 2007). The survey collects data on the surface schools observed from light planes that fly designated line transects according to established and consistent protocols, including strict requirements on environmental conditions (Eveson and Farley 2016). These data are used to estimate an annual index of relative abundance of 2-4 year olds in the GAB between January and March (Hillary et al. 2016). This index is central to the operation of the current CCSBT MP and is the only fisheries independent index of recruitment used in regular CCSBT stock assessments.

In light of the cost and potential logistic frailty of the scientific aerial survey, the CSIRO and CCSBT have been considering alternative approaches to monitoring recruitment (Davies et al. 2012; CCSBT 2013; Stobutzki et al. 2013). In 2015, suspension of the aerial survey increased the urgency and priority within the CCSBT of cost-effective methods that could be developed to replace the aerial survey as the primary recruitment monitoring approach (CCSBT 2014, 2015; Preece et al. 2015a). A design study of a genetic mark recapture approach to recruitment monitoring was conducted. Based on the results of this pilot study, the CCSBT subsequently agreed to a gene-tagging program to provide an abundance estimate for juveniles for use in the MP into the future (Preece et al. 2013, 2015b; Preece and Bradford 2016). This method relies on capture, genetic tagging and release of juvenile SBT for subsequent recapture at harvest the following year. Similar to commercial purse seine operations, the approach relies on identification of surface schools to facilitate catch and release of sufficient individuals to meet the design criteria. Given this, and the low status of the SBT stock, sufficient, consistent access to juvenile SBT in the GAB for the purposes of recruitment monitoring is essential for the monitoring of the stock, the effective implementation of the MP and setting of the global TAC for the foreseeable future[3].

[2] A Management Procedure (MP) is a fully specified combination of the fishery monitoring system, data analysis, harvest control rule (used to adjust management based on the outcome of the analysis) and management implementation used to achieve the required change in fishing mortality, which has been simulation tested using Management Strategy Evaluation. In the case of CCSBT MP, see Hillary et al. (2016) for an overview and CCSBT (2009, 2010, 2011, 2013) for full technical details.

[3] Under the current rebuilding plan and associated MP, the stock is expected to have rebuilt to the interim rebuilding target of 20% of unfished spawning biomass by 2035 (CCSBT 2013)

With this background, this project aimed to address two needs. First, to provide a detailed understanding of the spatial dynamics and role of SBT as an apex predator in the GAB. Second, to provide baseline information on the movements and behaviour of SBT and their variability that could be used in investigations of the potential impacts of oil and gas exploration on the migration and behaviour of SBT in the GAB. Within the context of the GAB, there is considerable concern by both industry and the general community that recent expansion of activities associated with oil and gas exploration, specifically activities associated with geophysical surveys and exploratory drilling activities, may impact on the migration and behaviour of a number of apex predators. Any potential changes to the migration and behaviour of SBT in the GAB, may have subsequent consequences for both activities carried out as part of monitoring the rebuilding of the population and commercial fishery operations.

Determining the impacts associated with a particular activity on a wild population of animals is a technically difficult issue to address. The existence of a substantial time series of data on SBT movement, surfacing and foraging behaviour in the GAB prior to the most recent exploration activities, combined with the collection of comparable contemporary data (to be collected through this and related projects), was considered to have the potential to provide a starting point to investigate this issue and provide the necessary models to design appropriate monitoring studies and/or experiments. Outputs from this study were then to provide inputs into the broader integrated analyses of spatial dynamics and habitat use of the GAB by apex predators and iconic species (Theme 4, Project 4.2) and the role of SBT in the trophic dynamics of the wider GAB ecosystem (Theme 7). Outputs also aimed to provide a sound quantitative foundation for future population risk assessments.

2.2 Objectives

1. Develop quantitative models of juvenile SBT movement, feeding and surfacing behaviour and preferred habitats in the GAB based on historical archival tag data (1994 – 2011).
2. Estimate the extent to which movement and/or behaviour between the historic period and current exploratory period differ and, if so, in what way by comparison with data from contemporary electronic tag deployments.
3. Summarise historical oil and gas exploration activities that have occurred within the GAB from publically accessible records of exploration surveys.
4. Contribute data products, spatial dynamics methods for SBT, and interpretation for integrated analysis of other iconic and apex predators (Project 4.2) and broader integrative modelling of Theme 7.

2.3 Structure of this report

This report has been written to provide a synthesis of a series of technical papers (Appendix 2) in a form that is accessible to a broad non-technical audience with an interest in the role of SBT in the GAB and historical and contemporary oil and gas exploration throughout the region. Given this, the report structure consists of an overview of common general methods in Section 3, followed by an the main results and associated discussion of results from each of the five technical components of the project: migration dynamics of juvenile SBT, surfacing behaviour within the GAB, foraging behaviour, distribution and habitat preference within the GAB, and history of oil and gas exploration in the GAB in relation to juvenile SBT in Sections 4-8. These are then discussed in light of the overall objectives of the project in the Section 9, and conclusions from the project can be found in Section 10. For those interested in further technical details of the specific methods and scientific

interpretations of associated analyses used in each technical component, these can be found in each of the papers listed in Appendix 2.

3. GENERAL METHODS

3.1 Study design

This project was designed to develop quantitative models of behaviour of SBT in the GAB ecosystem based on existing electronic tagging data from the period 1994 to 2011 from juvenile SBT and identify potential environmental/ecosystem factors that influence SBT behaviour in the GAB. Deployment of additional electronic tags during the project aimed at providing data on the behaviour of SBT during an exploratory phase of offshore oil and gas development by a number of companies in the GAB. Data derived from the contemporary tag deployments, combined with the behavioural models, would provide a basis for historical and contemporary comparisons of movement, residency, feeding and surfacing behaviour of SBT in the GAB between the two periods.

In order to undertake such comparisons, the focus of the first part of the project was the characterisation of the behaviour of juvenile SBT behaviour within the GAB and investigation of the influence of environmental variability on individual behaviour. This involved:

1. Improvement of statistical methods for estimating the position of individual SBT from archival tag data using state-space modelling methods and incorporating ancillary sensor data, such as sea-surface temperature, and, where appropriate, bathymetry
2. Investigation of variability in surfacing behaviour and relationships with environmental features within the GAB ecosystem
3. Developing statistical methods to determine feeding signals, through examination of internal temperature records from tagged fish, and development of models of feeding behaviour within the GAB
4. Refinement of statistical models for the preferred habitats of SBT within the GAB and seasonal variability in their distribution within the GAB

As a first step in examining the potential impacts of exploration associated with oil and gas on the movements and behaviour of juvenile SBT, it is important to establish the historical extent of oil and gas exploration in the extended area of the GAB. This study collated and summarised the publically available information on oil and gas exploration activities and provides a profile of historical exploration for the region that could be discussed in light of the use of the GAB by juvenile SBT.

3.2 Historical electronic tagging programs and data sets

3.2.1 Deployments during the 1990's

CSIRO has been testing and developing archival tags for deployment in SBT since 1992, firstly in conjunction with Zelcon Technic Pty Ltd (Tasmania, Australia) and later with Wildlife Computers (WA, USA). During the 1990s and 2000s, archival tags were deployed in juvenile SBT under a number of different programs (Table 3.1). The first set of deployments were associated with tag development and testing and involved the deployment of 189 CSIRO/Zelcon tags (SBT 100 and SBT 150 models) during the austral summers of 1993 and 1994 (Gunn et al. 1994) and 144 CSIRO/Zelcon tags (SBT 200 model) in 1995. These tags were deployed in juveniles ranging 88–115 cm length to caudal fork (LCF). A following set of deployments was associated with an ongoing program by CSIRO on juvenile SBT in the GAB and involved the deployment of 229 Wildlife Computers tags (Mk7 model, Redmond, USA) in juveniles 67–120 cm LCF across the austral summers of 1998–2002 (Gunn and Block 2001). A total of 74 CSIRO/Zelcon tags and 66 Wildlife Computers Mk7 tags have been returned to date.

A review of the data derived from the returned CSIRO/Zelcon tags revealed that the data were not suitable for position estimation due to the sub-sampling regimes programmed into the tags (data collected was duty cycled in order to maximise battery life) and as a result, the data from these tags was not included in the analyses presented here.

3.2.2 Deployments during the 2000's

During 2003, 29 Wildlife Computers (Mk9 model) archival tags were deployed in one-year old SBT (49–57 cm LCF) off Western Australia, of which four tags have been returned to date. During 2004–2009, as part of a large scale global tagging study conducted by CSIRO and supported by the Fisheries Research and Development Corporation and the Department of Agriculture Forestry and Fisheries (Basson et al. 2012), 568 Wildlife Computers Mk9 archival tags were released in juvenile SBT 49–150 cm LCF across five main areas spanning the range of juveniles: South Africa (n=27), the mid-Indian Ocean (n=159), West Australia (n=175), the GAB (n=122) and New Zealand (n=85). The project aimed to improve the current understanding of juvenile SBT movements and spatial dynamics across its range. The project also aimed to provide better estimates of mixing and migration rates of juvenile SBT and develop spatial population dynamics models to potentially underpin future assessments and management procedures. The project ran concurrently with the conventional tagging program run by the CCSBT and aimed to complement and improve the interpretation of the conventional tagging data (Basson et al. 2012). A total of 86 tags from this project have been returned to date.

Table 3.1. Numbers of historical archival tags deployed in juvenile southern bluefin tuna in the Great Australian Bight.

Program/Year	Tag model	Number of tags deployed	Number of tags recaptured
1993-1995	CSIRO/Zelcon (SBT100, SBT150, SBT200)	333	74
1998-2002	Wildlife Computers (Mk7)	229	66
2003	Wildlife Computers (Mk9)	29	4
2004-2009	Wildlife Computers (Mk9)	568	86
Total		**1,159**	**230**

Of tags recaptured, the total time at liberty (time from release to recapture) has ranged from 1–4,648 days. Individuals recaptured have been estimated to range in age from 1–15 years at recapture with the majority (86 %) less than 6 years. Almost all data recovered from tags are associated with juvenile SBT aged 6 years or less.

3.2.3 Data preparation and quality control

Each archival tag recorded light, depth, internal temperature and external temperature at regular intervals ranging from 30 seconds to four minutes depending on the settings at deployment. Earlier models had smaller memory and shorter battery life and so were programmed to collect data at longer intervals than later models which had larger memory and longer battery life. Light data are used to determine day and night, and are used to estimate position (see Section 3.2.4). The external temperature sensor measures water temperature, while the internal sensor measures body temperature, which can be used to identify feeding events (see Section 6). Information on depth provides measures of diving and vertical habitat use (see Section 5), and is also required to correct the light record for diving behaviour.

Data were downloaded from each tag using proprietary software and uploaded to a purpose built software program (Archtag Viewer, CSIRO) for pre-processing. Pre-processing involved:

- Identification of the start and end of the deployment. This was required because tags could only be turned on and off using proprietary software in the laboratory prior to tagging operations and once returned, so could be recording for days to weeks before or after deployment/recapture. Data prior to deployment and after capture were subsequently trimmed from the data file.
- Correction of depth sensor drift. Over time, the depth sensor on some tags no longer records the depth at the surface correctly and over time progressively drifts. Reasons for sensor drift vary and can result from excessive diving that compresses the depth sensor housing, or some other fault. The software allows multiple correction points to be added to the time series of depth measures, thereby allowing for correction of any drift.
- Identification and flagging of erroneous sensor data. On occasion, sensor readings might appear to be outside the possible values that they should be, or might demonstrate erratic behaviour which can include temporary failure before continuing to collect data. Where this occurred in the time series for a sensor, data were flagged as being invalid, allowing users to restrict data extraction for analyses to only those data flagged as valid.

Data were then uploaded via Archtag Viewer to a purpose built Oracle database (Hartog et al. 2009) housed and maintained by CSIRO.

Because a fault was identified with the external temperature sensor of a number of Mk9 tags (see Basson et al. 2012 for details), a further step in pre-processing was taken for all Mk9 tags. Briefly, the external temperature sensors in a number of tags were found to positively drift, resulting in external temperature records that were higher than internal temperature records. In SBT, 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). Time series of the internal temperature and external temperature records were compared and where external temperature sensor drift was identified as occurring in the records of the tag, the external temperature record for that tag was flagged as invalid and omitted from any analyses.

The number of tags used in the remaining sections of this report varies depending on the analysis and the data requirements for those analyses, but is based on a final set of 110 archival tag records each individually spanning <1 year and up to 3 years over the period 1998 to 2011. For example, the geolocation analysis requires light and external temperature data, while analyses of surfacing behaviour requires at a minimum, depth data only. Reasons for having to omit tags from analyses include a lack of geolocation estimates, very short deployment periods, and sensor drift or failure resulting in data being flagged as invalid (as described above).

3.2.4 Geolocation, position and track estimation and modelling

Geolocation, the process of estimating position from light data collected by each archival tag, was performed using the state-space modelling approach detailed in Basson et al. (2016). We briefly describe this method here, but refer readers to Basson et al. (2016) for further technical details.

Geolocation requires light readings at the ocean's surface, so for animals such as SBT that are perpetually under the ocean's surface, the light data collected by each tag needs to be corrected for light attenuation due to water depth. A depth correction method (CSIRO, unpublished data) similar to that developed by Ekstrom (2002) was used. This requires that data associated with day periods be firstly identified. A statistical "day-night" filter using a hidden Markov model (HMM) was used to estimate the probability of the sensor readings relating to day or night (CSIRO unpublished data). Surface light levels were then estimated from raw light-at-depth data using the above depth correction method. Once corrected, the light data were then 'windowed' around each twilight period for input into the twilight likelihood (TL) geolocation method. For each twilight event, a data summary statistic over a grid of locations is then computed and the summary statistics transformed to estimate a likelihood (i.e., the probability density) of the light data given any location on the globe.

The likelihood surfaces from the TL method were then input into a grid-based HMM model similar to that used in Basson et al. (2016) to estimate a "most probable track" for each animal (see Section 4). The hidden state of the fish is its location at each twilight (constrained to a discretised latitude-longitude grid) and the probability of moving between states (i.e. grid cells) is assumed to be a random walk. Temperature recorded by the tag in the top 20 m (as an estimate of Sea Surface Temperature; SST) and maximum depth recorded by the tag were compared against remotely-sensed SST data and bathymetry data, respectively, and the information included in the form of likelihoods in the HMM to inform position estimation.

The output of the HMM is the posterior probability of the fish being in each possible grid cell on the globe during each twilight event (which excludes any cells that correspond to land masses). Because of the large number of tags, many with long deployments, we used a 1° x 1° grid for computational purposes. For each tag, a "most probable track" was estimated by taking the weighted average of all grid positions using the posterior probabilities at each twilight as the weights, resulting in two mean position estimates per day.

The outputs from this method were treated as locations for input into analyses of migration, surfacing behaviour, feeding and habitat preferences, the details of which are provided in the papers listed in Section 13.1 and summaries of the results of which are provided in Sections 4–7.

3.3 Contemporary tag deployments

An important element in initiating a tagging program for a wide-ranging species is to establish effective communication with potential partners for the recovery of tags. Within Australia this involved:

- advising the SBT fishing industry of tag deployments, with CSIRO staff visiting Port Lincoln and providing annual updates on the project and associated tag deployments at the Australian Southern Bluefin Tuna Industry Association (ASBTIA) science workshops;
- advising relevant state recreational fishing organizations of the project including the Game Fishing Association of Australia (GFAA), Tasmanian Association for Recreational Fishing (TARFish), Victoria Recreational Fishing, Recreational Fishing South Australia, South Australian Game Fishing Association and providing material on the project for their websites. Further distribution of information on the project to state members was

facilitated by the GFAA. This included providing recreational fishing organisations with tag return posters updated to reflect current reward systems (Figure 3.1);
- advising relevant Australian Government and state fisheries management agencies;
- providing presentations to relevant community festivals and activities;
- developing a fact sheet for the project and a case study detailing the project on the CSIRO website;
- highlighting the project in articles generated for the CSIRO website on other tagging projects.

In addition, regular updates to the CCSBT were provided at annual meetings of the Scientific Committee and individual country members were provided with information on the project, including tag return posters (Figure 3.1), via the CCSBT.

Figure 3.1. Tag return posters in (a) English, (b) Chinese, (c) Indonesian, (d) Japanese and (e) Korean.

Tag return certificates, updated from those used in CSIRO–CCSBT tagging programs and specific to this project were also developed (Figure 3.2).

Requisite permits for tagging operations were obtained from the Tasmanian Department of Primary Industries Parks, Water and Environment Animal Ethics Committee (permit 17/2012-13) and the Australian Fisheries Management Authority (permits 1002702 and 1002875). Research Mortality Allowance was also obtained from the CCSBT for tagging operations (Evans et al. 2012; Anon 2015). Tagging operations were also considered in light of internal requirements for animal ethics by BP and approved.

Tagging methods by their nature are invasive, and the interpretation of the data collected using this technology requires that the impacts of such invasive techniques are minimised (data collected should represent as close to natural behaviour as possible). Because of the requirement to ensure that any impacts associated with tagging methods are minimised, CSIRO has invested heavily in developing best practice techniques and methods aimed at minimising the impacts of tagging. These have been developed into a publication, the *CSIRO Marine and Atmospheric Research, Pelagic Fisheries and Ecosystems Fish Tagging Protocols* (Bradford et al. 2015) and a CSIRO-wide recognised training program. Use of the protocols and associated training ensures that those involved in tagging

animals have the requisite experience and are capable of tagging animals using best practice methods, thereby ensuring that animals are returned to the water as quickly as possible and in as good a condition as possible.

This tag was deployed as part of the Great Australian Bight Research Program. The Great Australian Bight Research Program is a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI), the University of Adelaide and Flinders University.

Southern Bluefin Tuna
Tag Return Certificate

This certificate has been awarded to

[name of returning party]

For returning the following tag and thereby making a contribution to world research on southern bluefin tuna.

Primary Tag Number: *Primary Tag Colour:*

Companion Tag Number: *Companion Tag Colour:*

Fish Details

Released at [location] on [date]

Recaptured at [location] on [date]

Harvested at [location] on [date]

Days in wild: [#days] Distance from release: [#nautical miles]

The fish grew from [length at release] at release to [length at recapture/harvest] at [recapture/harvest]

Average Growth per Month: [average] cm

CSIRO, GPO Box 1538, Hobart, Tasmania 7001 Phone: (03) 62325222 Fax: (03) 62325000

Figure 3.2. Tag return certificate developed for the project. These were also generated in Japanese and Indonesian.

3.3.1 Archival tags

Collection of a contemporary dataset from juvenile SBT in the GAB was facilitated by the deployment of archival tags on 125 juveniles during a charter of the vessel *FV Yasmin* 19 November–5 December 2014. Deployments occurred across a region extending from 32 07–35 16˚S and 132 02–135 36˚E (Figure 3.3) and involved fish ranging 65–79 cm LCF (Figure 3.4).

Individual fish were caught using pole and line methods using barbless hooks which aim to minimise any hook damage to fish. Once hooked, fish were brought on board the vessel immediately and landed onto a padded and wet mattress before being transferred to a padded and wet tagging cradle (Figure 3.5).

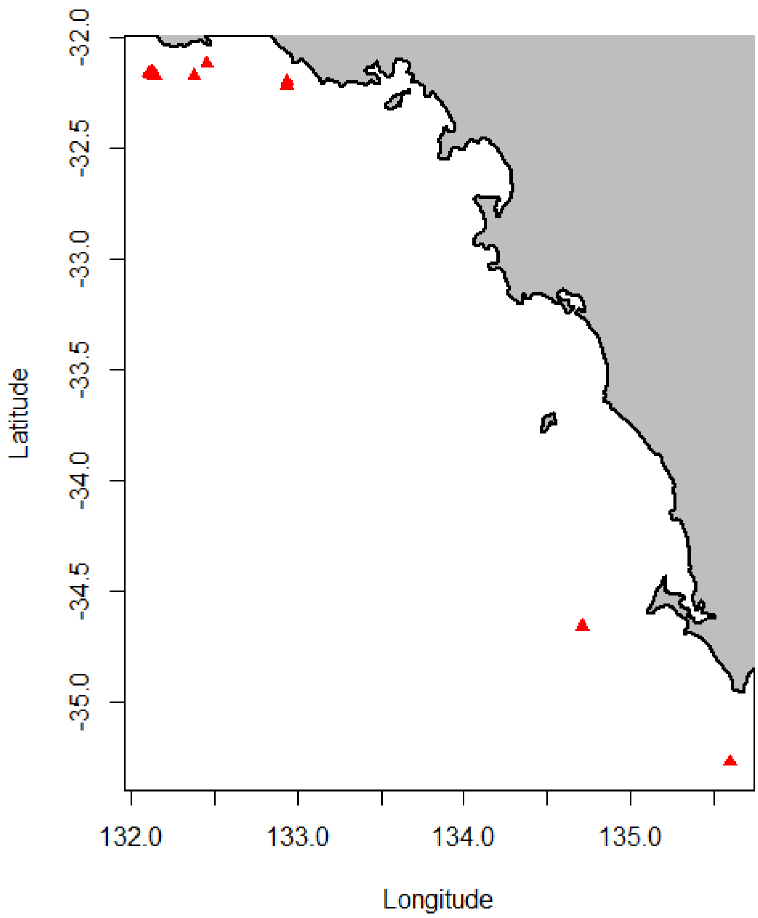


Figure 3.3. Locations of archival tag deployments (red triangles) in juvenile southern bluefin tuna November-December 2014.

Because the hook is barbless, the hook is released from the mouth of the fish in the process of landing on the padded mat and is not required to be actively removed. Wetting the surface of the mat and cradle ensures that the mucosal surface of the skin of the fish is not compromised. Once in the cradle, the eyes of the fish are covered by a single-use wet cloth, which acts to calm the fish, and the fish measured. The cloth used to cover the eyes is wet with local sea water and similarly to the wet mat, ensures that the mucosal layer of the eye and skin of the fish are not compromised.

Individual tags are sterilised prior to surgery by soaking each in the antiseptic Betadine prior to deployment.

Surgical procedures followed those detailed in CSIRO's standard operating procedures (Bradford et al. 2015). Briefly, a small incision along the ventral surface of the animal through the body wall to the peritoneum is made with a sterilised scalpel. The peritoneum is then opened and the archival tag is inserted into the peritoneum and pushed forward into the body cavity so that the light stalk of the tag sits near the front of the incision. The incision is then closed with a suture stitch and the suture tied off and knotted. A single conventional tag is then inserted into the dorsal musculature to the rear of the origin of the dorsal fin and to a depth where the head of the conventional tag anchors in and around the basal bone elements using a single use tag applicator, which has been sterilised with Betadine. Deployment of a conventional tag on animals within which internal archival tags are deployed serves to alert commercial fishers to the presence of an archival tag and increases the likelihood of return of archival tags from commercially caught fish.

A total of six tags from these contemporary deployments have been returned to date (Table 3.2). Of these, data were retrieved from five, with one tag failing on deployment.

3.3.2 Pop-up satellite tags

Under funding external to the Great Australian Bight Research Program, 35 miniaturised pop-up satellite archival tags (PSATs) were obtained by the project investigators and identified as potentially being able to provide the project with coarser scale data over shorter data retrieval times. This is because these tags are externally attached to individuals and can be programmed to release from the animal at a pre-specified time and transmit summarised data to a satellite network. This allows the data to be retrieved from deployments without the need to recapture the fish and have the tag returned.

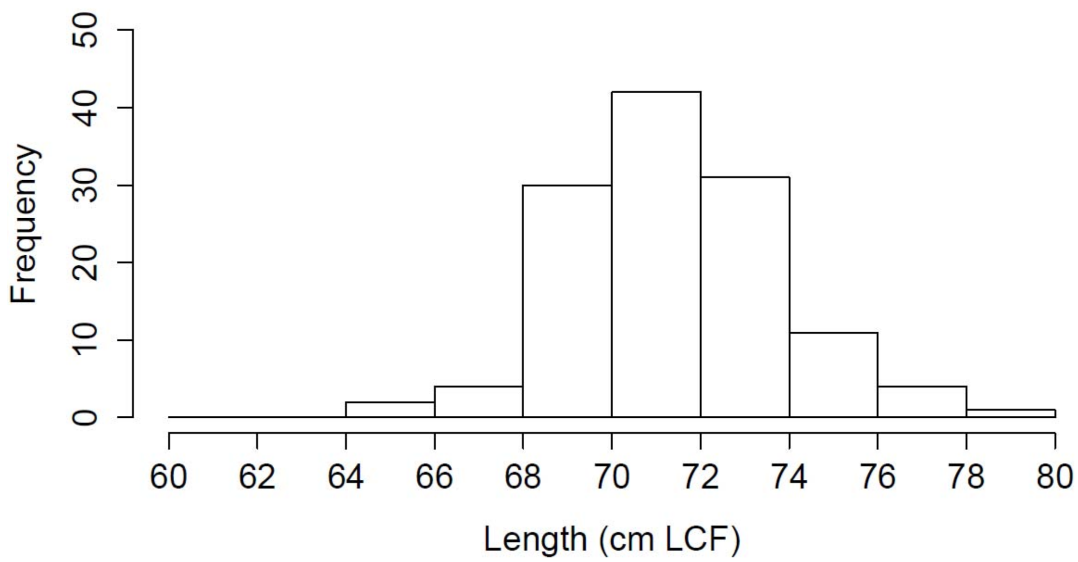


Figure 3.4. Distribution of lengths of juvenile southern bluefin tagged with archival tags November - December 2014. LCF: Length to caudal fork.

Table 3.2. Archival tags recaptured from juvenile southern bluefin tuna tagged in the Great Australian Bight in 2014.

Tag Number	Model	Deployment			Recapture				Days of data
		Date	Position	Fish length (cm LCF)	Date	Position	Fish length at harvest (cm LCF)	Time at liberty (days)	
L281-0886	Lotek 2810	01/12/2014	-32.16, 132.12	65	31/12/2015	-36.17, 137.50	103	395	0
L281-0887	Lotek 2810	01/12/2014	-32.16, 132.12	65	31/01 – 13/02/2016	-36.38, 138.35	101	426-439	426-439*
1390445	Wildlife Computers Mk9	02/12/2014	-34.66, 134.71	70	16/02/2016	-35.55, 136.65	104	441	441
1390422	Wildlife Computers Mk9	04/12/2014	-32.12, 132.46	72	10/01/2016	-35.33, 136.67	102	402	402
1390432	Wildlife Computers Mk9	01/12/2014		75	20/12/2016		115	750	750

*depth sensor failed on deployment, resulting in identification of catch and transfer to tow cage not being able to be identified.

Fish of adequate size for the deployment of the 35 miniaturised PSATs were not sighted during the first charter period and as a result a charter of the vessel *FV Saxon-S* was carried out 3–8 December 2015. Although tuna schools were encountered, the high abundance of baitfish in the region made it difficult to get fish to rise to the surface where they could be poled. Of five schools encountered, only one was able to be brought to the surface. Fish within this school were on average 6–8 kg and too small to tag with the PSATs.

Following the unsuccessful second charter, options to deploy the PSATs with the recreational sector during the remainder of 2016 were explored. Operators were identified in Victoria and Tasmania, and regular contact maintained. During this period, fish of the size required for effective deployment of PSATs (110–130 cm LCF) remained rare in recreational catches, with the majority of catches reported as being of fish either 60–70 cm LCF (~10 kg) or >150 cm LCF (>80 kg) in size. Given the time period for return of data from the tags and the reporting period of the project, it was decided in December 2016 not to pursue the deployment of these tags under the project. This outcome and the limited returns to date from the 125 archival tag deployments has constrained the extent to which Objective 2 of the project can be addressed (see Section 9).

Figure 3.5. A juvenile southern bluefin tuna caught on a pole and line and with the purpose built padded landing table directly behind the crew members on the pole and line.

4. MIGRATION DYNAMICS OF JUVENILE SOUTHERN BLUEFIN TUNA

4.1 Background

Annual migrations allow animals to exploit changes in spatially varying resources such as forage resources or breeding habitat (Alerstam et al. 2003; Durant et al. 2005; Guttal and Couzin 2010). In highly migratory pelagic species, the difficultly in observing movements and the activity in different parts of the range, limits understanding as to why large-scale migrations, which constitute a significant investment of energy, confer a benefit. While the development of telemetry technology has made migration cycles more observable (Costa 1993; Gunn and Block 2001; Block et al. 2011), quantifying variability and plasticity of migration schedules remains a challenge, particularly given the sample size required to understand populations rather than individuals.

The migration cycle of SBT has been recognized from seasonal distributions of catch records and from previous archival tagging studies (Gunn and Block 2001; Bestley et al. 2010; Basson et al. 2012). However, due to a lack of electronic data records lasting more than one year, the fidelity of individuals to winter foraging areas remains unknown and the movement dynamics of individuals whilst in the GAB largely unexplored. Further, the degree of synchronicity in departure and return dates is also unknown and understanding of what environmental drivers may be associated with annual migrations is limited.

Here, we classified the movements of juvenile SBT to determine areas of residency and in association potentially important habitat and to quantify the extent and synchronicity of the migrations of SBT to and from the GAB.

4.2 Methods

Position estimates were obtained using the state space models employing the “twilight likelihood” method of Basson et al. (2016) and as detailed in Section 3.2.4. A hidden Markov model was used to estimate changes in behaviour models when individuals were migrating and when individuals were resident. The model used distance from a central location (32°S, 130°E) in the GAB as a point of reference to determine whether SBT were in one of three states: (1) resident with no directed movement away or toward the GAB; (2) migrating outwards or (3) migrating towards the GAB.

Categorization of movements into the three states allowed for the calculation of (i) time spent in each state (ii) the run length of each state (i.e. time spent consecutively in each behavioural state); (iii) the proportion of the tagged fish in each behavioural state as a function of day of year; (iv) timing of the initiation of migration away from the GAB (as day of the year); (v) timing of the return of each individual to the GAB (as day of the year). The spatial distribution of behaviours was mapped along the estimated track of each individual providing for an aggregate picture of intra-annual variation in migration behaviours.

Kernel density estimation (Ripley et al. 2017) was applied to locations identified as being in a resident state to create a map of the core residence locations of SBT throughout their range. These identified areas of residence were then used to guide analysis of oceanic characteristics associated with the timing of migration in relation to annual cycles of ocean temperature and productivity.

4.3 Results

Movements of 110 juvenile SBT were estimated from archival tag deployments across 1998–2011 (Figure 4.1). The average duration of estimated tracks was 380 days (SD: 320 days). Cyclic migrations were a defining feature of all estimated tracks. Juvenile SBT ranged large distances from the GAB (mean: 4,262 km, SD: 2,181 km, maximum distance 10,251 km) in both westerly and easterly directions. The duration of each migration from and back to the GAB varied substantially between individual SBT and was as short and 61 days and as long as 481 days (mean: 172 days, SD: 89 days).

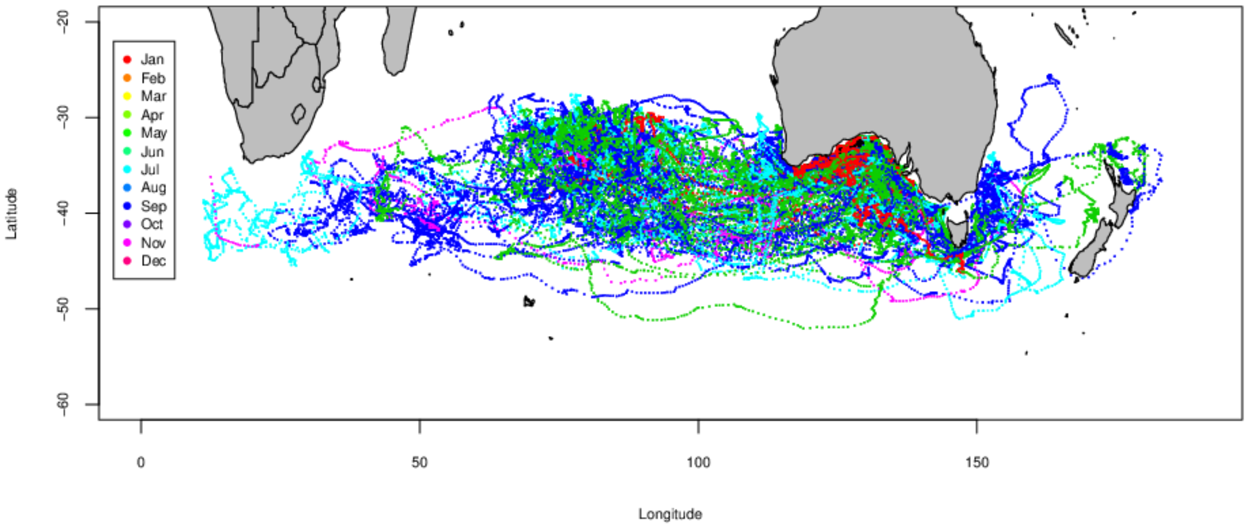


Figure 4.1. Estimated movements of juvenile southern bluefin tuna (coloured by month) derived from archival tag deployments across 1998–2011.

Migrations were highly variable between individual SBT (Figure 4.1) and were also highly variable from year to year within individuals. For example, one SBT (Figure 4.2) made four return-migrations across the period 2006–2010 between the GAB to the Indian Ocean (IO), travelling as far west as approximately 60°E. Migrations away from the GAB during the first two years of tag deployment were rapid and directed, punctuated by periods of residency before similarly rapid migrations back towards the GAB were initiated.

As the period across which this tag was deployed progressed, several changes to the migrations of this individual occurred. First, less time was spent in the GAB during the summer period. This was also observed in other long term deployments, identifying that as juvenile SBT age, they spend less time in the shelf waters of the GAB. Second, in the third year of deployment, rather than departing the GAB and heading west into the IO, this SBT moved east and into the Tasman Sea for a period before heading west and into the IO. This westward migration was also punctuated by a higher occurrence of periods of residence than in the first two years of the deployment. There was substantial variation and overlap between the distributions of the movement modes (Figure 4.2) with estimated outward movement steps approximately the same magnitude as the inward steps. This was a common feature across individuals.

The HMM classified SBT as being in a resident mode for nearly 60% of the time, with the outward migration from the GAB containing more periods of residence than the inward migration to the GAB (Figure 4.3). Intensive residence in the GAB was largely limited to the first 150 days of the year. By

the end of March, residency of individuals in the GAB begins to decline and SBT migrate both west into the IO and east toward the Tasman Sea. Most juvenile SBT (84%) were observed to migrate westwards out of the GAB and into the IO rather than eastwards and into the Tasman Sea. The departure date, of fish from the GAB was highly variable, but began in February and extended into August with the majority of fish having left the GAB by July (Figure 4.3). The distribution of return dates started to rise in November, peaking around December/January and continuing through to March, reflecting the extended period of residency associated with the GAB. The timing of the return of juvenile SBT to the GAB appeared to be more consistent across fish than their departure (Figure 4.3).

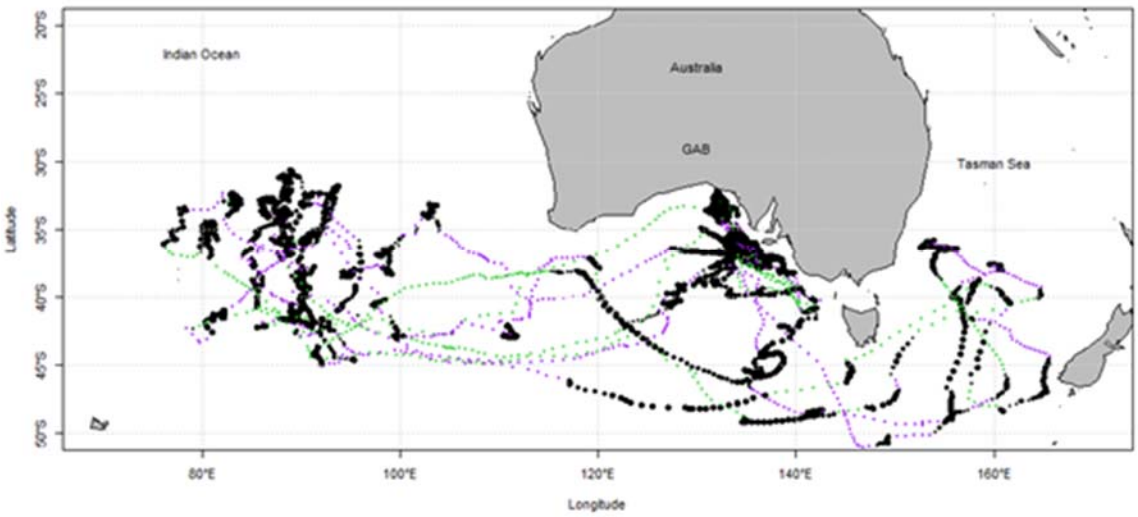


Figure 4.2. Example migration of an individual juvenile southern bluefin tuna. Locations are coloured according to most likely state classification with black identifying periods of residence, purple identifying migrations towards the Great Australian Bight and green identifying migrations away from the Great Australian Bight.

Kernel density estimation identified areas associated with residency in the IO, GAB and the Tasman Sea. To refine the analyses associated with identifying potential environmental variables associated with the timing of migration, the area identified in the Indian Ocean was further divided into Northern (NIO) and Southern (SIO) components at 37°S. The summer residence areas around the GAB was subdivided into three areas pertaining to the western GAB (WGAB), the central GAB (CGAB), and the upwelling region along the Bonney coastline in western Victoria to the east of the GAB (BONN).

Examination of seasonal cycles in oceanographic variables (SST and chlorophyll-a) in areas where juvenile SBT were classified as resident indicated that SBT are resident in the GAB during periods of lower productivity and highest temperatures when compared with other areas (Figures 4.5 and 4.6). Periods of residence in the IO are characterized by lower surface productivity and cooler temperatures than those of the GAB. Fish migrating into the Tasman Sea appear to experience relatively consistent SSTs and Chl-a surface conditions when compared with other areas.

4.1 Discussion

The GAB is clearly an important summer habitat for juvenile SBT, as demonstrated through their cyclical migration to the region each year. The data considered here suggests that juvenile SBT return to the GAB even if they spend subsequent winters in different oceanic regions (e.g. the southern Indian Ocean or the Tasman Sea). Additionally, summer spatial usage within the GAB appears relatively stable from electronic tagging records spanning two decades. For some individuals, continued use of the GAB beyond the summer months (through to September in some cases), suggests that the productivity of the region beyond the summer months is sufficient for a proportion of the juvenile population to remain.

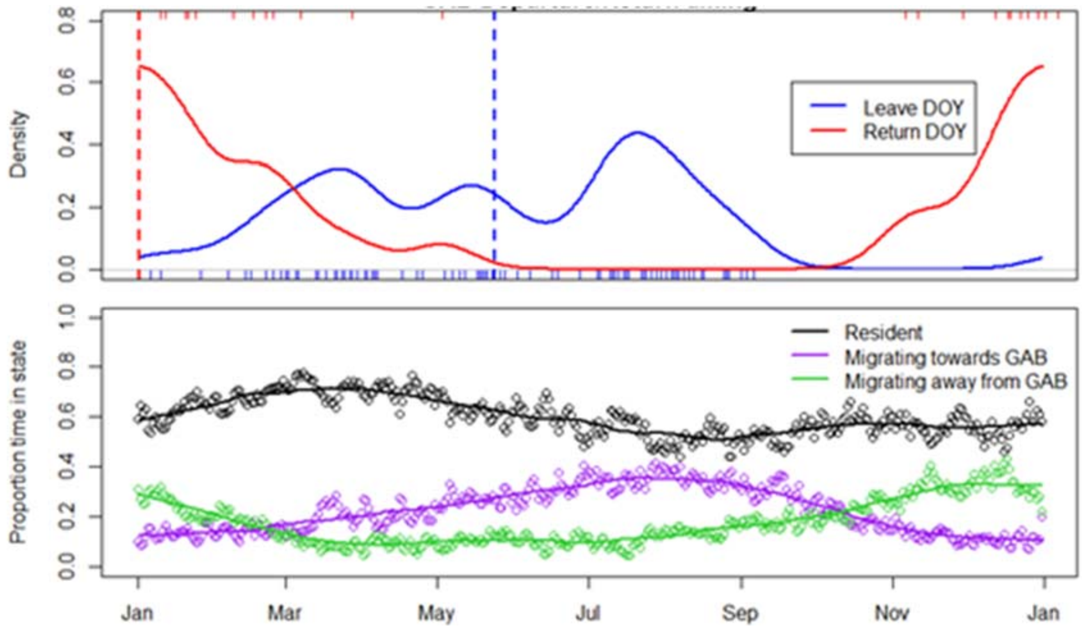


Figure 4.3. Density (proportion of positions either identified as migrating away from the GAB or migrating to the GAB) of juvenile southern bluefin tuna migrating away from the Great Australian Bight (blue) and towards the Great Australian Bight (red) by day of the year (top) and the proportion of positions in each behaviour state by day of the year (bottom).

The precise cues that trigger SBT to migrate away from the GAB are unclear. It has been hypothesised that a decline in the lipid content of prey items, such as sardines, associated with seasonal declines in productivity may be a driver for juvenile SBT leaving the GAB (Ward et al. 2006). The lipid content of sardines has been reported as having relatively high lipid content during the summer and autumn months, after which it decreases by more than half (Ward et al. 2006), suggesting potential linkages between the energetic benefits of prey items and the presence and distribution of juvenile SBT in the GAB.

The oceanography of the regions where juvenile SBT spent most time in a resident state suggests that Chl-a may not be an appropriate indicator of areas of high productivity of the trophic levels targeted by SBT. The physical and biological processes that support their utilization of such areas is not well understood. Several potential processes (which may work in association with each other) may explain the use of such regions by juvenile SBT. First, juvenile SBT, like other tuna species are

visual predators, preferring to hunt their prey in clear waters away from areas of high turbidity associated with high levels of primary productivity (Laurs et al 1984; White et al. 2004; Zagaglia et al. 2004). Second, the energy transfer from primary to intermediate levels in the food web and subsequent increased abundance of the intermediate food web species that are the prey species of pelagic predators such as SBT incurs a time lag. As intermediate species increase in abundance, resources of primary species are consumed and decline in abundance and as a result, the presence of higher order predators may be offset from high levels of primary productivity (Lehodey 2004; Hazen et al. 2013). Third, areas of concentrated productivity may operate at smaller spatial scales than those at which associations were investigated. This spatial mismatch may identify regions as being less productive than they might be at smaller spatial scales. Finally, satellite derived indices of productivity only provide an indication of productivity in the surface waters of the ocean and do not provide measures of sub-surface productivity. Further, in coastal regions close to land, spatial and optical resolution can become degraded, requiring *in situ* validation (Lynch et al. 2014). Without direct observations of the biological productivity of the water column in regions of residence, it is difficult to determine if such features are driving juvenile SBT behaviour.

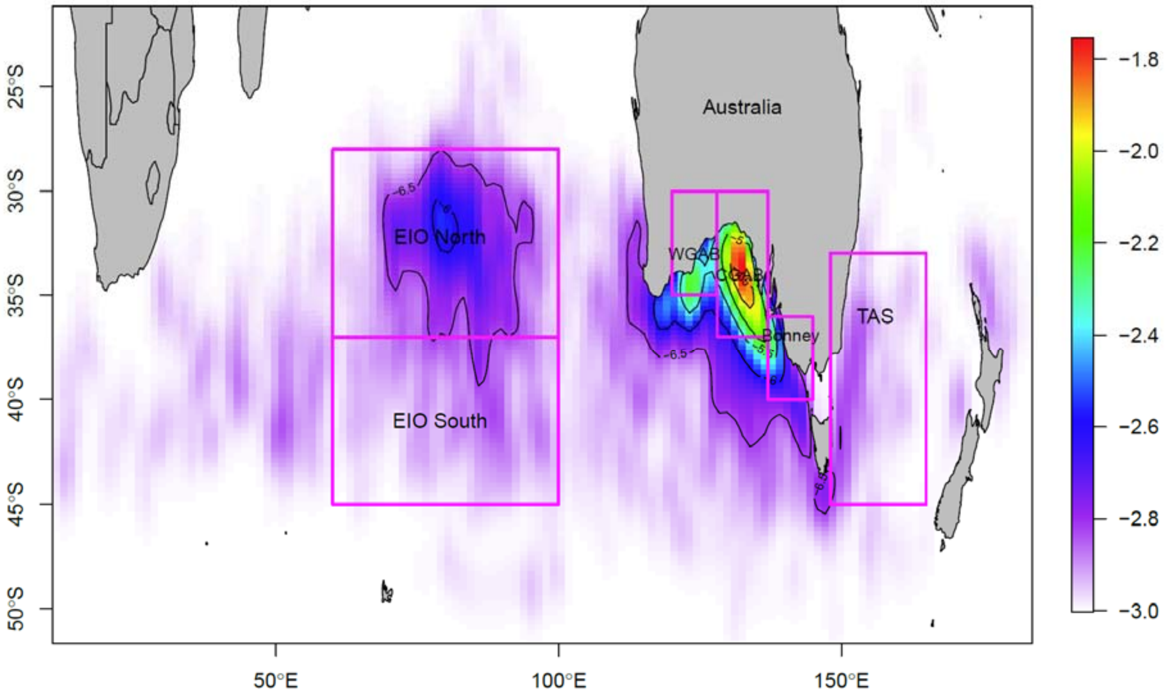


Figure 4.4. Areas of high residence utilised by juvenile southern bluefin tuna identified by kernel density estimation.

In other regions, the distributions of pelagic predators such as tuna have been associated with physical features of the ocean such as bathymetry, frontal features and subsurface structure of the water column (e.g. Zagaglia et al. 2004; Teo et al. 2007; Evans et al. 2014; Potier et al. 2014). It may be more appropriate to use such physical features rather than indicators of primary productivity for investigating drivers of habitats use. Further, a greater understanding of the intermediate links, in particular potential prey of juvenile SBT across regions of residence and their concentrations, is also required for better understanding drivers of the distribution of this top predator.

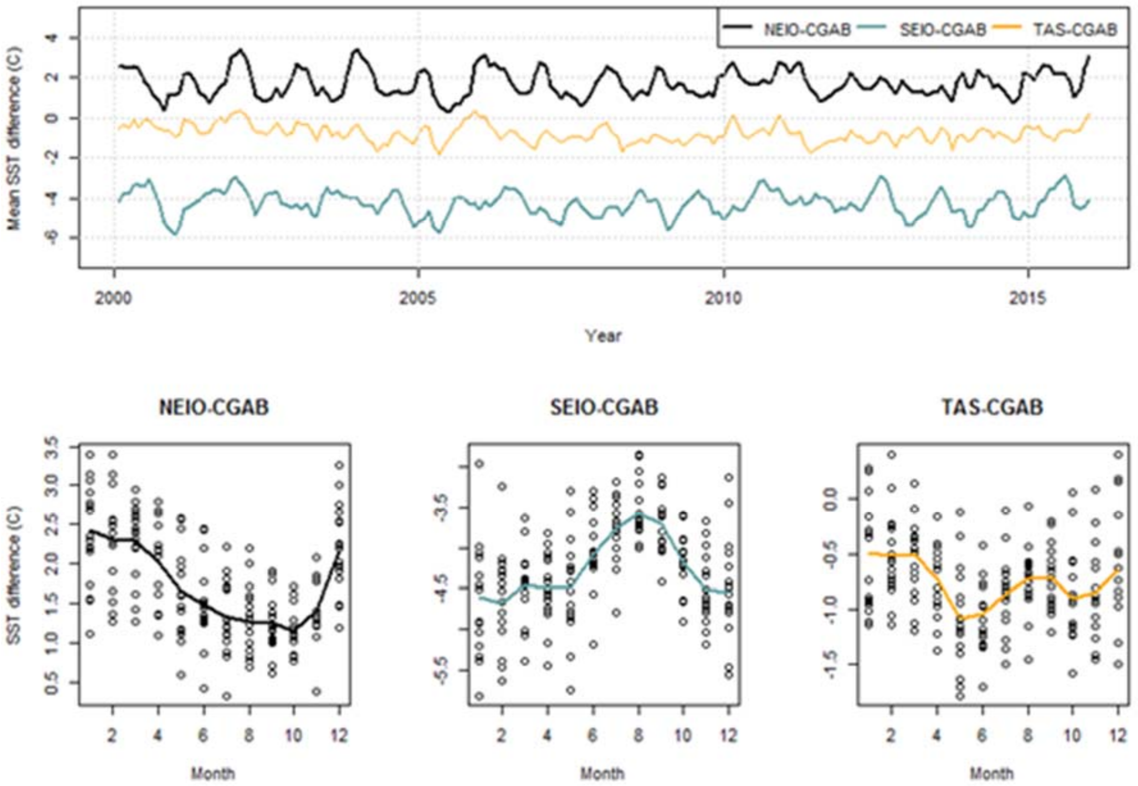


Figure 4.5. Time series of difference between sea surface temperature in the central Great Australian Bight (CGAB) and the northern eastern Indian Ocean (NEIO), southern eastern Indian Ocean (SEIO) and Tasman Sea (TAS) across 2000–2015 (top) and across months all years pooled (bottom). Lines highlight trends and note that the y-axis scales vary between plots.

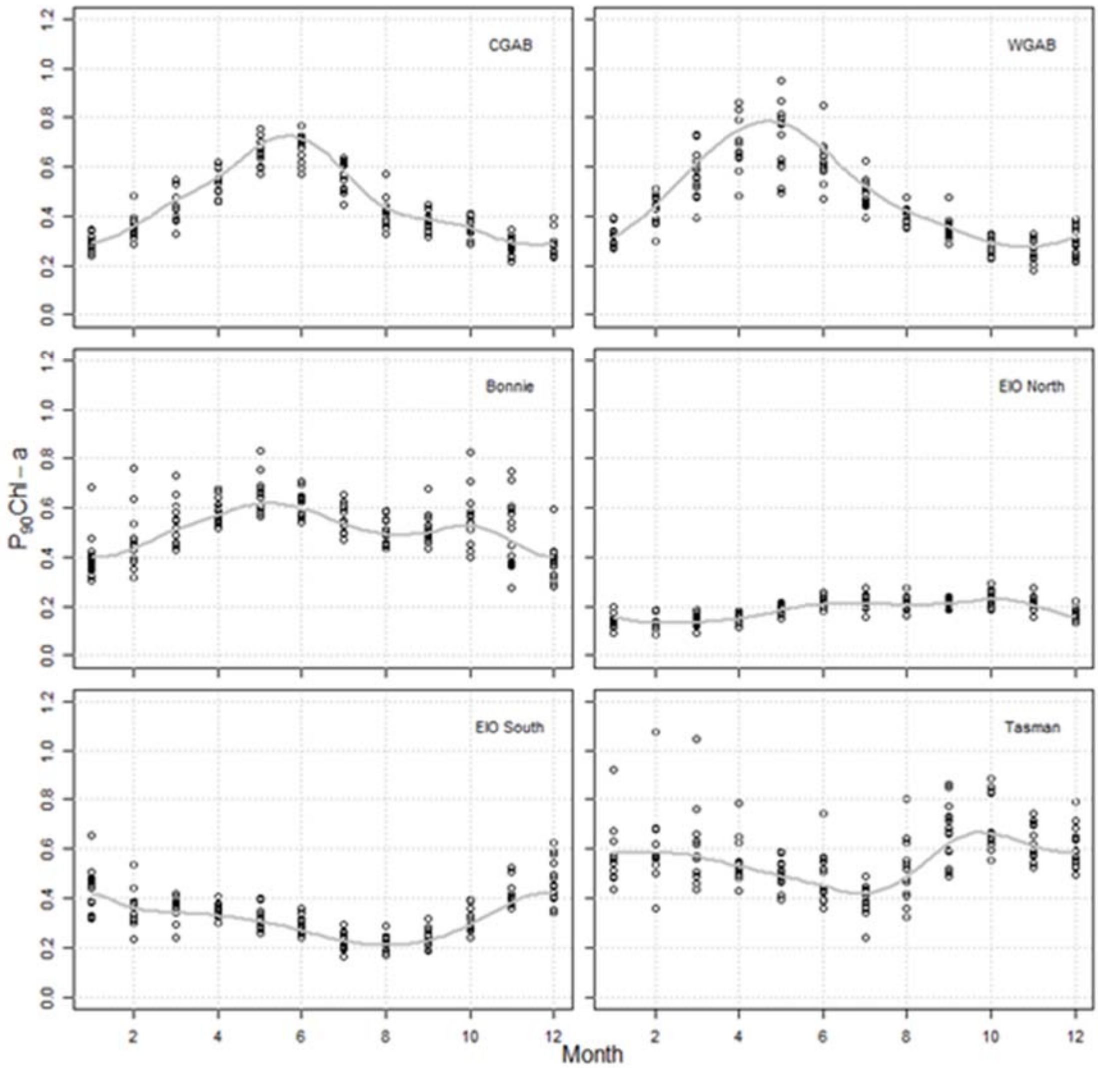


Figure 4.6. Model predictions of the annual cycle of the 90th percentile of surface chlorophyll-a for each of the residency regions.

5. SURFACING BEHAVIOUR OF SBT IN THE GREAT AUSTRALIAN BIGHT

5.1 Background

Whilst in the GAB, juvenile SBT tend to aggregate in large schools that spend substantial periods in the warm surface layers of the water column. The precise reasons for this surface activity are unclear, but it may be a form of behavioural thermoregulation which increases body temperature, with associated increases in digestive throughput (Gunn and Block 2001). This is consistent with juvenile SBT undergoing marked seasonal growth, with growth rates during the summer months being the highest (Eveson et al. 2004, Polacheck et al. 2004)

This surfacing behaviour is essential to both the large-scale commercial purse-seine fishery operating in the GAB that catches surfaces schools of SBT, as well as to the annual scientific aerial survey used for management in which spotters search for surface schools of SBT (see Section 2 for details of the fishery and the aerial survey).

Here, we model the surfacing rates of SBT in the GAB with respect to a number of spatial, temporal, biological and environmental factors, with the aim of investigating the influence these factors have on the surfacing behaviour of juvenile SBT in the GAB and providing a baseline against which future surfacing behaviour of SBT can be compared.

5.2 Methods

For this study, we again made use of the substantial archival tagging dataset described in Section 3. Position estimates were obtained for 100 tags using the "twilight likelihood" method as detailed in section 3.2.4 (Basson et al. 2016). For the purposes of this analysis, where we were primarily interested in surfacing behaviour of juveniles while they were in the GAB, we only included data for which the most probable position estimate fell within an area of 30–40°S, 120–140°E and across the months of January to March. These months encompass the peak period when juveniles are resident in the GAB (see Section 4).

The proportion of time that a fish spent at the surface, defined as 20m or less and abbreviated as P_{surf}, was calculated for each dawn, day, dusk and night time. P_{surf} was modelled using a Generalized Additive Model (GAM) with a beta error distribution, using the gam function in the mgcv library (Wood 2011) for R (R Core Team 2015). In order to investigate how surfacing behaviour varied with time of day, P_{surf} was modelled separately for dawn, day, dusk and night.

Initially, GAMs were used to investigate spatial and temporal patterns in surfacing behaviour by including latitude and longitude as a 2-dimensional smooth term and month as a factor. Next, to better understand the possible drivers behind the spatial and temporal patterns observed, GAMs were fit with a number of biological and environmental variables as covariates (Table 5.1). The correlations between pairs of continuous environmental variables were sufficiently low (Table 5.2) that inclusion of all variables in the models was considered appropriate[4]. All covariates were included as smooth terms, except for integer age, which was included as a factor. In all GAMs, fish ID was included as a random effect to account for the fact that there are multiple observations per fish.

[4] Turbidity was initially considered as a covariate, but it is highly correlated with chlorophyll, so we opted to only include chlorophyll in the models.

Table 5.1. Covariates included in models used to investigate the surfacing behaviour of juvenile southern bluefin tuna in the Great Australian Bight.

Covariate	Measurement	Notation	Source
Non-spatial			
Fish age	Integer years	Age	Estimated from length using growth curve adopted by CCSBT (CCSBT 2011, Eveson 2011)
Fraction of moon illuminated	0-100%	Moon Fraction	Calculated from tag date using standard astronomical algorithms
Tag-derived			
Month	December, January, February	Month	Archival tag clock
Sea surface temperature	Average temperature reading when the fish is in the top 20 m in degrees Celsius (°C)	SST	External temperature sensor
Feeding activity	Difference between internal and external temperature, with visceral warming indicating feeding activity (see Gunn et al. 2001)	Delta_T (ΔT)	Internal temperature sensor, external temperature sensor
Remotely sensed			
Log (Chlorophyll-a)	Milligrams per metre^3 (mg/m)	Log(chla)	SeaWiFS (NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group 2014)
Salinity	Practical salinity unit (psu)	Salinity	CSIRO SpinUp 6.8 (http://wp.csiro.au/bluelink/global/bran/)
Wind speed	Metres per second (m/s)	Wind Speed	NCEP (Kalnay et al. 1996)
Mixed layer depth	Metres (m)	MLD	CARS climatology (Ridgway et al. 2002)

Statistical significance of covariates was assessed using Wald-like chi-squared tests provided by the anova.gam function in R (see documentation in R package mgcv and references therein). Covariates were considered statistically significant at $p < 0.01$.

5.1 Results

Fish spent 2–272 days in the GAB over one or more summers (mean = 72.7 days, SD = 51.0 days). While in the GAB, fish were generally found at an average depth of less than 50 m (90% of all dawn, day, night and dusk time periods), and within an average temperature range of 16–23°C (96% of all time periods; Figure 5.1). Such a shallow average depth could in part be due to the bathymetry of the GAB since coastal waters are less than 50 m deep however, the majority (98%) of the most probable fish location estimates were in waters deeper than 50 m, and 83% were in waters deeper than 100 m.

The proportion of time spent at the surface (in the top 20 m; P_{surf}) varied depending on the time of day, with fish tending to spend a high proportion of most dawn, day and dusk periods at the surface, compared to a dichotomous high or low proportion of most nights at the surface (Figure 5.2). For brevity, GAM results are only reported for the day and night periods.

Table 5.2. Correlation between continuous explanatory variables included in the GAMs.

Explanatory variable	SST	ΔT	MLD	Log(chl a)	Salinity	Wind speed
SST	1	-0.514	-0.056	0.109	0.525	0.022
ΔT		1	0.092	-0.114	-0.326	-0.022
MLD			1	-0.308	-0.356	-0.009
Log(chl a)				1	0.240	0.094
Salinity					1	-0.015
Wind speed						1

Month had a significant influence on P_{surf} during the day only, with P_{surf} tending to decline over the summer months (average fitted P_{surf} values were 62% for January, 57% for February and 48% for March). Latitude and longitude were significant for both day and night, however spatial patterns during the two periods were quite different (Figure 5.3). During the day, P_{surf} tended to be similar in all areas where there were a lot of observations (range: 0.55 - 0.70), except in inshore regions, where P_{surf} tended to be higher. During the night, fish in an area roughly delineated by 32–35°S, 129–133°E tended to have lower P_{surf} values (range: 0.40 - 0.65) compared to other areas, particularly when compared to areas to the southeast (Figure 5.3).

During the day, all covariates used to explore spatial and temporal patterns in P_{surf}, except SST and salinity, were estimated to be statistically significant (Figure 5.4). It should be noted that the model was fit to approximately 2,500 observations (from 100 fish) and as a consequence, the magnitude of the effects can be regarded to be small in practical terms (Figure 5.4). Of the non-spatial variable investigated, age had the largest effect on P_{surf} , with P_{surf} tending to increase as age increased. The environmental variables with the largest effect were log(chl a) and MLD, with P_{surf} increasing as log(chl a) increased and decreasing as MLD increased (Figure 5.4).

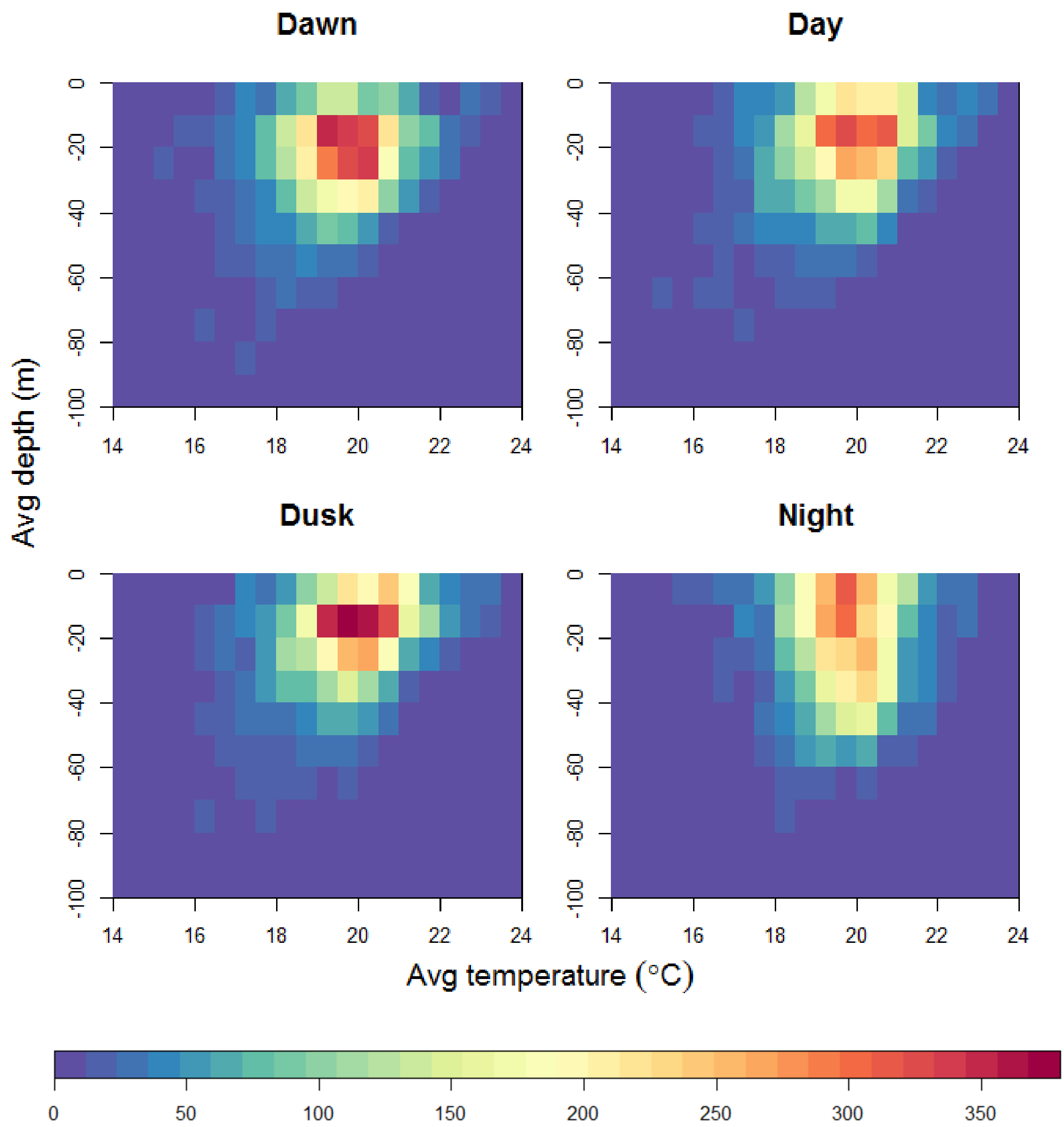


Figure 5.1. Two-dimensional frequency plots of average depth (m) and average external temperature (°C) during each period (dawn, day, dusk, night) for southern bluefin tuna in the Great Australian Bight during January–March. The colour bar indicates the number of observations.

During the night, all covariates used to explore spatial and temporal patterns in P_{surf}, except SST and log(chl a), were estimated to be statistically significant. Similar to P_{surf} during the day, the large number of observations included in the model (n = 2,408) meant that not all variables found to be statistically significant had a large effect on P_{surf}; however, for some variables the effect was large. Most noticeably, P_{surf} increased markedly as feeding activity (ΔT) increased, and decreased as moon fraction and salinity increased. The relationship with age was more complex, with P_{surf} declining between 2 and 4 years; observations from these age groups represented over 90% of the data (Figure 5.5).

The GAM for the night period explained a greater percent of the deviance than the GAM for the day period (49.3% vs. 28.5%), which is congruous with the effect sizes being larger for more covariates in the night model.

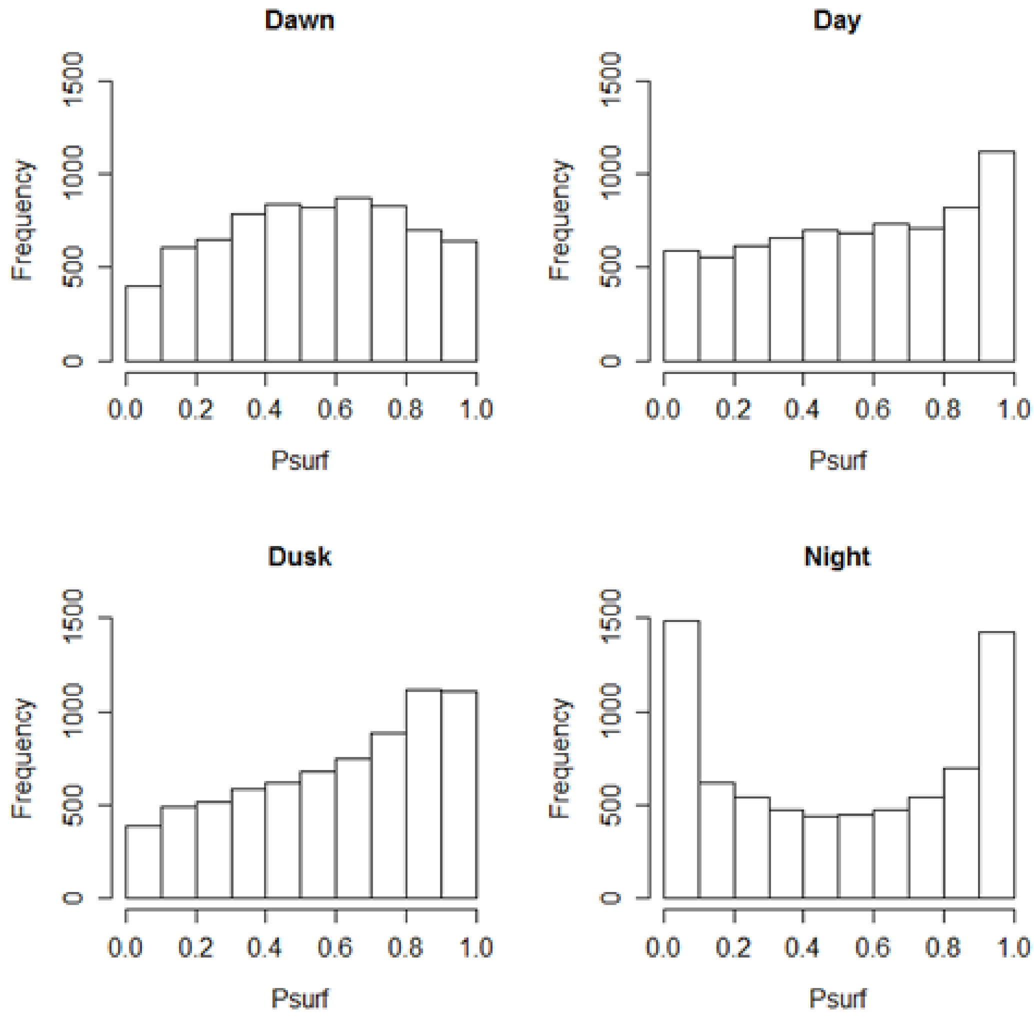


Figure 5.2. The proportion time spent at the surface (P_{surf}) during each period (dawn, day, dusk, night) by juvenile southern bluefin tuna in the Great Australian Bight during January–March.

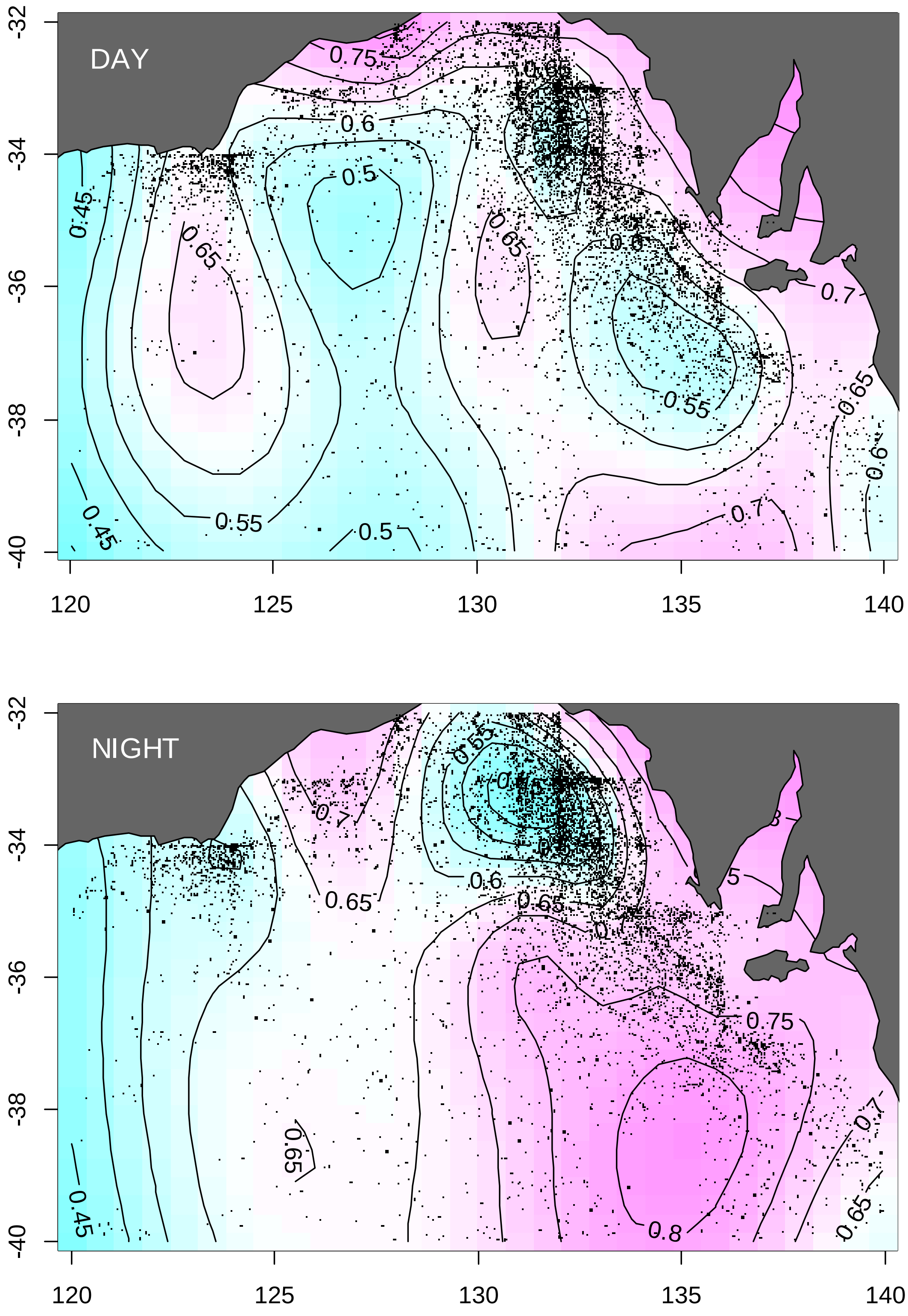


Figure 5.3. Spatial maps showing predicted proportion of time spent at the surface (P_{surf}) during the day (top) and the night (bottom) for the month of January overlaid with position estimates from tagged juvenile southern bluefin tuna (black dots). Blue indicates P_{surf} values < 0.55, white indicates P_{surf} values 0.55-0.70, and purple indicates P_{surf} values > 0.70.

Fish ID had a highly significant effect on P_{surf} during both the day and night, indicating a large degree of individual variability in surfacing behaviour not accounted for by the other covariates in the models. For example, using the day model to predict the average proportion of time each individual fish spends at the surface in a given day when the environmental conditions are fixed at a common set of values (we chose the average value for each covariate), the predictions range from 0.25 to 0.87 (mean=0.54, SD=0.09).

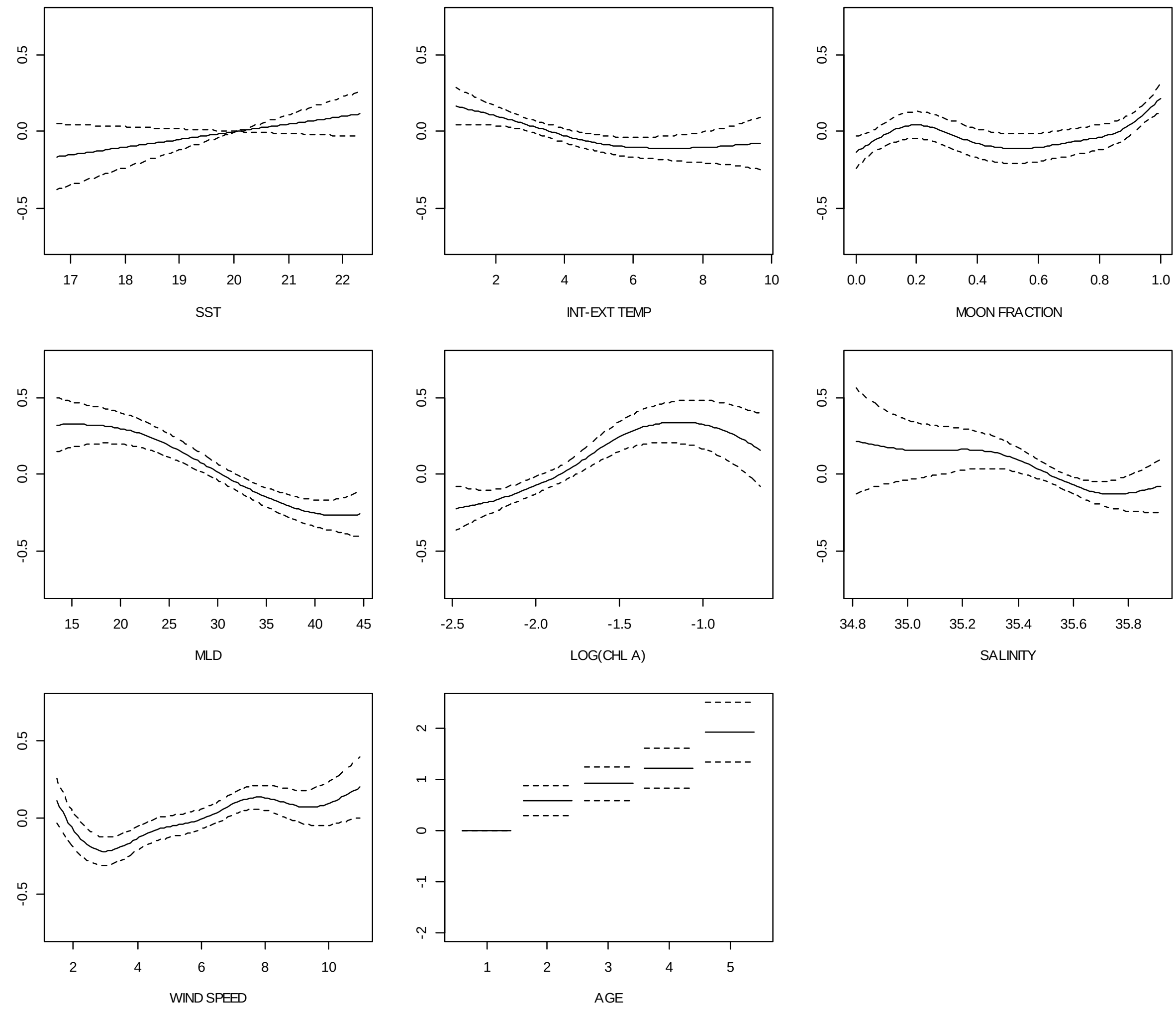


Figure 5.4. Plots of estimated partial effects for all terms included in the GAM for the proportion of time spent at the surface (P_{surf}) during the day for juvenile SBT in the GAB during January–March. The dashed lines indicate ±2 standard errors (note that the y-axis limits are different for age than the smooth terms).

5.1 Discussion

The results of this investigation suggest that a number of variables influence surfacing behaviour—which ones, and the strength and direction of the relationships, can vary depending on whether it is day or night. This made identifying clear relationships between behaviour with environmental

parameters difficult, suggesting that the drivers for the behaviour of juvenile SBT are complex, and likely to be interdependent and co-varying in nature.

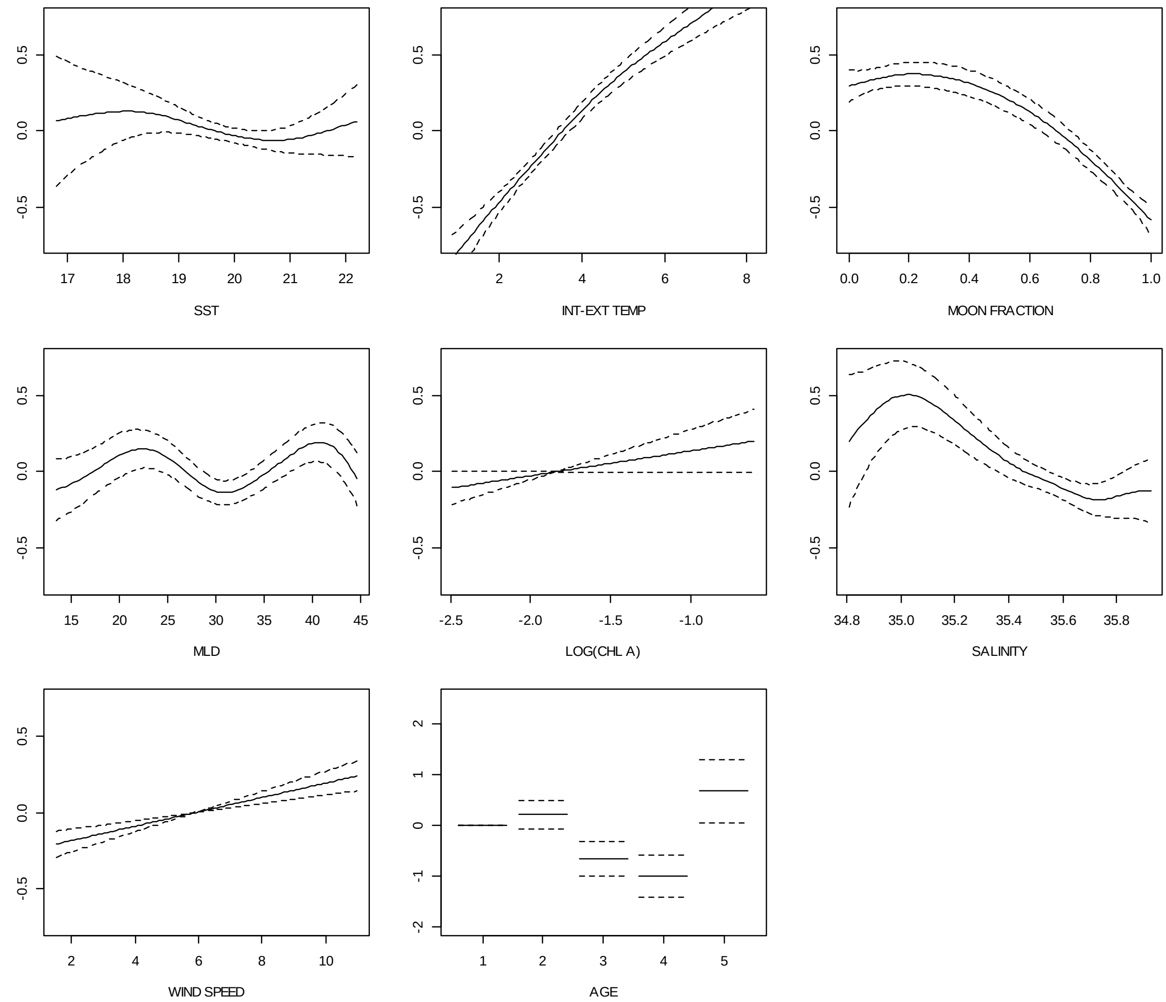


Figure 5.5. Plots of estimated partial effects for all terms included in the GAM for the proportion of time spent at the surface (P_{surf}) during the night for juvenile SBT in the GAB during January–March. The dashed lines indicate ±2 standard errors (note that the y-axis limits are different for age than the smooth terms).

The variables identified as influencing the surfacing behaviour of SBT in the GAB correspond with their movements being associated with diel vertical migration of the deep scattering layer (DSL). Diel patterns in vertical distribution have been observed in previous studies of SBT (Bestley et al. 2009) and other bluefin tunas (Wilson et al. 2005, Kitagawa et al. 2007), as well as in many other tuna (Schaefer and Fuller 2007, Evans et al. 2008, Schaefer et al. 2011) and billfish (Sippel et al. 2011, Evans et al. 2014) species. Within the GAB, the diet of the pelagic species comprising the prey of juvenile southern bluefin tuna has been identified as small fish and planktivores (Goldsworthy et al. 2013), species that regularly comprise the DSL (e.g. Robinson and Goómez-Gutieérrez 1998; Bertrand et al. 2002). Observations of diel vertical migration of Australian sardine larvae have been

recorded from the GAB (Fletcher 1999) and observations of diel migration of the DSL were also recorded by scientific voyages conducted in the GAB as part of the GAB Research Program (see Kloser et al. 2017). Across the area surveyed as part of the GAB Research Program, diel vertical migration of the DSL was more distinct in shelf break regions when compared to inshore regions.

Lunar influences on the depth of the DSL have also been documented elsewhere, with the DSL tending to be deeper during the full moon when compared to the depth of the DSL during the new moon (e.g. Hernández-León 2008; Benoit-Bird et al. 2009). The driver for this variation is likely the result of species within the DSL avoiding predation in more highly illuminated surface waters during the full moon. Within the GAB, as the fraction of the moon illuminated increased, the proportion of time SBT spent near the surface at night decreased. This is consistent with SBT tracking their prey as the depth of the DSL becomes deeper when the moon is brighter, and/or being able to see their prey at greater depths when moon illumination is greater (Prihartato et al. 2016).

A strong, positive relationship was observed between the proportion time spent at the surface during the night and the measure of feeding activity (ΔT). Further investigation of this finding revealed that this was driven by external temperature remaining almost constant, at an average value of ~19.6°C, regardless of the proportion of the night spent at the surface. This suggests that, when fish spent less time at the surface, they were in locations where temperature remained very warm below 20 m. These locations correspond to the areas identified in the spatial-temporal GAM for the night period as having below average surfacing rates (i.e. blue areas in the bottom panel of Figure 5.3).

Age was a significant factor in the surfacing behaviour of SBT during the day, with the proportion of time spent at the surface increasing with age. The reason for this is unknown and would be interesting to pursue, particularly given the opposite would be expected if SBT develop an increased capacity to maintain internal temperatures and buffer cooler conditions with age, as has been reported for Pacific bluefin tuna (*Thunnus thynnus orientalis*; Kitagawa et al. 2001). These findings suggest that a broad number of potential environmental and physiological factors (e.g. competition, predation, prey resources, metabolic needs) need to be considered when exploring drivers for behaviour.

Fish spent less time at the surface during the day as summer progressed from January through March, corresponding to a deepening of the MLD over these months. This is consistent with fish seeking warm surface waters during the day, and being able to find such waters below the surface layer when the MLD is deeper. In terms of other oceanographic covariates investigated, time spent at surface had the strongest (positive) relationship with chlorophyll during the day, and with salinity (negative) during the night. The reasons for these relationships are unknown, and likely involve complex interactions between the covariates themselves as well as other variables not considered, such as prey density. Prey density is almost certainly a significant driver in both the horizontal and vertical distribution of SBT in the GAB (also indicated by the diel and lunar variability in surfacing behaviour), but unfortunately prey data across the spatial and temporal range of this study are not available for inclusion in the models (see also Section 9).

6. FEEDING BEHAVIOUR OF SBT IN THE GREAT AUSTRALIAN BIGHT

6.1 Background

For several decades, it has been known that bluefin tunas release substantial amounts of heat during digestion (Carey et al. 1984, Stevens and McLeese 1984). In association, these tunas have extensive adaptations to their thermal physiology and anatomy that allows them to capture this heat, providing these species with endothermic capacity (Carey and Gibson 1983). Generally, it is thought that the endothermic capacity of bluefin tunas confers a range of advantages such as increased swim speeds (Watanabe et al. 2015) and expanded niche width (Madigan et al. 2015). This visceral warming is likely to increase digestive throughput, allowing for high rates of assimilation of food and associated growth (Stevens and McLeese 1984).

Electronic tags have allowed the first direct observations of heat production in fishes, including juvenile SBT (Gunn et al. 2001; Bestley et al. 2008). These studies have used manual visual classification of visceral temperature data to extract a binary response variable -- feeding or not feeding. Modern electronic tags however sample at high frequency and it is not feasible (or desirable) for analysis of thermal sensor data to be done manually. Relying on a manual visual assessment of feeding also introduces the possibility of subjective classification that has the potential to introduce unknown biases into classification. For these reasons, an algorithmic or statistical solution to identifying feeding events is desirable.

Here we use a Hidden Markov Model (HMM) to statistically classify feeding events from times series of visceral temperature from free-swimming SBT. It should be noted that this first approach to statically classifying feeding does not aim to develop a physiologically realistic model of heating and cooling (e.g. Malte et al. 2007), but rather develop an algorithm for detecting whether feeding has occurred or not.

6.2 Methods

6.2.1 Modelling feeding events

The temperature of the peritoneal cavity of juvenile southern bluefin tuna, as measured by an archival tag undergoes a largely predictable pattern of change in association with ingestion of prey (see Gunn and Block 2001; Bestley et al. 2009). The internal, or visceral, temperature typically starts at what might be a basal level (i.e. a minimal and roughly constant, differential between the ambient water temperature and the visceral temperature). After consumption of food, this temperature begins to increase, initially quite rapidly, before tailing off and slowly decreasing (Figure 6.1). This process of heating and cooling is such that it is not possible for the tuna to go from the basal state to cooling without heating in between. Similarly, it is not possible for the phases to transit from heating to basal without intermediate cooling.

While it is easy to identify feeding activity by eye, many feeding events are not always clearly able to be distinguished, particularly when several feeding events occur close to each other. When this occurs, the distinct heating and cooling associated with an individual event becomes confused with the heating and cooling of the other feeding events. Further, the data sets derived from archival tags are typically very large, hence identifying individual feeding events quickly becomes an infeasible and labour intensive task. Multi-individual, temporal assessments of feeding activity therefore requires an ability to be able to employ an objective automatic classification technique that reflects

the inherent uncertainty in the categorisation of feeding activity and makes use of any extra information on the temporal sequence of patterns in the data.

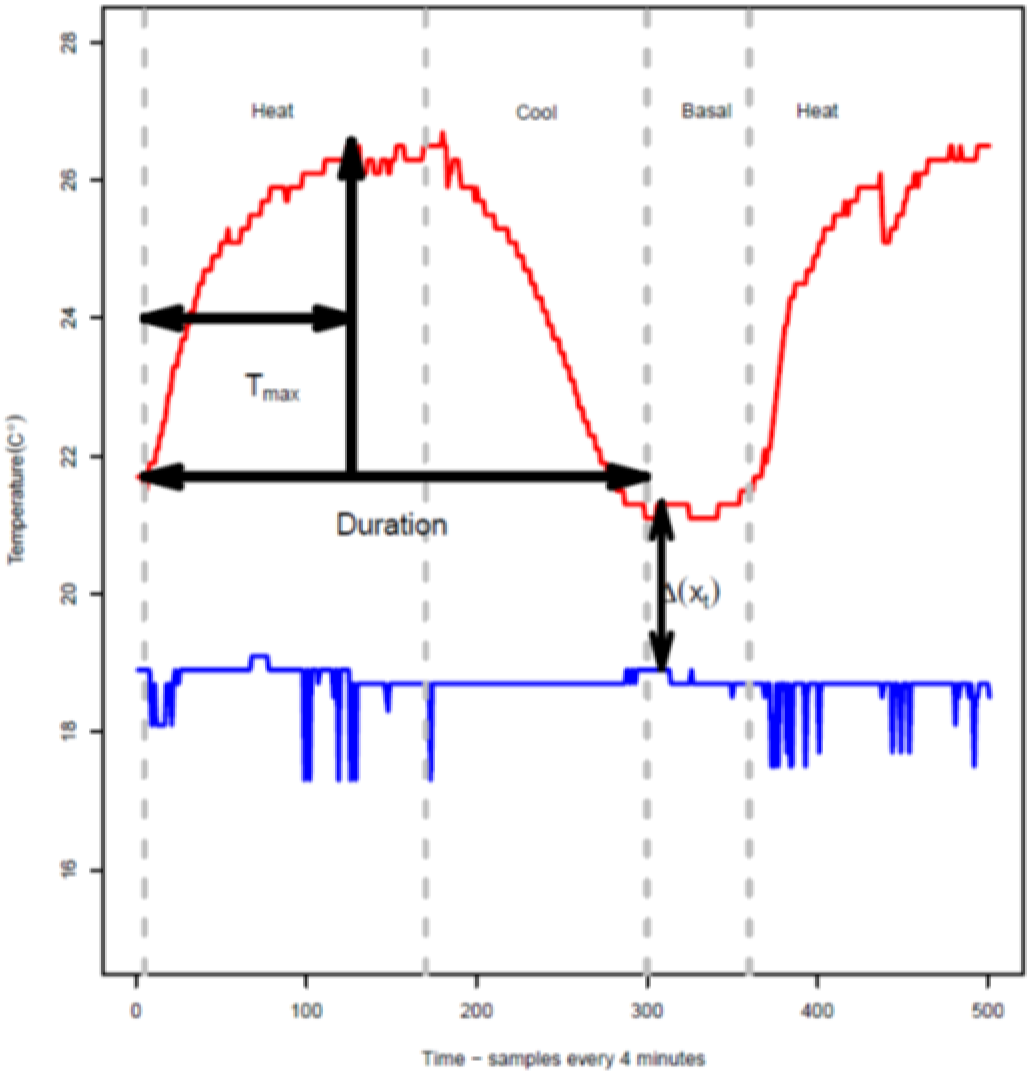


Figure 6.1. The sequence of heating and cooling associated with a feeding event as recorded by an archival tag (internal temperature record in red) deployed in a juvenile southern bluefin tuna with associated ambient water temperature (in blue).

Hidden Markov models can provide exactly this by calculating a probability of the latent state (i.e. the categorisation of feeding) and, importantly, do so in a time dependent and statistically rigorous manner. This means the prediction of the probability of the current state is a function of the data and the estimate of the previous state. Additionally, it is likely that ambient water temperature, vertical movements and other aspects of behaviour can influence the pattern of feeding reflected in the internal temperature record. It is, therefore, useful to use these extra data in the prediction of the current state.

Given the physical properties of digestion, certain aspects of the process are predictable in terms of the observed temperature. Based on records of internal temperature we can assume that the model is cyclic with three latent states: (1) Basal, (2) Heating, and (3) Cooling. If there is no further feeding, there will always be a return to a basal level. These properties were used to build an autoregressive HMM. The model uses the difference between internal temperature and ambient water temperature as recorded by an archival tag as input data to define a transition matrix between the three latent states. The Viterbi algorithm (Viterbi 1998; Zucchini and MacDonald 2009) was then applied to find the most likely state at any given point in the temperature record.

6.2.2 Estimating food intake

Gunn et al. (2001) conducted experimental trials to determine how food intake amount related to patterns in visceral heating in juvenile SBT and found strong relationships between feeding events as recorded by internal temperature records and the amount of food ingested by individual SBT. In order to investigate potential patterns in feeding in juvenile SBT, the data used in Gunn et al. (2001) are re-examined to then build a model to predict feeding intake from signals of feeding events in wild fish.

Two key signals were identified by Gunn et al. (2001) that appeared robust to seasonal signals in background ambient water temperatures: (1) T_{max} - the elapsed time (minutes) from the initiation of visceral warming to the maximum visceral temperature over the digestion event and (2) $Duration$ - the time of the digestion event (Figure 6.1).

Shape constrained additive models (SCAM, Pya and Wood 2015) were used to predict intake from feeding events as identified by the HMM. The 'shape constrained' component of these models constrain the model predictions of the shape of the curve so that they are monotonically increasing, but that they also reach an asymptote. This has the benefit of more effectively estimating a maximum intake amount. However, if the experimental data used to fit the model do not encompass the maximum intake, then the model will be biased toward underestimates of true ingestion rates. A threshold of T_{max} =58 minutes was applied to remove instances where the HMM had clearly failed to make reasonable inferences of feeding events. This is a very relaxed threshold, in the sense that it is likely to admit larger feeds rather than remove them. Further uncertainty may also be introduced into the estimates of feed intake because it is difficult to specify a zero-intercept with SCAMs. Because of this, apparent feeding events of $Duration$ less than 100 minutes are probably unreliable. Given the other uncertainties associated with estimating feeding amount (see also below), we assume this to be reasonable until further empirical studies of ingestion by SBT are conducted.

Additionally, it should be noted that the feeding behaviour of wild fish will generally be highly variable compared to the experimental results upon which these estimates used in these analyses depend. Variability in the frequency of feeding, prey type and calorific variability in prey will undoubtedly alter the characteristics of the heating signal. The analyses presented here should be regarded as a first step in identifying consistent patterns in predicted prey intake from wild tuna and a preliminary investigation of feeding behaviour of juvenile SBT in the GAB.

6.2.3 Data

Models were initially built using temperature records from a juvenile SBT spanning February to December 2002. They were then applied to records from 15 archival tags deployed on juvenile SBT 1998–2009.

To estimate the spatial distribution of feeding events, the time series of feeding events were linearly interpolated onto the estimated tracks of juvenile SBT (derived as per Section 4). Relationships between feeding events and ambient temperature and depth were explored using ambient temperature and depth records from each tag.

6.3 Results

The HMM classification scheme resulted in reliable estimates of the three cooling states and replication of the sequence of warming, cooling and basal temperatures (Figure 6.2). When applied to archival tag records, a total of 17,022 feeding events were extracted by the HMM. Feeding events predominately occurred during dawn periods (results not shown) and the average rate of feeding across the entire period was 2.2 (SD: 0.7) feeding events per day. Feeding rates were highest in March and April (Figure 6.3).

Application of SCAMs to the data from Gunn et al. (2001) showed clear, systematic, correlation between the T_{max} and $Duration$ of feeding events. Model results suggest data appear most informative in the mid ranges of both these variables, with uncertainty increasing around both very small ingestion events and very large ingestion events (see also below and notes on use of SCAMs in Section 6.2.2).

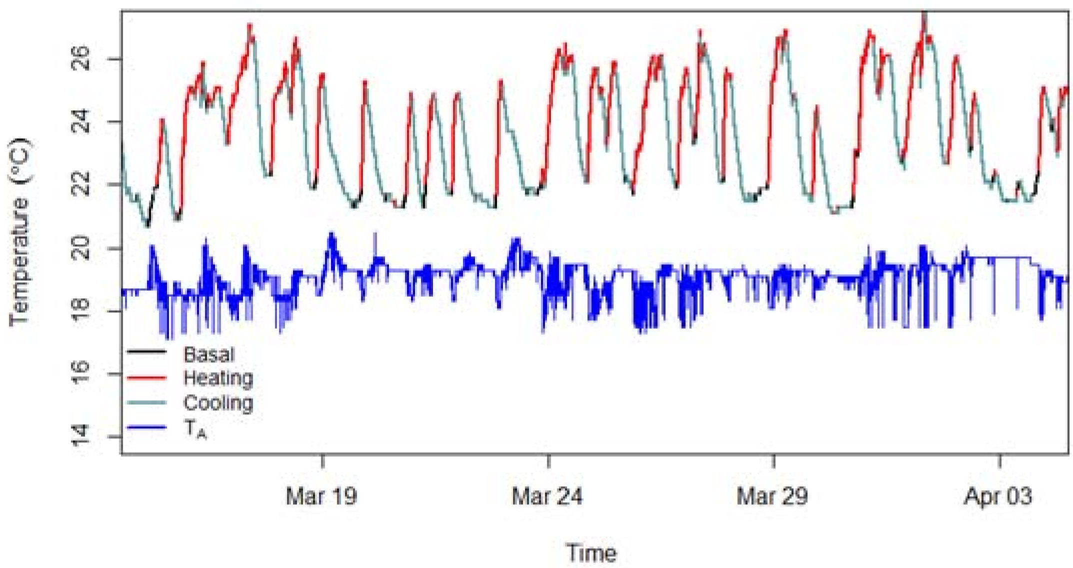


Figure 6.2. Predicted state of internal temperature of a juvenile southern bluefin tuna from the hidden Markov model.

Using T_{max} as a predictor of food intake, the model estimated a maximum food intake of 1,515 g and an average food intake of 325 g (SD: 341 g) across all SBT included in the model (Figure 6.3). For the model using $Duration$ as a predictor of food intake, the estimated maximum intake was 1,661 g.

Feeding events occurred most frequently when SBT were in the GAB, in particular in eastern areas of the GAB to the east of Kangaroo Island and offshore of the Bonney coast. A higher frequency of feeding events also occurred in the Indian Ocean, within an area of approximately 80–100° E (Figure 6.4). The HMM and SCAM predicted relatively fewer feeding events during periods of directed migration.

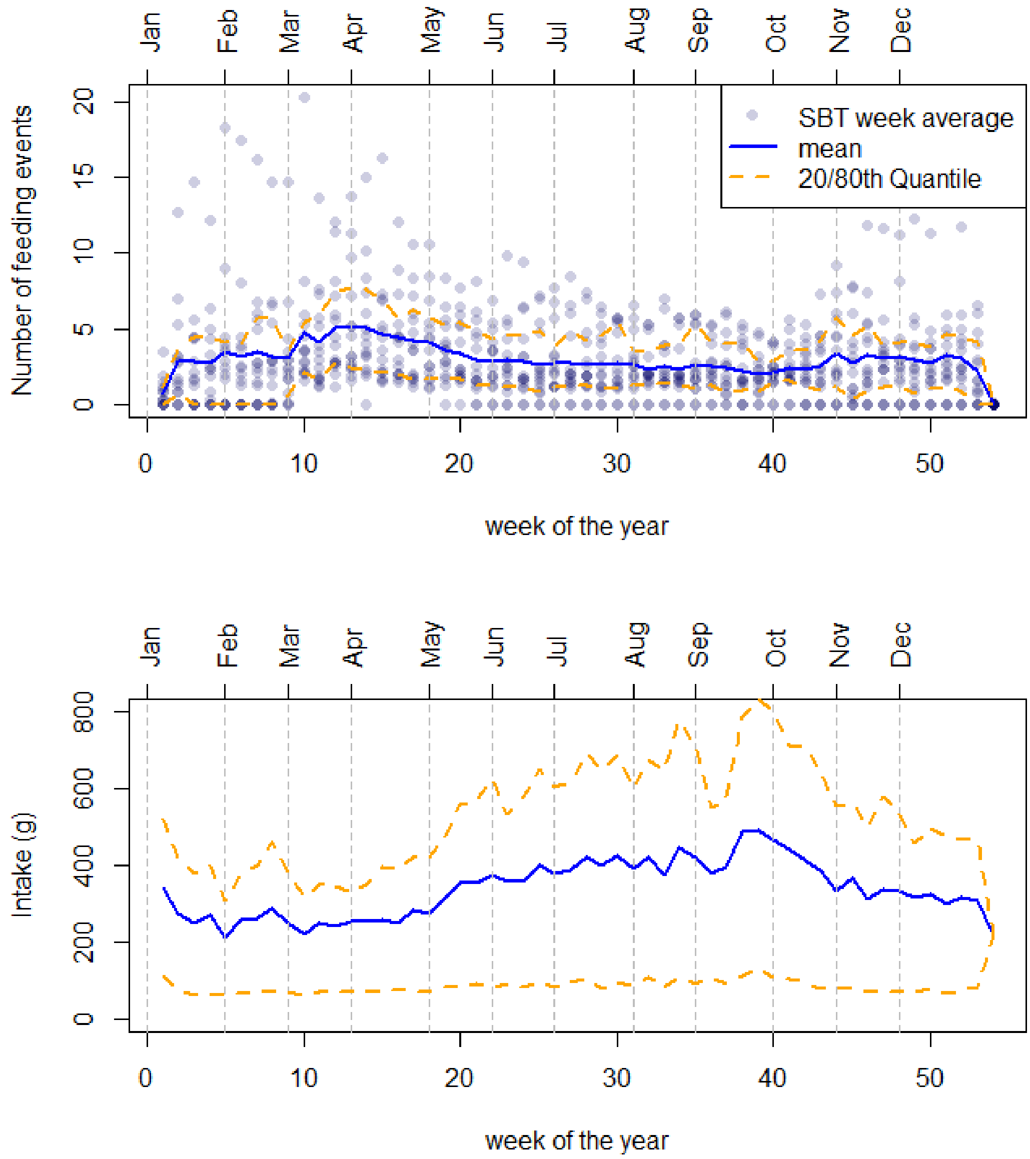


Figure 6.3. Number of feeding events by week of the year estimated by a hidden Markov model (top) and weekly average individual food intake (in gm) as estimated by a shape constrained additive model (bottom) for juvenile southern bluefin tuna (n=15) tagged with archival tags 1998–2009. The overall mean value is in blue and 20% and 80% quantiles in orange.

Food intake tended to be higher in areas outside of the GAB when compared to food intake within the GAB, with overall average intake 297 g (SD: 312 g) in comparison to 376 g (SD: 384 g) outside the GAB (Figure 6.5). Within the GAB, food intake was generally larger in the winter months when compared with other months.

When associated with ambient water temperature, feeding activity within the GAB occurred in warmer waters (mean water temperature at the beginning of feeding events: 18.3°C, SD: 2.2°C) than outside the GAB (Figure 6.6; mean: 14.4°C, SD: 2.6°C). Food intake tended to be higher in cooler waters both within and outside the GAB.

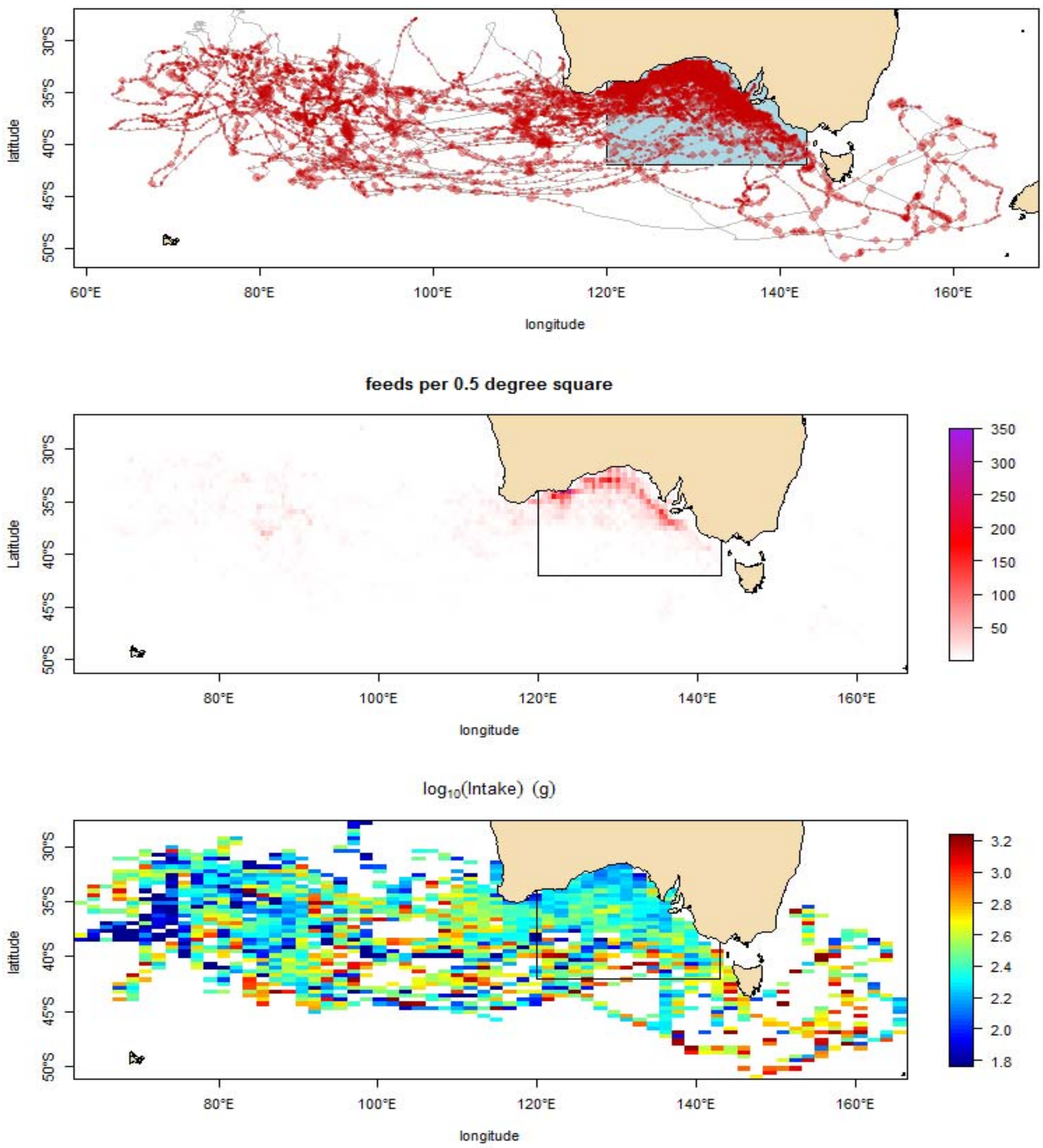


Figure 6.4. Feeding events and intake amounts interpolated onto the estimated tracks of juvenile southern bluefin tuna (n = 15; top). The size of the circle is proportional to the food intake amount. The number of feeding events per 0.5 x 0.5 degree grid square (middle). Food intake interpolated onto a grid and plotted on a base-10 log-scale to identify regions of high food intake (bottom). Values that fall on the same grid square are averaged.

The depth at which feeding events occurred was skewed toward shallower depths within the GAB region (mean: 33.2 m, SD: 51.0 m), although feeding events occurred predominantly at shallower depths also outside the GAB (mean: 62.8 m, SD: 86.1 m). Crepuscular feeding activity, especially at dawn was a marked feature of the timing of feeding events. Both within the GAB and outside the GAB feeding events were more frequent around dawn (at approximately 05:00 local time) and at dusk (at approximately 18:00 local time). In general, feeding was predicted to be less frequent during the night than at other times (Figure 6.6).

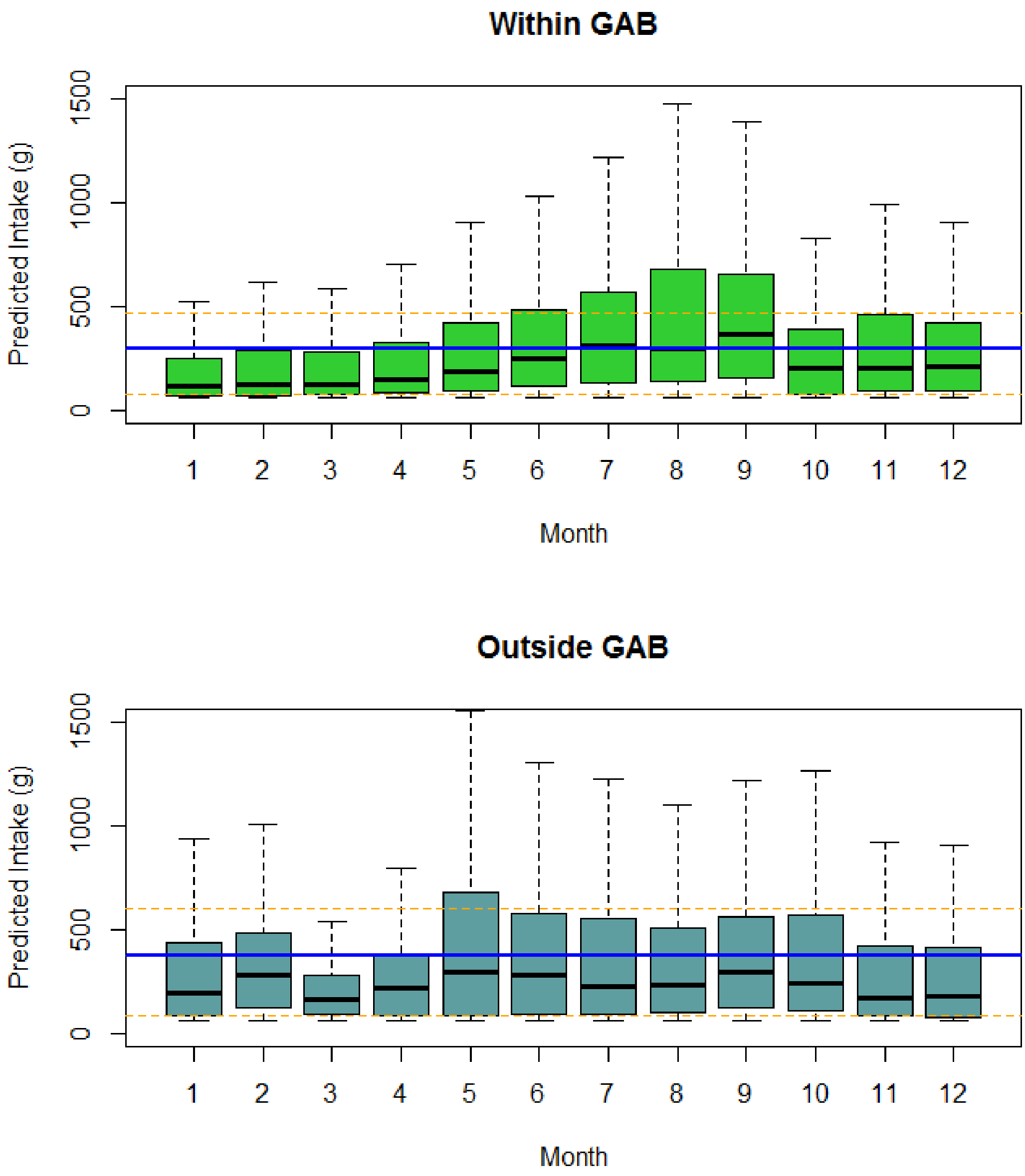


Figure 6.5. Estimated food intake per month within the GAB (top) and outside the GAB (bottom) for juvenile southern bluefin tuna tagged with archival tags 1998-2009.

6.1 Discussion

This study has detailed a new approach to estimating feeding rates in SBT in the wild. In summary the results indicate that SBT feed more frequently but, on average, with reduced intakes when in the GAB. Conversely, outside of the GAB, SBT feeds were larger and less frequent. These results are subject to several sources of variability. As would be expected, foraging in a pelagic system is a highly stochastic and complex process depending on the efficiency of the predator (SBT) and the variation in prey. Additionally, there is likely to be un-modelled error in the estimates of feed intake which stem from misclassification in the feed extraction algorithms and also from the limited data set of empirical data from captive SBT used to predict intake amounts. At a broad spatio-temporal scale however, we expect these results to reflect relative changes in food intake of individuals and overall, that the results capture the intensity and magnitude of feeding activity

The estimates of feeding activity in this study found that feeding was strongly associated with crepuscular periods which were also reflected in surfacing behaviour (see Section 5). Diel patterns in vertical distribution have been observed in juvenile SBT in an earlier analysis of some of archival data used in this study (Bestley et al. 2009), in other bluefin tunas (Wilson et al. 2005, Kitagawa et al. 2007), as well as in many other tuna (Schaefer and Fuller 2007, Evans et al. 2008, Schaefer et al. 2011) and billfish species (Sippel et al. 2011, Evans et al. 2014). This pattern in behaviour is likely associated with the diel vertical migration of their prey and their relationship to the deep scattering layer (DSL; Hays 2003), which has been suggested widely (e.g. Dagorn et al. 2000; Marcinek et al. 2001). Further, diel vertical migration of sardines and jack mackerel, both known prey species of juvenile SBT (see Ward et al. 2006; Itoh et al. 2011), in response to the diel vertical migration of their prey has been reported from a number of regions (e.g. Giannoulaki et al. 1999; Bertrand et al. 2006).

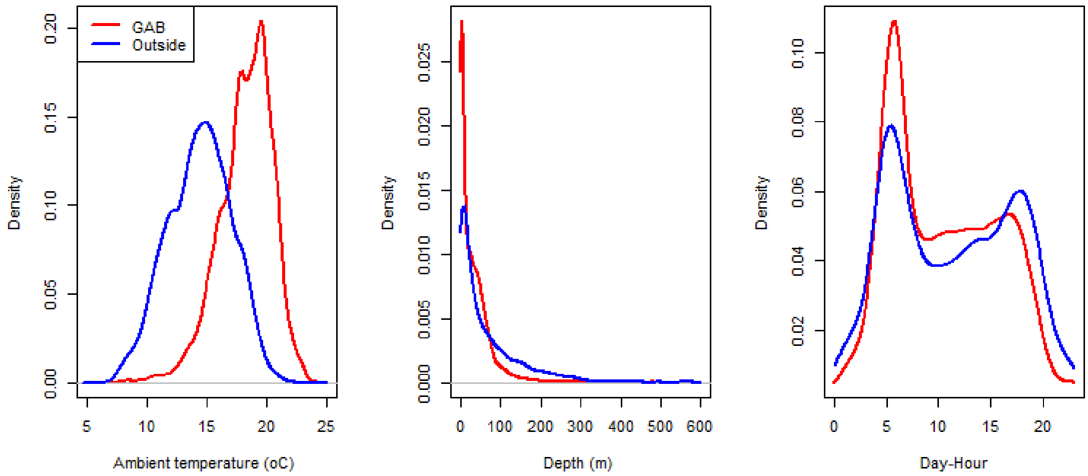


Figure 6.6. Relationship between the occurrence of feeding events and ambient water temperature (left), depth (middle) and time of day (right) in juvenile southern bluefin tuna within the Great Australian Bight (red line) and outside the Great Australian Bight (blue line).

The predominance of feeding events during dawn and dusk, suggests that SBT are best able to access the DSL during these periods. This could be that predation is favoured when prey as sufficiently accessible (i.e. shallow) and visible (given ambient light) to target and within water which is warm enough for juvenile SBT to remain within their physiologically preferred niche. The models used to investigate feeding behaviour suggest a feeding strategy whereby foraging of juvenile SBT in the GAB is characterised by smaller, frequent feeding events compared to activity on the winter foraging grounds in the Indian Ocean where feeding was more sporadic, but consisting of larger prey/feeding events. The temperatures associated with feeding events in the two regions are consistent with juvenile SBT moving into cooler offshore waters over the winter period.

If this result is general, it may be due to several related factors. One hypothesis consistent with these patterns is that prey resources in the GAB may be more predictable and numerous and, therefore, a "little and often" feeding strategy. Distant oceanic waters may have more patchily distributed and unpredictable food resources, but with the possibility of higher energy intake (i.e. larger/higher calorific prey items) within single feeding events. It seems reasonable that there must be a sufficient energetic return in oceanic waters to justify, in an evolutionary fitness sense, the large-scale migrations in terms of net-energetic benefit and therefore growth, reduced mortality and, ultimately, increased likelihood of maturity and reproductive success. To evaluate this hypothesis would require estimating an energy budget that accounts for allocation of consumption into physiological and metabolic processes such as growth, locomotion, digestion and excretion. In order to determine why SBT migrate when and where they do, such a model would also need to incorporate the relative availability and energetic value of prey resources across the juvenile range (i.e. in different regions of the SBT distribution) and throughout the year. While such a model would be challenging to parameterize, it would provide the benefit of being able to predict the likely impact on growth if SBT deviating from the migration and foraging patterns described here.

7. SEASONAL DISTRIBUTION AND HABITAT USE OF SOUTHERN BLUEFIN TUNA IN THE GREAT AUSTRALIAN BIGHT

7.1 Background

The factors that influence the distribution of juvenile SBT within the GAB region are not well understood, with seasonal movements over the summer-autumn period of residency in the GAB to date only described anecdotally, through inferences derived from commercial fishing activities (Basson and Farley 2014) and via scientific aerial surveys (Eveson and Farley 2016). These inferences suggest that smaller, younger juvenile SBT (1-2 year) appear to be more associated with inshore regions in Western Australia (Fujioka et al. 2010), while older age classes (2-4 year) appear tend to be more abundant close to the shelf break in central regions of the GAB (Basson and Farley 2014; Eveson and Farley 2016).

Here, we use data from a multi-year archival tagging data detailing the movements and residency of juvenile SBT to construct statistical models of spatial usage within the summer residence areas of the GAB and then relate the distribution of juvenile SBT to a range of spatio-temporal and environmental covariates. The quantitative understanding the general patterns of the distribution of juvenile SBT in the GAB provided by this analysis provides for a valuable baseline against which any future changes to the spatial dynamics of juvenile SBT in the GAB may be assessed.

7.2 Methods

Position estimates were obtained for 125 tags using the "twilight likelihood" method as detailed in section 3.2.4 (Basson et al. 2016). Position estimates calculated for the period 1998–2011 were then aggregated into counts within 0.5 × 0.5 degree squares by month within an area bounded by longitudes 120-143°E and by a latitudinal boundary at 42°S. This area was considered for the purposes of the analyses detailed here as the area of the GAB (Figure 7.1). Data were aggregated across the total number of years because of their uneven distribution across individual years (Figure 7.1).

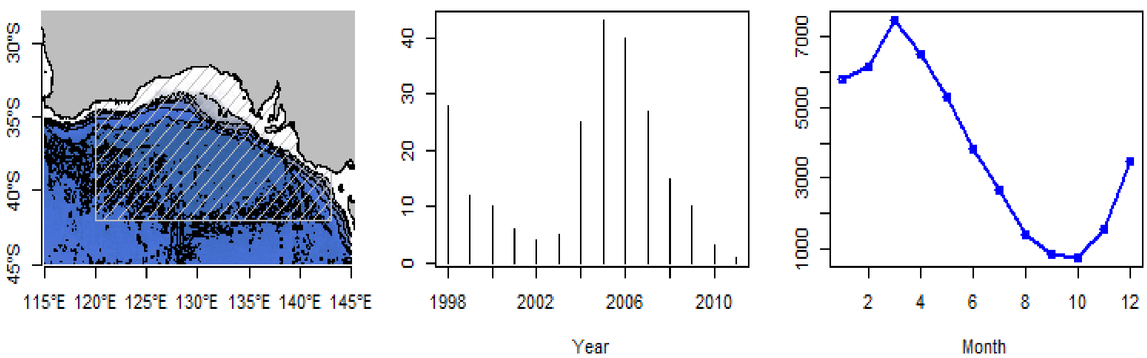


Figure 7.1. Area of the GAB (left); number of tags per year (middle) and sum of position estimates aggregated by year 1998-2011 (right) included in analyses.

Spatial models of the distribution (time spent) by juvenile SBT based on the counts of positions in each 0.5 x 0.5 degree grid cell and co-variates associated with depth, distance to the continental shelf, distance to the shore, sea surface temperature (SST) and mixed layer depth (MLD; Table 7.1) were developed using generalized additive models (GAMs; Wood 2006). Tweedie distributed error terms were incorporated to address over-dispersion due to the high proportion of cells with zero counts (Tweedie 1957; Miller et al. 2013; Virgili et al. 2017). Calendar month was included as a factor variable, either as a separate cyclical/periodic smooth term (Polansky and Robbins 2013), or as an interaction term by fitting a separate smooth on the longitude of each grid square for each month.

Table 7.1. Covariates included in models used to investigate the habitat use of juvenile southern bluefin tuna in the Great Australian Bight.

Covariate	Measurement	Source
Depth (D)	Depth to seafloor in metres (m)	NOAA ETOPO1 bathymetry via the R package 'marmap' (Pante and Simon-Bouhet 2013)
Distance to continental shelf break (DSB)	Distance to the 200 m isobaths in metres (m)	Calculated from NOAA ETOPO1 bathymetry (Amante and Eakins 2009)
Distance to shore (DS)	Distance to the shoreline in metres (m)	Calculated from NOAA ETOPO1 bathymetry (Amante and Eakins 2009).
Sea surface temperature (SST)	Average monthly in degrees Celsius (°C)	CARS climatology (Ridgway et al. 2002)
Mixed layer depth (MLD)	Average monthly in metres (m)	CARS climatology (Ridgway et al. 2002)

Models were constructed to test different scenarios or hypotheses regarding the factors potentially influencing SBT distribution, given the available covariates. A variety of GAMs were constructed and compared using model-fit diagnostics, assessment of fit (based on Akiake's Information Criterion – AIC) and also the amount of residual deviance explained. Models were also assessed for their ability to reproduce the broad-scale features of residence in the GAB, such as the general absence of SBT during the winter, peak residency in the summer months and the observed shifts in spatial distribution within the GAB over the summer-autumn residence period.

7.1 Results

The number of position estimates derived from recaptured tags was highest in 1998 and the mid-2000s, with seasonal distributions of numbers highest across the austral summer months (December–February; Figure 7.1).

During the summer months, juvenile SBT were concentrated in inshore shelf waters or around the shelf break (Figure 7.2). During March through to May, the distribution of individuals shifted to areas in the eastern side of the GAB with northern, more coastal shelf waters of the GAB less frequented.

During the winter months (June–August), those few SBT remaining in the GAB were concentrated around the shelf break and remained largely absent from the inshore regions of the shelf through September and October. As juvenile SBT returned to the GAB through November, fish started to frequent inshore areas of the GAB again.

Candidate models explained 33–67% of the total deviance in the data (Table 7.2). The preferred model included spatial and temporal terms (longitude, month, and distance-to-200m) and a joint smooth including SST and MLD. The spatiotemporal model (which included longitude, latitude, distance-to-200m contour and month) was the second most highly ranked model with the third also including SST and MLD but only longitude. Conversely, models the included only ocean variables (SST, MLD) performed the worst and were incapable of adequately describing changes in the distribution of juvenile SBT within the GAB . Exploration of the candidate models indicated that the month term was required for reasonable fit and predictive performance (Figure 7.3).

The model that explained the highest proportion of the variation in the data (the selected model) predicted a seasonal distribution that mostly declined with increasing distance from the shelf (there was a slight increase at the extreme), was highest at longitudes of approximately 132°E in January and shifted eastwards to 135°E though to May and increased with warmer SST and deeper MLD (Figure 7.4).

When the distribution prediction of the two models ranked the highest were compared, the spatiotemporal model predicted that juvenile SBT were distributed to a higher degree inshore than the preferred model. These differences suggest the occurrence of edge-effects, where the smooth terms of the GAM are spuriously high where there is relatively little data to allow the model to fit the area of the greatest mass of data better. Both models however, captured the tendency for increasing use of the eastern side of the GAB in the later summer months, with this tendency more pronounced in the selected model.

7.1 Discussion

From the population of tagged SBT in this study, it was clear that the central GAB around the shelf break was a region of high importance. The tendency for the distribution of SBT to shift toward the eastern sides of the GAB into late summer highlighted seasonal shifts in habitats of importance.

A purely spatial model which included position, month and distance to the shelf (given sufficient model flexibility) was able to predict the broad features of the seasonal SBT distribution within-GAB. Inclusion of the oceanographic variables (MLD and SST) improved the fit, demonstrating that juvenile SBT were responding to a number of environmental features. As also identified in Section 5, the deepening of the MLD across the summer months is likely to have expanded the thermal habitat available to juvenile SBT.

It should be noted that at least some of the covariates included in the models are proxies for the direct factors influencing SBT movement and distribution within the GAB. The distribution of SBT within the GAB is likely to be a response to thermal preferences but also the movements, or availability, of prey, who themselves are also responding to their environment (see also Sections 5 and 6).

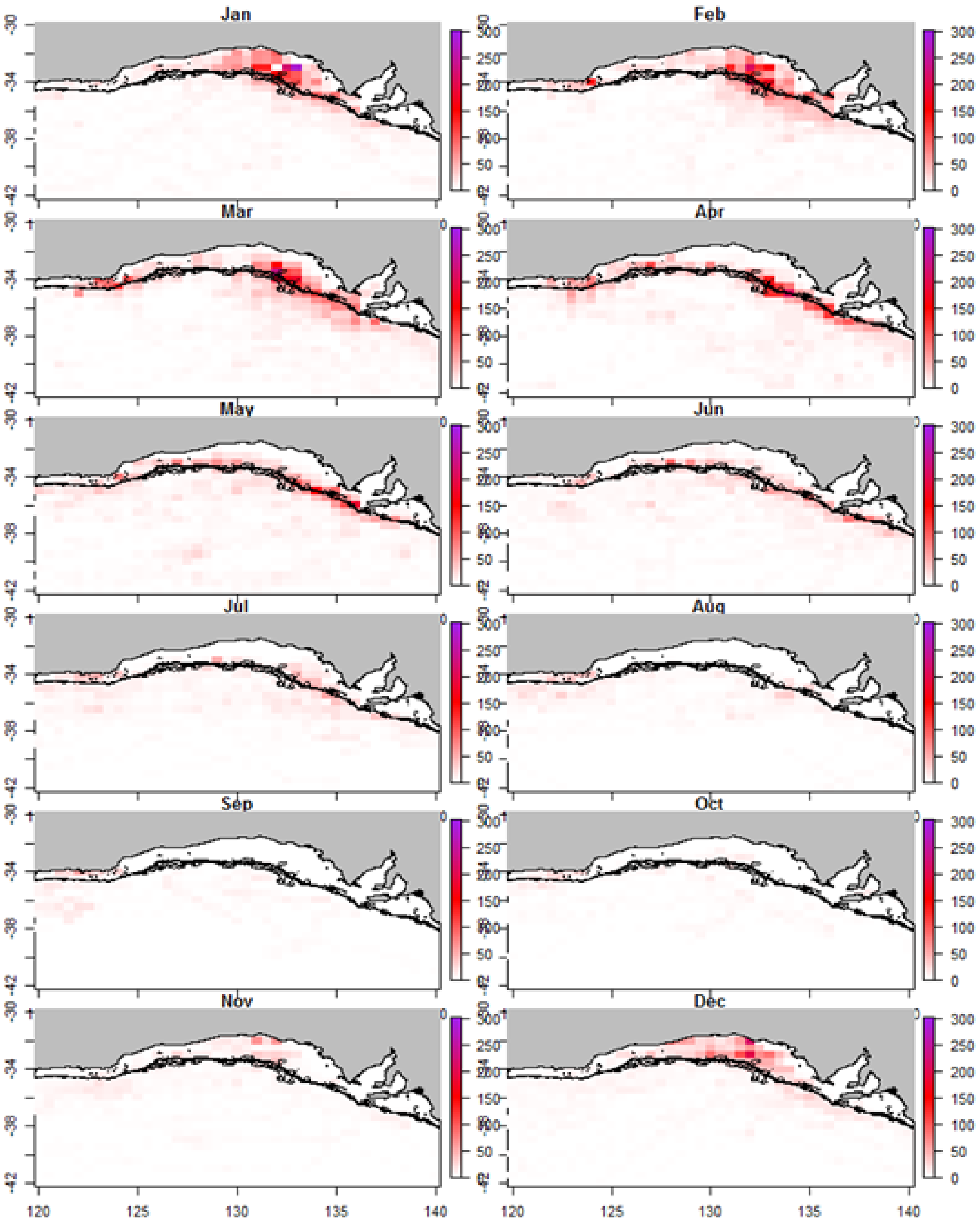


Figure 7.2. Monthly aggregated counts of position estimates derived from juvenile southern bluefin tuna tagged with archival tags 1998–2011. Bathymetric contour lines associated with the shelf break are included as black lines.

Table 7.2. Candidate GAMs constructed for exploring factors potentially influencing juvenile southern bluefin tuna distribution in the Great Australian Bight. Terms denoted by 's()' are non-parametric smoothed terms, those denoted by 'bs=cc' a cyclic/periodic smoothing function. Akiake's Information Criterion (AIC) values and the proportion of deviance explained are provided.

Model	AIC	Deviance explained
Time spent ~ s(month, longitude) + s(DSB) + s(SST, MLD)	25035.98	0.67
Time spent ~ s(month, bs = "cc") + s(longitude) + s(latitude) + s(DSB)	25392.74	0.64
Time spent ~ s(month, bs = "cc") + s(DSB) + s(longitude) + s(SST, MLD)	25588.74	0.63
Time spent ~ s(month, k = 6, bs = "cc") + s(D) + s(DSB) + s(SST, MLD, k = 10)	25928.26	0.60
Time spent ~ s(month, bs = "cc") + s(DSB, longitude) + s(SST, MLD)	25979.43	0.61
Time spent ~ s(month, bs = "cc") + s(DS) + s(SST) + s(MLD)	26049.59	0.60
Time spent ~ s(longitude, by = month) + s(DSB) + s(SST, MLD)	26154.15	0.59
Time spent ~ s(month, bs = "cc") + s(DSB) + s(SST, MLD)	26172.68	0.59
Time spent ~ s(depth) + s(DSB) + s(SST, MLD)	26243.81	0.58
Time spent ~ s(month, bs = "cc") + s(DSB)	26502.89	0.56
Time spent ~ s(DSB) + s(SST, MLD)	26513.56	0.56
Time spent ~ s(month, bs = "cc") + s(SST, MLD)	27751.61	0.46
Time spent ~ s(SST) + s(SST)	28923.38	0.33

The GAB and, in particular, the eastern part of the GAB is an area of seasonal coastal upwelling driven by south-easterly winds primarily during the austral summer and autumn. Areas of upwelling tend to be spatially limited and may operate across short temporal scales of only a few days (Schahinger 1987; Middleton and Bye 2007). Nutrient rich cooler waters are brought into surface waters within these upwelling regions, leading to enhanced phytoplankton biomass (McClatchie et al. 2006) and associated secondary and tertiary production across the summer and autumn months (Ward et al. 2006).

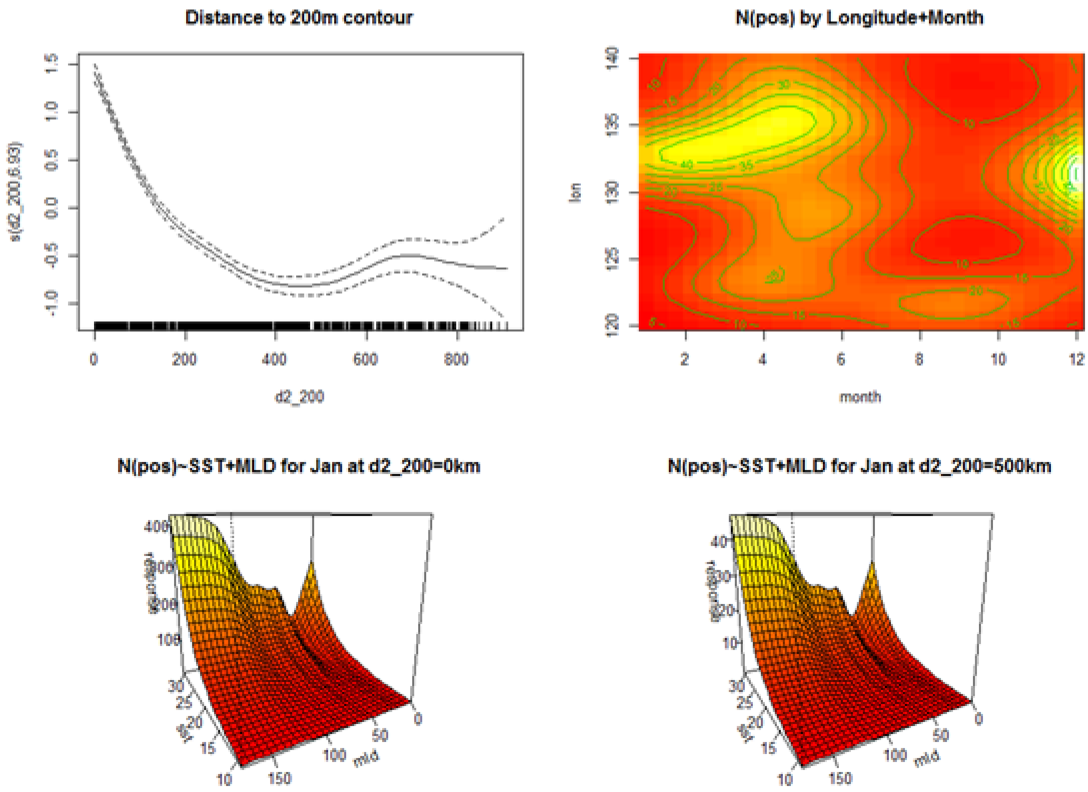


Figure 7.3. Model predictions of juvenile southern bluefin tuna distributions in the Great Australian Bight based on distance to the continental shelf (top left), longitude and month (top right), distance to the continental shelf, SST and MLD (bottom left and right) are shown for illustration as two instances of predictions of the response to these variables at different distances from the 200m contour. The GAM predicts approximately 10-fold increase in numbers of positions at the 200m contour (bottom left) compared to regions 500 km away from it (bottom right).

Perhaps surprisingly, few studies have been conducted on the diet of juvenile SBT. What has been done has predominantly focused on fish of age one or less off Western Australia (Serventy 1956; Itoh et al. 2011), and SBT of an unknown size or age off the western Eyre Peninsula in South Australia (Ward et al. 2006) and the New South Wales coast (Serventy 1956). Juveniles caught off the west coast of Western Australia were found to have stomachs containing a mix of small pelagic crustaceans and small jack mackerel (Serventy 1956). Australian sardines, blue mackerel (*Scomber australasicus*) and jack mackerel were found to dominate the stomachs of juveniles off southern

Western Australia (Itoh et al. 2011), with Australian sardines more abundant in the stomach of fish in coastal regions and jack mackerel more abundant in the stomachs of fish closer to the shelf edge (Itoh et al. 2011). The same study reported unpublished data from 3-year old SBT in other areas as comprising approximately equal quantities of fish and cephalopods or being dominated by amphipods depending on the region SBT were caught in (Itoh et al. 2011). Prey items in the stomachs of juveniles off South Australia were found to consist predominantly of Australian sardines and blue mackerel (Ward et al. 2006), while those off the NSW coast were described as being 'extraordinarily varied' (Serventy 1956).

Better understanding of the diet of juvenile SBT, both within and outside the GAB and spatio-temporal variation in diet would also facilitate an analysis of spatial correlation between SBT distribution and prey species. Further, understanding of ontogenetic changes in diet would be useful for better understanding variability in the spatio-temporal distribution of juvenile SBT whilst in the GAB. Incorporation of information on the spatial distribution of the prey of juvenile SBT would facilitate an analysis of spatial correlation between SBT distribution and prey species, thereby allowing predator-prey hypotheses to be tested.

The capability of the models developed here in projecting future habitat use of juvenile SBT can only be considered as preliminary. Because of the need to summarise data spatio-temporally, the models employed here fail to account for the likely high degree and complex spatio-temporal patterns in the data. Further, at present, the forecast skill of oceanographic models is largely limited to a few weeks (Evans et al. 2015, Hobday et al. 2016) and as a result projections beyond 1–2 months become highly uncertain. Because of these limitations, climatological distribution maps such as those developed here remain useful when exploring potential future states, particularly in cases where patterns in distribution, such as that of SBT in the GAB, appear sufficiently strong that an average picture of distribution is reasonable.

Within the GAB there have been shifts in the distribution of juvenile SBT over the past two decades. The historical over-exploitation of SBT has impacted both the range and distribution of the juvenile component of the stock across its range. Reduction in the average recruitment associated with overfishing and the depleted state of the stock is likely to have been reflected in the distribution of juvenile SBT in the GAB. Data from the scientific aerial survey used to monitor recruitment to the stock since the early 1990's (Eveson and Farley 2016) shows a contraction in the distribution of juveniles within the GAB to shelf waters and away from the western GAB (Figure 7.5). This is particularly evident during the period of the historically low recruitments from the late 1990's through to around 2007, after which the distribution begins to expand, with the distribution in 2010 and 2013-2016 being similar to the period prior to the late 1990's. The most recent levels of the recruitment index from the aerial survey are the highest since commencement of the survey and indicative, though not definitive, of an increasing trend in recruitment (CCSBT 2014).

Model projections under the MP used to recommend the global TAC, indicate that average recruitment is expected to increase over the coming decade to a level approximately 1.5-2 times the 2014 estimate of annual number of recruits, assuming the spawning stock continues to rebuild (CCSBT 2014). This would translate to a level of abundance of juvenile SBT not seen since the early 1980's and is likely to have a substantial effect on the distribution of juvenile SBT, both in the GAB and elsewhere.

As the skill of forecasting models (e.g. Lewison et al. 2015; Hobday et al. 2016) improves, investigations of changes to the distribution of juvenile SBT across their range and within the GAB may be possible. At the moment however, the skill of such models is limited to 1-2 months. Thus, climatological distribution maps such as those developed here are still the most useful when

predicting the broad features of the distribution of SBT in the GAB, particularly for use in planning activities that interact with fish abundance.

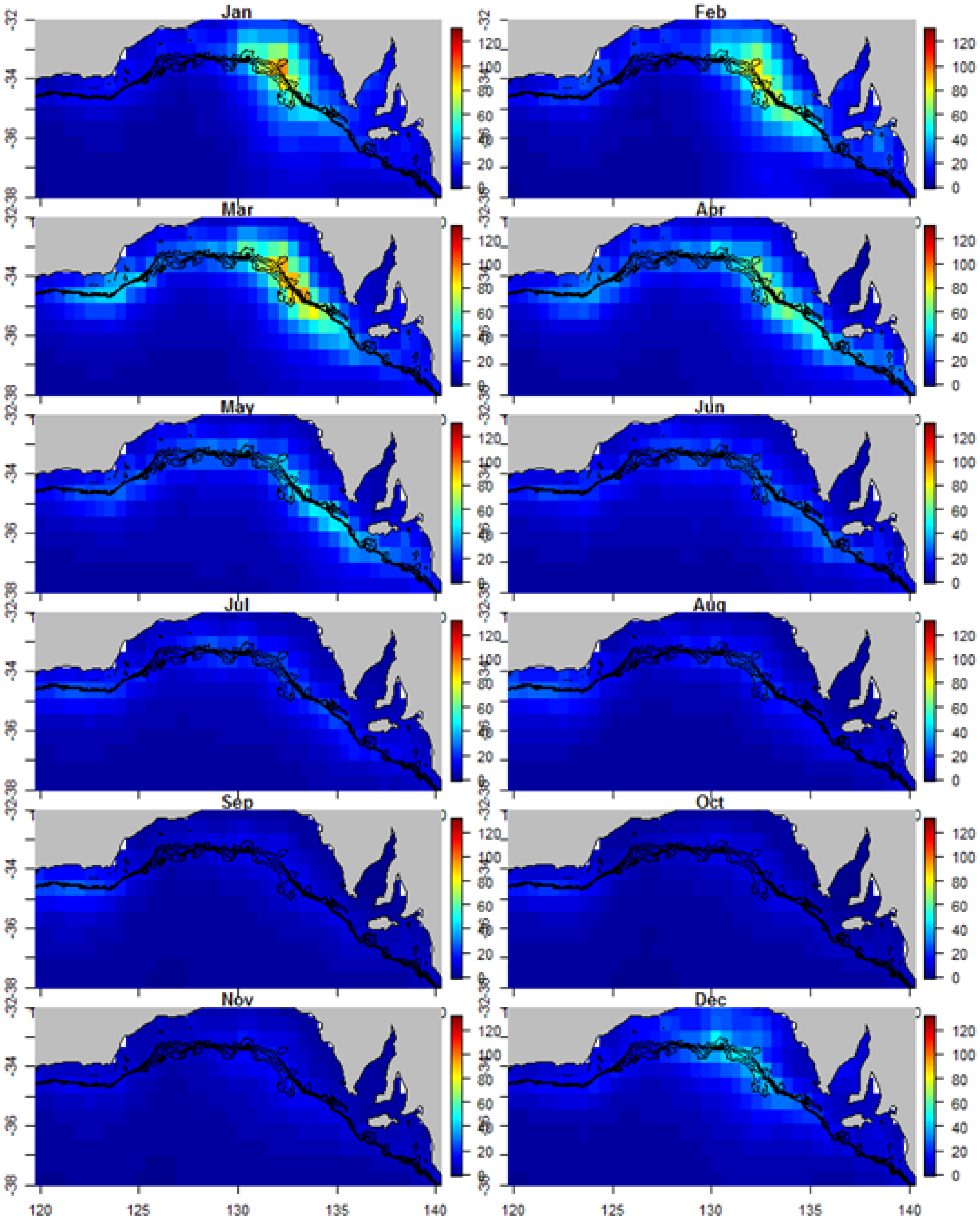


Figure 7.4. Predicted distributions of juvenile southern bluefin tuna in the Great Australian Bight derived from the selected GAM.

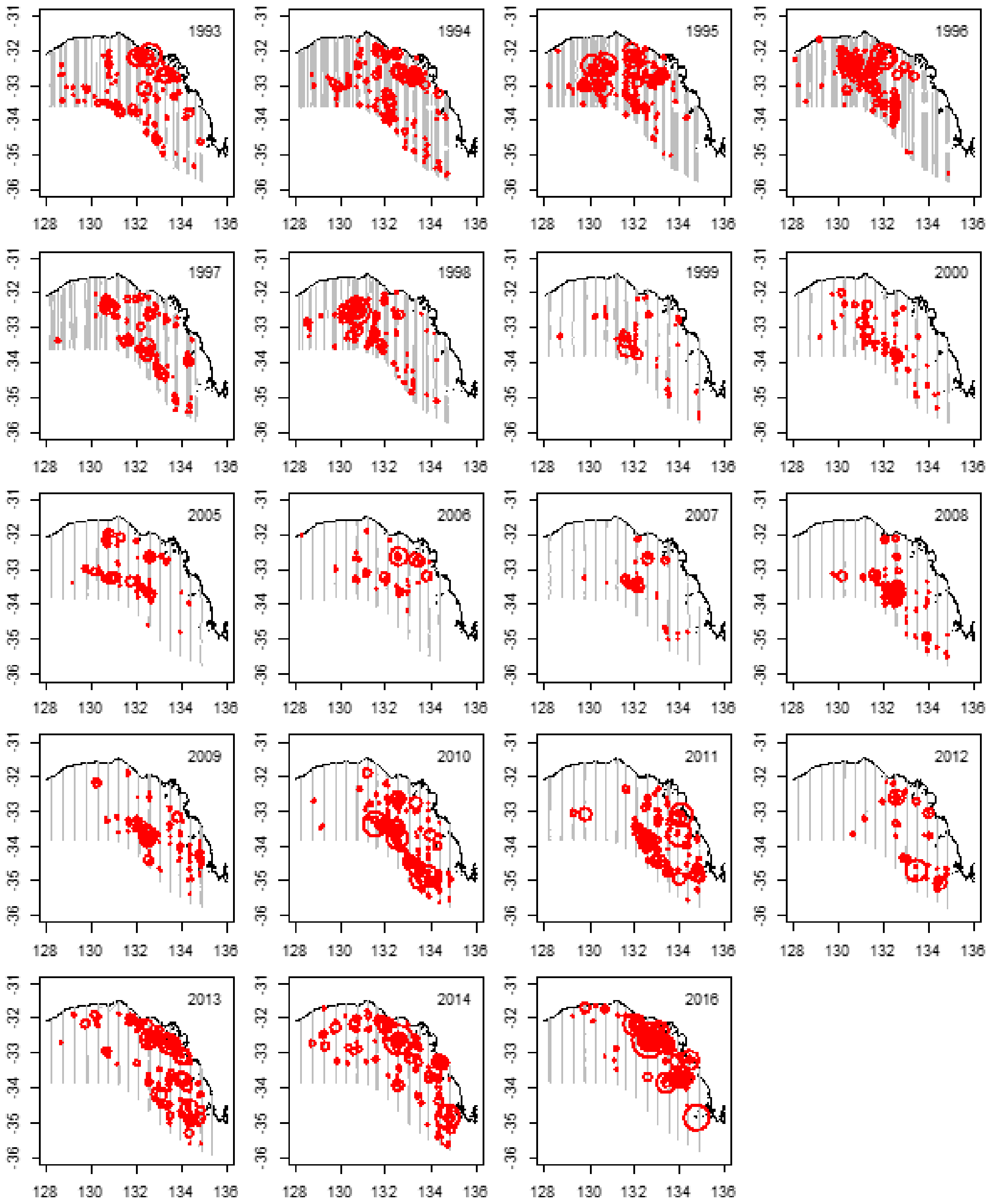


Figure 7.5. Distribution of SBT sightings made during each year of the scientific aerial survey. Red circles show the locations of SBT sightings, with the size of the circle proportional to the size of the sighting, and grey lines are the north/south transect lines of the survey.

8. A SUMMARY OF OIL AND GAS EXPLORATION IN THE GREAT AUSTRALIAN BIGHT WITH PARTICULAR REFERENCE TO SOUTHERN BLUEFIN TUNA

8.1 Background

As identified in Section 2, there is considerable concern that recent expansion of activities associated with oil and gas exploration in the GAB over the last five years, may impact on the migration and behaviour of a number of apex predators, including SBT. While a quantitative assessment of the impacts of sound generated by exploration activities is beyond the scope of this project, as a first step, it is important to establish the historical extent of oil and gas exploration in the area of the GAB and the potential for spatial and temporal overlap between juvenile SBT and exploratory activities.

Here, we bring together publically available information on oil and gas exploration in the region. Using a defined set of descriptors of this activity based on the information available, general trends in exploration activity through time are explored. It is important to note that oil and gas exploration is not the only source of sound in the extended area of the GAB and so some general discussion of other sound sources is also included.

8.2 Methods

8.2.1 Data

Metadata on exploration surveys conducted in the extended area of the Great Australian Bight were collected from multiple sources (Table 8.1). Key descriptors associated with the duration and area of each survey, the energy sound source and size, and the frequency of sound emitted (shot-point interval) from each survey were extracted from each data source and compiled into a single database for further exploration. Spatial data associated with each survey as well as exploratory and extraction wells, acreages released by the Australian and state governments and current active acreages were also compiled. All possible efforts were taken to ensure the accuracy of included records derived from inconsistent multiple records. However, it is important to recognise that this study seeks to characterize trends in activity and any remaining inaccuracies with any single record are unlikely to introduce appreciable biases. Further, while all efforts have been made to be as comprehensive as possible in the collation of information for this study, it is acknowledged that some information may not be available and, as a result, the summaries and results presented should not be assumed to be exhaustive.

8.2.2 Data exploration

Surveys within the extended area of the GAB have utilised a wide range of sound sources. We classified surveys on the basis of their sound sources and explored development in and variability in the types of sound sources utilised through time. Geophysical surveys conducted have either been two-dimensional (2D) or three dimensional (3D) in nature, with surveys differentiated by the geometry of the receivers, the density of measurements within the area of interest and type of sensor used. Three dimensional surveys incorporate a higher density of measurements than 2D surveys (IAOGP 2011) and represent collection of information on much finer scales. Although 3D surveys may not necessarily represent higher output of sound on the scale of an individual airgun than 2D surveys, because of the higher density and resolution of these surveys, 2D surveys were presented separately from 3D surveys.

A number of key metrics were included in the historical investigation of geophysical surveys within the study area (Table 8.2). These included descriptors of the number and type of surveys, the energy source size and the shot-point interval used in surveys.

Table 8.1. Metadata sources for petroleum lease, oil and gas exploration and petroleum wells across the Great Australian Bight^.

Source	Data
Geosciences Australia	Petroleum wells: dbforms.ga.gov.au/www/npm.well.search Geophyscial surveys: Soames et al. 2014. Petroleum wells and geophysical surveys: www.ga.gov.au/nopims
NOPTA	Petroleum wells and geophysical surveys: www.nopta.gov.au/data-mgmt/public-release.html Leases: www.nopta.gov.au/spatial-data/spatial-data.html
South Australian Department of State Development	Geophysical surveys: GIS and metadata provided directly Copies of survey acquisition reports scanned and digitally available Leases: https://sarig.pir.sa.gov.au/Map
Western Australian Department of Mines and Petroleum	Petroleum wells, leases and geophysical surveys: wapims.dmp.wa.gov.au/wapims
Victorian Department of Economic Development, Jobs, Transport and Resources	Petroleum wells and 3D geophysical surveys: earthresources.vic.gov.au/earth-resources/maps-reports-and-data/geovic
PGS	Geophysical surveys: GIS and metadata provided directly
TGS	Geophyscial surveys: GIS, metadata and specification report provided directly

^ Leases compiled by the National Environmental Science Program (NESP) Marine Biodiversity Hub and available at: http://www.nespmarine.edu.au/project/project-c1-improving-our-understanding-pressures-marine-environment.

The number of shots (the number of times the energy source is 'fired') for each survey was calculated for 2D surveys by firstly converting the recorded survey length (the total production line length of the survey in km) to metres and dividing by the shot-point interval. For 3D surveys, where production line length was available, the number of shots was determined as per 2D surveys. Where line length was not available, line spacing within the survey area was assumed to be constant and was calculated by multiplying the streamer separation distance by the number of streamers. Where streamer separation distance was not available, the distance was assumed to be 50 metres based on an average provided in IAGP (2011). For each 3D area, the potential number and length of survey lines was calculated by importing shapefile information on each survey into GIS software (Manifold version 8.0, Manifold Software Limited, Hong Kong). A total survey line length was then calculated which gave the number of shots as above. Once the potential maximum number of shots for each

survey was calculated, the potential daily number of shots was then calculated by dividing the number of shots by the number of days of the survey.

It is recognised that this metric does not provide a fully accurate measure of the number of times sound sources were fired. It does, however, provide a relative index of the potential number of times sound sources might be fired across the period of a survey and therefore effort.

Information associated with surveys was patchy with not all information required for calculating each metric available across all surveys (information for metrics were available for 53–100 % of all surveys – see Table 8.2). Where metrics were missing across surveys, the median or average value for those surveys within that year was assigned under the assumption that surveys with missing data would fall within the range of values captured by the surveys with data within any given year. Where metrics varied within a survey (e.g. shot-point interval, energy source size), the median was used in calculations. Metrics were assigned to each year based on the number of days that fell into each year and, for the purposes of comparison with the peak time that southern bluefin tuna, were in the Great Australian Bight across a summer-autumn period defined as the period between 1st November and 30th April (a total of 180 days).

Where surveys included areas outside of the extended area of the GAB and information on the period spent, or area of survey in the extended area of the GAB, was not available, the surveys were omitted from calculations of metrics (n=10; 1960–2016).

Table 8.2. Sample sizes of survey metadata for metric calculations.

Metric	N	Percent of total number of surveys
Number of surveys/year; 2D	176	100.0
Number of surveys/year; 3D	25	100.0
Total number of days of surveys/year; 2D	176	100.0
Total number of days of surveys/year; 3D	25	100.0
Median airgun energy source size/year, 2D	122	69.3
Median airgun energy source size/year, 3D	21	84.0
Total area explored/year, 2D	102	60.0
Total area explored/year, 3D	25	100
Median shotpoint interval/year, 2D	162	92.0
Median shotpoint interval/year, 3D	22	88.0
Total number of shots/year, 2D	94	53.0
Total number of shot/year, 3D	22	88.0

8.2.3 Overlap of oil and gas exploration with the distribution of juvenile SBT in the GAB

Position estimates were obtained for 125 tags using the "twilight likelihood" method as detailed in section 3.2.4 (Basson et al. 2016). Position estimates calculated for the summer period in each year 1998-2011 were then aggregated into counts within 1 × 1 degree squares by month within an area bounded by 30-40°S and 120-140°E (consistent with the boundary used in Theme 7). The proportion of time spent by tagged SBT in the area of the GAB in each 1-degree grid square was then plotted in relation to seismic survey activity for each year 1998–2011 to examine potential overlap of SBT with seismic survey activities across the summer period.

Potential shifts in the vertical distribution of juvenile SBT whilst in the GAB were explored by calculating the proportion of time spent at depth by juvenile SBT Pooled across the summer period in each year 1998-2011.

8.1 Results

Petroleum leases spanning almost all of the inshore extended area of the GAB have been released for exploration at various times since the 1960s (Figure 8.1), with exploration surveys reflecting this distribution (Figure 8.2). Leases and associated surveys have largely been limited to areas of less than 1000 m in depth with lease areas and associated surveys extending out to the edge of the exclusive economic zone only in the central area of the GAB (Figures 8.1 and 8.2). While 2D surveys are distributed extensively throughout the region, 3D surveys have largely been confined to two areas: the inshore area of the Otway Basin and the offshore area of the Bight Basin (Figure 8.2).

Exploration and development wells are distributed across the central and eastern parts of the extended area of the GAB, with the largest number located in the Otway Basin (Figure 8.3).

Numbers of surveys within a year ranged from 0–11, with the highest number of 2D surveys conducted in 1972 (n=11) and the highest number of 3D surveys conducted in 2014 (n=5). Transition from 2D surveys to 3D surveys began in the late 1990s/early 2000s (although the first 3D survey was in 1994), with an increase in the number of 3D surveys and a concurrent decrease in 2D surveys (Figure 8.4). No 2D surveys have been conducted in the region since 2010, with surveys conducted during 2011–2015 exclusively 3D in nature. While surveys have occurred in all months of the year, since the mid-2000s, fewer have occurred over the winter months than in previous decades.

The number of days surveys have been conducted over have varied in length with 2D surveys 1–308 days and 3D surveys 3–188 days in length. The cumulative total survey days ranged 0–455 days for 2D surveys and 0–270 for 3D surveys (Figure 8.5), with the highest number of survey days occurring in 1968 (2D) and 2014 (3D). The cumulative total number of days of 2D surveys during the summer period each year has declined through time from peaks in the late 1960s (305 in 1967, 265 in 1968), although peaks also occurred in 1990 (173 days) and 2001 (241 days). The number of days of 3D surveys during the summer period increased from 21 days in 1994 to 270 days in 2014 (Figure 8.5). Surveys spanned the whole summer period in 1966/67, 1967/68, 1968/69, 2011/12 and 2014/15.

The type of energy source used in 2D surveys has varied through time (Figure 8.6), with initial surveys largely using explosives as the sound source (one survey in 1961 used gas guns). Airguns were introduced into surveys in the late 1960s and while there has been some use of water guns, sparkers and boomers, airguns have dominated surveys since. All 3D surveys have used airguns as energy sources.

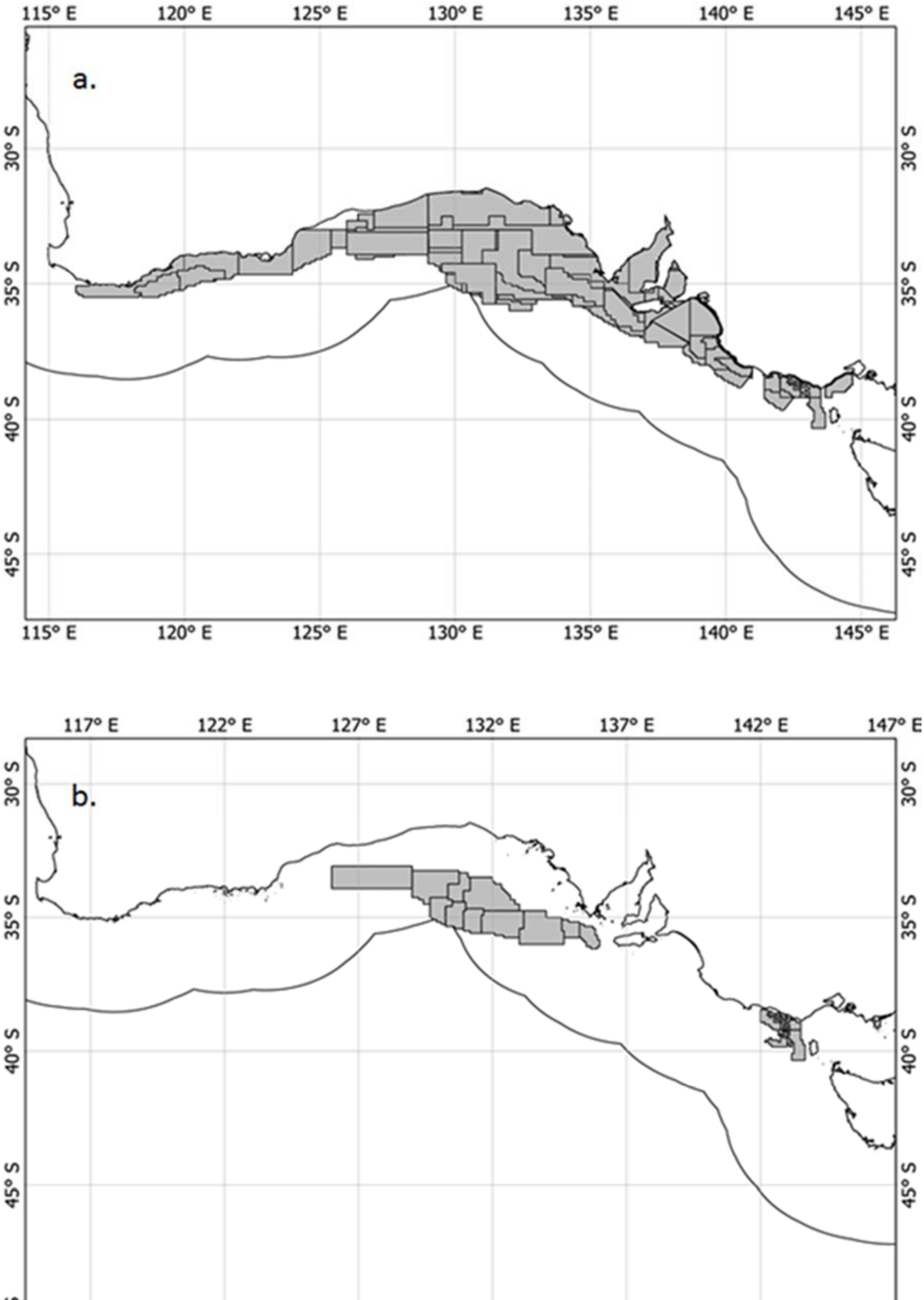


Figure 8.1. Oil and gas leases areas released across the extended area of the Great Australian Bight (a) 1960-2015 and (b) those currently active.

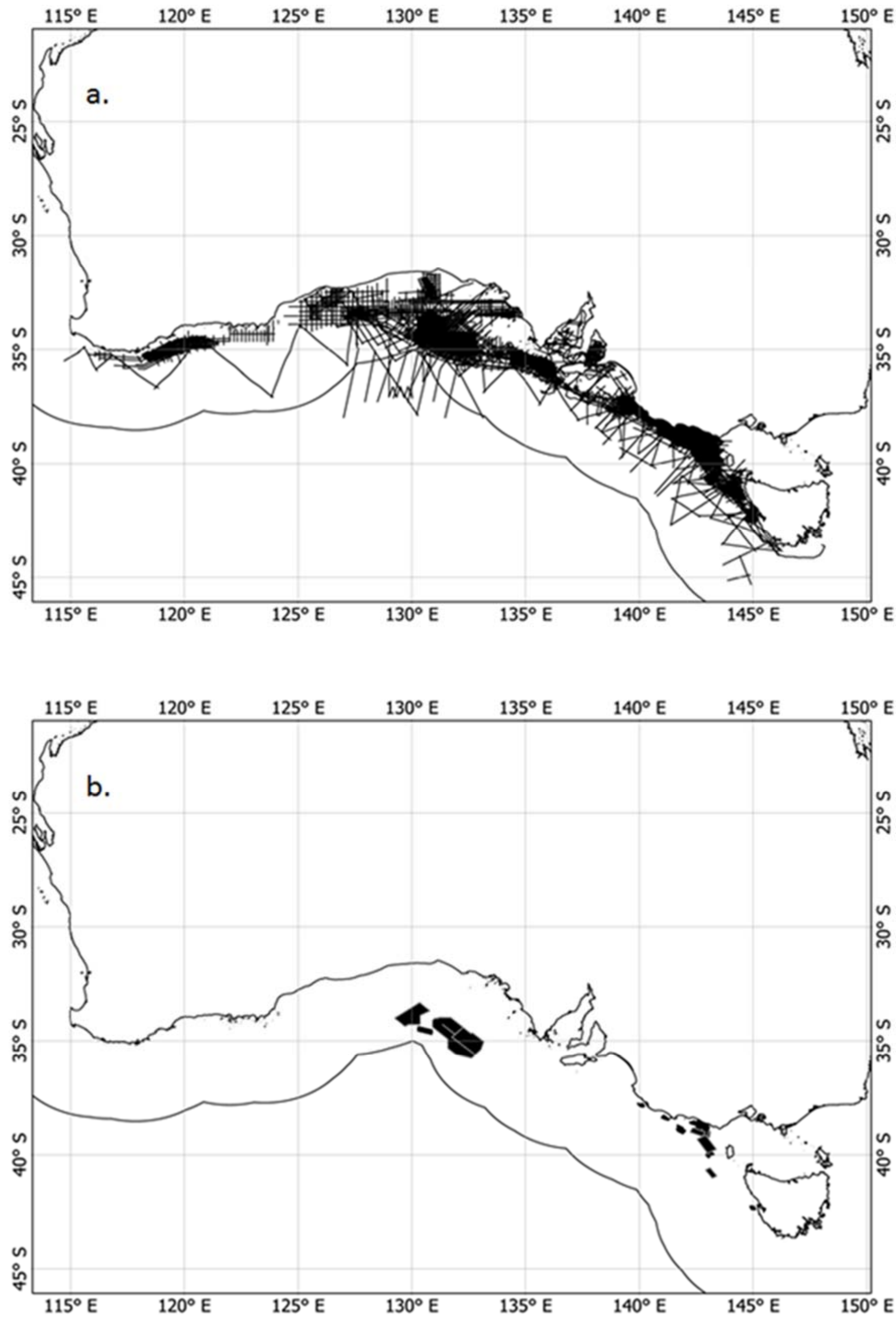


Figure 8.2. The distribution of (a) 2D and (b) 3D surveys across the extended Great Australian Bight region 1960-2016.

The median size of energy source (air guns only) used in both 2D and 3D surveys has increased through time (Figure 8.7), with the largest used in a 2D survey (2009) of 5,050 cubic inches, and 4,130 cubic inches used in a 3D survey in 2012. Overall, energy sources used in 2D surveys ranged 50–5,880 cubic inches while those used in 3D surveys 2,231–4,130 cubic inches. Shot-point intervals used within surveys have been relatively stable through time (with a median of around 25m), although much longer shot-point intervals have been used sporadically in 2D surveys (Figure 8.8). Shot point intervals used in 2D surveys ranged 6.25–16,000 m, while those used in 3D surveys ranged 12.5–37.5 m, reflecting the overall higher density of 3D surveys.

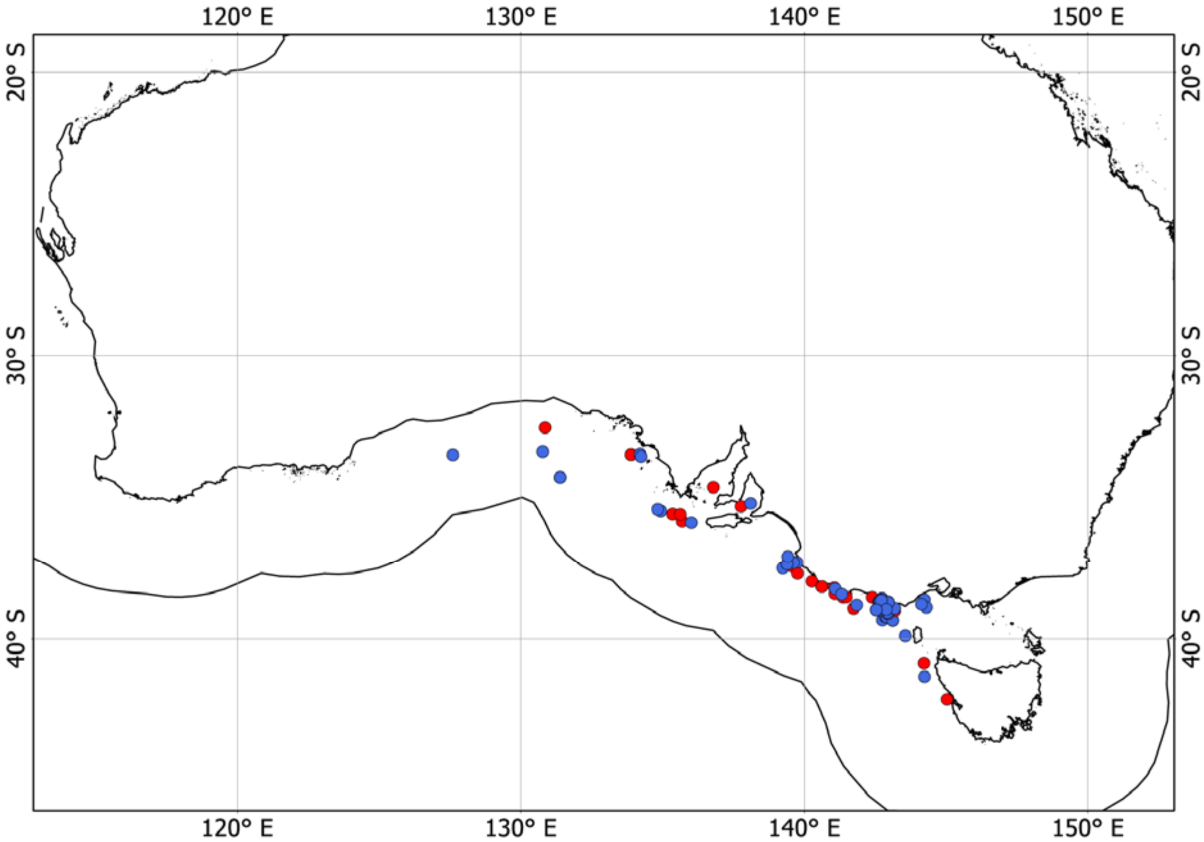


Figure 8.3. Location of exploration (blue) and development (red) wells across the extended Great Australian Bight region.

The total size of the area in which surveys have been conducted has also varied through time, with a 2D survey conducted across the period December 2000 to May 2001 being the largest area surveyed (15,007 km^2) in the time series. The largest area surveyed during a 3D survey was 13,179 km^2 across the period November 2014 to May 2015. The cumulative area surveyed in a year has largely been less than 10,000 km^2 in any one year for 2D and 3D surveys (Figure 8.9) with peaks occurring in 2001 for 2D surveys (25,116 km^2) and in 2014 for 3D surveys (15,589 km^2).

The estimated total number of shots fired in a survey closely reflected the area surveyed, with peaks occurring in 2001 (2D surveys) and 2014 (3D surveys). While the number of shots associated with 2D surveys has been quite variable through time, the number associated with 3D surveys has increased from an estimated low of 7,200 in 1994 to an estimated high of 670,653 in 2014, of which 581,987occurred during the summer period (Figure 8.10).

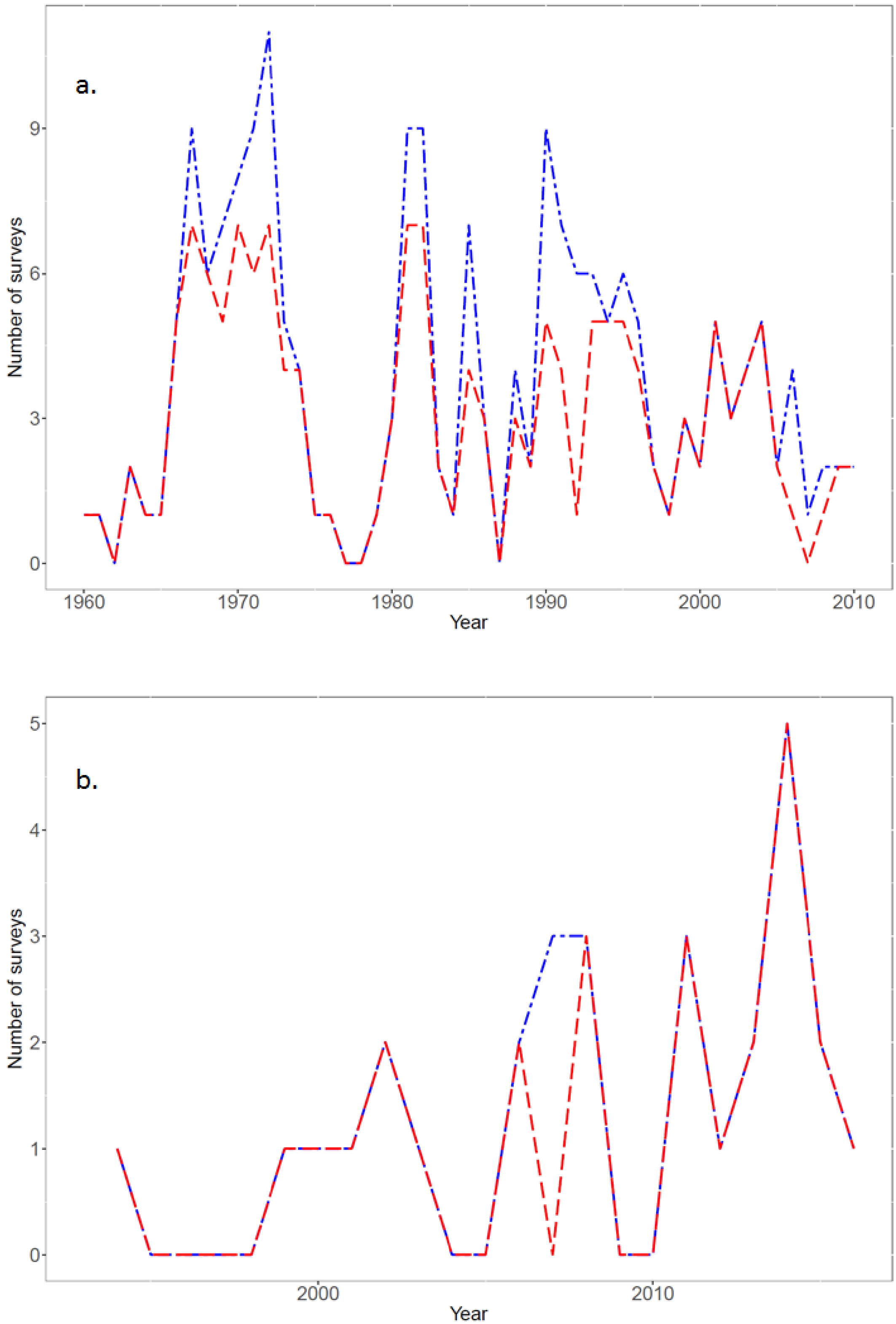


Figure 8.4. Number of (a) 2D and (b) 3D surveys per year 1960-2016. Number of surveys across the full year (blue dash-dot line), number of surveys across the 'summer' period (red dashed line).

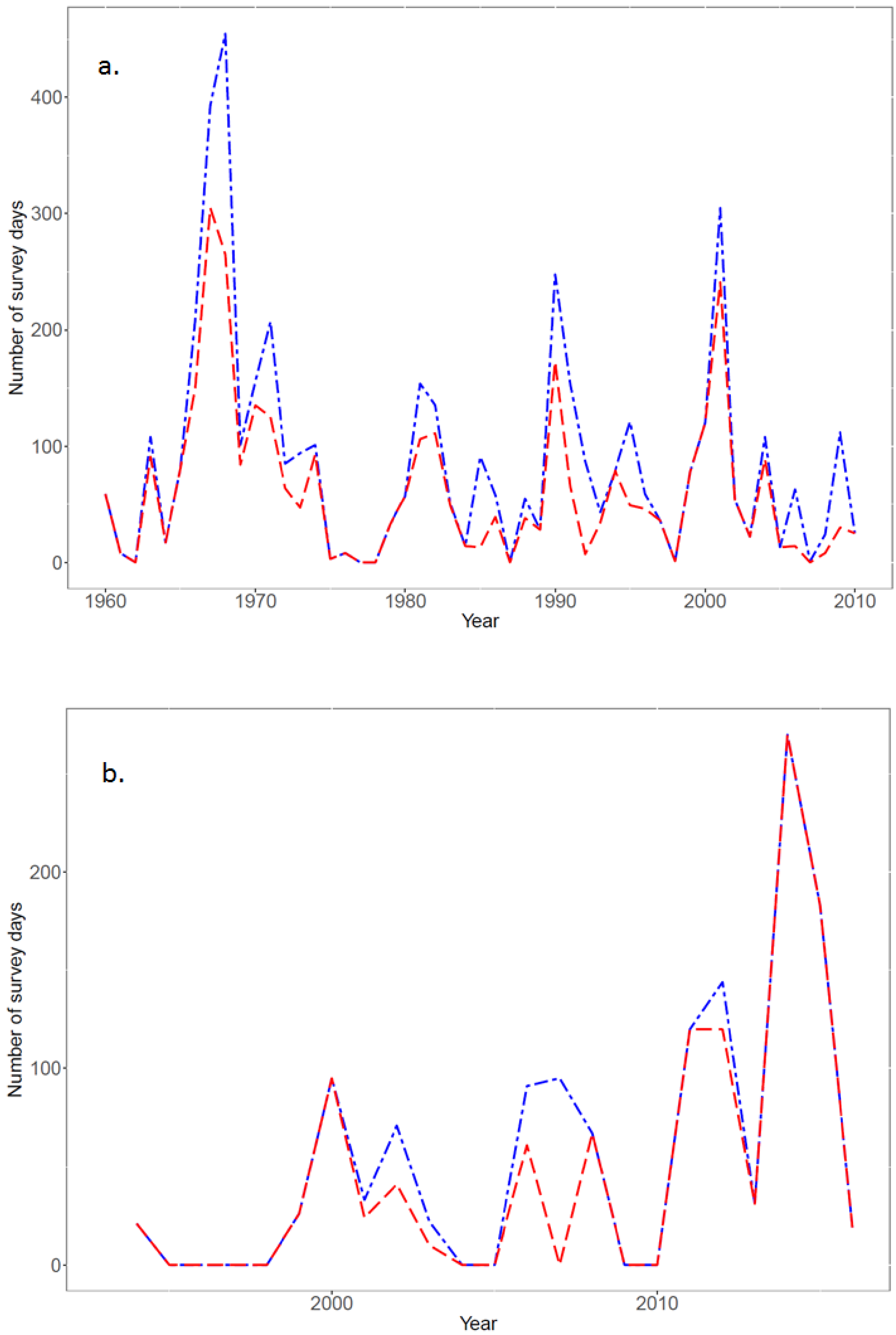


Figure 8.5. Total days of (a) 2D and (b) 3D surveys per year 1960-2016. Days of surveys across the full year (blue dash-dot line), days of surveys across the summer period (red dashed line).

When the distribution of geophysical survey activity and the movements of juvenile SBT were examined in relation to each other, varying degrees of overlap have occurred across the summer period in each year (Figure 8.11). Low or no overlap occurred between tagged fish and survey activity in 2002, 2003, and 2007–2010, with overlap being higher in 1998–2001, 2004–2006 and 2011.

If we compare the vertical behaviour of juvenile SBT during the summer months across years, considerable inter-annual variability in surfacing behaviour and the time spent at depth and temperature is evident (Figures 8.12 and 8.13), with no obvious large scale shifts occurring in years of higher and lower oil and gas exploration (e.g. 2004–2006 and 2007–2010).

8.2 Discussion

Exploration for oil and gas in the GAB (and regions to the immediate east and west) using geophysical surveys has been occurring for more than five decades at variable levels. Peaks in exploration activity have occurred at relatively regular intervals, with the most recent associated with the release of lease areas in the offshore waters of the Bight Basin. Use of more complex, higher density 3D surveys has increased gradually since the turn of the century, with coarser 2D surveys decreasing over the same period.

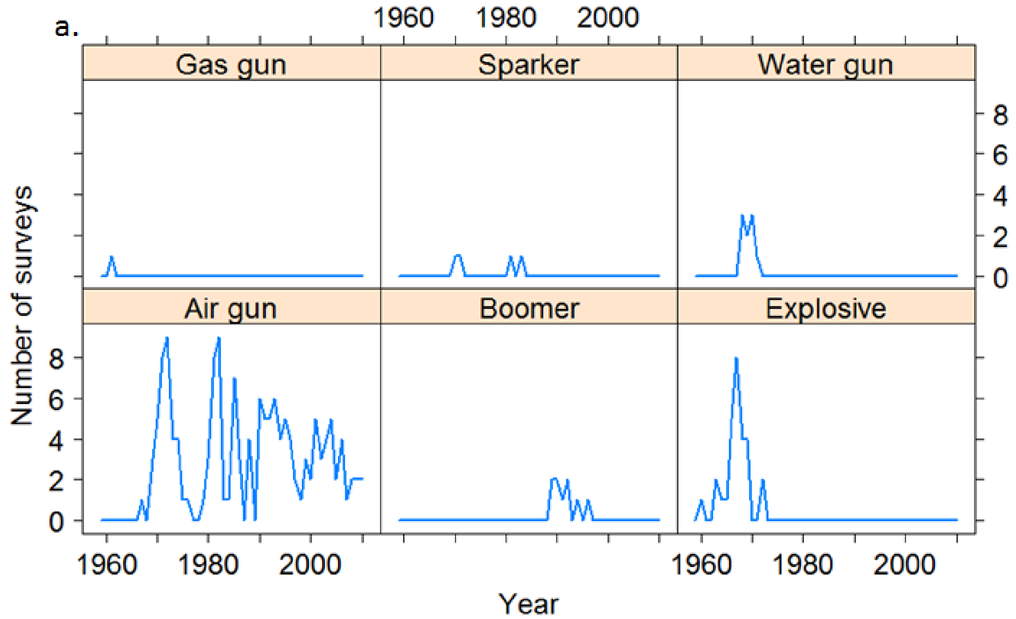
When the first leases were released there was no obligation for the lease area to be explored or developed (O' Neil 2003). Since then, licensing obligations have changed, intergovernmental agreements have been established and more recently, national regulators have been established for the administration of titles and for safety and environmental management which also act across state waters where relevant powers and functions have been conferred (see Evans et al. 2017). These changes to licensing, planning and regulating processes at the state and Australian government sectors have no doubt influenced the extent and types of activities occurring in association with oil and gas exploration in the greater GAB, although ascertaining the intricacies of this influence is beyond the scope of this study.

The technology associated with oil and gas exploration has developed over time with the vast majority of surveys utilising airguns from the 1980s. The progression from the utilisation of sounds sources has largely been driven by safety; use of explosive material such as dynamite, gas or electricity such as that used in gas guns, boomers and sparkers is inherently less safe than use of water or air in generating the sound required for penetration of sub-floor features.

Although lower than peaks that occurred around the turn of the century, both the amount of area being surveyed and, in association, the number of shots being fired during surveys have increased since 2010. This has occurred in association with 3D surveys being conducted in offshore areas of the Bight Basin. Airgun size has also increased largely in association with progressively deeper waters being explored through time and a need for higher sound production in order to reach and penetrate the seafloor.

With an increase in areas surveyed, greater complexity in surveys conducted (with the transition from 2D to 3D), and an increase in airgun array size, it could be assumed that the amount of sound being generated by oil and gas exploration activities has increased. However, direct calculations of the sound generated from each survey and the spatial footprint of that sound generated are difficult to determine given the directivity patterns of air gun arrays, the complexity of modelling airgun sound propagation in a real environment and the problem of dealing with cumulative sound loadings through time, for the moving source.

Without direct measurements of the soundscape of the greater area of the GAB, it is difficult first, to characterise the underwater sound produced by oil and gas exploration through time and second, to estimate the potential area exposed to levels of sound that might be associated with impacts for particular species (including cumulative impacts) and thereby the extent of impact of exploration activity on marine life within the region. Variability in the sound generated from a source for each shot fired has been recorded (see McCauley et al. 2016a), resulting in variability of the received level of sound at any range. This compounds any comparisons of both sound generated within a survey and sound generated between surveys.



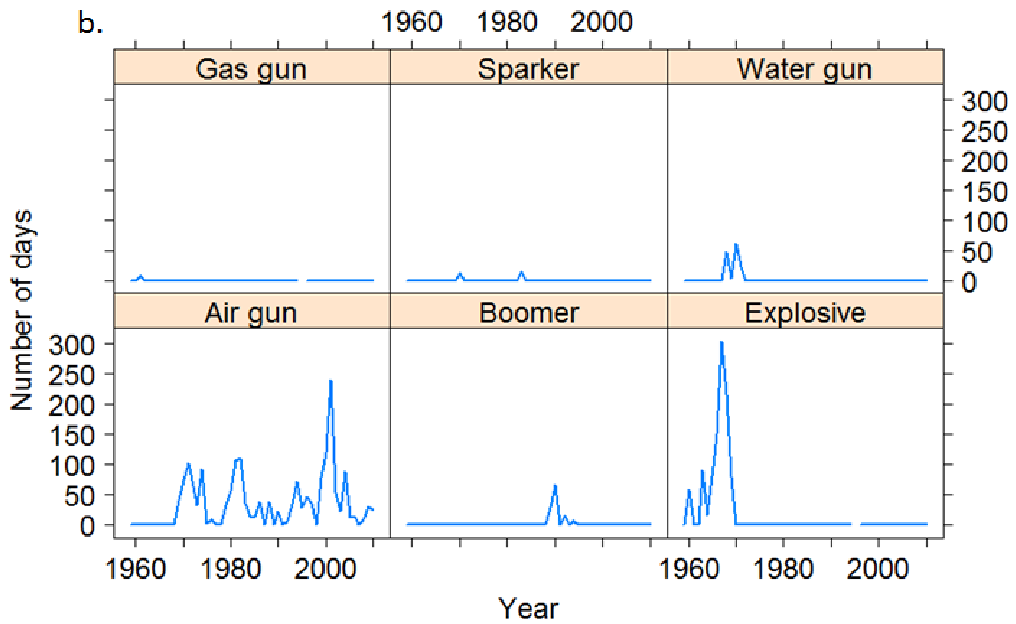


Figure 8.6. (a) Number and (b) days of 2D surveys per year by type of energy source.

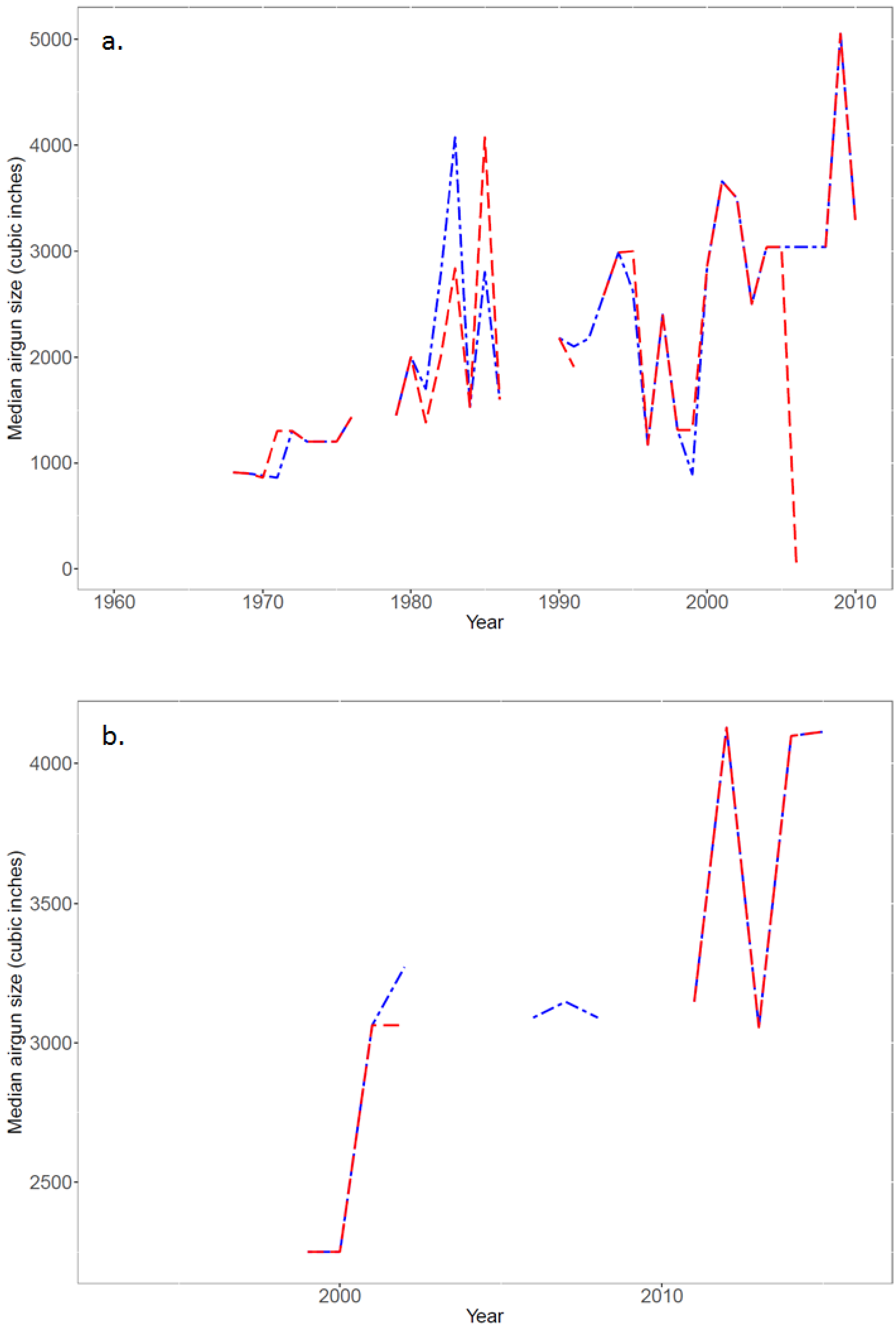


Figure 8.7. Median airgun size used in (a) 2D and (b) 3D surveys per year 1969-2016. Median size calculated across all surveys in a year (blue dash-dot line), surveys across the 'summer' period (red dashed line).

There are many other sources of sound generated by anthropogenic activities in the ocean with marine vessels (ranging from small recreational vessel to large commercial shipping), oil and gas production activities, naval operations and nearshore developments all contributing to soundscapes. The ocean is also naturally a noisy place. Winds and waves typically contribute the most to ocean soundscapes (e.g. Erbe et al. 2016), with marine animals (including invertebrates, fish and marine mammals) contributing to soundscapes to varying extents either incidentally (e.g. through feeding) or actively (e.g. fish choruses; see Radford et al. 2014 or McCauley and Cato 2016). Depending on the location, period and oceanographic conditions, sound from vast distances can also contribute to local soundscapes especially in the open ocean. For example, Antarctic ice cracking has been recorded by hydrophones deployed on the Australian continental shelf (McCauley et al. 2016b).

There is no doubt that there has been overlap in the timing of geophysical surveys and the occurrence of SBT in the extended area of the GAB and that this overlap has been occurring for substantial amounts of time. The extent of overlap, however, has varied through time, and direct measurements of overlap are largely impossible to quantify because of inherent errors in the light-based geolocation process used to estimate SBT position (see Basson et al. 2016). The likelihood method used allows for estimation of location uncertainty and integrates this uncertainty within the movement model, which vastly improves our capacity to determine overall movements. Nevertheless, it does not allow the “pinpointing” of an individual at an exact location at an exact time; hence, position estimates are generally aggregated into 0.5 to 1 degree of latitude squares for analysis. Further, the high degree of variability in the surfacing behaviour and depth distributions of juvenile SBT among years highlights difficulties in determining behavioural changes over and above individual variability in a wild population of individuals capable of large scale movements.

The hearing capabilities of SBT are unstudied; however, some initial measurements of hearing thresholds in a small number of juvenile Atlantic bluefin tuna (*Thunnus thynnus*) based on behavioural responses to sound sources have been recorded (Popper et al. 2013; Dale et al. 2015). Hearing in individuals was found to be most sensitive from 400 to 500 Hz in terms of particle motion (radial acceleration −88 dB re 1m s^{-2}; vertical acceleration −86 dB re 1m s^{-2}) and sound pressure (83 dB re 1µPa). An earlier study, measuring sound pressure only, found yellowfin tuna (*Thunnus albacares*) had similar hearing capabilities, being responsive to sound in the range of 200–800 Hz (Iversen 1967).

In general, airguns produce low frequency pulses below 250 Hz, with the strongest energy in the 10–120 Hz range and peak energy at 30–50 Hz. They also release low amplitude high frequency sound of varying energy, which can be as high as 100 kHz (see OSPAR 2009a; OSPAR 2009b; McCauley et al. 2013). The distance at which energy is propagated from an energy source is dictated by a large number of factors. Sound exposure levels at a particular location are influenced by ambient noise present in the environment, with lower frequencies ‘disappearing’ into background noise at some range. For example energy from a 4130 cubic inch sound source deployed at 7 m depth in the GAB was measured out to nearly 300 km from the sound source on the shelf edge, with sound exposure levels able to be measured reliably out to approximately 230 km (McCauley et al. 2013). Sound exposure levels ranged from approximately 135 dB re 1µPa^2.s at 40 km to approximately 110 dB re 1µPa^2.s at 110 km (McCauley et al. 2013).

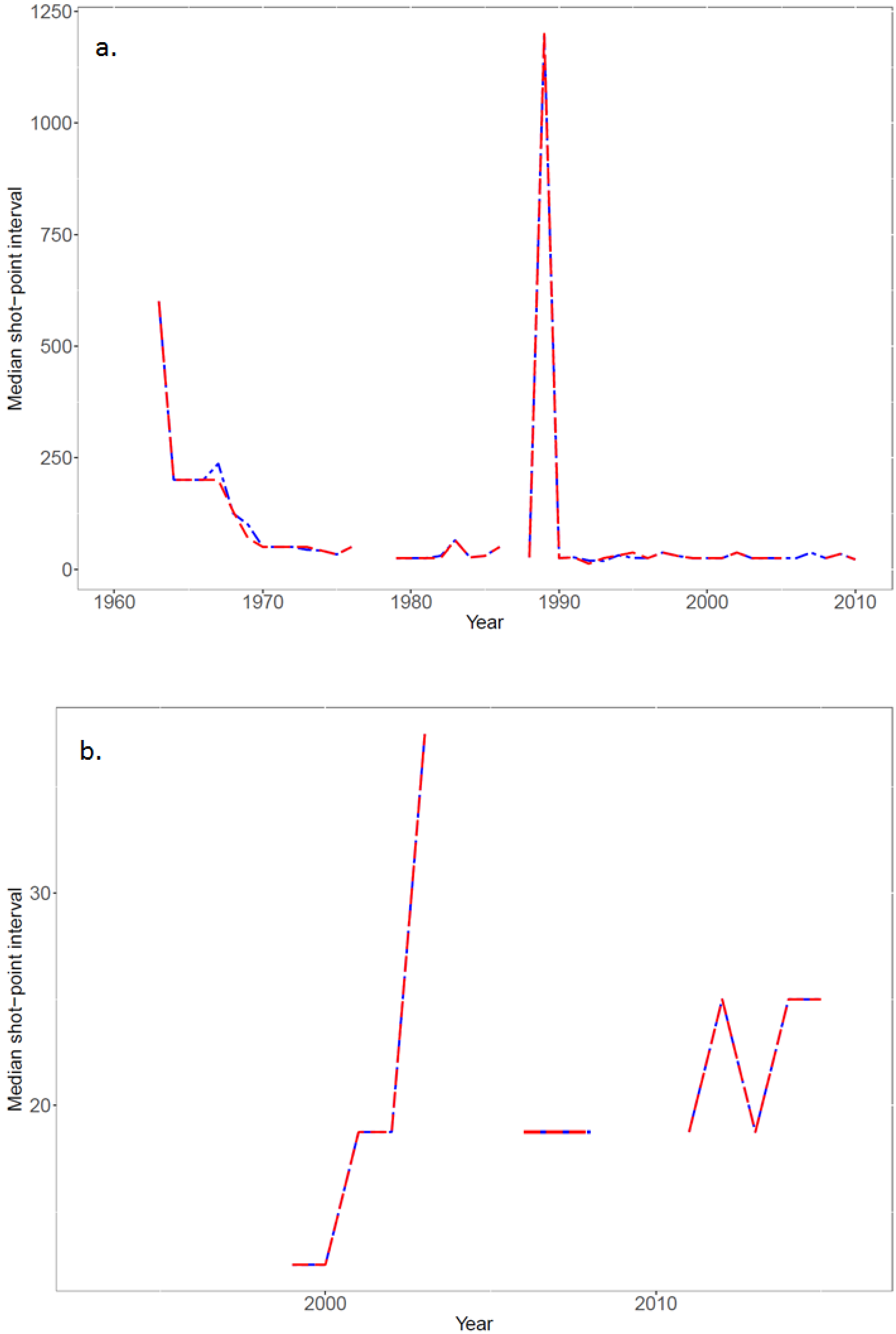


Figure 8.8. Median shot-point interval used in (a) 2D and (b) 3D surveys per year 1961-2015. Median interval calculated across all surveys in a year (blue dash-dot line), surveys across the 'summer' period (red dashed line).

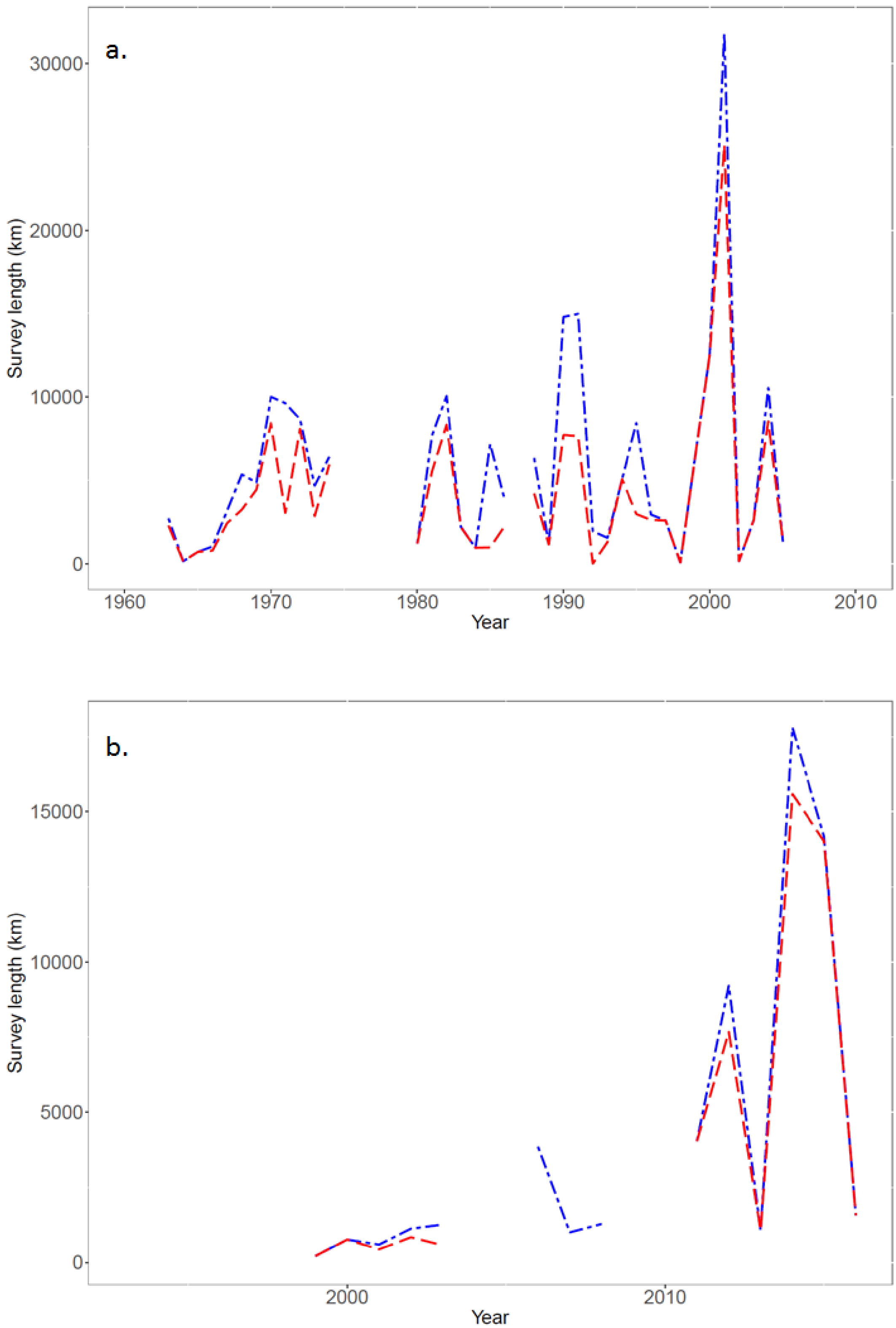


Figure 8.9. Estimated total area (km) surveyed in (a) 2D and (b) 3D surveys per year 1963-2015. Area calculated across all surveys in a year (blue dash-dot line), surveys across the 'summer' period (red dashed line).

If we assume that the hearing capabilities of SBT are similar to that recorded in other tuna species, it is highly likely that they are capable of detecting sounds generated by geophysical surveys within a certain range of the sound source. The behavioural responses of these highly mobile predators to such sound sources will determine the extent of overlap they might have with the sounds generated by exploration activity and thereby the level of impact such sound sources might have on individuals; behaviour that is currently unquantified. Further, the relationships between the environment of the GAB and the behaviours of juvenile SBT are highly complex, potentially interdependent and co-varying in nature (Basson et al. 2012; see also Section 5).

The numerous potential compounding factors influencing the movements and behaviour of juvenile SBT whilst in the GAB would need to be accounted for before the extent of overlap and any associated behavioural responses to exploration activities could be determined. At the broad-scale however, observations of movement suggest that tagged individuals remained within the region of the GAB during the overall period across which surveys were conducted and for those individuals for which observations are available across multiple years, continued to return to the GAB across the austral summer period.

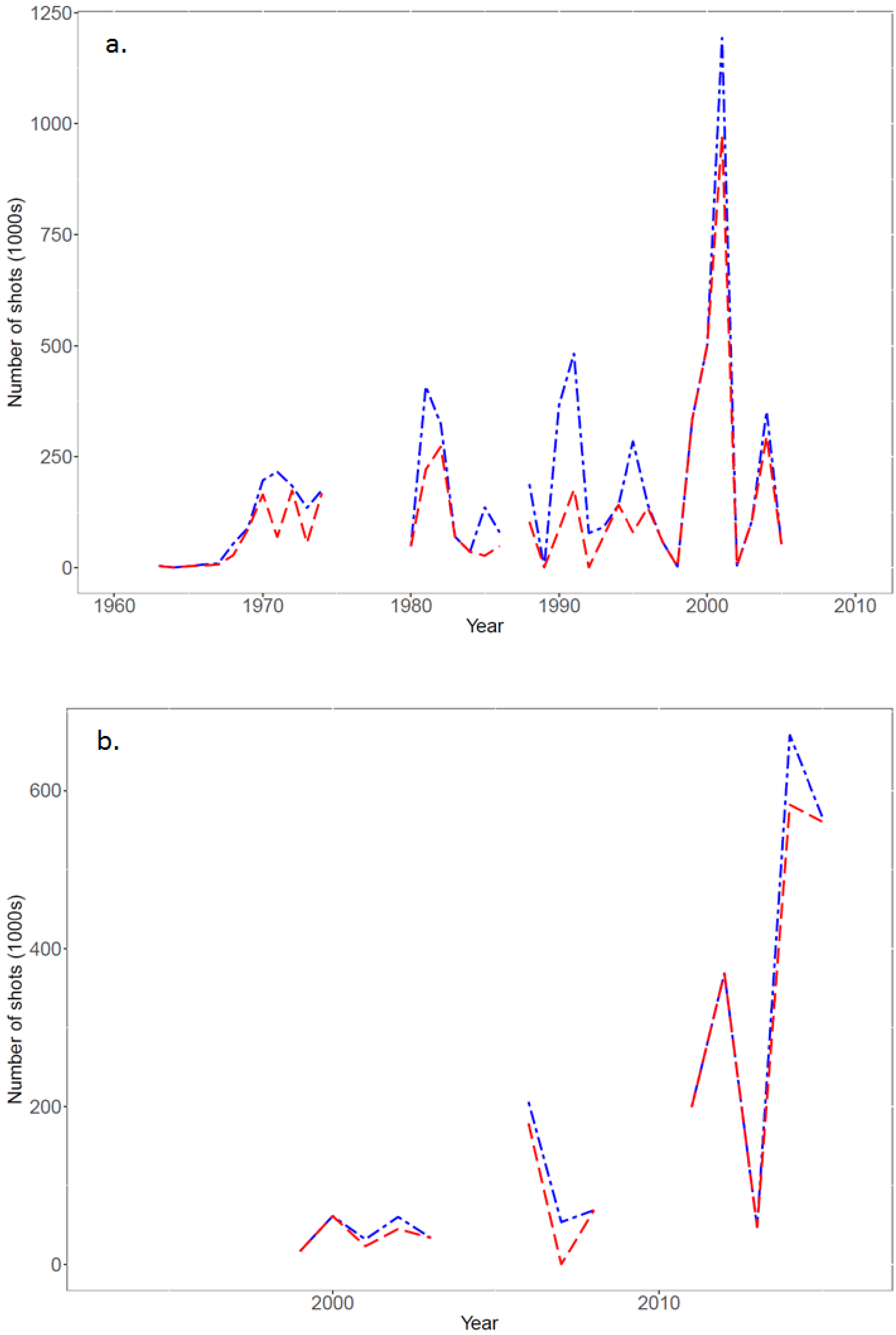


Figure 8.10. Estimated total number of shots fired in (a) 2D and (b) surveys per year 1963-2015. Number of shots calculated across all surveys in a year (blue dash-dot line), surveys across the 'summer' period (red dashed line).

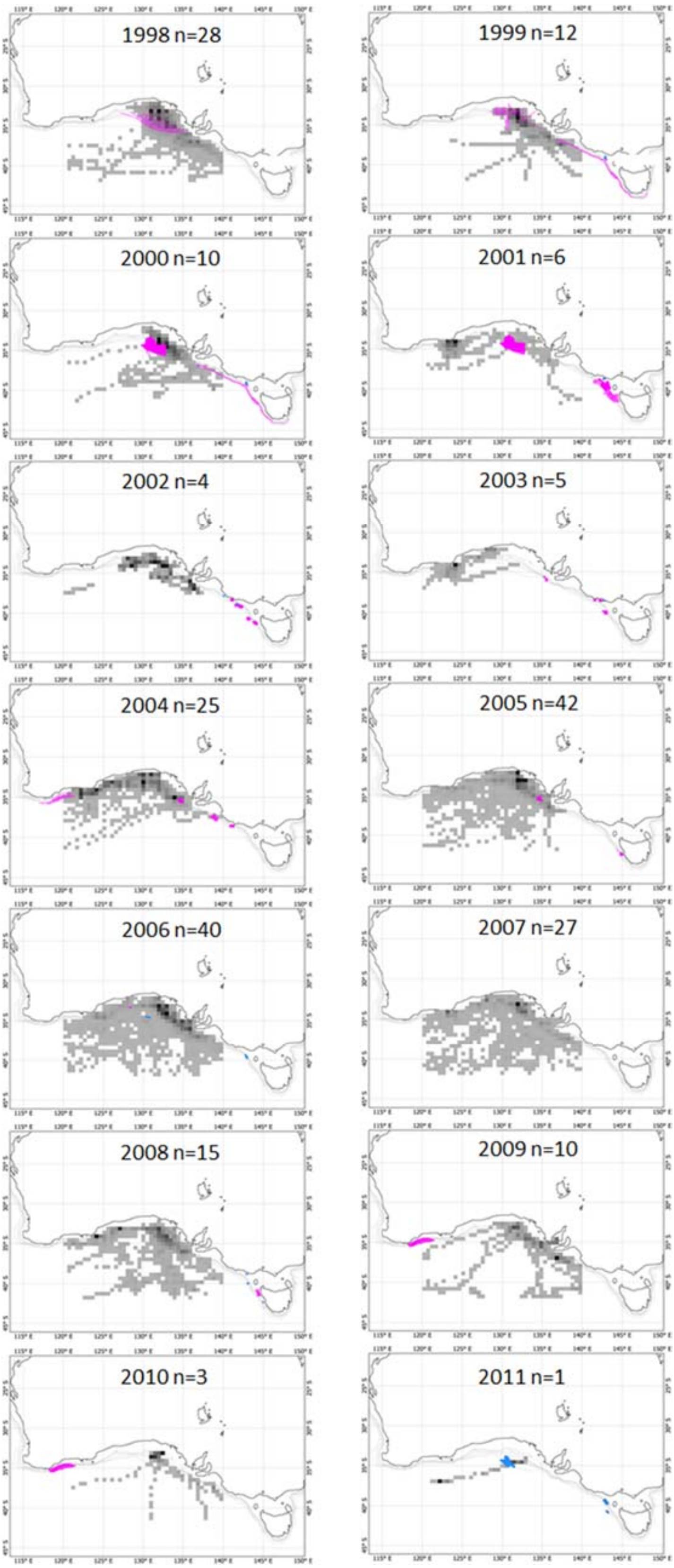


Figure 8.11. Spatial overlay of oil and gas exploration surveys and time spent by juvenile SBT across the summer months in each year 1998-2011. Time spent is defined as the number of tags in a one degree square in the area defined by Theme 7. 2D surveys are in pink, 3D surveys are in blue.

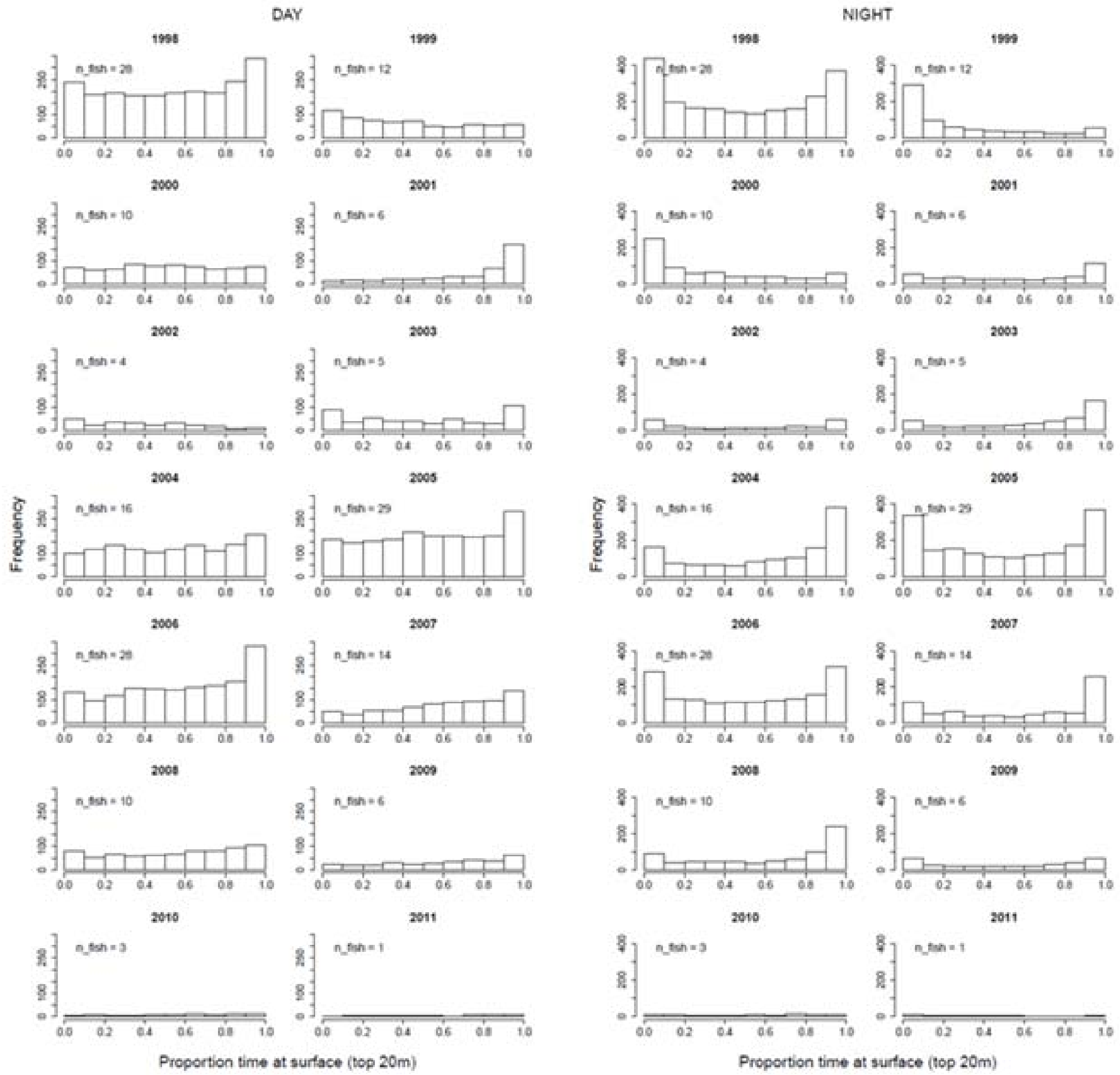


Figure 8.12. Proportion of time spent in the top 20m during the day (left) and at night (right) by juvenile SBT across the summer months whilst in the GAB in each year 1998-2011.

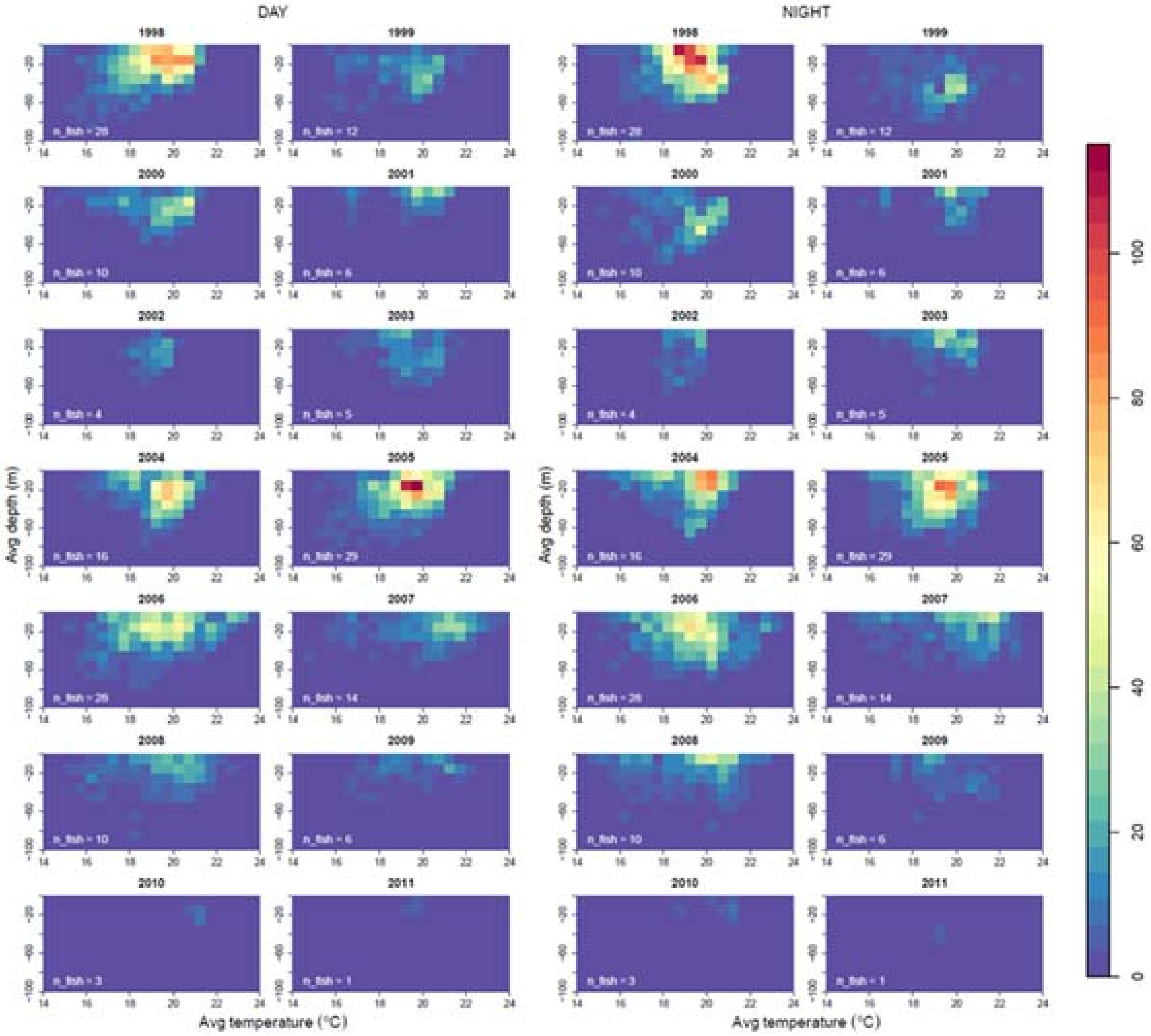


Figure 8.13. Two-dimensional frequency plots of depth (m) and external temperature (°C) during the day and at night from juvenile SBT across the summer months whilst in the GAB in each year 1998-2011. The colour bar indicates the number of observations.

9. DISCUSSION

This project set out to develop a series of quantitative models of juvenile SBT movement, surfacing behavior, feeding and preferred habitats in the GAB based on historical archival tag data. It also aimed to summarize historical oil and gas activities throughout the region. In the context of recent large-scale oil and gas exploration in the GAB region, we aimed to use data obtained from contemporary electronic tag deployments and the behavioral models developed to examine whether movement and/or behaviour of juvenile SBT may have changed between the historic period and current exploratory period and, if so, in what way and to what extent.

The project has delivered:

1. Improved statistical methods for estimating the position of individual juvenile SBT from archival tag data using state-space modelling methods and incorporating ancillary sensor data, such as sea-surface temperature, and, where appropriate, bathymetry;
2. A quantitative description of the migrations of juvenile SBT and, in particular, the temporal components of migrations to and from the GAB, as well as identifying potential drivers of this migration;
3. Characterized the surfacing behaviour of juvenile SBT in the GAB and associated relationships with physical and biological features within the GAB ecosystem;
4. Developed new statistical methods to automate the detection of feeding signals from large archival tag data sets, through examination of internal temperature records from tagged juvenile SBT;
5. Developed initial characterisations of the feeding behaviour of juvenile SBT across their range;
6. Extended statistical models of the seasonal distribution of SBT within the GAB to characterise the preferred habitat of juvenile SBT, based on available biological and physical covariates;
7. A database of publically available information on historical oil and gas exploration activities;
8. A historical characterisation of historical oil and gas exploration within the GAB.

Unfortunately, we were not able to compare the migrations of juvenile SBT and their distribution and behavior within the GAB derived from historical tag deployments with that derived from contemporary deployments. This was a result of: i) a lack of sufficient contemporary archival tag returns within the lifetime of the project, which therefore precluded the ability to undertake comparisons between the two periods; and ii) an inability to source juvenile SBT of a size suitable for tagging with miniaturized PSATs. Because of this, the planned examination of the extent to which movement and/or behaviour between the historic period and current exploratory period varied was unable to be done within the timeframe of the project. The potential to undertake such a comparison has not been lost. Deployment of an additional 125 electronic tags during the summer of 2014 in juvenile SBT in the GAB has facilitated ongoing collection of data from juvenile SBT beyond the timeframe of this project. As the tags deployed are returned over the coming years, they will add to the dataset generated by this study, providing a basis for future analysis.

It is our hope that the methods developed and results delivered from this project clearly demonstrate the essential nature of continuous, long-term data sets to building a deeper understanding of marine systems, such as the GAB, and addressing important questions about potential impacts of human activities on them. This is particularly the case for populations of long-lived species, such as SBT and other apex predators and iconic species, which display substantial lag effects as a result of natural variation (e.g. very strong cohorts due to recruitment variation or large-scales shifts in distribution or migration due to decadal trends in oceanographic conditions) and impacts of human activities (e.g. reduction in average recruitment due to historical depletion from

over-fishing and subsequent increases in average recruitment and abundance in the GAB as part of a rebuilding program). In the absence of continuous time-series, it is not possible to determine the major drivers of change or understand the effects of potential future impacts.

Using overall averages of environmental covariates across time when investigating relationships between the behaviour of SBT and ocean environments is a potential limitation that does not account for variability in ocean state; which is fundamentally what organisms in the ocean are responding to at an individual level. A challenge in these applications is to gather sufficient data to develop model predictions for movements and behaviour. As was the case here, even with what is considered a substantial dataset, the numbers of individuals within years are often insufficient to provide robust estimates, resulting in the need to pool across all years.

9.1 Importance of the Great Australian Bight to juvenile SBT

Individual SBT demonstrate substantive variability in their use of the GAB region. Notwithstanding this high level of individual variability, some general patterns in the behaviour of juvenile SBT could be identified, such as peaks in arrival and departure times, increased use of surface waters during the day when in the GAB, crepuscular patterns in feeding events, and use of particular regions within the GAB during the summer months.

For a fast growing, immature and ultimately large ocean predator such as the juvenile SBT that occupy the GAB on a seasonal basis, identifying abundant food sources and maximising growth is likely to be the key driver of their behaviour. As such, seasonal patterns in prey availability may be part of the reason the GAB is used as a summer residence ground. The GAB is the site of the largest fishery, by weight, in Australian waters, which primarily targets the Australian sardine or pilchard (*Sardinops sagax*). The fishery is highly seasonal, with catches highest throughout the austral summer and early autumn months (Ward et al. 2012). This broadly coincides with peak periods in juvenile SBT residency in the region. The shelf areas of the region also supports significant populations of other small pelagics such as jack mackerel (*Trachurus declivis*) in western and slope areas of the GAB (Ward et al. 2006; Itoh et al. 2011). Populations of small pelagic species are likely to provide an important seasonal resource for SBT, similarly to other pelagic predators in the region (Page et al. 2005; McIntosh et al. 2006; Ward et al. 2006).

Thermal regimes could also be important for growth and may provide additional drivers for the utilization of the GAB by juvenile SBT across the summer months. Previous growth studies (Eveson et al. 2004) have shown that a large proportion of the annual growth increment of SBT is gained in the summer while in the GAB. This could indicate that higher temperatures infer physiological benefits. Potentially juvenile SBT migrate to the GAB in summer, and spend a large proportion of their days at the surface whilst there, as a form of behavioural thermoregulation, allowing them to increase their body temperature and thereby speed up digestion and growth rates (Gunn and Block 2001). Quantitative assessments of the influence of water temperature on growth rates and digestion in tunas are largely lacking (Clark et al. 2010), with most understanding of the influence of temperature on growth based on modelling approaches (e.g. Chapman et al. 2011).

Seasonal cycles in ocean physical processes have been relatively stable on evolutionary timescales, and species within the marine environment have evolved in response. The use of the GAB by SBT is one such example. Any change in the duration or intensity of seasonal cycles on timescales shorter than that in which organisms in the marine environment can adapt may lead to mismatches in biological processes, resulting in deleterious impacts on marine populations.

Current projections of climate suggest that changes to seasonal cycles will continue to occur, but with considerable spatial variability. Extremes associated with the summer months will become more prevalent (Reisinger et al. 2014), particularly when coupled with climate phenomena cycles. The core transport in the Indonesian Through-flow and the Leeuwin Current is projected to continue to decrease (Sun et al. 2012) with Indian Ocean Dipole (IOD) events becoming more frequent. This will affect warming throughout the area that the Leeuwin Current and IOD influences, including the GAB. It will also influence the exchange of water between the open ocean and inshore regions within the GAB, influencing nutrient supply and species that rely on cross-shelf transport. Westerly winds are projected to decrease (Feng et al. 2009) and although the overall effect of this decrease is to enhance warming, how changes to westerly winds across the GAB might affect seasonal upwelling in the GAB is currently unclear. Warming of waters is also expected to result in decreases in ocean oxygen concentrations and increased stratification with effects on nutrient supply to surface waters and ocean productivity (Evans et al. 2017). How these ongoing changes to the ocean environment might influence the spatial distribution and productivity of SBT and the seasonal use of the GAB by juvenile SBT is currently unknown. The results from this study serve to form a baseline against which future changes might be compared against.

9.2 Interaction between oil and gas exploration and juvenile SBT

There is no doubt that there has been overlap in the timing of geophysical surveys and the occurrence of SBT in the GAB and that this temporal overlap within the GAB has been occurring for substantial amounts of time.

The extent to which individual fish and the sound generated by individual surveys directly overlap is not possible to determine with sufficient confidence for two reasons. First, the estimated position of individual tagged SBT using light-based geolocation process has inherent uncertainty. The likelihood method used here allows for both estimation of uncertainty and integration of location uncertainty within the movement model, which vastly improves our capacity to determine overall movements and regional residency. Nevertheless, it does not allow the "pinpointing" of an individual at an exact location at an exact time; hence, position estimates are generally aggregated into 0.5 to 1 degree squares for analysis.

Second, importantly, without direct measurements of the soundscape of the greater area of the GAB, it is difficult, firstly, to characterise the underwater sound produced by oil and gas exploration through time and, secondly, to estimate the potential area exposed to levels and frequencies of sound associated with impacts for particular species (including cumulative impacts) and thereby the extent of impact of exploration activity on marine life within the region. Variability in the sound generated from a seismic source for each shot fired has been recorded (see McCauley et al. 2016), resulting in variability of the received level of sound at any range. This compounds any comparisons of both sound generated within a survey and sound generated between surveys.

Further, as identified above, the distribution, movement and behaviour of juvenile SBT is influenced by a wide range of factors both environmental and anthropogenic in nature. The relationships between the environment of the GAB and the behaviours of juvenile SBT are highly complex, potentially interdependent and co-varying in nature. In addition, the nature of impacts of the many varying anthropogenic activities juvenile SBT might be exposed to (e.g. commercial fishing, shipping, oil and gas exploration etc.) are also likely to be complex and interactive in nature. These numerous potential compounding factors influencing the movements and behaviour of juvenile SBT whilst in

the GAB need to be accounted for before the extent of overlap and any associated behavioural responses to specific anthropogenic activities could be determined.

While some information is available for modelling the effects of sound on hearing in marine animals, far less is known of the behavioural responses of marine animals to sound and their significance at the individual through to population level. Controlled exposure experiments, where constrained fish have been exposed to sound generated by a seismic airgun at varying distances from the cages, have reported startle responses (McCauley et al. 2003; Boeger et al. 2006; Fewtrell and MCauley 2012), threshold shifts in hearing (Popper et al. 2005) and direct damage to organs including damage to sensory hair cells in the ears of fish (McCauley et al. 2003), bruised swim bladders, kidney trauma, renal edema and haemotomas (Popper et al. 2016). Assessment of open water systems have been variable in determining behavioural responses to sound generated by seismic operations. Behaviours documented have ranged from no response to marked changes in diving behaviour and alarm responses (Miller and Cripps 2013; Carroll et al. 2017).

Relying on observational data to determine the responses of animals to sound generated by anthropogenic activities is not sufficient, because observations do not allow cause-and-effect relationships to be established (Kunc et al. 2014). Further comparisons between the distribution of anthropogenic activities to sets of observational data collected could be undertaken, for example comparing the distributions of juvenile SBT schools recorded by the annual aerial survey with the distribution of oil and gas activity, but they would be limited by many of the same factors the comparisons undertaken here are.

Contrasting the results from this study with the analysis of data from the aerial survey (Eveson and Farley 2016) and previous investigations of habitat preferences (Eveson et al. 2015) further supports the unreliability of such comparisons. Two of the most influential factors identified in the model used to investigate the influence of the environment on the surfacing behaviour of SBT and/or the ability of spotter to see schools of fish have been found to be SST and wind speed, with the number of sightings increasing as SST increases and the number of sighting decreasing as wind speed increases (Eveson and Farley 2016). In contrast, the results from this study suggest that SST and wind speed are not significant factors that influence how much time juveniles spend at the surface during the day. Previous investigations of the habitat preferences of juvenile SBT in the GAB found that fish prefer to be in locations with SST values in the range of 19-22°C (Eveson et al. 2015). The results from this study suggest that once fish are in locations with these temperatures, the amount of time they spend at the surface does not vary greatly. The contrasting and complimentary results provided by this study suggest that the decrease in aerial survey sightings in windier conditions is due more to schools not being visible, rather than to fish not being present at the surface. This suggests that any comparisons of the presence or absence of juvenile SBT from the aerial survey to the distribution of anthropogenic activities such as geophysical surveys with the view of determining the influence of such activities on the distribution of juvenile SBT are therefore not appropriate.

Determining the range of responses of a fish species to sound generated by anthropogenic activities requires well designed experiments that include adequate sample sizes and the necessary controls to account for potential compounding factors to obtain reliable results. Such experiments are inherently complex, logistically difficult, and expensive. Moreover, any experimentation should not only be able to detect and measure changes in behaviour, but also be able to attribute changes in behaviour to the factors that are driving them, factors that may be associated with exposure to sound, but also may be associated with other factors such as the physical environment. Further, the many activities required for a successful experimental design, execution, and analysis require expertise from a range of disciplines including expertise in animal behaviour, experimental design

and statistical analysis, hearing and auditory perception, sound generation and propagation in the ocean, ambient sea noise, and signal detection (Cato et al. 2016). Without due consideration of the requirements for adequately assessing the behavioural responses to sound generated by activities such as oil and gas exploration, assessing the impacts of these activities on marine animals will continue to be difficult and as a result, largely either a qualitative or modelling exercise with inherent uncertainties.

9.3 Key knowledge gaps and recommendations

Understanding how natural variability drives processes within the marine environment, and how extremes in this variability affect marine organisms and processes is essential to both quantifying and understanding the impacts associated with anthropogenic pressures. In order to ascertain population-level responses to environmental variability and pressures associated with human activity, long time series from animal populations are required. Such time series allow for seasonal and inter-annual variability in behaviours to be quantified and longer term trends to be identified.

Continued monitoring of the movements and behaviour of juvenile SBT, particularly in light of anticipated rebuilding of the population, through further deployments of archival tags across the range of the species and across age groups will be important for understanding how components of the population respond and are impacted by pressures placed on them, what effects rebuilding of the population might have on overall distributions and what flow-on impacts these might have for associated industries such as commercial and recreational fisheries.

The distribution of juvenile SBT is ultimately driven by a combination of the distribution of food resources and environmental conditions conducive to suit the physiological requirements for metabolic functioning. The investigations conducted here explored variability in the behaviour of juvenile SBT with a range of proximal factors rather than direct observation of factors likely to directly influence SBT behaviour, such as the distribution of prey species. This is largely because few data relating to factors directly influencing juvenile SBT behaviour exist such as that relating to the diet of juvenile SBT whilst in the GAB, particularly in relation to spatial and temporal variability in these factors. A next step in investigating the drivers associated with juvenile SBT movements and habitats would be to use data such as the distribution of prey species (e.g. spawning habitat of sardines, meso-pelagic species survey data) as covariates in models to allow for the testing of a range of predator-prey hypotheses.

The analysis of the feeding behaviour of juvenile SBT can only be considered preliminary at this stage. The data used to generate the feed intake prediction models (from Gunn et al. 2001) are restricted to a single prey type (pilchards) and are also a relatively small data set. As such, any extension of interpretation of results in relation to migration and habitat use can also only be considered preliminary. Ascertaining the links between the productivity and energetic benefits of the prey items of juvenile SBT and how these might be associated with the movements of juveniles and their habitat preferences requires considerable further work. Targeted collection of empirical data ideally from cage-based feeding experiments would help elucidate the response of visceral temperature signals to a mixed diet and the response of feeding to variability in water temperature.

At the same time, such cage based experiments would also allow further investigation of the response of digestion to variability in water temperature and what role this might have in driving juvenile SBT to use the GAB over the summer months. Although such experiments are labour intensive and expensive, they provide an opportunity to investigate a wide range of physiological

components potentially driving the behaviour of juvenile SBT, thereby providing the possibility for step changes in understanding these drivers.

The exploration of oil and gas activities and their potential impacts on juvenile SBT presented here was based on observational data only and, as a result, is limited in its ability to provide quantitative insights into the responses of juvenile SBT to these activities. In order to better understand of the impacts of oil and gas exploration activities on juvenile SBT, further work across a range of disciplines would be required. This would include (i) better understanding the processes involved in hearing in SBT and associated thresholds, thereby providing a direct basis for testing behavioural responses and thresholds associated with the impacts of noise and (ii) extending monitoring of sound in the marine environment of the GAB to allow development of ocean soundscape models that capture the spatial and temporal variation inherent in the ocean environment and provide an overall baseline understanding of the sounds generated in the environment that SBT are exposed to.

Cage based experiments would provide the opportunity to further understand processes involved in hearing in SBT and via controlled exposure experiments, also provide for the testing of behavioural responses and thresholds associated with the generation of sound by anthropogenic activities across a range of intensities and distances. The information generated by such experiments would provide valuable information for providing guidelines for use by the oil and gas industry particularly in relation to management of operations in the vicinity of the commercial fishery.

In association, ongoing, monitoring of soundscapes in the marine environment facilitated through the Integrated Marine Observing System (IMOS) network of National Reference Stations should be maintained. The international community is encouraging the establishment of a Global Ocean Acoustical Observing System, building on platforms and capability such as IMOS in Australian waters (Boyd et al. 2011). Such a system would allow the ocean soundscape in Australian waters to be established, including its spatial and temporal variance, and provide direct input into processes to regulate anthropogenic activities generating sound in the marine environment.

10. CONCLUSION

Evolutionary theory suggests that the behaviour and habits of juvenile SBT have evolved in response to seasonal changes in availability of resources. Cyclical migrations between the GAB and offshore waters of the Indian Ocean and Tasman Sea allow SBT to capitalize on predictable prey resources in the GAB and maximize their energetic return by concentrating a greater proportion of energy into somatic growth while resident in warmer GAB waters during the summer months. Yet the complexities of their behaviour and our imprecise understanding of the relationships with indices of ocean state suggest that being able to identify clear predictors of behaviour and potential responses to change, be they environmental or anthropogenic, is difficult.

There is no doubt that juvenile SBT, similarly to other marine animals in the pelagic environments of the GAB, are exposed to sounds generated by a variety of sources, both natural and anthropogenic. Anthropogenic generation of sound in the GAB has a variety of sources and has been generated throughout the GAB for many decades. Anthropogenic sound sources including those associated with oil and gas exploration and commercial shipping however, have been increasing over the last two decades (see also Evans et al. 2017). Whether acute sources of sound such as that associated with oil and gas exploration and production will continue to increase is largely unknown and will depend on many social and economic factors. Low intensity chronic sources of sound are likely to continue to increase given ongoing increases over the last decade, and will be an increasingly

prominent source of anthropogenically derived sound not only in the GAB, but in Australian waters in general (see Evans et al. 2017). How this ongoing increase in chronic sources of sound and any increase in acute sources of sound will impact SBT remain, at least at present, unknown.

This study has vastly improved our knowledge of the behaviour of juvenile SBT and has progressed quantitative approaches for establishing the foundations for assessments of the behaviour of juvenile SBT in relation to their environment into the future. The predictive models developed and results obtained in this project, along with the results of the oceanography and pelagic themes of the Great Australian Bight Research Program, provide the necessary foundation for the design and implementation of targeted research projects to directly address the questions of the interaction of physical and biological oceanography, meso-pelagic abundance and distribution and higher order predator spatial and trophic dynamics. It also has provided for the ongoing collection of data from juvenile SBT into the near future; tags deployed under this study are likely to continue to be returned over the coming years, adding to the dataset generated by this study. This provides the opportunity for monitoring the spatial components of the dynamics of juvenile SBT as the rebuilding program for the population progresses.

11. REFERENCES

Alerstam, T., Hedenström, A., Åkesson, S., 2003. Long-distance migration: evolution and determinants. Oikos 103, 247–260.

Amante, C., Eakins, B.W., 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA. doi:10.7289/V5C8276M.

Anon., 2015. Australian research mortality allowance request. Working paper CCSBT-ESC/1509/17 prepared for the twentieth CCSBT Extended Scientific Committee meeting, 1–5 September, Incheon, South Korea.

Basson, M., Bravington, M.V., Hartog, J.R., Patterson, T.A., 2016. Experimentally derived likelihoods for light-based geolocation. Methods Ecol Evol 7, 980–989. doi:10.1111/2041-210X.12555.

Basson, M., Farley, J.H., 2014. A standardised abundance index from commercial spotting data of southern bluefin tuna (*Thunnus maccoyii*): random effects to the rescue. Plos One 9, e116245. doi:10.1371/journal.pone.0116245

Basson, M., Hobday, A.J., Eveson, J.P., Patterson, T.A., 2012. Spatial interactions among juvenile southern bluefin tuna at the global scale: a large scale archival tag experiment. Report 2003/002 to the Fisheries Research Development Corporation. CSIRO, Hobart.

Benoit-Bird, K.J., Au, W.W.L., Wisdom, D.W., 2009. Nocturnal light and lunar cycle effects on diel migration of micronekton. Limnol. Oceanogr. 54, 1789–1800.

Bertrand, A., Barbieri, M.A., Gerlotto, F., Leiva, F., Córdova, J., 2006. Determinism and plasticity of fish schooling behaviour as exemplified by the South Pacific jack mackerel *Trachurus murphyi*. Mar. Ecol. Prog. Ser. 311, 145–156.

Bertrand, A., Josse, E., Bach, P., Gros, P., Dagorn, L., 2002. Hydrological and trophic characteristics of tuna habitat: consequences on tuna distribution and longline catchability. Can. J. Fish. Aquat. Sci 59, 1002–1013. doi:10.1139/F02-073.

Bestley, S., Gunn, J.S., Hindell, M.A., 2009. Plasticity in vertical behaviour of migrating juvenile southern bluefin tuna (*Thunnus maccoyii*) in relation to oceanography of the south Indian Ocean. Fish. Oceanogr. 18, 237–254. doi:10.1111/j.1365-2419.2009.00509.x.

Bestley, S., Patterson, T.A., Hindell, M.A., Gunn, J.S., 2008. Feeding ecology of wild migratory tunas revealed by archival tag records of visceral warming. J. Animal Ecol. 77, 1223–1233. doi:10.1111/j.1365-2656.2008.01437.x.

Bestley, S., Patterson, T.A., Hindell, M.A., Gunn, J.S., 2010. Predicting feeding success in a migratory predator: integrating telemetry, environment, and modelling techniques. Ecol. 91, 2372–2384. doi:10.1890/08-2019.1.

Block, B.A., Jonsen, I.D., Jorgensen, S.J., Winship, A.J., Shaffer, S.A., Bograd, S.J., Hazen, E.L., Foley, D.G., Breed, G.A., Harrison, A.-L., Ganong, J.E., Swithenbank, A., Castleton, M., Dewar, H., Mate, B.R., Shillinger, G.L. Schaefer, K.M., Benson, S.R., Weise, M.J., Henry, R.W., Costa, D.P., 2011. Tracking apex marine predator movements in a dynamic ocean. Nature 475, 86–90. doi:10.1038/nature10082.

Boeger, W.A., Pie, M.R., Ostrensky, A., Cardoso, M.F., 2006. The effect of exposure to seismic prospecting on coral reef fishes. Brazil. J. Oceanogr. 54, 235–239. doi:10.1590/S1679-87592006000300007.

Boyd, I.L., Frisk, G., Urban, E., Tyack, P., Ausubel, J., Seeyave, S., Cato, D., Southall, B., Weise, M., Andrew, R., Akamatsu, T., Dekeling, R., Erbe, C., Farmer, D., Gentry, R., Gross, T., Hawkins, A., Li, F., Metcalf, K., Miller, J.H., Moretti, D., Rodrigo, C., Shinke, T., 2011. An International Quiet Ocean Experiment. Oceanogr. 24, 174–181, doi:10.5670/oceanog.2011.37.

Bradford, R.W., Evans, K., Hobday, A.J., Lansdell, M., 2015. CSIRO Code of practice for tagging marine animals. CSIRO Marine and Atmospheric Research Paper 028, second edition. CSIRO, Hobart.

Carey, F.G., Gibson, Q.H., 1983. Heat and oxygen exchange in the rete mirabile of the bluefin tuna, *Thunnus thynnus*. Comp. Biochem. Physiol. A 74, 333–342.

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

Carroll, A.G., Przeslawski, R., Duncan, A., Gunning, M., Bruce, B., 2017. A critical review of the potential impacts of marine seismic surveys on fish and invertebrates. Mar. Poll. Bull. 114, 9–24. doi:10.1016/j.marpolbul.2016.11.038.

Cato, D.H., Dunlop, R.A., Noad, M.J., McCauley, R.D., Kneist, E., Paton, D., Kavanagh, A.S., 2016. Addressing challenges in studies of behavioural responses of whales to noise, in: Popper, A.N., Hawkins, A. (Eds.). The effects of noise on aquatic life II, Springer Science + Business Media New York, pp 145–152.

Caton, A.E., 1991. Review of aspects of southern bluefin tuna biology, population, and fisheries. IATTC Special Rep. 7, 181–350.

CCSBT., 2006. Report of the eleventh meeting of the Scientific Committee, 12–15 September, Tokyo, Japan. Commission for the Conservation of Southern Bluefin Tuna, Canberra.

CCSBT., 2009. Report of the fourteenth meeting of the Scientific Committee, 5–11 September, Busan, South Korea. Commission for the Conservation of Southern Bluefin Tuna, Canberra.

CCSBT., 2010. Report of the fifteenth meeting of the Scientific Committee, 11 September, Narita, Japan. Commission for the Conservation of Southern Bluefin Tuna, Canberra.

CCSBT., 2011. Report of the sixteenth meeting of the Scientific Committee, 19–28 September, Bali, Indonesia. Commission for the Conservation of Southern Bluefin Tuna, Canberra.

CCSBT., 2013. Report of the eighteenth meeting of the Scientific Committee. 7 September, Canberra, Australia. Commission for the Conservation of Southern Bluefin Tuna, Canberra.

CCSBT., 2014. Report of the nineteenth meeting of the Scientific Committee. 6 September, Auckland New Zealand. Commission for the Conservation of Southern Bluefin Tuna, Canberra.

CCSBT., 2015. Report of the twentieth meeting of the Scientific Committee, 5 September, Incheon, South Korea. Commission for the Conservation of Southern Bluefin Tuna, Canberra.

CCSBT., 2016. Report of the twenty first meeting of the Scientific Committee, 10 September, Kaohsiung, Taiwan. Commission for the Conservation of Southern Bluefin Tuna, Canberra.

Chapman, E.W., Jørgensen, C., Lutcavage, M.E., 2011. Atlantic bluefin tuna (*Thunnus thynnus*): a state-dependent energy allocation model for growth, maturation and reproductive investment. Can. J. Fish. Aquat. Sci. 68, 1934–1951. doi: 10.1139/f2011-109.

Clark, T.D., Brandt, W.T., Nogueira, J., Rodriguez, L.E., Price, M., Farwell, C.J., Block, B.A., 2010. Postprandial metabolism of Pacific bluefin tuna (*Thunnus orientalis*). J. Exp. Biol. 213, 2379–2385. doi:10.1242/jeb.043455.

Collette, B., Chang, S.-K., Di Natale, A., Fox, W., Juan Jorda, M., Miyabe, N., Nelson, R., Uozumi, Y., Wang, S., 2011. *Thunnus maccoyii*. The IUCN Red List of Threatened Species 2011: e.T21858A9328286.

Costa, D. P., 1993. The secret life of marine mammals: Novel tools for studying their behaviour and biology at sea. Oceanogr. 6, 120–128.

Cowling, A., Hobday, A., Gunn, J., 2003. Development of a fishery-independent index of abundance for juvenile southern bluefin tuna and improvement of the index through integration of environmental, archival tag and aerial survey data. FRDC Final Report 96/118 and 99/105, CSIRO Marine Research, Hobart.

Dagorn, L., Bach, P., Josse, E., 2000. Movement patterns of large bigeye tuna (*Thunnus obesus*) in the open ocean, determined using ultrasonic telemetry. Mar. Biol. 136, 361–371.

Dale, J.J., Gray, M.D., Popper, A.N., Rogers, P.H., Block, B.A., 2015. Hearing thresholds of swimming Pacific bluefin tuna. J. Comp. Physiol. A 201, 441–454. doi:10.1007/s00359-015-0991-x.

Davies, C.R., Preece, A., Patterson, H., Stobutzki, I., 2012. Strategic Research Plan: summary of progress since 2007 review and potential directions for future collaborative activities. Working paper CCSBT-ESC/1208/24, prepared for the seventeenth CCSBT Extended Scientific Committee meeting, 27–31 August, Tokyo, Japan.

Durant, J. M., Hjermann, D.Ø., Anker-Nilssen, T., Beaugrand, G., Mysterud, A., Pettorelli, N., Stenseth, N.C., 2005. Timing and abundance as key mechanisms affecting trophic interactions in variable environments. Ecol. Lett. 8, 952–958. doi:10.1111/j.1461-0248.00798.x.

Econsearch, 2014. The economic impact of aquaculture on the South Australian State and regional economies, 2012/13. Report to PIRSA Fisheries and Aquaculture. Econsearch, Marryatville.

Ekstrom, P.A., 2002. Inferring the surface irradiance from measurements made at depth. http://www.lotek.com/irradiance.pdf.

Erbe, C., Ainslie, M.A., de Jong, C.A.F., Racca, R., Stocker, M., 2016. Summary report Panel 1: The need for protocols and standards in research on underwater noise impacts on marine life, in: Popper, A.N., Hawkins, A. (Eds.). The effects of noise on aquatic life II. Springer Science + Business Media, New York, pp 1265–1271.

Evans, K., Abascal, F., Kolody, D., Sippel, T., Holdsworth J, Maru, P., 2014. The horizontal and vertical dynamics of swordfish in the South Pacific Ocean. J. Exp. Mar. Biol. Ecol. 450, 55–57. doi:10.1016/j.jembe.2013.10.025

Evans, K., Brown, J.N., Sen Gupta, A., Nicol, S.J., Hoyle, S., Matear, R., Arrizabalaga, H., 2015. When 1 + 1 can be > 2: Uncertainties compound when simulating climate, fisheries and marine ecosystems. Deep Sea Res. II 113, 312–322. doi:10.1016/j.dsr2.2014.04.006.

Evans, K., Bax, N., Smith, D.C., 2017. Australia state of the environment 2016: marine environment, independent report to the Australian Government Minister for the Environment and Energy, Australian Government Department of the Environment and Energy, Canberra.

Evans, K., Langley, A., Clear, N.P., Williams, P., Patterson, T., Sibert, J., Hampton, J., Gunn, J.S., 2008. Behaviour and habitat preferences of bigeye tuna (*Thunnus obesus*) and their influence on longline fishery catches in the western Coral Sea. Can. J. Fish. Aquat. Sci. 65, 2427–2443. doi:10.1139/F08-148.

Evans, K., Patterson, T.A., Hartog, J., Davies, C., 2012. Proposed use of CCSBT Research Mortality Allowance to facilitate electronic tagging of SBT as part of Australia's contributions to SBT research in 2012/13 and 2013/14. Working paper CCSBT-ESC/1208/26 prepared for the seventeenth CCSBT Extended Scientific Committee meeting 27–31 August, Tokyo, Japan.

Eveson, J.P., Laslett, G.M., Polacheck T., 2004. An integrated model for growth incorporating tag-recapture, length-frequency, and direct aging data. Can. J. Fish. Aquat. Sci 61, 292–306. doi:10.1139/F03-163.

Eveson, P., 2007. Southern bluefin tuna aerial survey in the Great Australian Bight - 2007: preliminary results of aerial survey and commercial spotting data. Final report to the Department of Agriculture, Fisheries and Forestry, CSIRO, Hobart.

Eveson, P., 2011. Updated growth estimates for the 1990s and 2000s, and new age-length cut-points for the operating model and management procedures. Working paper CCSBT-ESC/1107/09 prepared for the sixteenth CCSBT Extended Scientific Committee meeting, 19–28 September, Bali, Indonesia.

Eveson, P., Farley, J., 2016. The aerial survey index of abundance: 2016 updated results. Working paper CCSBT-ESC/1609/09 prepared for the twenty first CCSBT Extended Scientific Committee meeting, 5–10 September, Kaohsiung, Taiwan.

Farley, J.H., Davis, T.L.O., Bravington, M.V., Andamari, R., Davies, C.R., 2015. Spawning dynamics and size related trends in reproductive parameters of southern bluefin tuna, *Thunnus maccoyii*. Plos One 10, e0125744. doi:10.1371/journal. pone.0125744.

Farley, J.H., Eveson, J.P., Davis, T.L.O., Andamari, R., Proctor, C.H., Nugraha, B., Davies, C.R., 2014. Demographic structure, sex ratio and growth rates of southern bluefin tuna (*Thunnus maccoyii*) on the spawning ground. Plos One 9, e96392. doi:10.1371/journal.pone.0096392.

Feng, M., Weller, E., Hill, K., 2009. The Leeuwin Current. Marine climate change in Australia. Impacts and adaptation responses. A marine climate change impacts and adaptation report card for Australia 2009. Publication 05/09. Southport, Queensland: National Climate Change Adaptation Research Facility. Downloaded from: www.oceanclimatechange.org.au/

Fewtrell, J.L., McCauley, R.D., 2012. Impact of air gun noise on the behaviour of marine fish and squid. Mar. Poll. Bull. 64, 984–993. doi:10.1016/j.marpolbul.2012.02.009.

Fletcher, W.J., 1999. Vertical distribution of pilchard (*Sardinops sagax*) eggs and larvae off Southern Australia. Mar. Freshw. Res. 50, 117–122.

Fujioka, K., Hobday, A.J., Kawabe, R., Miyashita, K., Itoh, T., Takao, Y., 2010. Interannual variation in summer habitat use by juvenile southern bluefin tuna (*Thunnus maccoyii*) in southern Western Australia. Fish. Oceanogr. 19, 183–195. doi:10.1111/j.1365-2419.2010.00536.x.

Giannoulaki, M., Machias, A., Tsimenides, N., 1999. Ambient luminance and vertical migration of the sardine *Sardina pilchardus*. Mar. Ecol. Progr. Ser. 178, 29–38.

Goldsworthy, S.D., Page, B., Roger, P.J., Bulman, C., Wiebkin, A., McLeay, L.J., Einoder, L., Baylis, A.M.M., Braley, M., Caines, R., Daly, K., Huveneers, C., Peters, K., Lowther, A.D., Ward, T.M., 2013. Trophodynamics of the eastern Great Australian Bight ecosystem: Ecological change associated with the growth of Australia's largest fishery. Ecol. Model. 255, 38–57. doi:10.1016/j.ecolmodel.2013.01.006.

Gunn, J.S., Block, B.A., 2001. Advances in acoustic, archival, and satellite tagging of tunas, in: Block, B.A., Stevens, E. (Eds.). Tuna physiology, ecology and evolution. Academic Press, San Diego, California, pp 167–224

Gunn, J., Hartog, J., Rough, K., 2001. The relationship between food intake and visceral warming in southern bluefin tuna (*Thunnus maccoyii*), in: Sibert, J., Nielsen, J.L. (Eds.). Electronic tagging and tracking in marine fisheries. Springer Science + Business Media, Dordrecht, pp 109–130.

Gunn, J., Polacheck, T., Davis, T., Sherlock, M., Betlehem, A., 1994. The development and use of archival tags for studying the migration, behaviour and physiology of southern bluefin tuna, with an assessment of the potential for transfer of the technology to groundfish research. Proceedings of the ICES MiniSymposium on Fish Migration 21, 23.

Gunn, J., Young, J., 1999. Environmental determinants of the movement and migration of juvenile southern bluefin tuna, in: Hancock, D.A., Smith, D.C., Koehn, J.D. (Eds.). Australian Society for Fish Biology Workshop Proceedings: Fish Movement and Migration. Australian Society for Fish Biology, Bendigo, pp. 123–128.

Guttal, V., Couzin, I.D., 2010. Social interactions, information use, and the evolution of collective migration. Proc. Natl. Acad. Sci. 107, 16172–16177. doi: 10.1073/pnas.1006874107.

Hartog, J.R., Patterson, T.A., Hartmann, K., Jumppanen, P., Cooper, S., Bradford R., 2009. Developing an integrated database system for the management of electronic tagging data, in: Nielsen, J.L., Arrizabalaga, H., Fragoso, N., Hobday, A., Lutcavage, M., Sibert, J. (Eds.). Tagging and tracking of marine animals with electronic devices, Springer Dordrecht, pp 367–380.

Hays, G.C., 2003. A review of the adaptive significance and ecosystem consequences of zooplankton diel migrations. Hydrobiologia 503, 163–170.

Hazen, E.L., Suryan, R.M., Santora, J.A., Bograd, S.J., Watanuki, Y., Wilson, R.P., 2013. Scales and mechanisms of marine hotspot formation. Mar. Ecol. Prog. Series 487, 177–183. doi:10.3354/meps10477.

Hernández-León, S., 2008. Natural variability of fisheries and lunar illumination: a hypothesis. Fish Fish. 9, 138–154. doi:10.1111/j.1467-2979.2008.00272.x.

Hillary, R., Preece, A., Davies, C., 2014. Assessment of stock status of southern bluefin tuna in 2014 with reconditioned operating model. Working paper CCSBT-ESC/1409/21 prepared for the nineteenth CCSBT Extended Scientific Committee meeting, 1–6 September, Auckland, New Zealand.

Hillary, R.M., Preece, A.L., Davies, C.R., Kurota, H., Sakai, O., Itoh, T., Parma, A.M., Butterworth, D.S., Ianelli, J., Branch, T.A., 2016. A scientific alternative to moratoria for rebuilding depleted international tuna stocks. Fish Fish. 17, 469–482. doi:10.1111/faf.12121.

Hobday, A.J., Spillman, C.M., Eveson, J.P., Hartog, J.R., 2016. Seasonal forecasting for decision support in marine fisheries and aquaculture. Fish. Oceanogr. 25, 45–56. doi:10.1111/fog.12083.

Hobday, A.J., Lough, J.M., 2011. Projected climate change in Australian marine and freshwater environments. Mar. Freshw. Res. 62, 1000–1014. doi:10.1071/MF10302.

Itoh, T., Kemps, H.A., Totterdell, J.A., 2011. Diet of young southern bluefin tuna *Thunnus maccoyii* in the south western coastal waters of Australia in summer. Fish. Sci. 77, 337–344. doi: 10.1007/s12562-011-0340-0.

Itoh, T., Takahashi, N., 2016. Update of the core vessel data and CPUE for southern bluefin tuna in 2016. Working paper CCSBT-ESC/1609/21 prepared for the twenty first CCSBT Extended Scientific Committee meeting, 5 – 10 September, Kaohsiung, Taiwan.

Iversen, R.T.B., 1967. Response of the yellowfin tuna (*Thunnus albacares*) to underwater sound, in: Tavolga, W.N. (Ed.), Marine bioacoustics II. Pergamon Press, Oxford, pp 105–121.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Am. Met. Soc. 77, 437–471.

Kitagawa, T., Nakata, H., Kimura, S., Tsuji, S., 2001. Thermoconservation mechanisms inferred from peritoneal cavity temperature in free-swimming Pacific bluefin tuna *Thunnus thynnus orientalis*. Mar. Ecol. Prog. Ser. 220, 253–263.

Kitagawa, T., Kimura, S., Nakata, H., Yamada, H., 2007. Why do young Pacific bluefin tuna repeatedly dive to depths through the thermocline? Fish. Sci. 73, 98–106.

Kloser, R.J., Van Ruth, P.D., Doubell, M., Downie, R., Flynn, A., Gershwin, L., Patten, N., Revill, A., Richardson, A.E., Ryan, T.E., Sutton, C., 2017. Characterisation of spatial variability of offshore/slope plankton and micronekton communities. Project 2.2, Pelagic Ecosystem and Environmental Drivers. Great Australian Bight Research Program, GABRP Research Report Number 22, 289 pp. CSIRO, Hobart.

Kunc, H.P., Lyons, G.N., Sigwart, J.D., McLaughlin, K.E., Houghton, J.D.R., 2014. Anthropogenic noise affects behaviour across sensory modalities. Am. Nat. 184, E93–E100. doi:0.1098/rspb.2016.0839.

Laurs, R.M., Fiedler, P.C., Montgomery, D.R. 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. Deep Sea Res. 31, 1085–1099.

Lehodey, P., 2004. Climate and fisheries: an insight from the Pacific Ocean, in: Stenseth, N.C., Ottersen, G., Hurrel, J., Belgrano, A. (Eds.). Ecological effects of climate variations in the North Atlantic. Oxford University Press, pp. 137–146.

Lewison, R.L., Hobday, A.J., Maxwell, S.M., Hazen, E.L., Hartog, J.R., Dunn, D.C., Briscoe, D.K., Fossette, S., O'Keefe, C.E., Barnes, M., Abecassis, M., Bograd, S.J., Bethoney, N.D., Bailey, H., Wiley, D., Andrews, S., Hazen, L., Crowder, L.B., 2015. Dynamic ocean management: Identifying the critical ingredients of dynamic approaches to ocean resource management. BioScience 65, 486–498. doi:410.1093/biosci/biv1018.

Lynch, T.P., Morello, E.B., Evans, K., Richardson, A.J., Rochester, W., Steinberg, C.R., Roughan, M., Thompson, P., Middleton, J.F., Feng, M., Sherrington, R., Brando, V., Tilbrook, B., Ridgway, K., Allen, S., Doherty, P., Hill, K., Moltmann, T.C., 2014. IMOS National Reference Stations: A Continental-Wide Physical, Chemical and Biological Coastal Observing System. PLoS ONE 9: e113652. doi:10.1371/journal.pone.0113652.

Madigan, D.J., Carlisle, A.B., Gardner, L.D., Jayasundara, N., Micheli, F., Schaefer, K.M., Fuller, D.W., Block, B.A., 2015. Assessing niche width of endothermic fish from genes to ecosystem. Proc. Nat. Acad. Sci. 112, 8350–8355. doi:10.1073/pnas.1500524112

Malte, H., Larsen, C., Musyl, M., Brill, R., 2007. Differential heating and cooling rates in bigeye tuna (*Thunnus obesus*, Lowe): A model of non-steady state heat exchange. J. Exp. Biol. 210, 2618–2626. doi:10.1242/jeb.003855.

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

McCauley, R. D., Cato, D. H., 2016. Evening fish choruses in the Perth Canyon and their potential link with Myctophidae fishes. J. Acoust Soc. Am. 140, 2384–2398. doi:10.1121/1.4964108.

McCauley, R.D., Cato, D.H., Duncan, A.J., 2016b. Regional variations and trends in ambient noise: Examples from Australian waters, in: Popper, A.N., Hawkins, A. (Eds.) The effects of noise on aquatic life II, Springer Science + Business Media New York, pp 687–696.

McCauley, R., Duncan, A., Garilov, A., 2013. Air gun signal transmission, ambient noise, whale and fish signals recorded during and after the *Ceduna* seismic survey in the Great Australian Bight, November 2011 to June 2012. Report 2012-39. Centre for Marine Science and Technology, Curtin University, Perth.

McCauley, R. D., Duncan, A. J., Gavrilov, A. N., Cato, D. H., 2016a. Transmission of marine seismic survey, air gun array signals in Australian waters. Proceedings of ACOUSTICS 2016, 9–11 November 2016, Brisbane, Acoustics Australia.

McCauley, R.D., Fewtrell, J., Popper, A.N., 2003. High intensity anthropogenic sound damages fish ears. J. Acoust. Soc. Am.113, 638–642. doi:10.1121/1.1527962

McClatchie, S., Middelton, J.F., Ward, T.M., 2006. Water mass analysis and alongshore variation in upwelling intensity in the eastern Great Australian Bight. J. Geophys. Res. 111, C08007. doi:10.1029/2004JC002699.

McIntosh, R.R., Page, B., Goldsworthy, S.D., 2006. Dietary analysis of regurgitates and stomach samples from free-living Australian sea lions. Wild. Res. 33, 661–669. doi:10.1071/WR06025.

Middleton, J.F., Bye, J.A.T., 2007. A review of the shelf slope circulation along Australia's southern shelves: Cape Leeuwin to Portland. Prog. Oceanogr. 75, 1–41. doi:10.1016/j.pocean.2007.07.001.

Miller, D.L., Burt, M.L., Rexstad, E.A., Thomas, L., 2013. Spatial models for distance sampling data: Recent developments and future directions. Method. Ecol. Evol. 4, 1001–10. doi:10.1111/2041-210X.12105.

Miller, I., Cripps, E., 2013. Three dimensional marine seismic survey has no measurable effect on species richness or abundance of a coral reef associated fish community. Mar. Poll. Bull. 77, 63–70. doi:10.1016/j.marpolbul.2013.10.031.

NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group., 2014. Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Ocean Color Data, NASA OB.DAAC. http://doi.org/10.5067/ORBVIEW-2/SEAWIFS_OC.2014.0.

OSPAR., 2009a. Assessment of the environmental impact of underwater noise. OSPAR Commission, London.

OSPAR., 2009b. Overview of the impacts of anthropogenic underwater sound in the marine environment. OSPAR Commission, London.

Page, B., McKenzie, J., Goldsworthy, S.D., 2005. Dietary resource partitioning among sympatric New Zealand and Australian fur seals. Mar. Ecol. Progr. Ser. 293, 283–302.

Pante, E., Simon-Bouhet, B., 2013. marmap: a package for importing, plotting and analyzing bathymetric and topographic data in R. Plos One 8, e73051. doi:10.1371/journal.pone.0073051.

Patterson, H., Stobutski, I., 2016. Southern bluefin tuna. Status of Australian fish stocks. Fisheries Research and Development Corporation, Canberra. Available at: http://fish.gov.au/report/62-Southern-Bluefin-Tuna-2016.

Polacheck, T., 2012. Assessment of IUU fishing for southern bluefin tuna. Mar. Pol. 36, 1150–1165. doi:10.1016/j.marpol.2012.02.019.

Polacheck, T., Davies, C.R., 2008. Considerations of implications of large unreported catches of southern bluefin tuna for assessments of tropical tunas, and the need for independent verification of catch and effort statistics. CSIRO Marine and Atmospheric Research, Hobart.

Polacheck, T., Eveson, J.P., Laslett, G.M., 2004. Increase in growth rates of southern bluefin tuna (*Thunnus maccoyii*) over four decades: 1960–2000. Can. J. Fish. Aquat. Sci. 61, 307–322. Doi:10.1139/F04-005.

Polansky, L., Robbins, M.M., 2013. Generalized additive mixed models for disentangling long-term trends, local anomalies, and seasonality in fruit tree phenology. Ecol. Evol.3, 3141–3151. doi:10.1002/ece3.707.

Popper, A.N., Dale, J., Gray, M.D., Keith, W., Block, B., Rogers, P.H., 2013. Threshold hearing for swimming bluefin tuna (*Thunnus orientalis*). Proc. Meet. Acoust. 19, 010005. doi:10.1121/1.4799299.

Popper, A.N., Smith, M.E., Cott, P.A., Hanna, B.W., MacGillivray, A.O., Austin, M.E., Mann, D.A., 2005. Effects of exposure to seismic airgun use on hearing of three fish species. J. Acoust. Soc. Am. 117, 3958–3971. doi:10.1121/1.1904386.

Popper, A.N., Gross, J.A., Carlson, T.J., Skalski, J., Young, J.V., Hawkins, A.D., Zeddies, D., 2016. Effects of exposure to the sound from seismic airguns on pallid sturgeon and paddlefish. Plos One 11, e0159486. doi:10.1371/journal.pone.0159486.

Potier, M., Bach, P., Ménard, F., Marsac, F., 2014. Influence of mesoscale features on micronekton and large pelagic fish communities in the Mozambique Channel. Deep Sea Res. II 100, 18–189. doi:10.1016/j.dsr2.2013.10.026.

Preece, A., Bradford, R., 2016. Gene-tagging 2017 work plan and RMA request. Working paper CCSBT-ESC/1609/10 prepared for the twenty first CCSBT Extended Scientific Committee meeting, 5–10 September, Kaohsiung, Taiwan.

Preece, A., Davies, C.R., Bravington, M., Hillary, R., Eveson, P., Grewe, P., 2013. Preliminary cost and precision estimates of sampling designs for gene-tagging for SBT. Working paper CCSBT-ESC/1309/18 prepared for the eighteenth CCSBT Extended Scientific Committee meeting, 2–7 September, Canberra, Australia.

Preece, A., Eveson, P., Davies, C.R., Grewe, P., Hillary, R., Bravington, M., 2015b. Report on gene-tagging design study. Working paper CCSBT-ESC/1509/18 prepared for the twentieth CCSBT Extended Scientific Committee meeting, 1–5 September 2015, Incheon, South Korea.

Preece, A., Hillary, R., Davies, C.R., Farley, J., Eveson, P., 2015a. Implications of cessation of the aerial survey for the MP and TAC setting. Working paper CCSBT-ESC/1509/09 prepared for the

twentieth CCSBT Extended Scientific Committee meeting, 1–5 September, Incheon, South Korea.

Prihartato, P.K., Irigoien, X., Genton, M.G., Kaartvedt, S., 2016. Global effects of moon phase on nocturnal acoustic scattering layers. Mar. Ecol. Prog. Ser. 544, 65–75. doi:10.3354/meps11612.

Pya, N., Wood, S.N., 2015. Shape constrained additive models. Stat. Comput. 25, 543–559. doi:10.1007/s11222-013-9448-7.

Radford, A.N., Kerridge, E., Simpson, S.D., 2014. Acoustic communication in a noisy world: can fish compete with anthropogenic noise. Behav. Ecol. 25, 1022–1030. doi:10/1093/beheco/aru029.

R Core Team., 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Reisinger, A., Kitching, R.L., Chiew, F., Hughes, L., Newton, P.C.D., Schuster, S.S., Tait, A., Whetton, P., 2014. Australasia, in: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.). Climate change 2014: impacts, adaptation and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, pp 1371–1438.

Ridgway, K.R., Dunn, J.R., Wilkin, J.L., 2002. Ocean interpolation by four-dimensional weighted least squares - application to the waters around Australasia. J. Atmos. Ocean. Tech. 19, 1357–1375.

Ripley, B., Venables, B., Bates, D.M., Hornik, K., Gebhardt, A., Firth, D., 2017. Package 'MASS'. Available at: https://cran.r-project.org/web/packages/MASS/MASS.pdf.

Robinson, C.J., Goómez-Gutieérrez, J., 1998. Daily vertical migration of dense deep scattering layers related to the shelf-break area along the northwest coast of Baja California, Mexico. *J. Plank. Res*. 20, 1679–1697. doi: 10.1093/plankt/20.9.1679

Schaefer, K.M., Fuller, DW., 2007. Vertical movement patterns of skipjack tuna (*Katsuwonus pelamis*) in the eastern equatorial Pacific Ocean, as revealed with archival tags. Fish. Bull. 105, 379–389.

Schaefer, K.M., Fuller, D.W., Block, B.A., 2011. Movements, behaviour and habitat utilisation of yellowfin tuna (*Thunnus albacares*) in the Pacific Ocean off Baja California, Mexico, determined by archival tag data analyses, including unscented Kalman filtering. Fish. Res. 112, 22–37. doi:10.1016/j.fishres.2011.08.006.

Schahinger, R.B., 1987. Structure of coastal upwelling vents observed off the south-east coast of South Australia during February 1983–April 1984. Aust. J. Mar. Freshw. Res. 38, 439–459.

Serventy, D.L., 1956. The southern bluefin tuna (*Thunnus maccoyii*) (Castenau) in Australian waters. Aust. J. Mar. Freshw. Res. 7, 1–43.

Sippel, T., Holdsworth, J., Dennis, T., Montgomery, J., 2011. Investigating behaviour and population dynamics of striped marlin (*Kajikia audax*) from the southwest Pacific Ocean with satellite tags. Plos One 6, e21087. doi:10.1371/journal.pone.0021087.

Soames, C.L., Sexton, M., Tully, M., McLachlan, A., Fleming, A., 2014. Marine Seismic Survey Shape and Kml Files - 2014 Version. Geoscience Australia, Canberra.

Stevens, E., McLeese, J., 1984. Why bluefin tuna have warm tummies: Temperature effect on trypsin and chymotrypsin. Am. J. Physiol.-Regul. Integr. Comp. Physiol. 246, R487–R494.

Stobutzki, I., Davies, C., Preece, A., 2013. Scientific Research Program for CCSBT: Suggestions for structuring and points for discussion. Working paper CCSBT-ESC/1309/20 prepared for the eighteenth CCSBT Extended Scientific Committee meeting, 2–7 September, Canberra, Australia.

Sun, C., Feng, M., Matear, R.J., Chamberlain, M.A. Craig, P., Ridgway, K.R., Schiller, A., 2012. Marine downscaling of a future climate scenario for Australian boundary currents. J. Climate 25, 2947–2962. doi:10.1175/JCLI-D-11-00159.1.

Teo, S.L.H., Boustany, A.M., Block, B.A., 2007. Oceanographic preferences of Atlantic bluefin tuna, *Thunnus thynnus*, on their Gulf of Mexico breeding grounds. Mar. Biol. 152, 1105–1119. doi:10.1007/s00227-007-0758-1.

Tweedie, M.C.K., 1957. Statistical properties of inverse Gaussian distributions. The Ann. Math. Stat. 28, 696–705.

Virgili, A., Racine, M., Authier, M., Monestiez, P., Ridoux, V., 2017. Comparison of habitat models for scarcely detected species. Ecol. Model. 346, 88–98. doi:10.1016/j.ecolmodel.2016.12.013.

Viterbi, A.J., 1998. An intuitive justification and a simplified implementation of the map decoder for convolutional codes. IEEE J. Select. Areas Comm. 16, 260–264.

Ward, T.M., Burch, P., Ivey, A.R., 2012. South Australian sardine (*Sardinops sagax*) fishery: stock assessment report 2012. Report to PIRSA Fisheries and Aquaculture. SARDI Publication No. F2007/000765-4. SARDI Research Report Series No. 667. SARDI Aquatic Sciences, Henly Beach.

Ward, T., McLeay, L., Dimmlich, W., Rogers, P., McClatchie, S., Matthews, R., Kampf, J., Van Ruth, P., 2006. Pelagic ecology of a northern boundary current system: effects of upwelling on the production and distribution of sardine (*Sardinops sagax*), anchovy (*Engraulis australis*) and southern bluefin tuna (*Thunnus maccoyii*) in the Great Australian Bight. Fish. Oceanogr. 15, 191–207. doi:10.1111/j.1365-2419.2006.00353.x.

Watanabe, Y.Y., Goldman, K.J., Caselle, J.E., Chapman, D.D., Papastamatiou, Y.P., 2015. Comparative analyses of animal-tracking data reveal ecological significance of endothermy in fishes. Proc. Nat. Acad. Sci. 112, 6104–6109. doi:10.1073/pnas.1500316112.

White, W.B., Gloersen, K.A., Marsac, F., Tourre, Y.M., 2004. Influence of coupled Rossby waves on primary productivity and tuna abundance in the Indian Ocean. J. Oceanog 60, 531–541

Wilson, S.G., Lutcavage, M.E., Brill, R.W., Genovese, M.P., Cooper, A.B., Everly, A.W., 2005. Movements of bluefin tuna (*Thunnus thynnus*) in the northwestern Atlantic Ocean recorded by pop-up satellite archival tags. Mar. Biol. 146, 409–423. doi:10.1007/s00227-004-1445-0.

Wood, S., 2006. Generalized Additive Models: An introduction with R. Chapman Hall/CRC Press, Boca Raton.

Wood, S.N., 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. J. Roy. Stat. Soc. B 73, 3–36. doi:10.1111/j.1467-9868.2010.00749.x.

Zagaglia, C.R., Lorenzzetti, J.A., Stech, J.L., 2004. Remote sensing data and longline catches of yellowfin tuna (*Thunnus albacares*) in the equatorial Atlantic. Rem. Sens. Environ. 93, 267–281. doi:10.1016/j.rse.2004.07.015.

Zucchini, W., MacDonald, I.L., 2009. Hidden Markov models for time series: An introduction using R. Chapman Hall/CRC Press, Boca Raton.

12. APPENDIX 1: DATA MANAGEMENT

12.1 Raw dataset created

12.1.1 Archival tags

See section 3 of this report for a summary of archival tags returned to date as part of this study.

12.1.2 Oil and gas exploration

See section 8 of this report for a summary of metadata on oil and gas exploration activities in the Great Australian Bight collated as part of this study.

12.2 Data processing and derived datasets

12.2.1 Archival tags

See sections 3-7 of this report for details of data processing and the derived datasets created from historical archival tag data as part of this study.

12.2.2 Oil and gas exploration

See section 8 of this report for details of details of data processing and the derived datasets created from metadata on oil and gas exploration activities in the Great Australian Bight collated as part of this study.

12.3 Data curation and archive

All archival tag data (both historical and contemporary) are housed in a centrally located purpose built Oracle database (Hartog et al. 2009) maintained by CSIRO. Data are quality controlled before upload to the database (see section 3 for details) and individual data records housed in the database have associated data quality control identifiers.

A purpose build Access database was developed for the metadata on oil and gas exploration activities in the Great Australian Bight collated as part of this study.

12.4 Data access, use agreements and licensing

Data access, use agreements and licensing for data generated by and used in this study follow that set out under Schedules 1 and 2 of the contract agreement for this study.

12.5 Publication of datasets

Data generated by this study will be made publically available via the CSIRO data portal (as per CSIRO data management policy) and via the Integrated Marine Observing Systems Australian Ocean Data Network once publication of results has been finalised as per the project agreement for this study.

13. APPENDIX 2: PROJECT PUBLICATIONS

13.1 Papers

Evans, K., McCauley, R.D., Eveson, P., Patterson, T. A summary of research on juvenile southern bluefin tuna as part of the Great Australian Bight Research Program (submitted).

Eveson, P., Patterson, T., Hartog, J., Evans, K., Modelling surface rates of juvenile southern bluefin tuna in the Great Australian Bight (submitted).

Patterson, T.A., Statistical classification of feeding activity in southern bluefin tuna (*Thunnus maccoyii*) (in prep).

Patterson, T.A., Eveson, P., Hartog, J., Evans, K., Lansdell, M., Hobday, A., Basson, M., Davies, C., Cyclical migration dynamics in juvenile southern bluefin tuna (in prep).

Patterson, T.A., Hobday, A.J., Hartog, J., Eveson, P., Davies, C., Evans, K., Seasonal residency and distribution of southern Bluefin tuna in the Great Australian Bight (in prep).

13.2 Presentations

Davies, C., Evans, K., Patterson, T., Eveson, P., Overview of SBT spatial dynamics project and wider Great Australian Bight Research program. CCSBT Scientific Committee 2012, 2013, 2014, 2015, 2016.

Evans, K., Great ocean wanderers: southern bluefin tuna. Portland Upwelling Festival, Portland, Australia, 1 November 2014.

Evans, K., Southern bluefin tuna: spatial dynamics and potential impacts of noise associated with oil and gas exploration. Australian Southern Bluefin Tuna Industry Association science workshop, Port Lincoln, Australia, 27 November 2014.

Evans, K., Davies, C., Eveson, P., Patterson, T., Southern bluefin tuna spatial dynamics and potential impacts of noise associated with oil and gas exploration. ASBTIA industry workshop, Port Lincoln, 11 November 2015.

Evans, K., Patterson, T., Eveson, P., Davies, C., Multi-decadal variability in the spatial dynamics of juvenile southern bluefin tuna. Fifth Symposium on Biologging Science, Strasbourg, France 22 – 27 September 2014.

Evans, K., Patterson, T., Eveson, P., Hartog, J., Hobday, A., Cooper, S., Lansdell, M., Davies, C., Southern bluefin tuna spatial dynamics and potential impacts of noise associated with oil and gas exploration. ASBTIA industry workshop, Port Lincoln, 15 November 2016.

Evans, K., Patterson, T., Eveson, P., Davies, C., Lansdell, M., Hobday, A., Cooper, S., Multi-decadal variability in the spatial dynamics of juvenile southern bluefin tuna. Fourth International Conference on the Effects of Noise on Aquatic Life, Dublin, Ireland 10-15 July 2016.

Eveson, P., Patterson, T., Hartog, J., Evans, K., Modelling surfacing rates of southern bluefin tuna in the Great Australian Bight. Australian Marine Science Association Conference, Darwin, Australia 2 – 6 July 2017.

Patterson, T.A., Eveson, J.P., Hartog, J., Evans, K., Hobday, A.J., Cooper, S., Lansdell, M., Davies, C., Cyclical migration dynamics in juvenile southern bluefin tuna. Australian Marine Science Association Conference, Darwin, Australia 2 – 6 July 2017.

Patterson, T.A., Eveson, J.P., Hartog, J., Evans, K., Hobday, A.J., Davies, C.R., Separating observation uncertainty from individual variability in movement and migration: a step toward more accurate habitat prediction for large pelagic predators. Third CLIOTOP Symposium, San Sebastian, Spain 14-18 September 2015.

13.3 Media Releases

SBT research. TARFish Bulletin. January 2015.

Use of the Bight by southern bluefin tuna and potential impacts of noise associated with oil and gas exploration. Great Australian Bight Research Program fact sheet. August 2015.

13.4 Brochures

Evans, K., Patterson, T., Eveson, P., Davies, C., Hobday, A., Cooper, S., Lansdell, M., McCauley, R. A summary of research on juvenile southern bluefin tuna as part of the Great Australian Bight Research Program (in prep).

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