GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

RESEARCH REPORT SERIES

Offshore survey of the biodiversity, distributions and habitat use of pelagic sharks in the Great Australian Bight

P.J. Rogers, M. Drew, F. Bailleul, and S.D. Goldsworthy

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CORRESPONDING AUTHOR

Dr Paul Rogers
SARDI
t: +61 (0) 8 8207 5487
e: Paul.Rogers@sa.gov.au

FOR FURTHER INFORMATION

Dr Steven Lapidge
Research Director
Great Australian Bight Research Program
e: steven.lapidge@sa.gov.au
www.misa.net.au/GAB

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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EXECUTIVE SUMMARY

The Great Australian Bight pelagic ecosystem encompasses distributions of several highly migratory marine predator species with national and international conservation and management significance.

Geographical ranges of these species extend across multiple State and Commonwealth management jurisdictions, and in some cases, the high seas.

Project 4 of the collaborative Great Australian Bight Research Program, entitled *Ecology of Iconic Species and Apex Predators,* had objectives that included describing key habitats of the pelagic shark assemblage in the Great Australian Bight.

An offshore pelagic survey was conducted on *FPV Southern Ranger* and represented the first dedicated effort to investigate the pelagic shark assemblage in continental shelf-break, slope and near slope oceanic habitats in the Great Australian Bight.

We applied a combination of pelagic long-line survey and satellite telemetry techniques in the Great Australian Bight in May 2015. Seven long-line sets were completed between the du Couedic Canyon and the continental shelf-break to the south of Head of Bight.

Five pelagic and oceanic shark species belonging to four families, Lamnidae, Alopiidae, Carcharhinidae and Triakidae, were recorded during the survey long-line sets. Nine blue sharks *Prionace glauca*, six shortfin makos *Isurus oxyrinchus*, one common thresher *Alopias vulpinus*, one bigeye thresher *A. superciliosus*, and two school sharks *Galiorhinus galeus* were caught. In addition, 12 white sharks (*Carcharodon carcharias*) were observed while at anchor at South Neptune Island. Five white sharks were satellite tagged using pop-up satellite tags.

The highest species diversity and abundance of pelagic sharks occurred at the eastern-most location adjacent to the head wall of the du Couedic Canyon, to the south-west of Kangaroo Island, South Australia.

A female bigeye thresher (~500 cm total length, TL) was captured and tagged at the upper continental shelf slope to the south of Fowlers Bay. This species is rare in southern and south-western Australian waters, and the study region was not previously considered to be part of its known distribution (Last and Stevens 2009).

Blue sharks between 180 and 250 cm TL were geographically widespread in the Great Australian Bight.

Satellite telemetry data were collected for 14 individuals of four shark species.

Largest N-S and E-W movements by blue sharks occurred during spring and summer. Blue sharks traversed areas with median depths ranging from 1505–5179 m; 67% exhibited fidelity in regions with higher variability in depth gradients as compared to areas used as transit paths.

The spatial range occupied by the shortfin mako tagged in the Great Australian Bight extended to the offshore Indian Ocean ~211 km from North West Cape, Exmouth, Western Australia. Shortfin mako was the second-most widespread species.

Displacement distances of white sharks from the tagging site were 19–1,931 km. North- and west-ward extents of movements ranged from Spencer Gulf, to the upper shelf slope SSW of Cape Leeuwin, Western Australia. Southern and eastern movements were limited.

White sharks exhibited substantial variation in depth and thermal habitat use. Depth profiles and tag pop-up locations inferred that southern Spencer Gulf and the approach, continental shelf and slope areas were important to the individuals tracked.

Estimated minimum displacement distance of the bigeye thresher was 3263 km; it travelled from the Great Australian Bight to the 1800 m isobath at the Exmouth Plateau, 353 km offshore from North West Cape, near Exmouth, Western Australia.

The bigeye thresher spent ~84% of the tracked time below the average estimated mixed layer depth (MLD) of 103.5 ± 25.9 m. Minimum and maximum depths occupied by the bigeye thresher ranged from the surface to 1240 m. Average minimum and maximum daily depths were 13.7 ± 9.0 m and 661.3 ± 152.9 m, respectively.

Time-spent-per-area (TSA) analyses indicated focal areas for blue sharks were those with bottom depths >1000 m in oceanic zones beyond the lower continental shelf slope in the eastern and central Great Australian Bight, Bonney Upwelling Region, and Tasman Sea. Time-spent-per-area analyses of the shortfin mako track indicated areas of highest use were the continental shelf break and slope adjacent to the Lacepede Shelf, Murray Canyons to the south of Kangaroo Island, and outer shelf, shelf break and upper shelf slope areas between the 100 to 300 m isobaths in the western Great Australian Bight.

The shortfin mako spent 10.8% of its time in petroleum exploration lease areas (all combined). Three blue sharks spent 66.7, 43.1 and 48.9% of their time in the lease areas (all combined), respectively. Blue sharks spent 0–14.5% of their time in the multi-jurisdiction area where the oil and gas leases overlap with the Great Australian Bight Marine Reserve. The shortfin mako spent 0.7% of its time in this region.

Pelagic shark populations represent considerable value to the community and regional economies of southern Australia and neighboring Pacific and Indian Ocean regions.

There are fundamental gaps remaining in predator diet data-sets for shelf, continental shelf slope, and submarine canyon habitats of the Great Australian Bight, which are required to understand and explain ecological functioning, trophic relationships and potential ecological impacts of anthropogenic stressors.

INTRODUCTION

Overview

A new focus on petroleum exploration in the Great Australian Bight recently included the granting of several exploration leases, and a program of seismic surveys and drilling of exploration wells to assess these leases for commercial quantities of hydrocarbons. This formed the impetus for development of the Great Australian Bight Research Program, which incorporated a series of baseline ecological surveys to assess the biodiversity, distribution and habitat use by threatened, endangered and protected marine predator species in this globally unique temperate marine ecosystem. The Great Australian Bight is a geographically expansive coastal, continental shelf and oceanic bio-region located between Cape Pasley, Western Australia and Cape Otway, Victoria off southern Australia (Fig. 1). Pelagic ecosystems in the region support important regional economies, and fisheries, and can be defined as the Bonney Upwelling Region between Cape Otway and Cape Jaffa, the Lacepede Shelf between Cape Jaffa and Cape Gantheaume, eastern Great Australian Bight between Cape du Couedic, Kangaroo Island and Cape Adieu, and central and western Great Australian Bight between Cape Adieu and Cape Pasley, near Esperance (Fig. 1).

Oceanographic and physical features that support pelagic productivity in these ecosystems include upwelling in coastal and shelf waters (Kaempf *et al.* 2004), fronts that form at the interfaces between coastal water masses and the in-flowing tropical Leeuwin Current and warm water masses originating in the shallow shelves (McClatchie *et al.* 2006), and seasonal up- and down-welling events in the coastal, neritic, and shelf slope habitats (Middleton and Cirano 2002; Kaempf 2007; Middleton and Bye 2007). Australia's continental shelf margin also has 423 identified submarine canyons (Heap and Harris 2008), including 26 named canyons in the Great Australian Bight. These complex habitats include submarine valleys and plateaus that extend outwards along a predominantly south-east to north-west running continental shelf slope. Submarine canyons in the region (Fig. 1) are mostly 'slope limited' and located within the upper (200–500 m) to lower (500–1500 m) shelf slope regions without extension onto the shelf break, and to a lesser extent 'shelf-incising', where they extend onto the shelf-break (160–200 m)

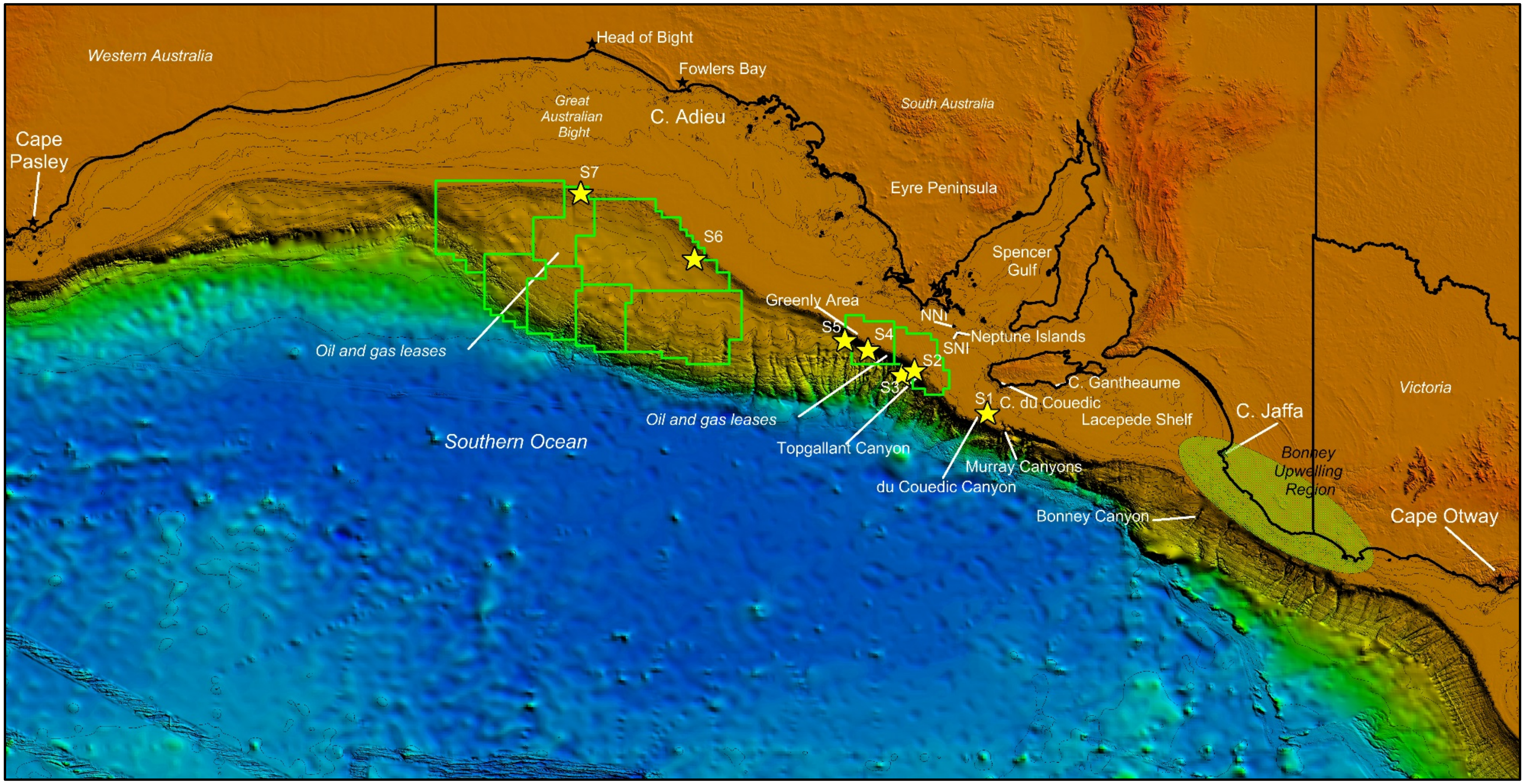


Figure 1. Locations of pelagic survey sets S1–S7 (yellow star symbols) conducted in the Great Australian Bight during May 2015. The green area boundaries show the BP Statoil, Murphy Santos, Chevron and Bight Petroleum Pty Ltd leases. South and North Neptune islands are indicated by acronyms, SNI and NNI respectively. The Bonney Upwelling Region is shown as a green ellipse. The orange layer shows the ≤200 m isobaths, light orange-yellow shows the 200–1000 m isobaths, green to dark blue shows 1000–5000 m isobaths (The Australian bathymetry and topography grid 250 m, Geoscience Australia).

with a distinct head or inner face (Huang *et al*. 2014; Conlan *et al*. 2015). In other continental shelf systems, these deep-water features are integral to the processes that drive pelagic productivity (Greene *et al.* 1988; Allen 2001; Bosley *et al.* 2004; Genin 2004). The importance of these features to pelagic and mesopelagic biodiversity and their role in supporting fauna that comprise the deep scattering layer in Australian shelf and oceanic waters are poorly understood, as are the drivers of spatial, seasonal and diurnal variation in productivity within these ecosystems. Benthic biodiversity in the du Couedic and the Bonney Canyons were examined by Currie *et al*. (2012) and Currie and Sorokin (2014). These authors determined that these features represented separate bio-regions where community structure varied with depth; highest diversities were observed at the canyon heads. These oceanographic and physical features also support highly migratory marine predators, including pelagic sharks, large pelagic teleosts, cetaceans, seabirds, and marine turtles. Recent research has highlighted that these include the blue whale (*Balaenoptera musculus*) (Gill *et al.* 2011), white shark (*Carcharodon carcharias*) (Bruce *et al*. 2006), shortfin mako (*Isurus oxyrinchus*) (Rogers *et al.* 2015a, b), southern bluefin tuna (*Thunnus maccoyii*) (Bestley *et al*. 2008, 2009; Patterson *et al*. 2008), short-tailed shearwater (*Puffinus tenuirostris*) (Einoder and Goldsworthy 2005; Einoder *et al.* 2011), and Australasian gannet (*Morus serrator*) (Bunce *et al.* 2002).

The Great Australian Bight comprises habitats and movement pathways of several listed, threatened, endangered and protected species, including the white shark (Bruce *et al.* 2006), shortfin mako (Rogers *et al*. 2015a), and gulper sharks — *Centrophorus* spp. (Williams *et al.* 2012; Daley *et al.* 2014). The collection of fishery-independent information on the spatial distribution of pelagic sharks can be challenging due to the large extent of their oceanic habitats combined with their highly migratory behaviour. While there are substantial logistical challenges associated with conducting research on these large predator species in isolated oceanic areas, other global examples include pelagic long-line based surveys by the US National Oceanographic and Atmospheric Administration (NOAA) to assess the status of juvenile pelagic shark populations in the Southern California Bight (Vetter *et al*. 2006), and north-west Atlantic Ocean (Simpfendorfer *et al.* 2002; NOAA, 2016).

A large part of the scientific understanding of the oceanic shark assemblage in the eastern Indian Ocean and south-west Pacific Ocean has been gleaned from analyses of fishery data from domestic and high seas fishery observer programs, and patterns largely reflect spatial and temporal trends in fishery effort (Stevens 1992; Bruce *et al.* 2014). In response to the need to maximise opportunities when accessing the distant areas inhabited by pelagic sharks, we developed a survey design that could be undertaken in a fast, cost-effective vessel to optimise data collection during short periods of suitable weather. Central to this strategy was the application of satellite telemetry to enable collection of high-resolution tracking data following the survey, to understand species distributions and overlaps with human processes, movements and habitat use in relation to oceanographic, environmental and seasonal factors.

Theme 4 of the Great Australian Bight Research Program, *Ecology of Iconic Species and Apex Predators,* addresses scientific knowledge gaps by providing information on the distribution and abundance of iconic and apex predator species in the Great Australian Bight (Rogers *et al.* 2013). Project 4.1 comprised four components, including characterising the spatial and temporal distribution of pelagic sharks in the Great Australian Bight. Satellite telemetry data collected during Project 4.1 will be included in subsequent multi-species analyses within Project 4.2 to identify shared habitats for apex predators in the Great Australian Bight.

Background and Need

Pelagic sharks exert top-down foraging pressure on lower trophic levels of marine ecosystems, including other benthic and pelagic fishes, squids, and marine mammals in the Great Australian Bight (Rogers *et al.* 2012; Goldsworthy *et al.* 2013). Despite what we understand about the roles of pelagic sharks in ecosystems, there remain substantial gaps in available information on species diversity, patterns of distribution, and habitat use by the pelagic shark assemblage in the Great Australian Bight (Rogers *et al.* 2013). Also lacking is information on species overlaps with commercial industries (e.g. fishery and petroleum lease areas) and spatially managed areas aimed at maintaining national marine habitat and biodiversity values (e.g. marine reserves).

The pelagic shark assemblage in the Great Australian Bight comprises species also found in other eastern and western boundary current ecosystems, and includes the white shark, shortfin mako,

longfin mako (*I. paucus*), porbeagle (*Lamna nasus*), blue shark (*Prionace glauca*), bronze whaler (*Carcharhinus brachyurus*), dusky shark (*C. obscurus*), common thresher (*Alopias vulpinus*), bigeye thresher (*A. superciliosus*), smooth hammerhead (*Sphyrna zygaena*), and school shark (*Galeorhinus galeus*). The white shark, shortfin mako, longfin mako, and porbeagle have varying levels of protection under the Australian Government *Environment Protection and Biodiversity Conservation Act*, EPBC Act (1999), and in the case of the white shark, State-based fisheries legislation. Two thresher sharks, *A. vulpinus* and *A. superciliosus,* have a management status that are pending current national and international assessment processes.

Objectives

1. Assess the biodiversity and composition of the pelagic shark assemblage in shelf slope and offshore regions of the Great Australian Bight.

2. Determine the spatial and temporal distributions of pelagic sharks in shelf slope and offshore regions of the Great Australian Bight.

3. Identify key habitats of pelagic sharks in the shelf slope and offshore regions of the Great Australian Bight.

4. Collect dietary information for pelagic sharks in the shelf slope and offshore regions of the Great Australian Bight to contribute to aligned trophodynamic models for this region in Theme 7 of the Great Australian Bight Research Program.

METHODS

Survey design, equipment and approach

The pelagic survey was conducted on *FPV Southern Ranger* in May 2015 (Table 1). Site selection during the survey was based on depth strata, proximity of submarine canyons, patterns in currents and sea-surface temperatures (oceancurrent.imos.org.au) (Appendix 1), and satellite telemetry data. This information was examined to identify areas where combinations of suitable habitat variables combined and were hypothesised to support pelagic predator species. Survey locations were selected within and outside the oil and gas lease areas (Fig. 1).

Seven pelagic long-line sets (S1–S7) were completed. Operational dates and vessel tracks during the two survey legs are shown in Appendix 2. Descriptions of pelagic long-line set locations are provided in Table 1. Set locations were du Couedic Canyon (S1), Topgallant Canyon (S2 and S3), 'Greenly area' south-west of southern Eyre Peninsula (S4 and S5), shelf break and upper slope to the south of Fowlers Bay (S6), and Head of Bight (S7) (Fig. 1). Survey set location details, dates, depth ranges, sea-surface temperatures, and habitat types are shown in Table 1.

Pelagic long-line equipment comprised a 4 mm monofilament main-line, with 4 m long, 2 mm diameter wire branch-lines attached to 16/o tuna circle hooks and v-notch stainless steel long-line clips. Circle hooks were spaced along the main-line at ~40–50 m intervals. The number of hooks deployed per set ranged from 60 to 120 (mean = 98 ± 23). Twelve inch surface floats with Xenon™ strobes with 8 m rope dropper lines were attached at intervals of one float per five hooks. The long-line was set at depths of ~24–40 m.

A Taiyo™ radio beacon and direction finder were used to maintain contact between the vessel and terminal end of the line during the sets. Floats (40 mm diameter) with high visibility flags on poles were attached to the line at intervals of 30–40 hooks. Hooks were baited manually using thawed frozen Australian salmon (*Arripis trutta*), arrow squid (*Nototodarus gouldi*), and southern bluefin tuna (*Thunnus maccoyii*). During each set, the line was soaked for ~2 hours (from time of last hook set) to maximise survivorship of sharks. At the end of each set, the long-line was retrieved on the starboard side as the vessel travelled at speeds of ~2–3 knots.

Table 1. Physical and oceanographic characteristics of pelagic survey set locations S1–S7. Sea-surface temperatures sourced from http://oceancurrent.imos.org.au/

Set location	Date	Depth range (m)	SST (°C)	Habitat type	Canyon area
S1	1 May 15	120–170	18	Shelf break	du Couedic Canyon
S2	3 May 15	2000+	17–18	Oceanic	Topgallant Canyon
S3	14 May 15	213–394	17	Upper slope	Topgallant Canyon
S4	15 May 15	182–694	17	Shelf break to lower slope	Greenly area
S5	15 May 15	139–804	18	Shelf to lower slope	Greenly west
S6	16 May 15	199–265	18	Shelf break to upper slope	Fowlers South
S7	17 May 15	190–226	18	Shelf break to upper slope	South Head of Bight

Seabird bycatch mitigation techniques were adopted during the setting and retrieval process (Appendix 3). Wheel-house data describing each set were collected, including latitude and longitude of sets, time, wind speed, and bottom depth at start and end positions. Seabird and marine mammal species observed at and near each set location were recorded (Appendix 4).

In addition to the long-line survey, white sharks were censused visually at the Neptune Islands while the vessel was at anchor during poor weather.

Shark capture and handling

Small to medium sharks (≤ 2.5 m natural total length TL) captured on the long-line were lifted from the water using a sling with a solid, rectangular aluminium frame and inner platform covered in soft netting and smooth canvas. Once on-board, the gills of each shark were aerated using a reinforced deck-hose and their eyes were covered with a wetted micro-fiber cloth. The posture of each shark was supported using a wetted, high-density foam mattress. Sharks were identified, measured, sexed and fin-clips were taken for genetics. External copepod parasites were sampled from some individuals. Maturity of each shark was assessed based on methods of Francis and Duffy (2005). Bolt-cutters were used to cut and remove hooks prior to the release of tagged sharks. Individuals that were not satellite tagged were sampled and/or released in the water by cutting the leader. Specimens >2.5 m TL were tagged in the water using 4 m tag poles and sizes were estimated based on known lengths on the gunwale. Moribund and dead

specimens were dissected to collect biological data and samples for ecosystem modelling studies in Theme 7.

Satellite tag deployments

Satellite tags were mounted on the first dorsal fin of blue sharks and the shortfin mako captured during the long-line sets. Tags deployed on these species were Sirtrack™ K2F161A, and Wildlife Computers smart position or temperature (SPOT) tags (Table 2). Dorsal fin-mounted satellite tags were attached using two 3.5 mm diameter stainless steel bolts, nylex lock-nuts and washers. Lock-nuts were fastened through two or three small holes made in the dorsal fin using a cordless drill and deep socket.

Wildlife Computers™ (WC) miniature pop-up archival transmitting tags (mini-PAT) were deployed on white sharks and a big-eye thresher using a 4 m aluminium tag pole. The mini-PATs were deployed on sharks that were either free-swimming next to the vessel in the case of the white sharks, or captured on the long-line in the case of the big-eye thresher. Deployment summary details are provided in Table 2. The mini-PATs were tethered to sharks using a plastic umbrella dart attached to 200–250 mm of 2 mm diameter plastic coated 316 stainless steel multi-strand wire. Umbrella darts tethered to mini-PATs were inserted into the dorsal musculature of each shark to depths of 5–10 cm using a stainless steel applicator attached to the tag pole.

Data analyses

Species distributions: survey information

Spatial analyses of species distributions were prepared using count data collected during the long-line sets. Patterns were shown using MapInfo Ver. 11.5 geographical information software (GIS) (MapInfo Corporation, New York).

Spatial and temporal distributions: telemetry

Satellite tags transmitted signals to satellite network receiver stations, which were forwarded to Argos centres in France and the USA (Argos, 2008). Position estimates were downloaded in seven location quality classes (cls) ranging from highest to lowest manufacturer predicted accuracies of 3 = <250 m, 2 = 250–500 m, 1 = 500–1500 m and 0–B = >1500 m, Z = no position (www.argos-

system.org). Position error has been compared to GPS positions and the 68th percentile errors were 3 = 0.49 km, 2 = 1.01 km, 1 = 1.2 km, 0 = 4.18 km, A = 6.19 km, and B = 10.28 km (Costa *et al*. 2010). Extreme outliers, positions on land and those with unclassified error estimates (cls-Z) were removed. Positions were mapped using MapInfo GIS software. Initial mini-PAT pop-up locations were taken as the first position estimates (cls 3–1).

Table 2. Summary of satellite tag deployments during offshore survey. Refer to deployment location codes shown in figure 1. M = male, F = female, NS = not sexed. Mini-PAT = miniature pop-up satellite archival tag, SPOT = smart position or temperature satellite tag, ST = Sirtrack satellite tag.

Shark ID	Argos freq.	Tagging date	Species	Tag type	Deployment location	Size	Sex
B1	148956	1 May 15	*P. glauca*	SPOT	S1	200	F
B2	134878	3 May 15	*P. glauca*	ST	S2	180	M
B3	148954	3 May 15	*P. glauca*	SPOT	S2	224	F
B4	148957	15 May 15	*P. glauca*	SPOT	S4	208	M
B5	148955	15 May 15	*P. glauca*	SPOT	S4	233	M
B6	148965	15 May 15	*P. glauca*	SPOT	S5	235	M
B7	148962	16 May 15	*P. glauca*	SPOT	S6	250	M
S1	148963	17 May 15	*I. oxyrinchus*	SPOT	S7	232	F
W1	148949	2 May 15	*C. carcharias*	mini-PAT	SNI	420	F
W2	148953	2 May 15	*C. carcharias*	mini-PAT	SNI	330	M
W3	148950	6 May 15	*C. carcharias*	mini-PAT	SNI	220	NS
W4	148951	6 May 15	*C. carcharias*	mini-PAT	SNI	300	NS
W5	148952	6 May 15	*C. carcharias*	mini-PAT	SNI	420	F
BET1	148948	16 May 15	*A. superciliosus*	mini-PAT	S6	500	F

State-space models (SSM) were used to filter the raw Argos data (Jonsen *et al.* 2005). Locations were interpolated along each filtered track to reduce sampling bias due to irregular transmission of the Argos data. Estimation errors associated with Argos quality classes vary through time. Argos-derived locations are observed irregularly through time, which can impose an artificial perspective on the movement processes, which is why Bayesian filtering methods tend to be used. For each individual track, the raw satellite derived Argos locations were filtered using Bayesian SSM following the methods of Jonsen *et al.* (2005). The state-space distribution models are time-series methods that allow unobserved assumed behavioural states and biological parameters to be estimated from data observed with position estimation error. This approach enables the management of the biological and statistical complexities associated with satellite tracking data. We used hierarchical switching models (hDCRWS) that account for these features of the data and allow both filtering spatial positions and estimating behavioural states. The model was fit using Markov Chain Monte Carlo (MCMC) methods to approximate the multi-dimensional integration required in Bayesian analyses. Because behavioural patterns estimate is a discrete parameter — values can only be 1 or 2 — we used the means of the MCMC samples as a convenient way to visualize behavioural switches. We, therefore, delineated the behavioural modes by adopting cut-offs at 1.25 and 1.75, where estimates <1.25 were assumed to represent transit or migratory behaviours and those >1.75 were assumed to represent fidelity related behaviours (see Jonsen *et al.* 2007 for details). Estimates between 1.25 and 1.75 were treated as uncertain as per Jonsen *et al*. (2007). Spatial models were fitted using JAGS 3.1.0 (Just Another Gibbs Sampler, http://martynplummer.wordpress.com; http://mcmc-jags.sourceforge.net) accessed from R (R Core Team 2014) using the package 'bsam' (Jonsen *et al.* 2014). Two Markov chains with a total of 50,000 simulations were computed, only keeping one out of ten samples to minimise sample autocorrelation.

Analyses used a time-step of 4 hours and generated 25000 samples per chain for each position. A 0.4° x 0.4° grid was drawn over the study area. From the filtered tracks, the time spent by each individual in each square of the grid (Time-spent-per-area) was calculated using the function 'tripGrid' (package 'trip', R Core Team 2014), and subsequently the percentage of the total record duration each individual spent in spatial areas of management interest. Estimated positions were

allocated to the Austral seasons: summer = December, January and February; autumn = March, April and May; winter = June, July and August, and spring = September, October and November. Movement statistics are reported as mean ± standard error with 25th and 75th percentiles, and medians unless otherwise stated.

Habitat use

To describe environmental correlates during fidelity (area restricted search) and transitory (migratory) behavioural states extracted from the eight satellite tracks for the blue sharks and shortfin mako, we interrogated available bathymetry and remote-sensed data. Bathymetry data were extracted using the ETOPO1 database, sea-surface temperature data were extracted using NOAA's Optimum Interpolation data (https://www.ncdc.noaa.gov/oisst), and sea-surface height were extracted from AVISO Satellite Altimetry Data (www.aviso.altimetry.fr). Bathymetry, sea-surface temperature and sea-surface height gradients were calculated in R using the 'terrain' function from the package 'raster'. Sea-surface height and gradient represent indicators of proximity to eddies and associated meso-scale processes that support pelagic production (Bakun 2006). Anti-cyclonic warm core eddies have higher sea-surface height values than the surrounding ocean, compared to cyclonic cold core eddies that have lower sea-surface height values (Bakun 2006).

Vertical habitat distributions

The vertical habitats of sharks tagged with mini-PAT tags were characterised using time at depth (TAD) summaries and high resolution depth and temperature time series data transmitted via the Argos satellites. Mini-PATs were programmed to release from the sharks after a 100 day deployment. Upon release, the mini-PAT tags floated to the surface and transmit data to Argos satellites as per the SPOT tags. Data were analysed at the individual level.

RESULTS

Species composition and diversity

A total of five species of pelagic sharks were recorded during the long-line survey, representing four families: Lamnidae (1 sp.), Alopiidae (2 spp.), Carcharhinidae (1 sp.), and Triakiade (1 sp.). Pelagic sharks encountered during the long-line sets were nine blue sharks, six shortfin makos, one common thresher, one bigeye thresher, and two school sharks. Figure 2a shows species by proportion during the survey long-line sets. One juvenile southern bluefin tuna was sampled at S4. A total of 12 white sharks were sighted whilst sheltering from bad weather in the South Neptune Islands anchorage on 2, 3, 6 and 13 May 2015. Five yellowtail kingfish (*Seriola lalandi*) were also caught at this location using a line to source diet samples.

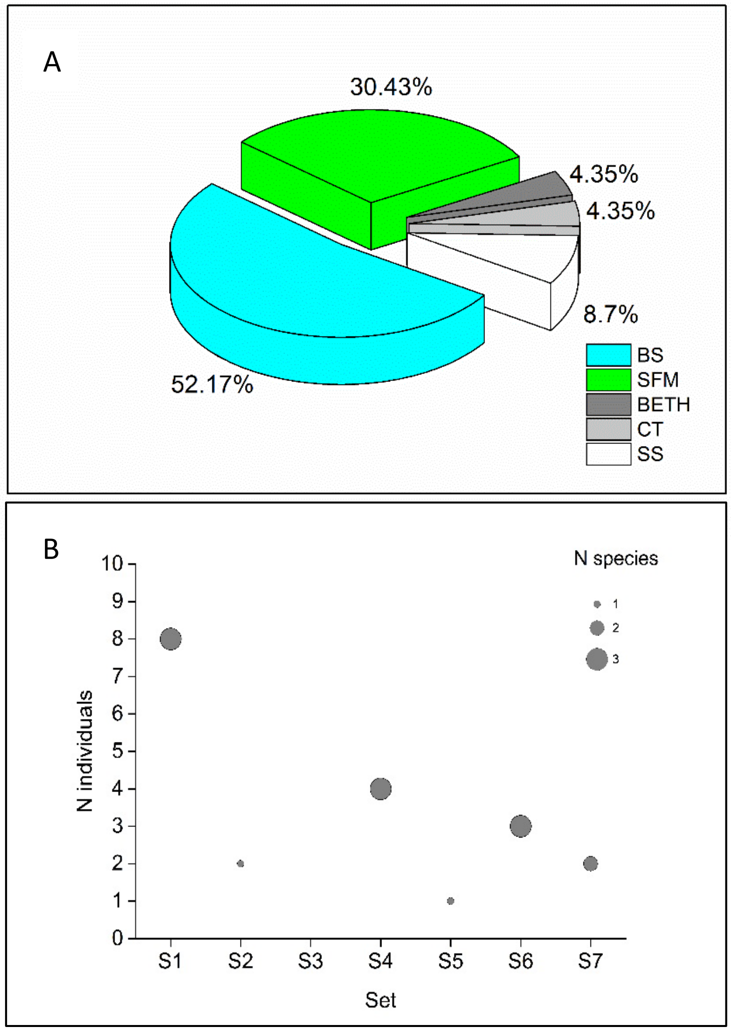


Figure 2. A. Pelagic shark species encountered by proportion in the Great Australian Bight during the survey sets. Blue shark = BS, shortfin mako = SFM, bigeye thresher = BETH, Common thresher = CT, and school shark = SS. **B.** Species diversity and numbers of individuals encountered by set.

Spatial distributions of species during survey

Species presence and abundance varied between sites in the Great Australian Bight during the survey. The equal highest species diversity (n=3) and count of individual sharks (n=8) per set occurred at the eastern-most location at du Couedic Canyon during S1 (Figs 1 and 2a, b). This set was conducted at the continental shelf break, across the inner northern face of the canyon, where bottom depths ranged between 120 m and 170 m (Fig. 3). No sharks were sampled during S3 at the upper slope, along the north-western side of Topgallant Canyon (Fig. 1).

Blue sharks were geographically widespread during the survey (Fig. 4). A total of nine blue sharks were recorded that ranged in size between 180 and 250 cm TL. Blue sharks comprised six males, two females and one unsexed individual (released live and untagged). This species was present during all survey sets except S3 (Fig. 4) with two caught at S1, S2 and S4 and one caught at S5, S6 and S7 (Fig. 4). The shortfin mako was the second-most geographically widespread species sampled. A total of six shortfin makos ranging in size from a juvenile of ~70 cm TL to an adult of ~300 cm TL were caught at three of the seven set locations (S1, S4 and S7). One female shortfin mako of 232 cm TL was tagged at S7 (Fig. 4).

One large common thresher of ~460 cm TL was caught at S6, located to the south of Fowlers Bay (Fig. 4). The common thresher was released live and untagged, as all electronic tags of a suitable size and configuration (e.g. mini-PAT) for the species had been deployed by that stage of the survey. This shark species is uncommon in southern Australian waters. A large shark >280 cm fork length (FL) escaped from the long-line at S1 following one sighting at ~10 m below the vessel. The head shape, blue-grey dorsal and white colouration on the ventral side suggested this specimen was also a large common thresher, however the species could not be verified with a suitable level of confidence. One large, mature sized female bigeye thresher of ~500 cm TL was identified and satellite tagged at S6 (Fig. 4).

Two female school sharks of 143 cm and 150 cm TL were captured and retained dead at S1 (Fig. 4). School sharks were not present at S2–S7. No white sharks were encountered during the pelagic long-line sets. One juvenile southern bluefin tuna (710 cm FL) was sampled and retained for dietary analysis at S4.

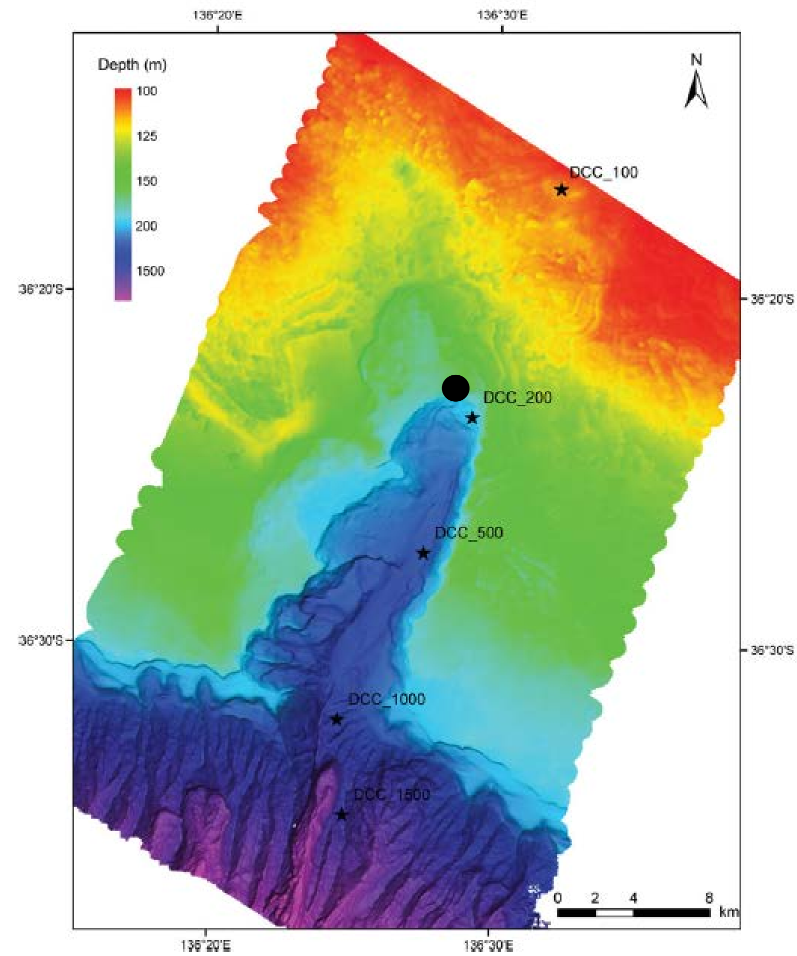


Figure 3. Bathymetry of the du Couedic Canyon. The black symbol shows the location of S1 relative to the canyon front wall. Stars show approximate depths. (Image courtesy of Currie and Sorokin 2014).

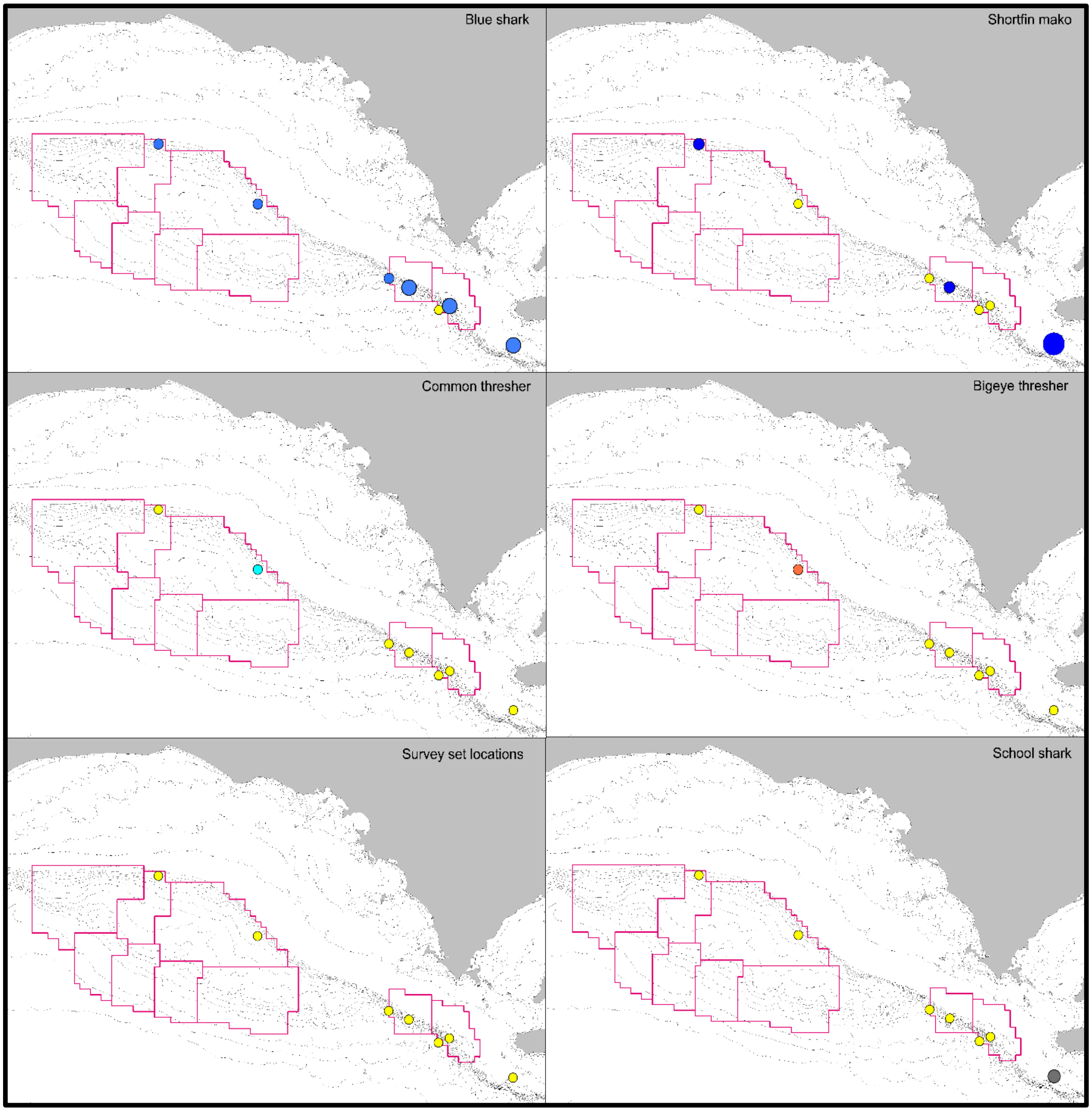


Figure 4. Spatial patterns of distribution of pelagic sharks during the survey sets. Symbol size represents count during each set (small = 1, medium = 2, large = 4). Yellow symbols show set locations where no individuals of that species were caught. Shapes show oil and gas lease areas.

Figure 5. Clockwise from top left. Blue shark, shortfin mako and bigeye thresher during satellite tagging in the Great Australian Bight.

Electronic tag deployments

Satellite tags were deployed on 14 pelagic sharks of four species. Data describing tag types, tagging location, size and sex are provided in Table 2. Deployments included five mini-PATs on white sharks between ~220 and 420 cm TL (pole tagged at South Neptune Islands), one mini PAT on a bigeye thresher (~500 cm), seven SPOT tags on blue sharks of 180–250 cm TL and one SPOT tag on a large female shortfin mako of 230 cm TL (Fig. 5). Blue sharks and shortfin makos spend considerable time swimming at the surface and this allows the platform terminal transmitter (PTT) tags (e.g. SPOT and Sirtrack tags) sufficient time to send signals to the polar orbiting Argos satellite network.

Tag performance

Initial status checks on 20 May 2015 showed no mini-PATs deployed on white sharks and the bigeye thresher had reported to satellites immediately following the survey, indicating 100% survival of the mini-PAT tagged sharks. All dorsal-fin mounted satellite tags had reported position estimates indicating functionality of the eight tags and survival of all tagged sharks. Tables 2 and 3 provide a summary of tag deployment information.

Satellite tags deployed on blue sharks (B1–B7) (Table 3) provided data for 997 PTT days (PTT days = days platform transmitted) (mean = 142 ± 81, median = 167 days), and comprised 4057 position estimates (mean = 581 ± 394, median = 642 days) of quality classes 3–b.

The satellite tag deployed on the shortfin mako (S1) provided 258 PTT days and 1181 satellite position estimates of quality classes 3–b. This tag was transmitting regular position estimates at the time of preparation of this report (February 2016).

The mini-PAT tag deployed on the bigeye thresher (BET1) released on the programmed date after 100 days and reported high resolution time series depth records (n = 25959), daily binned time spent at temperature and depth histogram frequency data (94% data recovery), daily min-max temperature profiles (n = 97), and sea-surface temperature (SST) values (n = 104). This tag surfaced in an oceanic area and was not recovered.

All five mini-PATs deployed on white sharks W1–W5 transmitted summary data to Argos (Table 3). The tag on shark W3 dislodged after 64 days, which was 26 days prior to the programmed pop-up date. Three tags, including those deployed on W1, W2, and W4 surfaced within two days of the programmed dates. The five mini-PATs deployed on white sharks reported binned time spent at depth and temperature histogram frequency data for 295 of the 500 (59%) pre-programmed days. Data included time series depth records (n = 75398), daily min-max temperature profiles in 16 depth layers (n = 282), SST values (n = 820) at 0–4 m, and mixed layer depth and temperature data (n = 296). Only one, possibly erroneous temperature summary data point for 27 July was transmitted by the tag on shark W5, which surfaced and transmitted late after 125 days. Temperature and depth data reported by the mini-PAT on W1 were transmitted 2 days late, and only comprised records for the first 14 days. We suggest this individual moved offshore and possibly damaged and removed the tag before it drifted ashore in northern Spencer Gulf and transmitted late, or the tag was damaged or malfunctioned during day 14 of the deployment, and the animal subsequently travelled to the northern Spencer Gulf location where the tag released. This tag didn't record temperature and depth data for the remaining 86 days of the deployment. Transmitted water temperatures suggest the tag was drifting near the surface as shown by the pressure/depth data. Two tags were recovered from the shoreline at Marion Bay, Yorke Peninsula and Louth Island, Boston Bay in southern Spencer Gulf following transmission of summary data. Archived data will be analysed in Project 4.2.

Table 3. Summary of information on deployments and performance of satellite tags deployed on pelagic sharks in the Great Australian Bight. NSG = northern Spencer Gulf, SSG = southern Spencer Gulf, ST = Sirtrack, SPOT = smart position or temperature tag, mini-PAT = miniature pop-up archival transmitting tag.

Shark ID	Tag	Tag ID	Date deployed	Popup date	Date last pos	Days at liberty	Pop-up lat	Pop-up long	Pop-up region/location	Last lat	Last long
B1	SPOT	148956	1 May 15	Na	12 Mar 16	317	-	-		-40.58	135.03
B2	ST	134878	3 May 15	Na	22 Feb 16	294	-	-		-34.10	89.60
B3	SPOT	148954	3 May 15	Na	26 Feb 16	298	-	-		-15.86	110.86
B4	SPOT	148957	15 May 15	Na	17 Jun 15	34	-	-		-33.72	129.93
B5	SPOT	148955	15 May 15	Na	27 Feb 16	288	-	-		-35.69	121.80
B6	SPOT	148965	15 May 15	Na	21 Dec 15	221	-	-		-39.90	148.63
B7	SPOT	148962	16 May 15	Na	14 Jan 16	244	-	-		-34.09	132.39
S1	SPOT	148963	17 May 15	Na	10 Mar 16	298	-	-		-37.06	137.72
W1	mini-PAT	148949	2 May 15	11 Aug 15	-	102	-33.24	137.82	NSG	na	na
W2	mini-PAT	148953	2 May 15	11 Aug 15	-	101	-34.88	114.86	C. Leeuwin, WA	na	na
W3	mini-PAT	148950	6 May 15	9 Jul 15	-	64	-35.39	136.31	SSG	na	na
W4	mini-PAT	148951	6 May 15	15 Aug 15	-	102	-35.18	136.56	SSG	na	na
W5	mini-PAT	148952	6 May 15	8 Sep 15	-	125	-32.31	131.15	Central GAB	na	na
BET1	mini-PAT	148948	16 May 15	23 Aug 15	-	100	-20.14	111.27	Exmouth	na	na

Spatial, temporal and seasonal distributions: telemetry

Blue shark

Six satellite tags deployed on blue sharks B1–B3, B5–B7 transmitted for periods ranging from 221 to 317 days (mean = 242 ± 97.86, median = 288 days). The tag on blue shark B4 provided data for 34 days (Table 3). Maximum distal displacement distances traversed by individual blue sharks ranged between 535–4190 km (during 15 and 196 days, respectively) (mean = 1952 ± 1384, median = 1440 km) (Table 4). Spatial ranges occupied by blue sharks B1–B7 were expansive (Fig. 6). Tables 3 and 4 provide summary statistics describing the extent of movements.

Telemetry data indicated a seasonal component to latitudinal movements of blue sharks into and away from the Great Australian Bight (Fig. 7a, b). The smallest spatial extents of movements by blue sharks occurred in autumn, which was the season in which the survey was conducted (Fig. 7a, b). The largest latitudinal movements by blue sharks occurred during spring (24.6°S to 42.9° S) and summer (13.9° S to 41.5° S). Longitudinal movements by blue sharks were also greatest in spring (103.5° E to 160.5° E) and summer (88.4° E to 149.8° E). Seasonal patterns in movements are summarised in Fig. 8. Blue shark B2 migrated to the central Indian Ocean and B6 traveled to the Tasman Sea and central SW Pacific Ocean between Australia and New Zealand (Fig. 6).

Shortfin mako

The tag deployment duration on the shortfin mako was 298 days (Table 3). Estimated distal displacement distance from the tagging site was 2910 km (Table 4). The spatial range occupied by the shortfin mako extended from the tagging location in the central Great Australian Bight to an oceanic area of the Indian Ocean located ~211 km west-south-west of North-west Cape, Exmouth, Western Australia (22.13° S, and 112.16° E) (Figs. 6 and 8). The highest variation in latitudinal and longitudinal movements by the shortfin mako occurred during spring and summer when it migrated to the offshore (~174 km from land) oceanic area in the north-west Indian Ocean near Exmouth, Western Australia (Figs. 6 and 8).

White shark

Satellite tag deployment durations on white sharks ranged from 64 to 125 days (mean = 99 ± 22, median = 102 days) (Table 3). Minimum displacement distances travelled by white sharks ranged

between 19 and 1,931 km (mean = 568 ± 793, median = 279 km) (Table 4). Movements extended from the South Neptune Islands to 280 km north (33.3° S) in Spencer Gulf, and 34.9° S and 114.9° E off Western Australia (Fig. 9). The largest movement extended from South Neptune Islands to the continental shelf slope region located 62 km SSW of Cape Leeuwin, Western Australia (Fig. 9). The pop-up location of the tag deployed on shark W2 (330 cm TL male) was at the 300 m isobath, and showed a west-ward movement during winter 2015 (Fig. 9). Southern and eastern movements by white sharks were limited. White shark W5 (420 cm TL female) moved west into the central Great Australian Bight, and covered a minimum distance of 569 km. The tag surfaced on 8 September 2015 at a position between the 60 m and 80 m isobaths and due south of Head of Bight.

Bigeye thresher

The mini-PAT deployment duration on the bigeye thresher was 100 days (Table 3). Estimated minimum displacement distance was 3263 km (Table 4). The tag surfaced at the 1800 m isobath at the Montebello Saddle and Exmouth Plateau, 353 km offshore from North West Cape, near Exmouth, Western Australia (Fig. 10). Patterns of vertical habitat use indicated the bigeye thresher used shelf slope and oceanic habitats during a substantial west- and north-ward tropical migration during autumn and winter.

Table 4. Summary of information on deployments and data collected by satellite tags on pelagic sharks in in the Great Australian Bight. Ptt days = days of data for each platform transmitter terminal (tag), ST = Sirtrack, SPOT = smart position or temperature tag, mini-PAT = miniature pop-up archival transmitting tag.

Shark ID	Tag	Tag ID	Deploy loc.	cls 3	cls 2	cls 1	cls 0	cls a	cls b	cls z	All cls3-b	Ptt days	Max displ. dist. (km)
B1	SPOT	148956	S1	8	19	63	32	76	442	2	642	167	3150
B2	ST161	134878	S2	9	20	28	22	34	88	1	202	63	1440
B3	SPOT	148954	S2	13	61	127	94	113	306	0	714	196	4190
B4	SPOT	148957	S4	0	2	3	1	6	20	0	32	15	535
B5	SPOT	148955	S4	5	22	140	87	125	548	3	930	230	1186
B6	SPOT	148965	S5	6	11	37	22	64	266	1	407	114	2560
B7	SPOT	148962	S6	28	78	116	64	141	715	0	1142	212	600
S1	SPOT	148963	S7	36	103	111	60	176	695	5	1186	258	2910
W1	mini-PAT	148949	SNI	-	-	-	-	-	-	-	-	-	279
W2	mini-PAT	148953	SNI	-	-	-	-	-	-	-	-	-	1931
W3	mini-PAT	148950	SNI	-	-	-	-	-	-	-	-	-	19
W4	mini-PAT	148951	SNI	-	-	-	-	-	-	-	-	-	43
W5	mini-PAT	148952	SNI	-	-	-	-	-	-	-	-	-	569
BET1	mini-PAT	148948	S6	-	-	-	-	-	-	-	-	-	3263

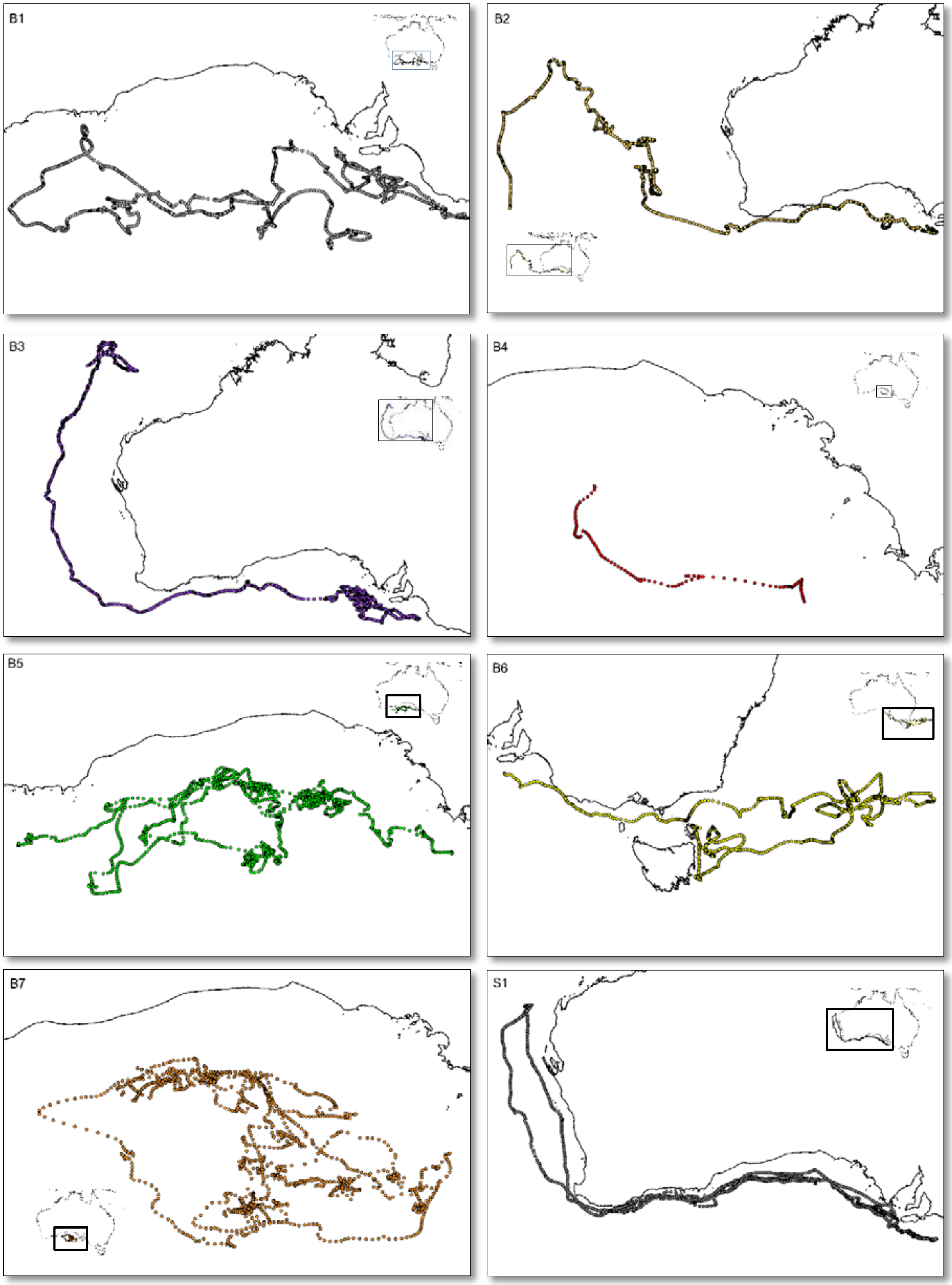


Figure 6. Spatial distribution of blue sharks B1–B7 and shortfin mako S1 tracked following the offshore survey in the Great Australian Bight in 2015.

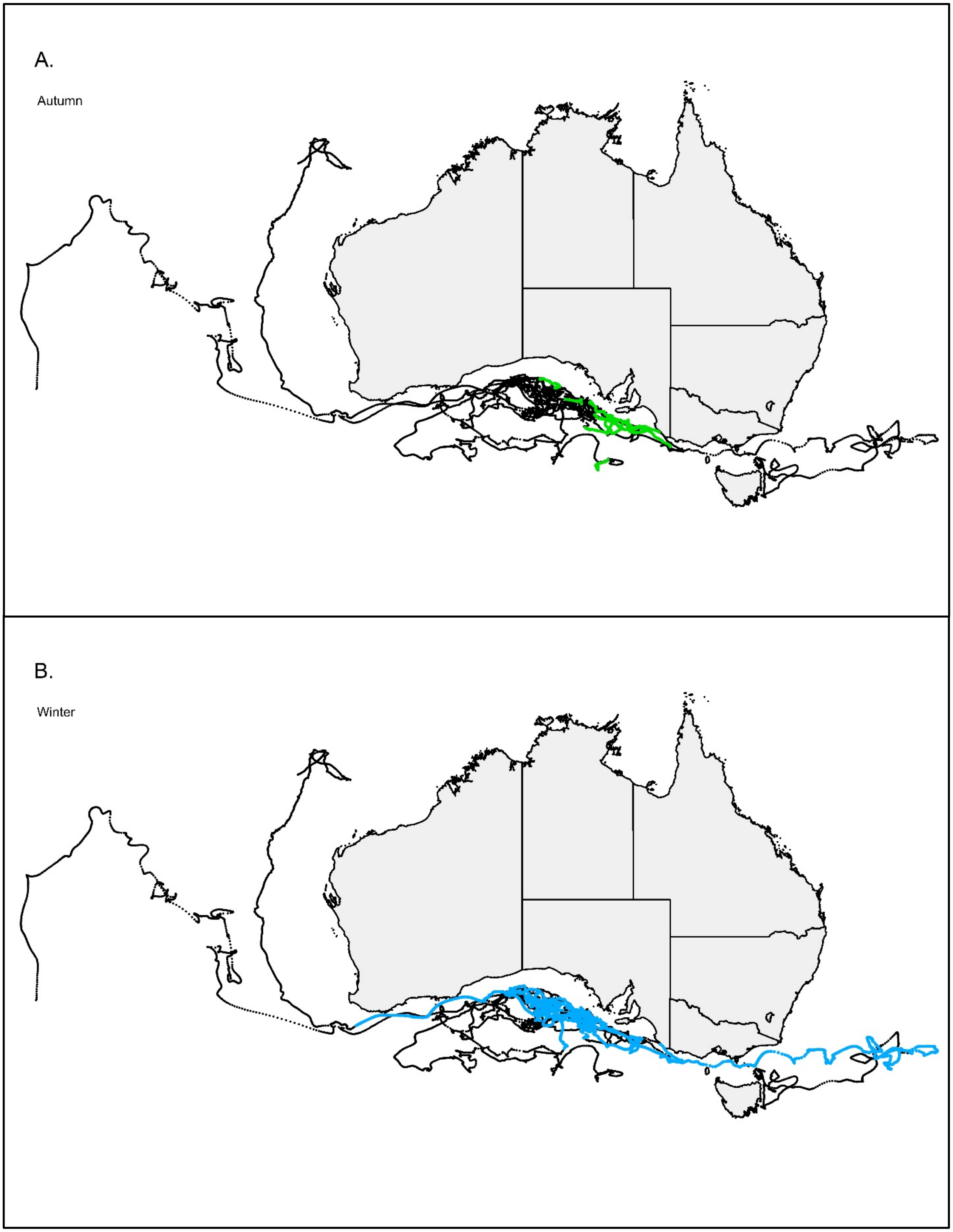
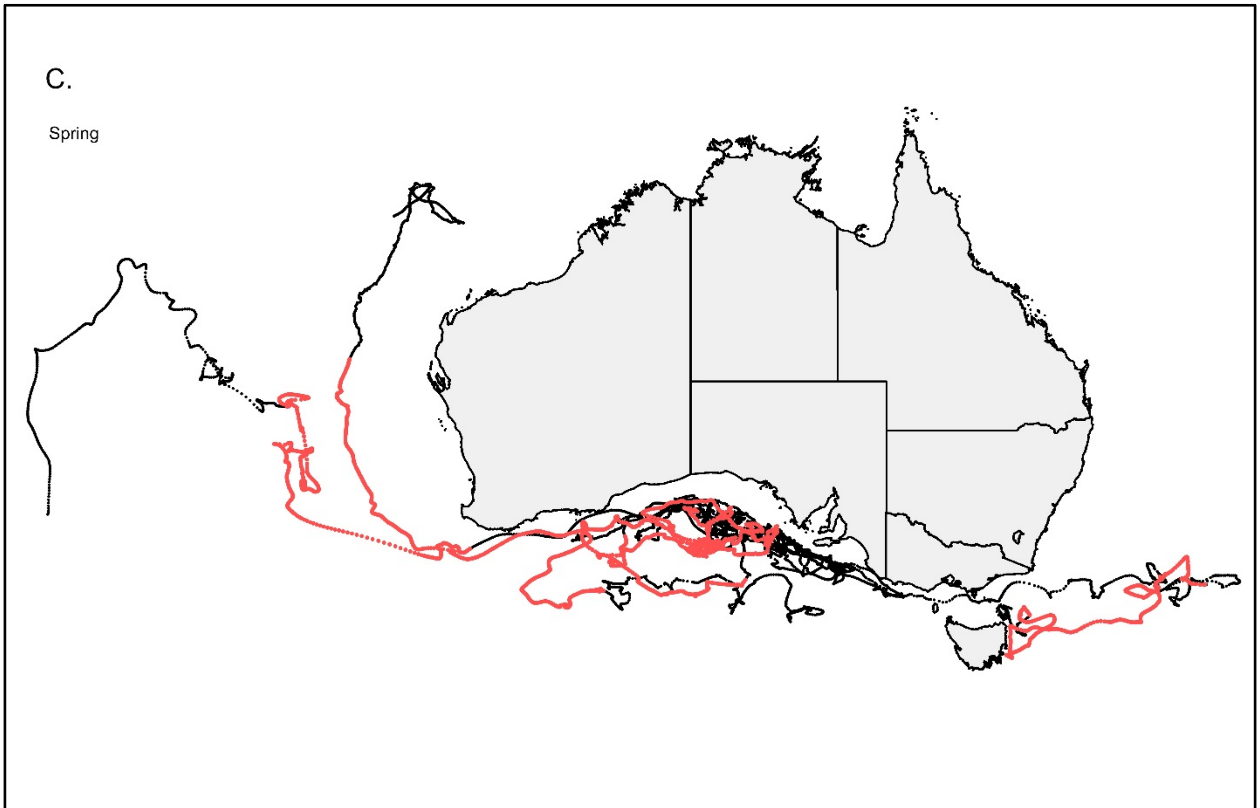


Figure 7. Seasonal distribution of blue sharks in the Great Australian Bight during 2015 and 2016. A. Autumn 2015 (green symbols), B. Winter 2015 (blue symbols).



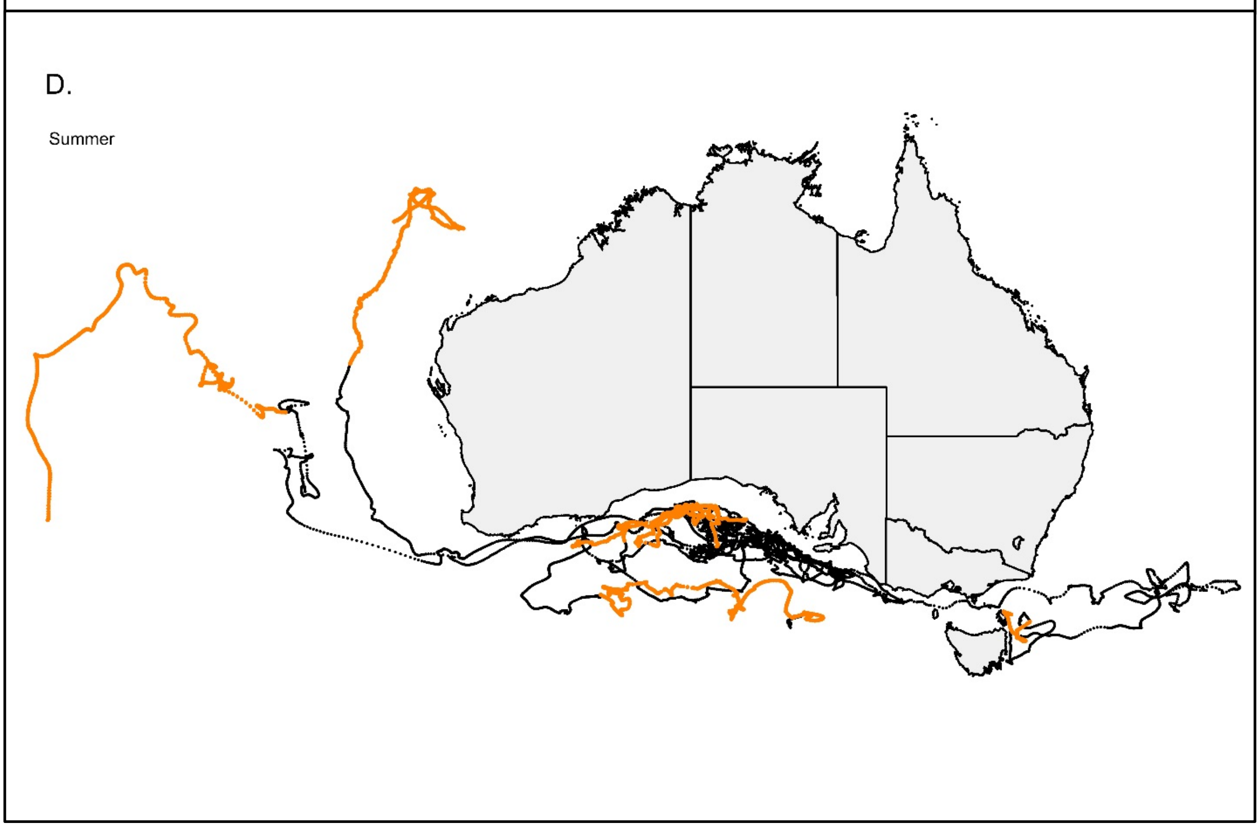


Figure 7. (cont). Seasonal distribution of blue sharks in the Great Australian Bight during 2015 and 2016. C. Spring 2015 (red symbols), and D. Summer 2015–16 (orange symbols)

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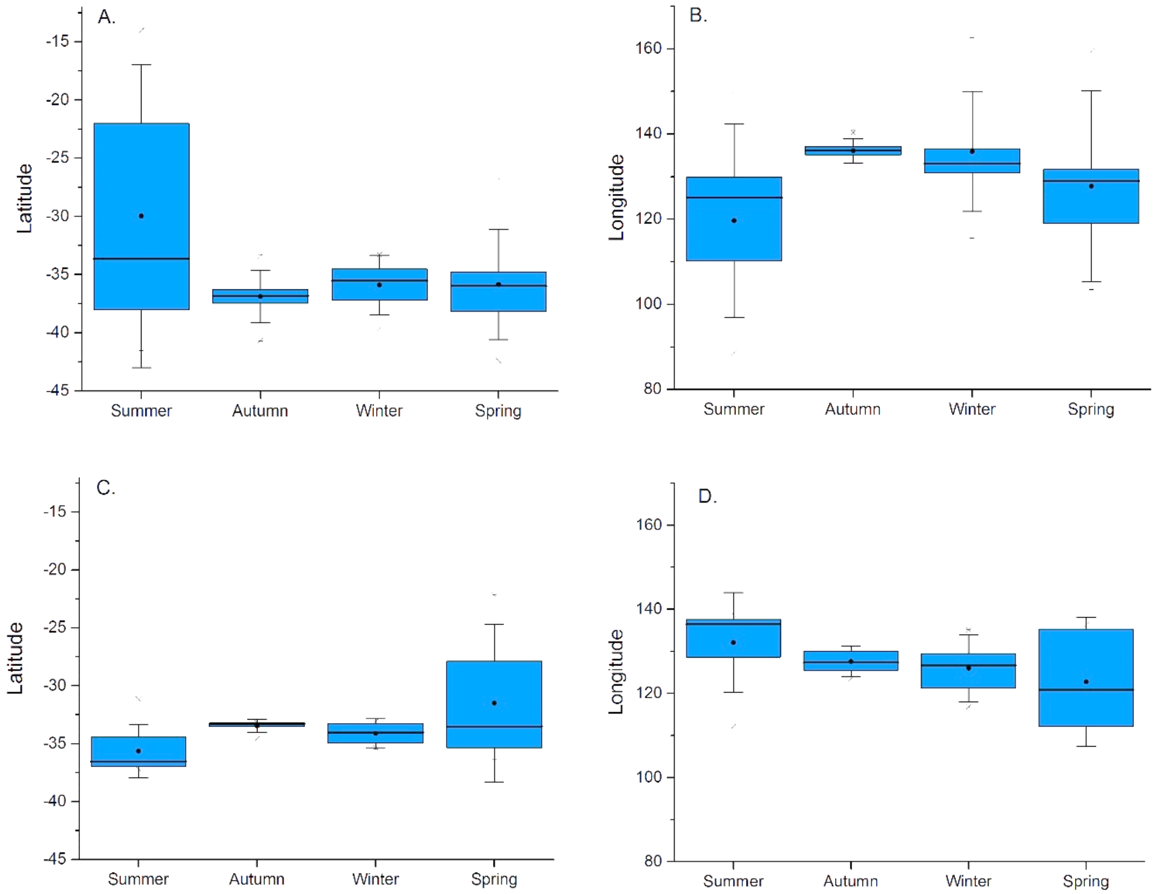


Figure 8. Seasonal patterns in latitude (A) and longitude (B) of positions of blue sharks (B1–B7) and latitude (C) and longitude (D) of positions of the shortfin mako (S1) in 2015–16. Shows mean (circle symbol), error bars are standard deviation, median (slash in box), 25 and 75 percentiles (box upper and lower bounds), 1 and 99 percentiles (cross symbol), max and min values (dashed line above and below error bars).

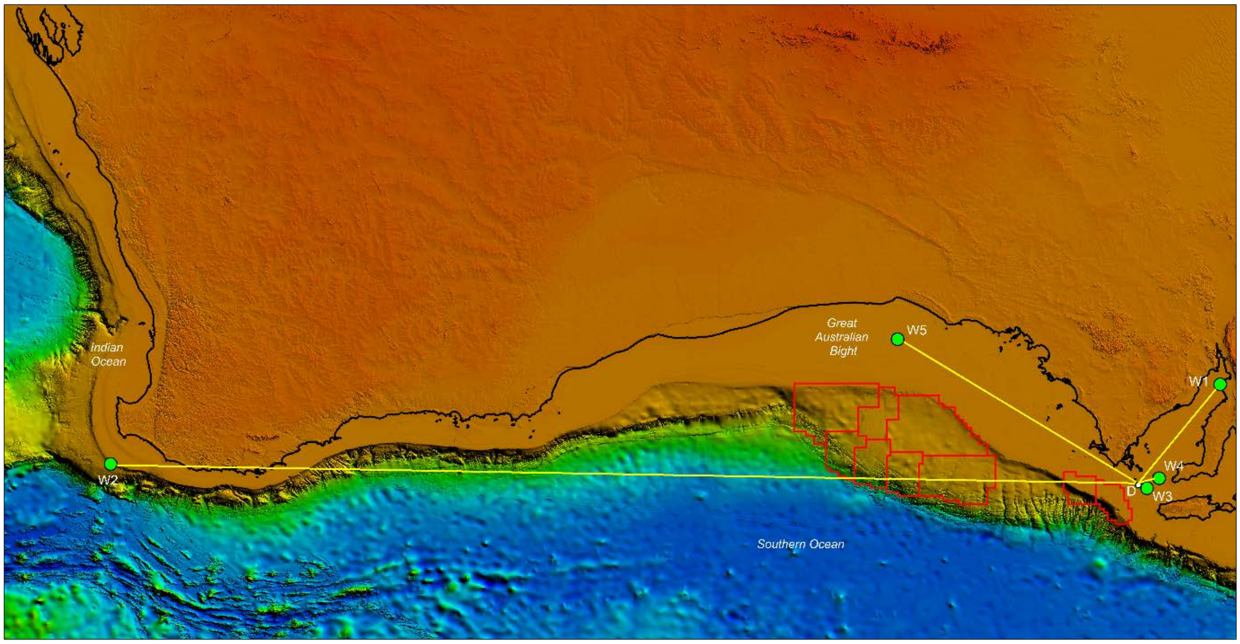


Figure 9. Map showing tagging (white D) and pop-up locations (green symbols W1–W5) showing movements of white shark into the Great Australian Bight, southern and northern Spencer Gulf, and to the continental shelf slope off Cape Leeuwin, Western Australia. Petroleum exploration lease areas are shown as red lines.

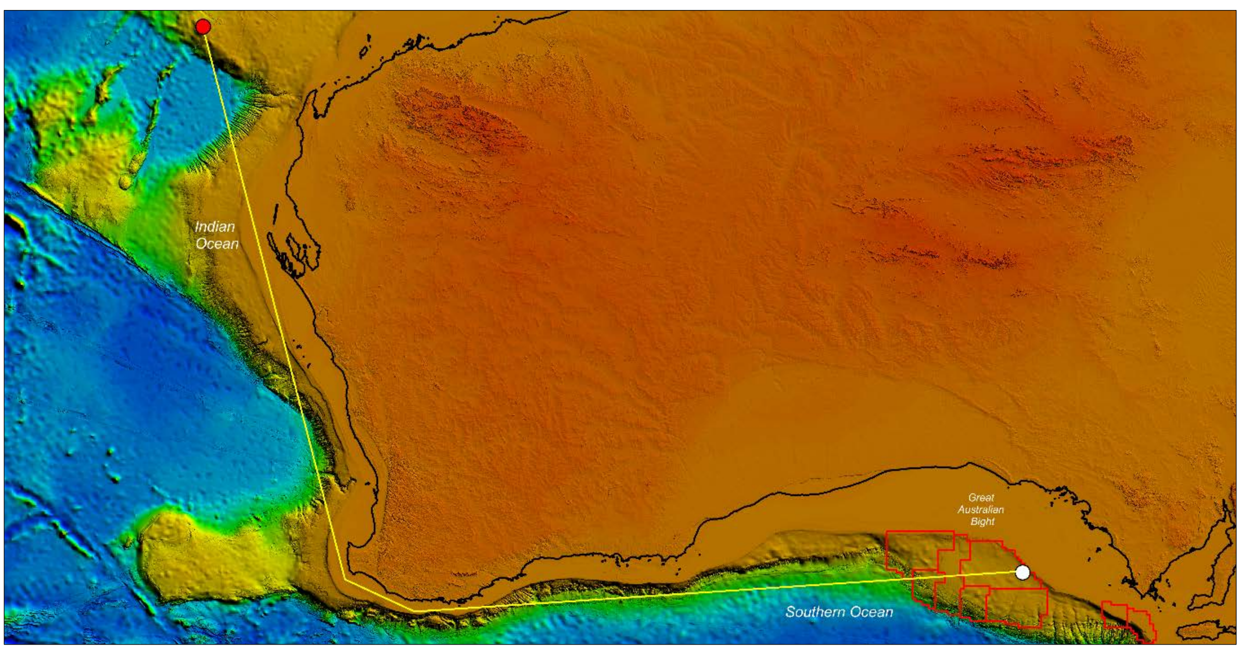


Figure 10. Map showing tagging (white symbol) and pop-up location (red symbol) for the bigeye thresher. Shows movement from the Great Australian Bight to the Montebello Saddle, in the north-west Indian Ocean. Petroleum exploration lease areas are shown as red lines.

Overlap with spatial management regions

Time-spent-per-area (TSA) analyses of the blue shark (n=7) tracking data indicated focal areas of habitat use correlated with bottom depths >1000 m in oceanic areas beyond the lower continental shelf slope (Figs. 11–17). They included, but were not restricted to the regions directly adjacent to the eastern (134.5°E) and central Great Australian Bight (129.5–131°E), Bonney Upwelling Region (138°E), and Tasman Sea (155–160°E). Several tracked blue sharks visited oceanic regions to the north of the Sub-tropical Front and south of the eastern, central, and western Great Australian Bight (36–40°S), which were characterised by bottom depths ≥5000 m. Oceanic areas between 34°S, 130°E and 36°S, 130°E; represented key regions for three tracked blue sharks (B4, B5 and B7) (Figs. 14, 15 and 17).

TSA analyses of the shortfin mako tracking data (Table 5) for the (S1) (Fig. 18) indicated areas of highest habitat use were the continental shelf break and slope adjacent to the Lacepede Shelf, Murray Canyons to the south of Kangaroo Island, and outer shelf (100 m), shelf break (160–200 m) and upper shelf slope (300 m) areas in the western Great Australian Bight. The cline of high relief bathymetry between the 80–130 m isobaths, which is considered to be the ancient coastline of the Last Glacial Maximum (~15–25,000 years before present) (Mulvaney and Kamminga 1999) was visited by this shark.

Individual-based TSA analyses for blue sharks and the shortfin mako were undertaken to quantify overlap with Commonwealth marine reserves, and oil and gas lease areas in the Great Australian Bight (Figs 11–17, Table 5). Time spent in the oil and gas lease areas by individual blue sharks ranged between 0 and 120 days (mean = 43 ± 51 days, median = 23 days) (Figs. 11–17, Table 5). Time spent by the blue sharks in the central Great Australian Bight lease area (BP-Statoil, Chevron and Murphy leases combined) ranged between 0 and 34 days (mean = 10 ± 13 days, median = 3 days) (Table 5).

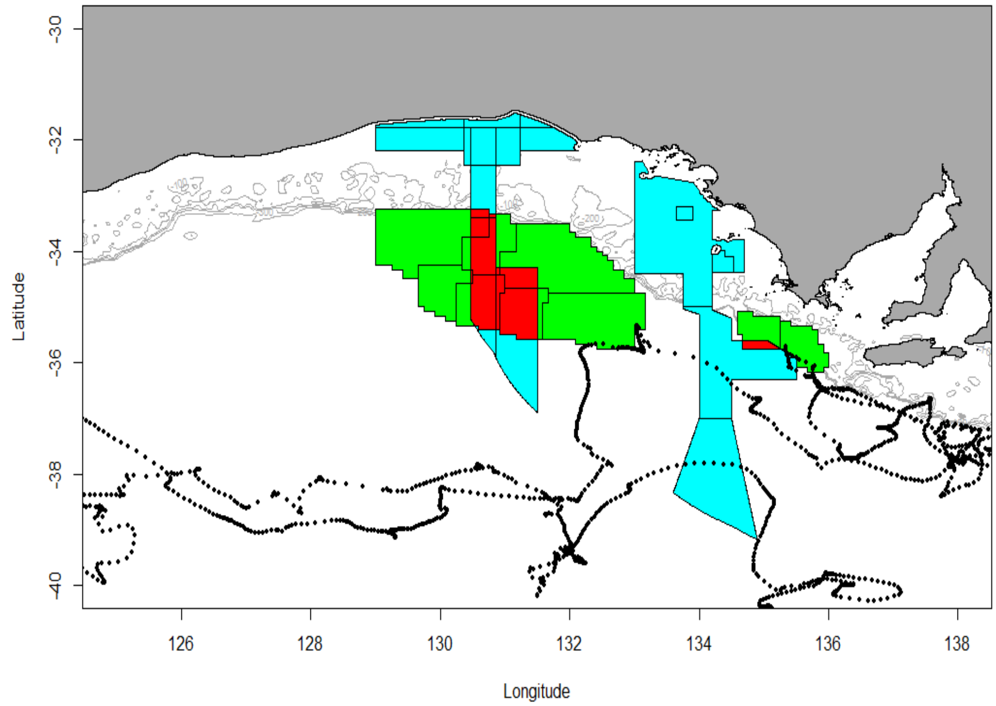
Time in the oil and gas leases by the shortfin mako was 2 days in the central Great Australian Bight BP-Statoil, Chevron and Murphy leases, and 32 days in the lease areas (all combined) (Table 5). Blue sharks B4, B5 and B7 spent 66.7% (14 days), 43.1% (120 days) and 48.9% (115 days) of

their tracked time in the lease areas, respectively (Figs. 14, 15 and 17, Table 5). Blue sharks B1–B3, and B6 each spent <10% of their tracked time inside leases (Figs. 11, 13 and 16). Time spent by blue sharks in the central Great Australian Bight Marine Reserve, which overlaps with oil and gas lease areas, ranged between 0 and 38 days (mean = 11 ± 14 days, median = 4 days) (Table 5). A similar pattern was observed in the Western Eyre Commonwealth Marine Reserve in the eastern Great Australian Bight, where blue sharks spent 0–50 days (mean = 10 ± 18 days, median = 3.5 days).

The shortfin mako spent 4 days in the Great Australian Bight Marine Reserve, and 6 days in the Western Eyre Commonwealth Marine Reserve where the oil and gas leases overlap with the Great Australian Bight Marine Reserve (Table 5). Blue sharks spent between 0 and 34 days in this multi-use jurisdiction (Figs 11–16), while the shortfin mako spent 2 days in the same offshore zone (Fig 17), reflecting their greater preference for the mid and outer continental shelf and shelf-break.

Table 5. Percentage time-spent-per-area in petroleum leases and Commonwealth Marine Reserves (GAB Marine Reserve and Western Eyre Reserve) in the Great Australian Bight.

Shark ID	Duration (days)	Time in leases (days)	%	Time in GABMR. (days)	%	Time in Western Eyre Res. (days)	%	Time in GAB lease & park (days)	%
B1	315	4	1.3	0	0	4	1.3	0	0
B2	294	23	7.8	14.5	5	7	2.4	11	3.7
B3	297	28	9.4	4	1.3	50	17	0	0
B4	21	14	66.7	3	14.3	0.2	1	3	14.3
B5	278	120	43.1	19	6.8	3	1.1	19	6.8
B6	208	0	0	0	0	0	0	0	0
B7	235	115	48.9	38	16.2	3.5	1.5	34	14.5
S1	297	32	10.8	4	1.3	6	2	2	0.7



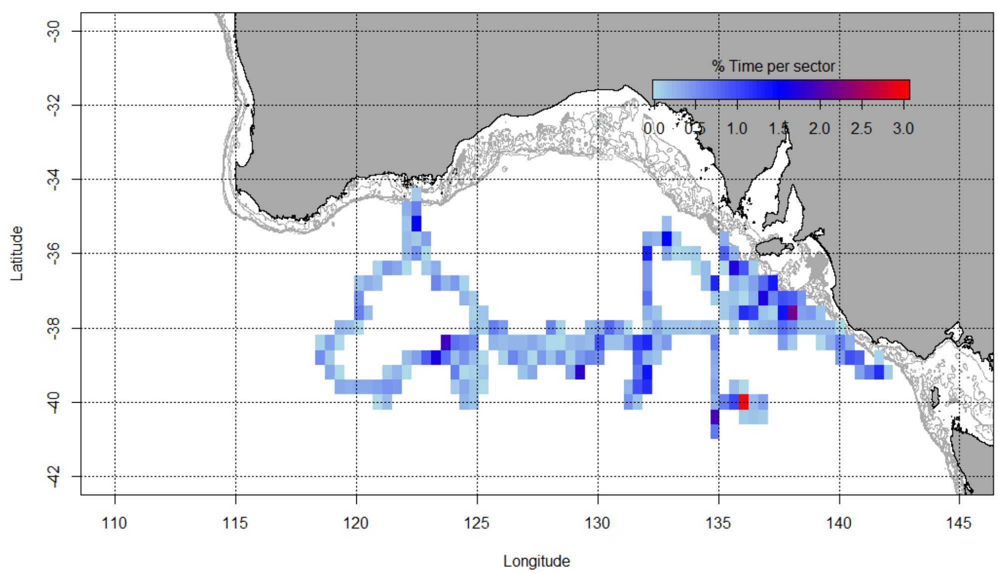


Figure 11. Bottom map shows time-spent-per-area for blue shark B1 (200 cm female) for the entire extent of the track in the Great Australian Bight and Southern Ocean. Top map shows spatial overlap of the shark track (dotted black line) with the petroleum lease areas (green), two Commonwealth marine reserves in the Great Australian Bight (blue), and the lease areas that intersect both management regions (red).

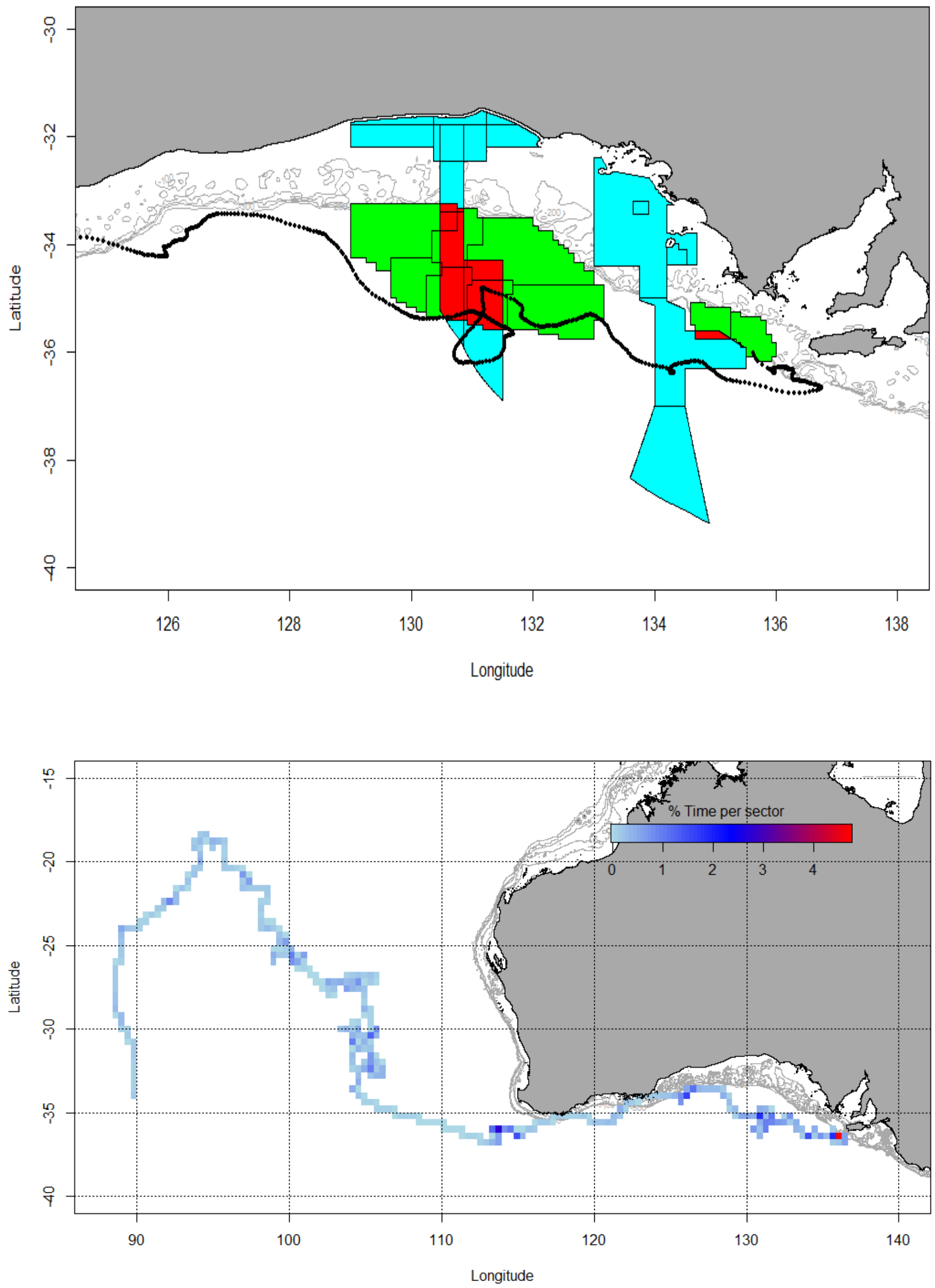
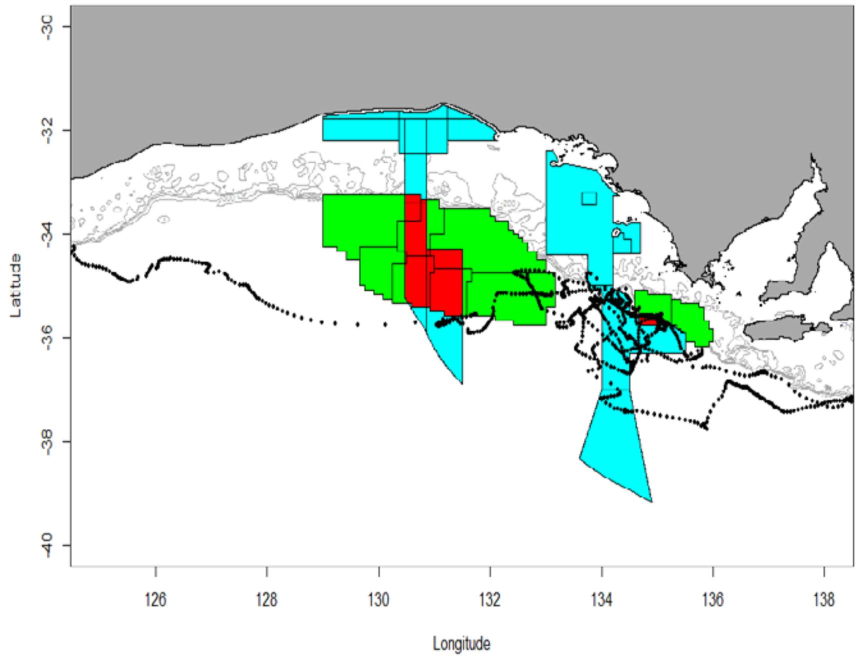


Figure 12. Bottom map shows time-spent-per-area for blue shark B2 (180 cm male) for the entire extent of the track in the Great Australian Bight and Southern Ocean. Top map shows spatial overlap of the shark track (dotted black line) with the petroleum lease areas (green), two Commonwealth marine reserves in the Great Australian Bight (blue), and the lease areas that intersect both management regions (red).



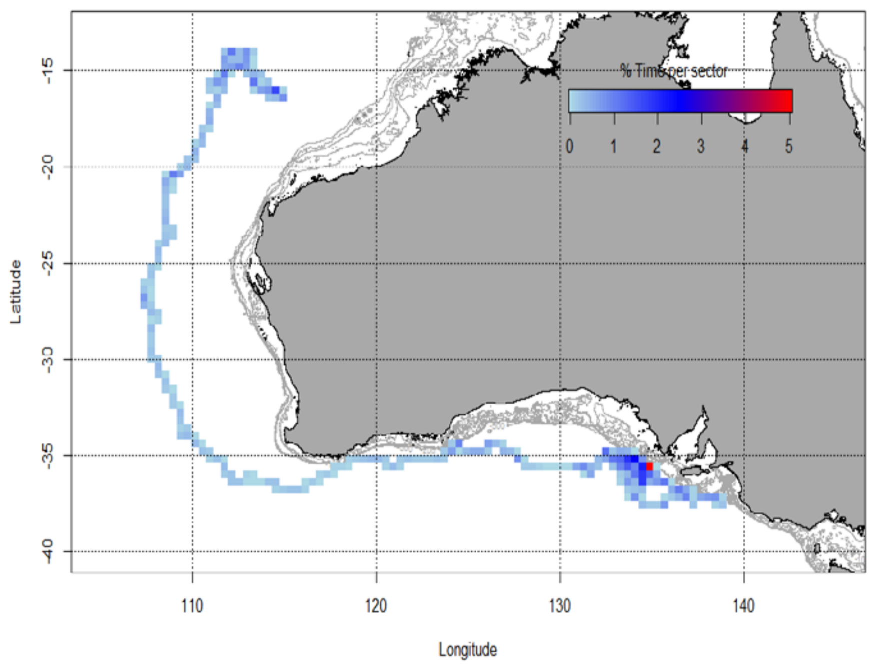


Figure 13. Bottom map shows time-spent-per-area for blue shark B3 (224 cm female) for the entire extent of the track in the Great Australian Bight and Southern Ocean. Top map shows spatial overlap of the shark track (dotted black line) with the petroleum lease areas (green), two Commonwealth marine reserves in the Great Australian Bight (blue), and the lease areas that intersect both management regions (red).

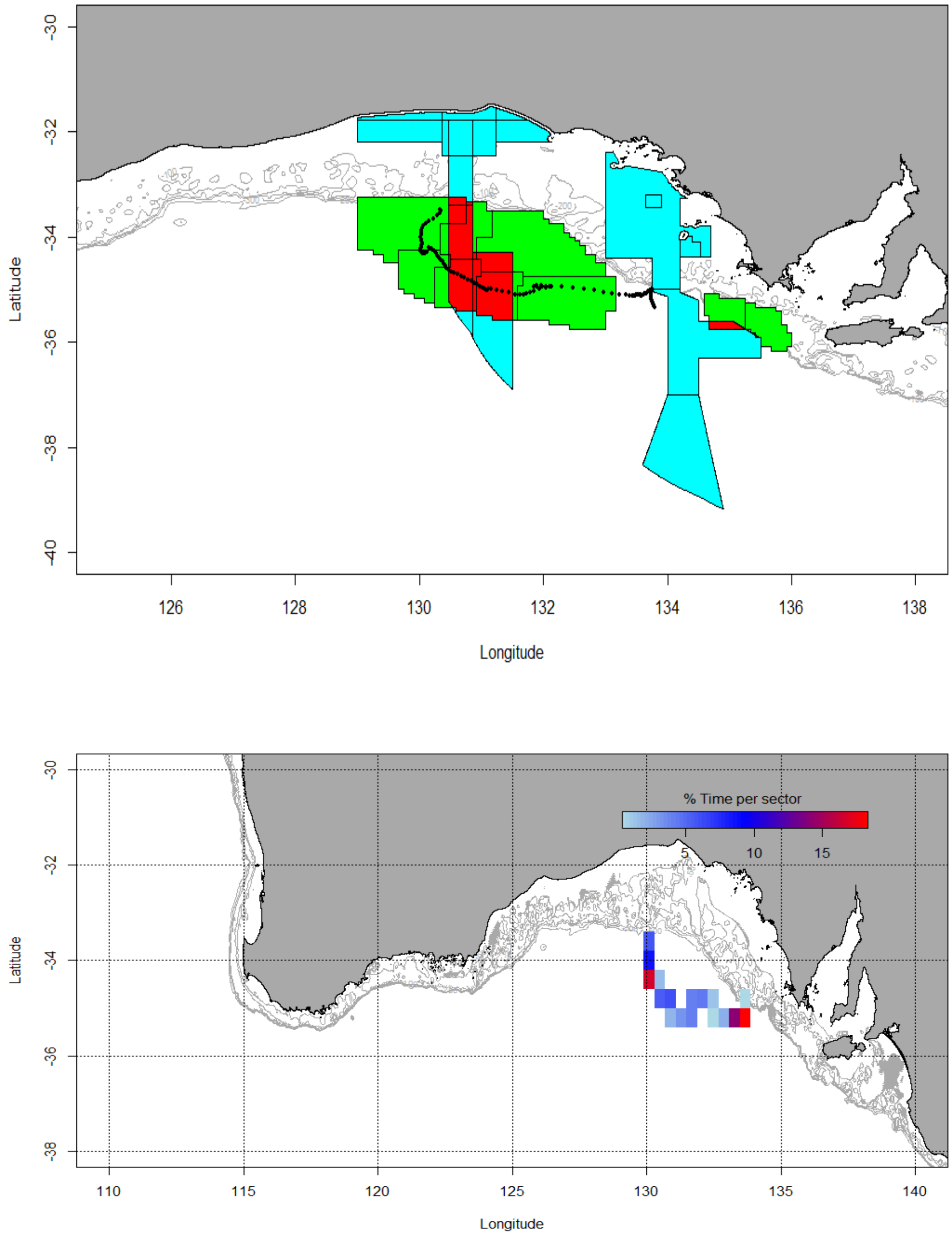
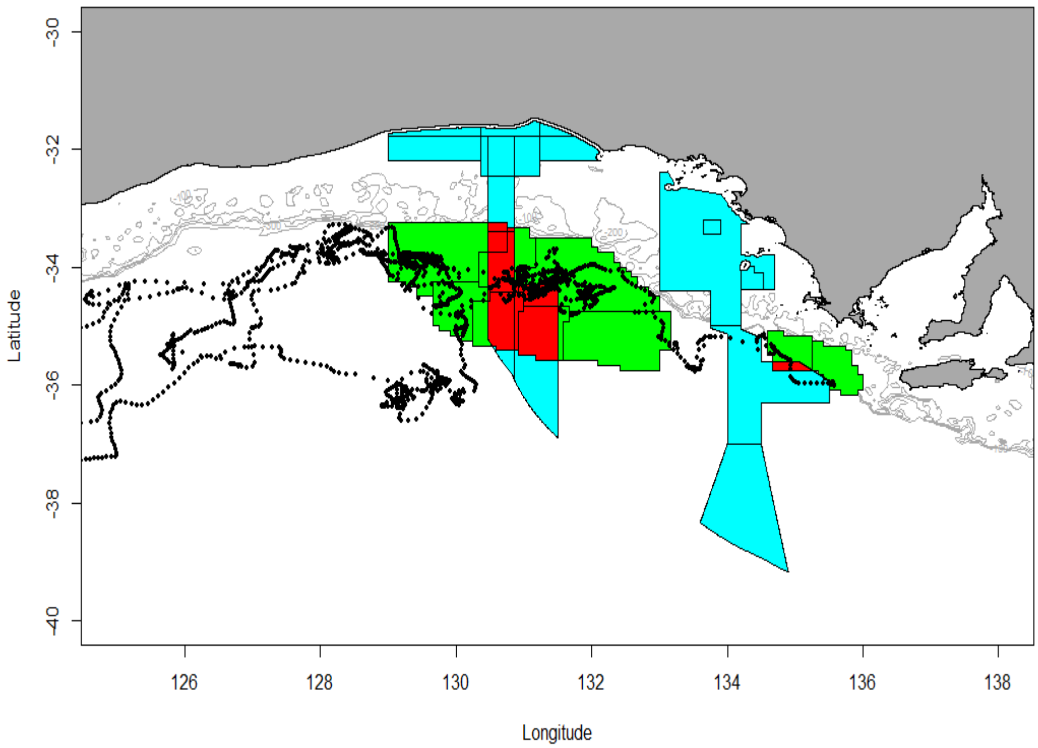


Figure 14. Bottom map shows time-spent-per-area for blue shark B4 (208 cm male) for the entire extent of the track in the Great Australian Bight and Southern Ocean. Top map shows spatial overlap of the shark track (dotted black line) with the petroleum lease areas (green), two Commonwealth marine reserves in the Great Australian Bight (blue), and the lease areas that intersect both management regions (red).



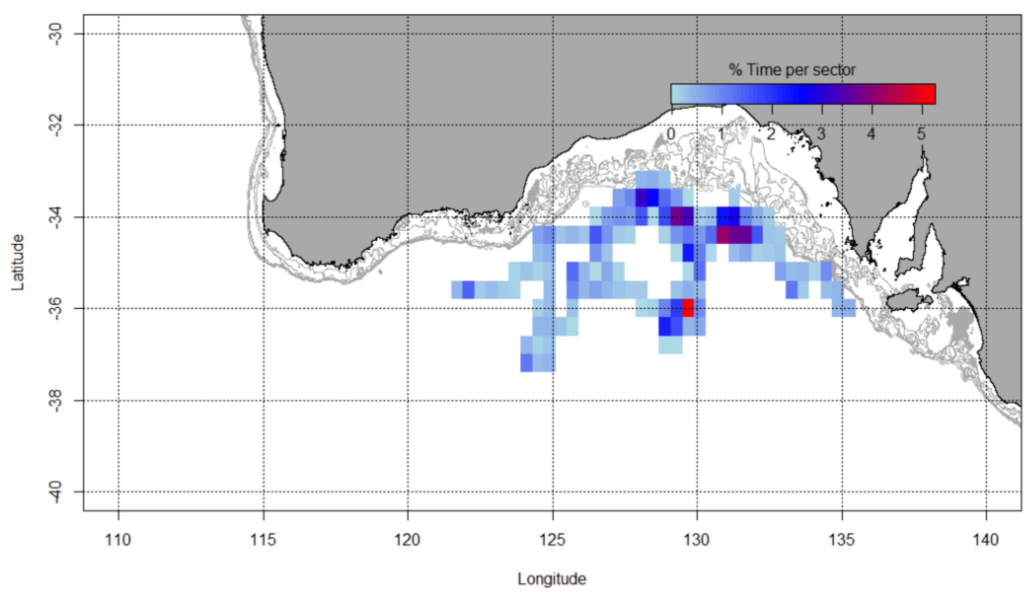


Figure 15. Bottom map shows time-spent-per-area for blue shark B5 (233 cm male) for the entire extent of the track in the Great Australian Bight and Southern Ocean. Top map shows spatial overlap of the shark track (dotted black line) with the petroleum lease areas (green), two Commonwealth marine reserves in the Great Australian Bight (blue), and the lease areas that intersect both management regions (red).

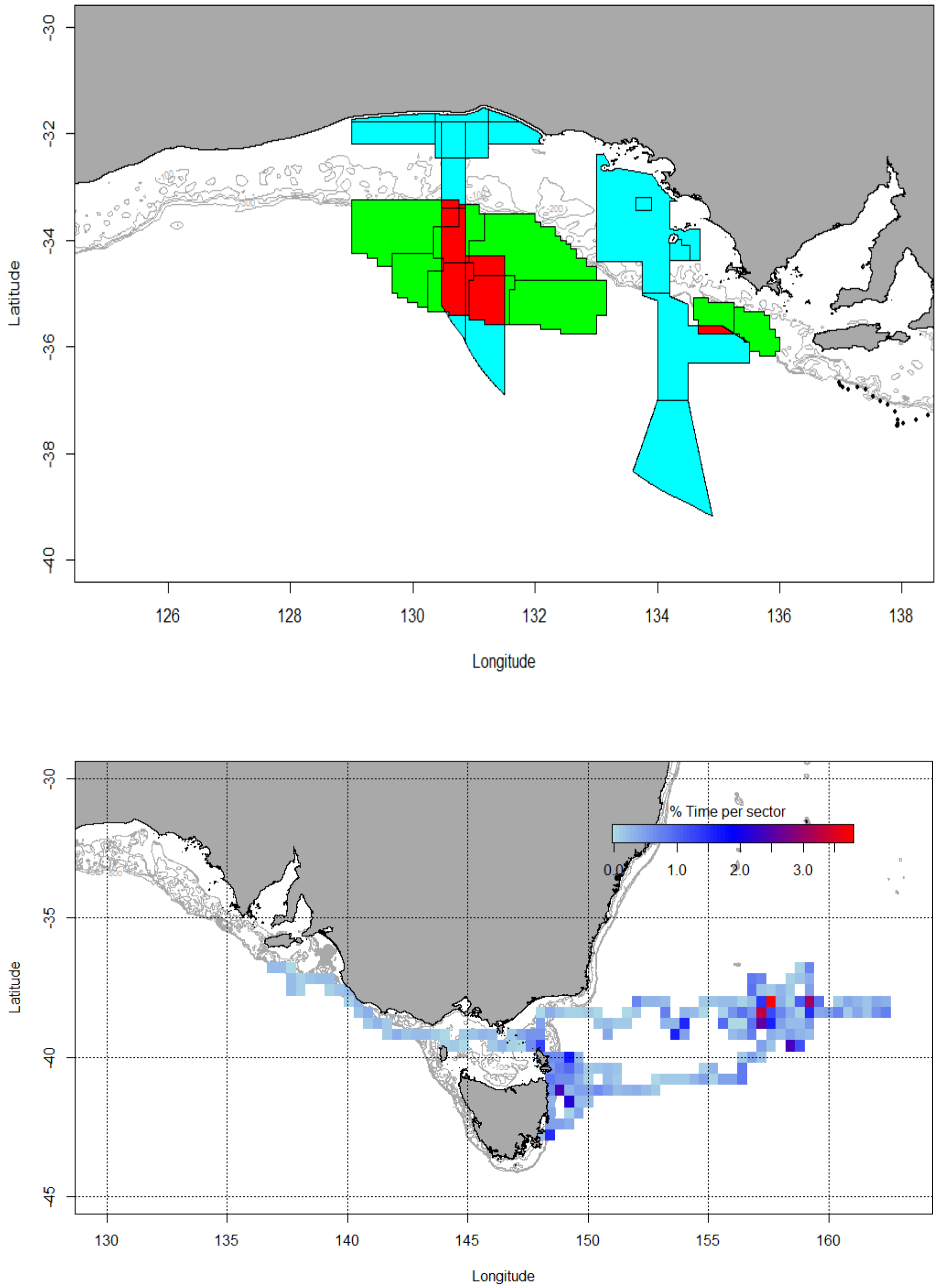


Figure 16. Bottom map shows time-spent-per-area for blue shark B6 (235 cm male) for the entire extent of the track in the Great Australian Bight and Southern Ocean. Top map shows spatial overlap of the shark track (dotted black line) with the petroleum lease areas (green), two Commonwealth marine reserves in the Great Australian Bight (blue), and the lease areas that intersect both management regions (red).

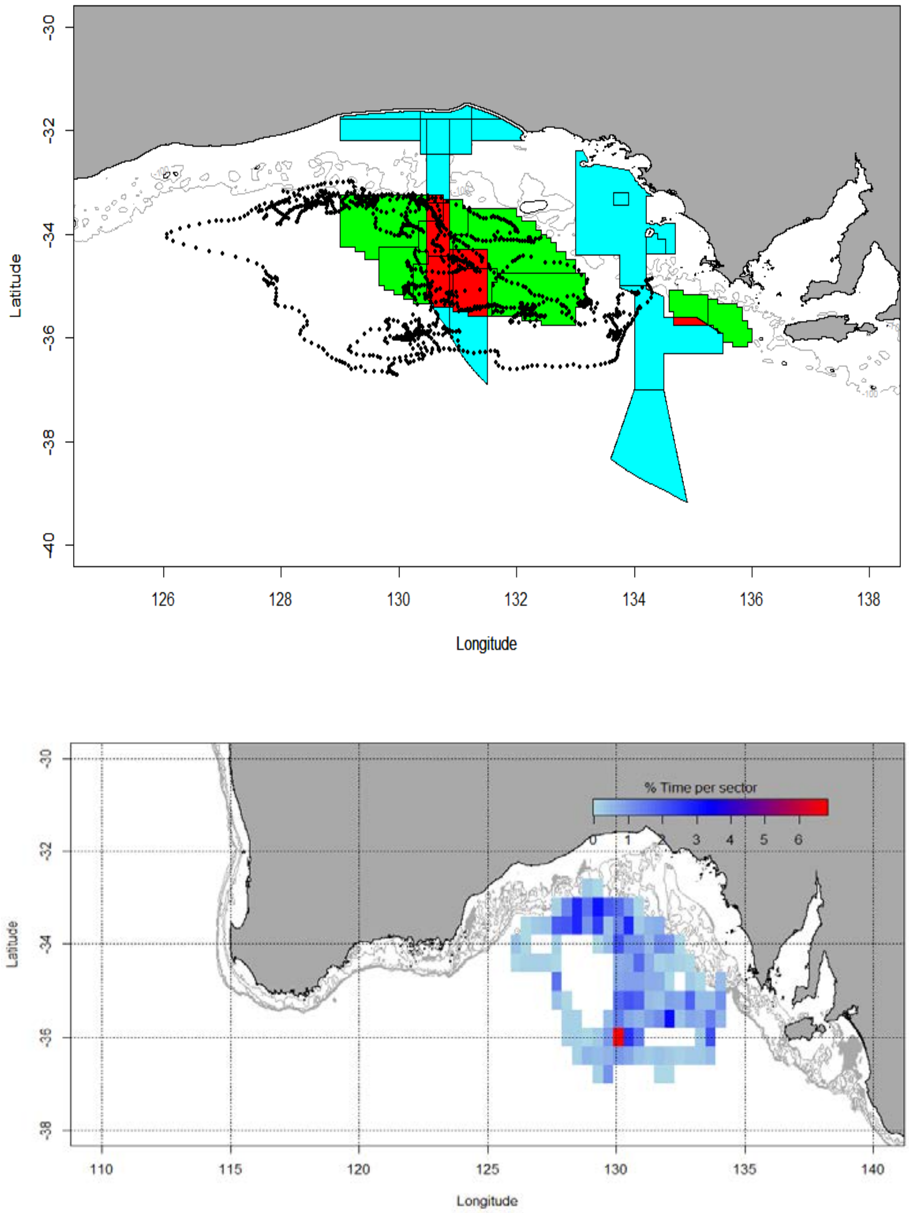
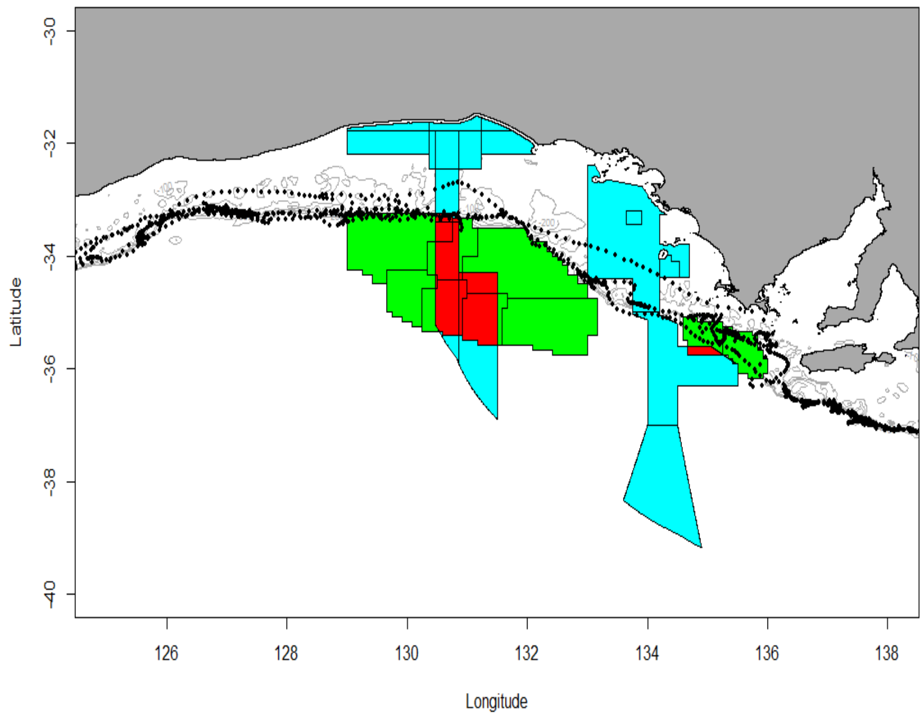


Figure 17. Bottom map shows time-spent-per-area for blue shark B7 (250 cm male) for the entire extent of the track in the Great Australian Bight and Southern Ocean. Top map shows spatial overlap of the shark track (dotted black line) with the petroleum lease areas (green), two Commonwealth marine reserves in the Great Australian Bight (blue), and the lease areas that intersect both management regions (red).



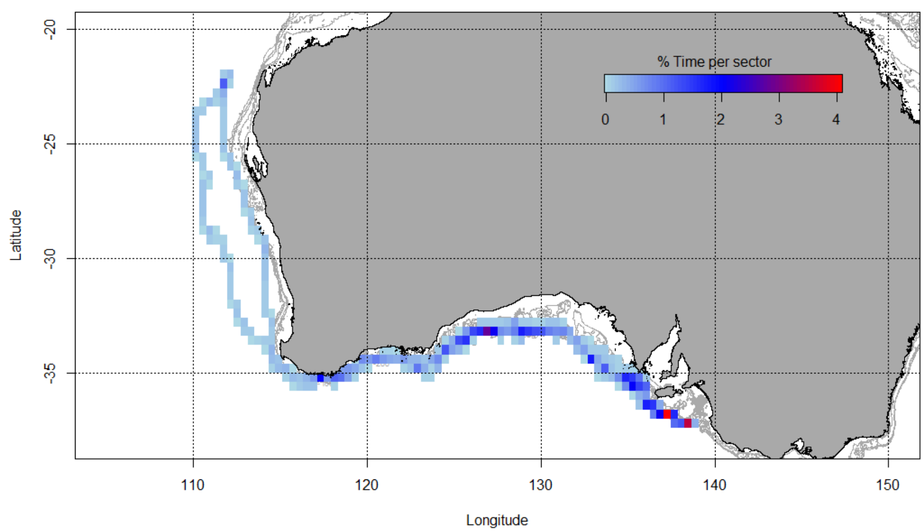


Figure 18. Bottom map shows time-spent-per-area for the shortfin mako S1 (232 cm female) for the entire extent of the track in the Great Australian Bight and Southern Ocean. Top map shows spatial overlap of the shark track (dotted black line) with the petroleum lease areas (green), two Commonwealth marine reserves in the Great Australian Bight (blue), and the lease areas that intersect both management regions (red).

Habitat use

Depth and bathymetry gradient

Blue sharks

Blue sharks traversed areas with maximum water depths of 6250 m (mean = 3603 ± 1769 m, s.d.) (Fig. 19, Table 6). Habitat plots show median depths ranged from 1505–5179 m; the lower end of the range should be interpreted cautiously as B4 was a short duration deployment (< 50 days) (Fig. 19). Four of the six blue sharks for which there were long-term tracks (excluding B4) preferred shallower, oceanic areas during fidelity or area restricted search (fidelity) movement stages (Fig. 19). Blue sharks traversed a varied array of habitats where bathymetric slopes ranged from 0.01 to 15.85 degrees (mean = 1.98 ± 1.99 degrees) (Fig. 20, Table 6). Four of the six (67%) animals (excluding B4) exhibited area restricted search classified movements in regions with higher variability in depth gradients as compared to areas used as transit paths (Fig. 20).

Shortfin mako

The shortfin mako inhabited areas characterised by mean bottom depths of 755 ± 1344 m, s.d.; median = 206 m, and maximum bottom depths in oceanic areas of 5845 m (Fig. 19, Table 6). The shortfin mako inhabited areas with shallower mean depths during ARS classified movements, than during transit.

Position estimates at the surface corresponded to bathymetric gradients ranging from 0 to 16.50 m (mean = 2.10 ± 1.04 m) (Fig. 20, Table 6). This individual exhibited area restricted search classified movements in regions characterised by larger mean, median and ranges of depth gradients when compared to areas it used as transit paths (Fig. 20).

Table 6. Summary of physical and oceanographic habitat variables describing areas used by tracked blue sharks (combined) and the shortfin mako. Depth = bottom depth (m), bathymetry gradient (m), SST = sea-surface temperature (°C), SST grad = sea surface temperature gradient (°C), SSH = sea-surface height (m), SSH grad. = sea-surface height gradient (m).

Species	Parameter	N	Mean	sd	Median	Min	Max
Shortfin mako S1	Depth	1784	755	1344	206	1	5845
	Bath gradient	1782	2.01	2.84	1.04	4.97E-17	16.50
	SST	1784	18.1	2.2	18.4	13.6	24.2
	ST grad	1726	0.00047	0.00032	0.00041	0.000033	0.0019
	SSH	1784	0.57	0.16	0.55	0.38	0.95
	SSH grad	1753	0.000049	0.000035	0.000041	0.0000016	0.00025
Blue shark B1–B7	Depth	9895	3603	1769	4359	0	6250
	Bath gradient	9891	1.99	1.99	1.40	0.0063	15.86
	SST	9896	17.2	3.5	16.2	12.1	30.1
	ST grad	9844	0.00057	0.00040	0.00048	0.0000052	0.0030
	SSH	9896	0.61	0.13	0.57	0.28	1.26
	SSH grad	9871	0.000056	0.000047	0.000045	0.00000046	0.00066

Sea-surface temperature and gradient

Blue sharks

Blue sharks occupied areas where sea-surface temperatures ranged from 12.1 to 30.1 °C (mean = 17.2 ± 3.5 °C; median = 16.2 °C) (Fig. 19, Table 6). The high variability directly reflected the broad scale movements (1000s of km) of blue sharks into the Indian, Southern and SW Pacific Oceans. Most blue sharks exhibited area restricted search classified movement in areas with lower median sea-surface temperatures. Periods when sharks were transiting were mostly characterised by areas with high variability in sea-surface temperatures (Fig. 19).

The mean sea-surface temperature gradient that correlated with satellite positions of blue sharks was 0.00047 ± 0.00032 °C (median = 0.000041 °C) (Fig. 20, Table 6). The range of this parameter spanned several orders of magnitude, indicating blue sharks inhabited a diverse range of water masses and frontal features (Table 6). As for correlations with sea-surface temperature, over half (67%) the tracked individuals exhibited movements classified as area restricted search in regions

with low variability in the sea surface temperature gradient, yet higher mean and median values (Fig 20, Table 6).

Shortfin mako

The shortfin mako inhabited areas where sea-surface temperatures ranged from 13.6 to 24.2 °C (mean = 18.1 ± 2.2 °C; median = 18.4 °C) (Table 6), and exhibited movements classified as area restricted search in regions with lower mean and median sea-surface temperatures (Fig. 19) and marginally lower variability, as compared to transited regions. Mean sea-surface temperature gradient for the shortfin mako was 0.0005 ± 0.0003 °C (Fig. 20). This individual exhibited movements classified as area restricted search in regions with low variability in sea surface temperature gradient when compared to the areas it transited across with higher directionality. Median values were similar during area restricted search and transit stages (Fig. 20, Table 6).

Sea-surface height and gradient

Blue sharks

Blue sharks occupied areas where sea-surface height anomaly values ranged from 0.28 to 1.26 m (mean = 0.61 ± 0.13 m; median = 0.57 m) (Fig 19, Table 6). State space model fits indicated four of the six sharks (67%) exhibited area restricted search classified movements in regions with comparatively low variability in sea-surface height as compared to areas they used as transit paths. This was similar to patterns observed for sea-surface temperature and its gradient. No observable pattern was apparent in the state space modelled position and sea-surface height gradient data, with high individual level variation between area restricted search and transit stages. Overall, the individual-level estimate of variability in sea-surface height gradient was highest during the transit stages of sharks B2, B3 and B6 (Fig. 20, Table 6).

Shortfin mako

The shortfin mako inhabited areas where sea-surface height anomaly values ranged from 0.38–0.95 m (mean = 0.57 ± 0.12 m; median = 0.55 m). The shortfin mako exhibited area restricted search classified movements in regions with lower mean and median sea-surface heights than for transited areas (Fig. 19). Variability in sea-surface height was substantially lower in areas

where the shortfin mako exhibited area restricted search classified movements when compared to areas the individual transited across with higher directionality. The large range of sea-surface height observed reflected the expansive spatial area of the migration that extended from the temperate waters of the central Great Australian Bight to the sub-tropical waters of the Indian Ocean. Mean and median sea-surface height gradient (Fig. 20) were similar for transit and restricted search stages, while variability was highest in the areas used as transit paths.

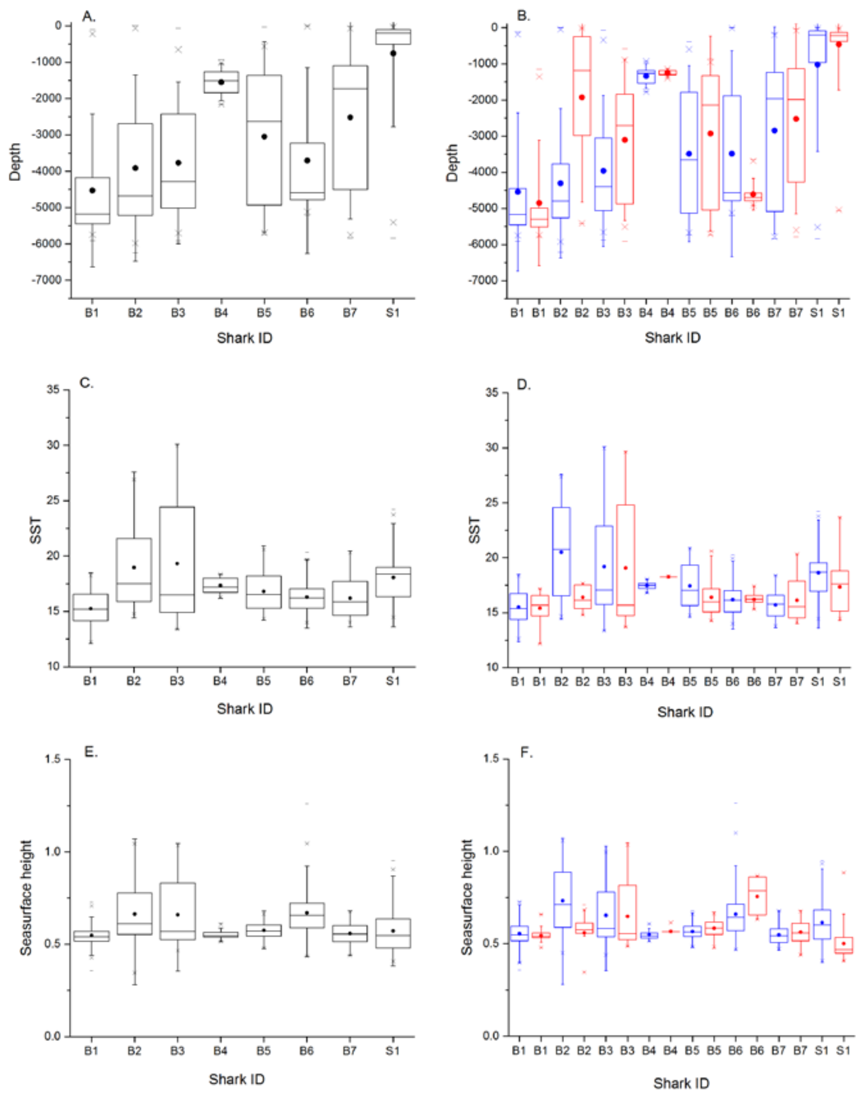


Figure 19. Habitat summary plots for blue sharks B1–B7 (combined), and the shortfin mako, S1 showing patterns of depth use (A and B), sea-surface temperature (C and D), sea-surface height (E and F). Plots B, D and F show the parameters during area-restricted search and transit classified movements where blue = transit and red = fidelity (searching) classified positions. Plots show mean (circle symbol), median (slash in box), 25 and 75 percentiles (box upper and lower bounds), outliers are error bars, 1 and 99 percentiles (cross symbol), maximum and minimum values (dashed line above and below error bars).

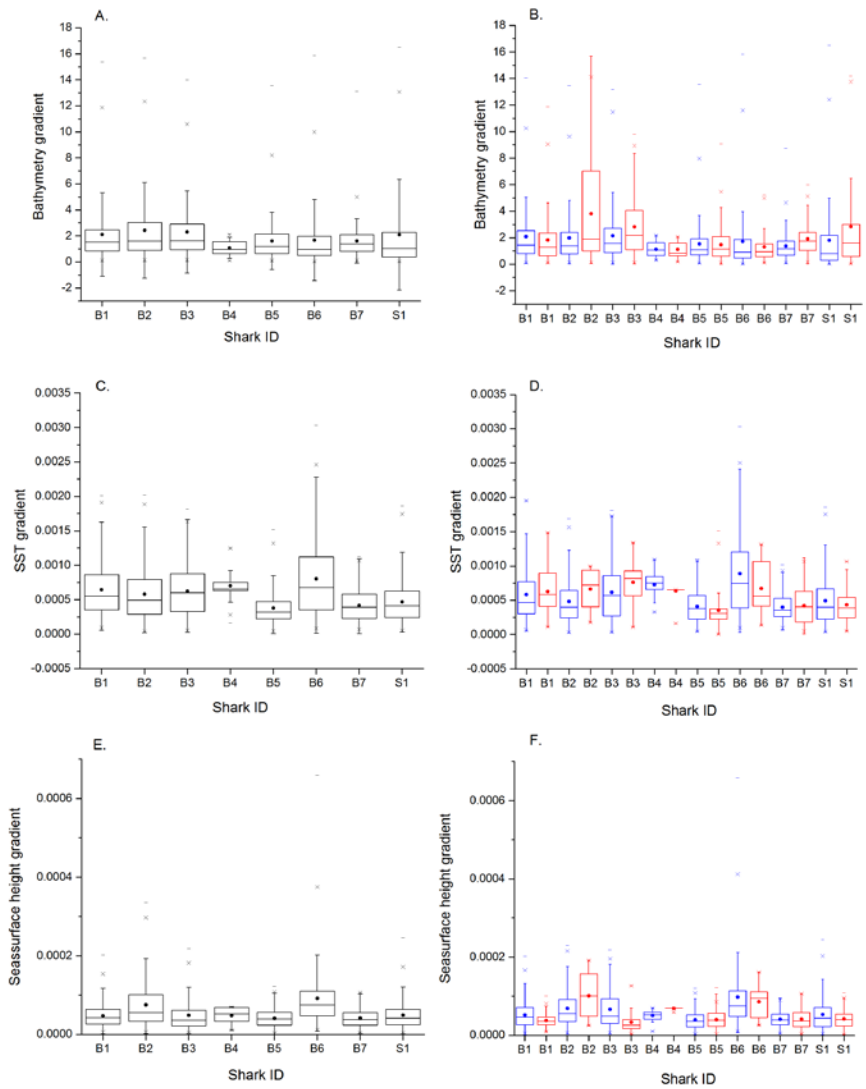


Figure 20. Habitat summary plots for blue sharks, B1–B7 (combined) and the shortfin mako, S1. Plots show gradients of bathymetry (A and B), sea-surface temperature (C and D) and sea-surface height (E and F). Plots B, D and F show the parameters during area-restricted search and transit classified movements where blue = transit and red = fidelity (searching) classified positions. Box plots show mean (circle symbol), standard deviation (error bars), median (slash in box), 25 and 75 percentiles (box upper and lower bounds), 1 and 99 percentiles (cross symbol), max and min values (dashed line above and below error bars).

Vertical habitat use

White sharks

Depth and temperature data provided by mini-PATs on five white sharks during 64 to 102 day deployments showed individuals inhabited a diverse range of depth and thermal environments characteristic of regions ranging from the shallow gulfs to the lower continental shelf slope (Table 7). Based on the depths inhabited, and surfacing locations of the pop-up tags, we can infer that southern Spencer Gulf and its entrance were important habitats for white sharks W1, W3 and W4, whereas sharks W2 and W5 migrated to shelf and continental shelf slope waters.

A total of 62296 depth records (2077–26668 per shark) were transmitted by the five mini-PATs deployed on white sharks. White sharks that remained in the vicinity of the gulf and its approach (W1, W3 and W4) inhabited average depths ranging from 17.7 ± 18 m (W4) to 32.1 ± 20.4 m (W3), with minimum and maximum depths ranging between 0–95 m (W4) and 0.5–105 m (W3) (Table 7). Sharks W1, W3 and W4 experienced autumn and winter tag-measured SSTs from 9.5–17.7 °C: averages ranged from 14.8 ± 1.9 to 16.6 ± 0.4 °C. Average daily temperature minima experienced by these three individuals ranged from 14.7 ± 1.9 to 16.4 ± 0.4 °C, whereas the lower temperature values reflect the large depth ranges traversed by the white sharks that visited shelf and slope habitats (13.9–16.1 °C, for W2 and W5 respectively; estimated thermal minima = 4.7 °C at 783 m (W2).

Sharks W2 and W5 inhabited average depths of 103.5 ± 184.7 m and 22.5 ± 22.3 m, respectively. Depth ranges were 0–917 m (W2) and 0–163 m (W5) (Table 7). Reported sea-surface temperatures inhabited by these two individuals ranged from 15.8–20.3 °C. The average reported SST experienced by shark W2 was 17.7 ± 1.1 °C, as it travelled across the Great Australian Bight to Cape Leeuwin, Western Australia. Shark W5 experienced SST ranging from 15.4 to 17.2°C (average = 16.1 ± 0.52 °C) as it travelled north-west from the South Neptune Islands to the mid-continental shelf region to the south of Head of Bight.

Table 7. Habitat parameters for five tagged white sharks (W1–W5) in autumn and winter 2015. Parameter estimates shown here are measured by the mini-pop-up satellite tags during the deployments.

Parameter and statistic	W1	W2	W3	W4	W5
N depth records	2077	26668	11362	19776	2413
Ave depth (m)	20.7	103.5	32.1	17.8	22.5
SD depth	18.9	184.7	20.4	18.1	22.3
Min depth	0.0	0.0	0.5	0.0	0.0
Max depth	98.0	916.5	105.0	95.0	162.5
N tag-measured SST records	141	191	108	171	32
Ave SST (° C)	14.8	17.7	16.6	15.7	16.1
SD SST	1.9	1.1	0.4	1.0	0.5
Min SST	9.5	15.8	15.9	13.8	15.4
Max SST	17.7	20.3	17.6	17.7	17.2
N water temp minima records (° C)	821	1350	803	1196	241
Ave water temp minima	14.7	13.9	16.4	15.1	16.1
SD water temp min	1.9	4.8	0.4	1.2	0.5
Min water temp min	9.5	4.7	15.2	13.2	15.3
Max water temp min	17.6	18.3	17.2	17.4	16.8

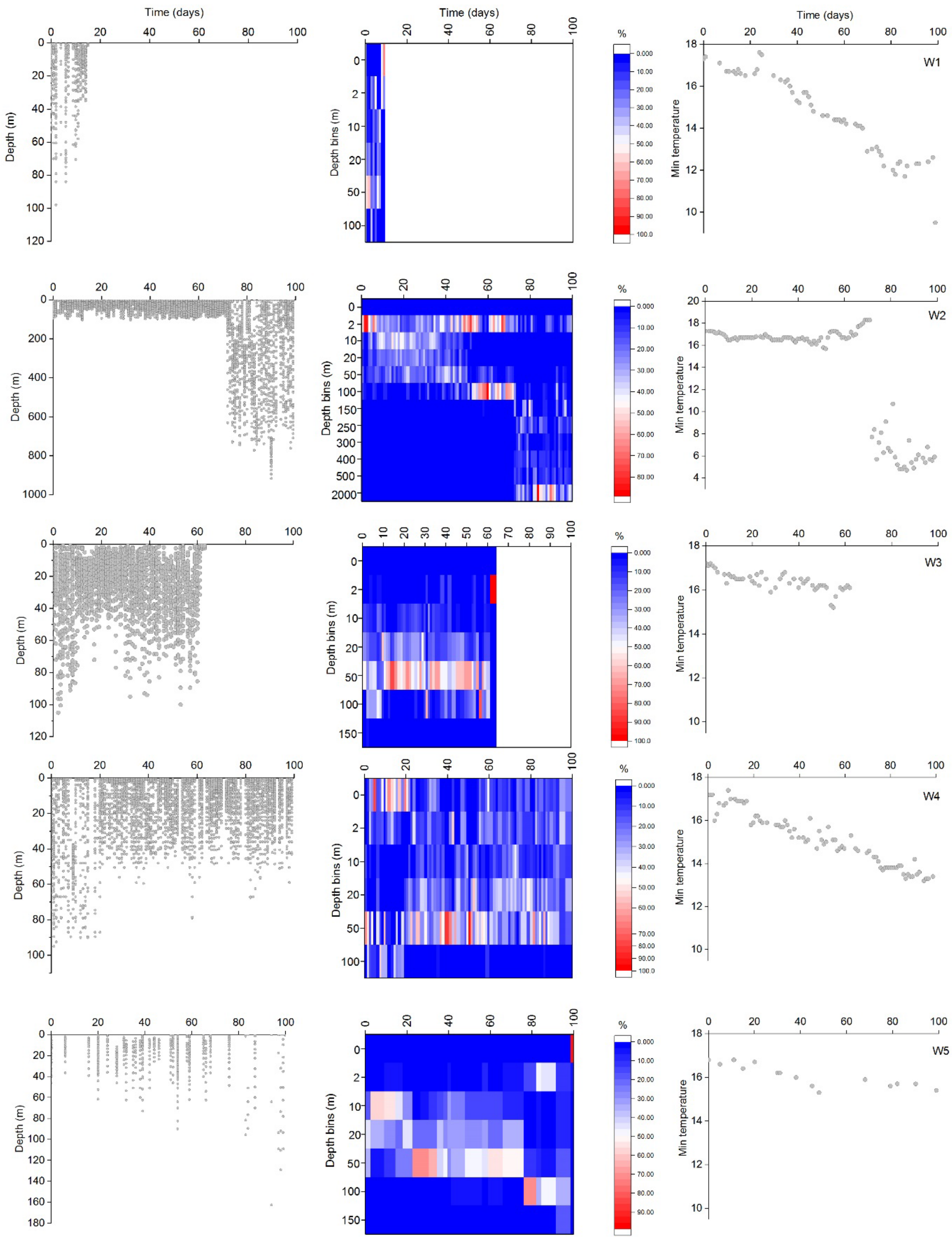


Figure 21. Time spent at depth and temperature by white sharks from transmitted histogram summary data.

Bigeye thresher

The bigeye thresher spent ~84% of the tag deployment time below the average tag-estimated mixed layer depth (MLD) of 103.5 ± 25.9 m (MLD range = 43–199 m) (Fig. 22). Minimum and maximum depths occupied by the bigeye thresher ranged from the surface to 1240 m. Average minimum and maximum daily depths were 13.7 ± 9.0 m and 661.3 ± 152.9 m, respectively (98 records). Average thermal minima experienced by the bigeye thresher was 7.8 ± 1.8° C. Average temperature minima and maxima experienced by the shark in the mixed layer were 20.5 ± 3.4 and 21.7 ± 3.3 °C.

Biological samples

Stomachs were collected from yellowtail kingfish, southern bluefin tuna, shortfin mako and school sharks. Biological samples including tissue biopsies, fin clips and external parasites were collected from a sub-set of the captured and released specimens. The sample set is archived at SARDI, West Beach, South Australia.

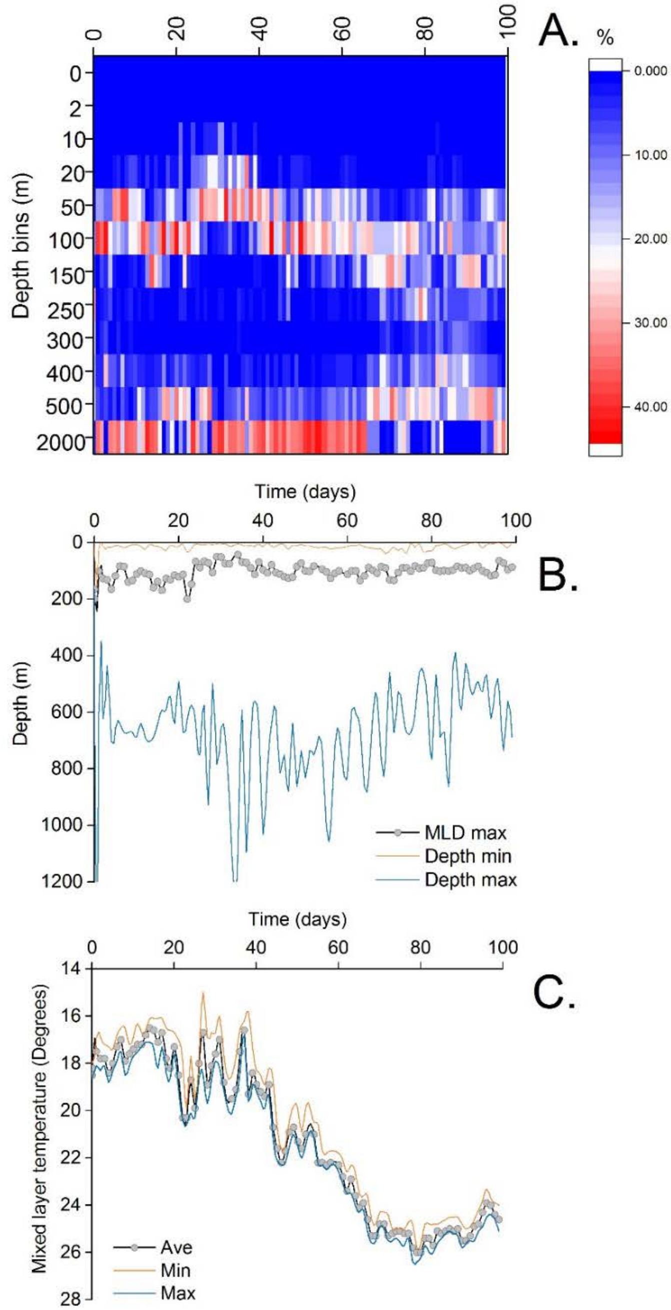


Figure 22. A. Time spent at depth by the bigeye thresher. **B.** Mixed layer, minimum and maximum depth. **C.** Mixed layer minimum, maximum and average temperature.

DISCUSSION

The Great Australian Bight encompasses the distributions of several species of marine mega-fauna with national and international significance. A recent literature review identified a need to understand the distributions, biodiversity, and habitat use of several nationally and internationally listed threatened, endangered and protected pelagic shark species that traverse between the Great Australian Bight and productive neighboring oceanic regions (e.g. the northern Sub-tropical Front within the South West Marine Region; Rogers *et al.* 2013). Pelagic shark species found in the region (longfin mako, shortfin mako, porbeagle and white shark) are listed under the Convention on the Conservation of Migratory Species (CMS, Appendix II), Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), IUCN Red List of Threatened Species and *Environmental Protection and Biodiversity Conservation Act* (1999), protected and threatened (Vulnerable) species and/or have a management and conservation status that is pending current national and international assessment processes (e.g. two thresher shark species).

The offshore pelagic survey reported here was one of a series of related components of Theme 4 of the collaborative Great Australian Bight Research Program that aimed to combine new and existing datasets to identify shared areas of ecological significance (e.g. habitats used by multiple marine predator species). Specifically, this pelagic survey represented the first dedicated effort to assess the biodiversity, species composition, distributions and habitat use of the pelagic shark assemblage in the shelf break, slope and near slope oceanic habitats in the Great Australian Bight. The first facet that must be acknowledged when interpreting the findings, is the 'snap-shot' nature of the survey relative to the vast spatial scales and complexity of physical and oceanographic processes that occur in these environments. Further work is required to assess the importance on submarine canyon and slope habitats to listed pelagic shark species (e.g. those South-west and South of Kangaroo Island in the Commonwealth Marine Reserve).

Biodiversity and composition

Previous diet studies suggest blue sharks forage on highly productive prey taxa, including the ommastrephid squids (Stevens, 1984) that also represent the prey of a range of other sympatric medium to high trophic level predators (Rogers *et al.* 2012; Goldsworthy *et al.* 2013). Blue sharks and shortfin makos were the two most commonly encountered species during the survey, with the highest relative abundances occurring in the eastern study region. The highest relative number and diversity of species encountered during the survey was at the du Couedic Canyon, which is the most significant bathymetric feature in the region, with a large and distinctive scalloped front wall. At du Couedic Canyon (S1), we observed a large predator aggregation comprising multiple species foraging at the surface directly adjacent to the shelf-break and canyon head wall, including nine species of seabirds, pinnipeds (Australian fur seals), and cetaceans (100s of common dolphins) (see Appendix 1). However, as a result of three periods of poor weather, we were unable to conduct the pelagic fish sets, and some of the pelagic shark sets in this eastern region of the study area, which reduced the spatial coverage of the survey in some of the key, high relief submarine canyons.

Size and sex information of the sample of blue sharks analysed showed mature-sized individuals comprised of males from 180–250 cm TL, and females from 200–224 cm TL. This provides the first preliminary evidence that slope and oceanic habitats of the Great Australian Bight region represent foraging habitats of reproductively mature blue sharks. However, the total sample size was small. Prior to this survey, there were no published fishery-independent data describing the size range, distribution, and habitat use of blue sharks in the Great Australian Bight, or elsewhere in the south-east Indian, and Southern Oceans. The size and sex composition of the other three pelagic shark species examined during the survey suggested that small juvenile to maturing shortfin mako, and mature-sized *Alopias* species were using the Great Australian Bight shelf break, slope and oceanic near slope habitats.

The occurrence of the large female bigeye thresher in the continental shelf waters of the Great Australian Bight, and its subsequent migration through the south-east Indian Ocean to tropical waters off Exmouth, Western Australia was a significant new scientific discovery. Deployment of

bio-logging equipment on this specimen, and the subsequent data collected advanced the knowledge of the distribution of this rare, nocturnal oceanic predator (Last and Stevens 2009). Prior to this survey, there were only three published records of deployment of satellite telemetry equipment on bigeye threshers, being the capture and PAT deployment on one female by fishery observers and the CSIRO in the south-west Pacific Ocean (Stevens *et al*. 2010), and two that were PAT tagged by researchers and fishers in the Gulf and Mexico and off Kona, Hawaii (Weng and Block 2004).

In summary, despite its snap-shot nature and reductions in spatial coverage of the survey due to weather restrictions, we confirmed previous expectations that offshore shelf-break, slope and adjacent oceanic habitats in the Great Australian Bight supported similar species compositions of highly migratory shark fauna to the productive ecosystems of the California Current (Southern Californian Bight), where white sharks, shortfin makos, blue sharks, and common threshers form components of the large pelagic predator fauna and upper trophic levels of the ecosystems (Block *et al.* 2011). Further work is required in the shelf slope and offshore submarine canyon habitats to improve both the spatial resolution of the survey, and assessments of pelagic shark biodiversity and species composition, as several other species are known to inhabit the area (based on strandings and recreational fisheries catches), e.g. porbeagle, long-fin mako, smooth hammerhead, dusky shark, and bronze whaler were not encountered or fitted with bio-logging equipment.

Spatial and temporal distributions

Key findings of the satellite telemetry deployments included the vast spatial and temporal distribution of blue sharks, and their preference for oceanic and lower slope habitats adjacent to the continental shelf. During previous studies in the region, no pelagic shark species equipped with telemetry equipment had exhibited such strong and protracted preferences for open ocean habitats adjacent to the continental shelf slope. Satellite tracked blue sharks migrated south-wards to oceanic areas between the shelf slope and latitudes aligned with the northern side of the Sub-tropical Front region, and oceanic areas in the south-east and tropical north-east Indian Ocean. This northern Sub-tropical Front area is also the focus of migrations of several predator

species that use pelagic habitats of the Great Australian Bight, including shortfin makos (Rogers *et al.* 2015a, b, c), Australian fur seals (Page *et al.* 2006), and southern bluefin tuna (Bestley *et al*. 2008). Affinity of predators to, and across the Sub-tropical Front during the Austral autumn and summer months warrants further investigation. One blue shark also migrated through the Bonney Upwelling Region and Bass Strait and into oceanic areas of the Tasman Basin. This shark reached a turn-around point at the rising bathymetric gradient ~200 km west of a mid-oceanic ridge, the Belona Saddle, which is located ~950 km from North Island, New Zealand. Our findings were consistent with telemetry and observer data from the north-west Atlantic Ocean, showing that blue sharks were seasonally migratory, and mostly had oceanic ranges interspersed with occasional forays into shelf-break habitats (Campana *et al.* 2011, 2016).

The common thresher and bigeye thresher were encountered at the shelf-break during set S6, although encounters with Alopiidae were infrequent. The bigeye thresher and common thresher were encountered in water depths of 199–265 m to the south of Fowlers Bay. Following instrumentation with a mini-PAT, the bigeye thresher migrated ~1600 km across south-western Australia during the Austral autumn and winter to tropical oceanic waters off Exmouth, Western Australia. During this migration, the shark mostly remained below the typical mixed layer depths, and underwent regular dives to >500 m, suggesting the large-scale movement indicated by the tags final pop-up location had mostly occurred outside the depth ranges characteristic of the shelf break. The common thresher has elongated longitudinal red-muscle that provides metabolic advantages and supports sustained swimming behaviour (Bernal *et al.* 2010), and this may partly explain the dive behaviours we observed. Given its oceanic distribution (Last and Stevens 2009), it is likely the bigeye thresher is encountered by pelagic long-line fleets operating in outer slope and oceanic areas (high seas) of both the Southern and SE Indian Oceans.

During the survey, we extended the knowledge of the spatial and seasonal distributions of sub-adult female shortfin makos in these rarely accessed oceanic and continental shelf slope environments. Shortfin makos were patchily distributed from east to west through the survey area, albeit in comparatively lower abundances than the blue shark. Telemetry-based distribution patterns, and areas where they were encountered during the survey, were similar to

that found during recent studies of habitat use and movements of juveniles in the central and eastern Great Australian Bight (Rogers *et al.* 2014, 2015a), and analogous to observations in northern hemisphere pelagic ecosystems (Vetter *et al.* 2008; Block *et al*. 2011; Abascal *et al*. 2011). Patterns of spatial distribution of the tagged shortfin mako showed it occupied a range of neritic, shelf break and shelf slope waters with a preference for the outer shelf and break habitats. This individual migrated into oceanic waters of the Indian Ocean as found for juvenile (1.7–2.4 m) con-specifics during the Austral winter and spring of 2015 (Rogers *et al.* 2014, 2015a).

For the five white sharks (220–420 cm, TL) we instrumented with mini-pop-up satellite tags, the key finding was the high diversity of movement strategies and depth habitats used during autumn and winter 2015. These included three white sharks that remained in the 'gulf and approach' habitats, and two that traversed longer distances to the central Great Australian Bight, and the lower shelf slope area off Cape Leeuwin, Western Australia. Transmitted water temperature data, pop-up locations and depth profiles suggested Spencer Gulf and its approach were important for three white sharks, which was generally consistent with the seasonal patterns of sightings and residency in this region between May and September (Rogers and Huveneers 2016). Tracked white sharks showed an affinity for depths >15 m and water temperatures of 15–17 °C, which are typical of the gulf and inner to central continental shelf regions. However, as found during a recent acoustic telemetry study off Western Australia (McAuley *et al.* 2016), individuals exhibited highly varied spatial distributions and maximal extents as shown via our pop-up tag reporting locations that ranged from the gulf habitats to neritic, near-slope oceanic waters.

Patterns of distribution of the five white sharks were consistent with previous satellite telemetry studies (Bruce *et al*. 2006) and depth ranges, while proximity to shore aligned with spatial patterns of acoustic detections in neritic areas off Western Australia (McAuley *et al.* 2016). Pop-up locations and maximal depths of white sharks W2 and W5 indicated these individuals visited the shelf break and slope during winter during large scale movements to the central Great Australian Bight and south-east Indian Ocean. This is consistent with previous studies of white sharks and shortfin mako, and in conjunction with depth habitat data collected by the mini-PAT tags, represents further evidence that complex, high relief shelf-break and slope habitats may

form migratory paths and/or navigational cues for the Lamnidae and Alopiidae (Bruce *et al.* 2006; Rogers *et al*. 2015a, b).

The timing of the first leg of the survey coincided with the passage of three strong Southern Ocean frontal systems across the Great Australian Bight. Immediately prior to this period, white sharks had returned to the Neptune islands following a two month hiatus (Rogers and Huveneers 2016). In 2015, this return movement was hypothesised to relate to a change-over period between small-medium sized males that dominate sightings and visitations during summer, arrival of medium to large individuals of mixed sexes that visit in autumn and early winter (Bruce and Bradford 2015), and a visit by killer whales in February 2015 (Rogers and Huveneers 2016). We formed hypotheses that the intrusion of the Leeuwin Current across the shelf from the west may form a migratory cue for white sharks, as the eastward, cross-shelf flow of warm tropical water could provide energetic savings for groups migrating from the Indian Ocean, as well as contain aggregations of suitable pelagic prey taxa; this could be investigated when explaining other potential factors that may drive observed movement and residency patterns.

Migration-mediated linkages between the Great Australian Bight and north-eastern Indian Ocean by three of the four pelagic shark species show the broader importance of shelf-break, slope and adjacent oceanic habitats in the offshore NE Indian Ocean, Bonney Upwelling Region, Tasman Sea, and northern Sub-tropical Front. The deep scatter layer (DSL) was prominent on the vessel sonar at the shelf slope during some of the survey sets. Our observations were that this layer of unidentified mesopelagic biota extends vertically as a ~50–80 m thick mass of acoustic back-scatter at depths varying from ~120–400 m. Although, no quantitative data were collected on the DSL during this survey, its presence and prevalence during May 2015 was noteworthy, consistent with previous observations (Hall *et al.* 1981; Rogers *et al.* 2015a).

Identification of key habitats

By correlating remote-sensed environmental variables with surface swimming positions, and measurements collected by the mini-PATs, we were able to summarize the habitat characteristics of four pelagic shark species found in the Great Australian Bight.

Blue sharks

Most blue sharks exhibited area-restricted search movements in oceanic areas characterised by low sea-surface temperatures, high variability in depth gradients, low variability in sea-surface height and surface thermal gradient. Habitat modelling approaches that manage biases (e.g. those stemming from spatial auto-correlation) should be adopted to explain the suites of factors behind the variability in habitat selectivity we observed in the individual tracks. We also suggest that prey field data continues to be a major gap in explaining, the trophic role of this species and why individuals display preferences for particular sets of environmental variables.

Shortfin mako

During some seasons, the offshore pelagic habitats of the Great Australian Bight and Bonney Upwelling Region support large aggregations of the pelagic squid, *Nototodarus gouldi* (Smith, 1983), which are important prey of the shortfin mako (Rogers *et al*. 2012). The tracked shortfin mako inhabited a broad range of outer continental shelf, shelf-break, and to a lesser extent, oceanic areas characterised by median bottom depths of 206 m (shelf-break isobaths). Notably, this individual exhibited low levels of spatial overlap with bottom depths/areas used by the tracked blue sharks, however, it should be noted this comparison stems from a single track. As found for blue sharks, the shortfin mako inhabited areas with shallower mean bottom depths and larger ranges of depth gradients during area-restricted (fidelity) classified movement stages, compared to areas it traversed quickly and directly. The notable exception was during a migration to the Indian Ocean, when it spent most of its time in oceanic habitats. The observed switch in preference from continental shelf and shelf break to oceanic habitats was consistent with our previous study of juvenile and sub-adult shortfin makos, during which we tracked multiple individuals of both sexes (some of over multiple years) with similar seasonal migration routes (Rogers *et al.* 2015a, b, c). One previous study found that the surface gradient environmental

parameters (SST, Chl-*a*) associated with oceanographic frontal features, and distance from the shelf slope best explained observed variation in ARS classified satellite positions of tracked shortfin makos (Rogers, 2011).

White sharks

Spatial distribution and habitat data we collected for white sharks using satellite tags showed this iconic species used the Great Australian Bight continental shelf habitats during medium and large scale autumn and winter migration events, one of which directly traversed the Ceduna sub-basin with the end-point to the SSW of Cape Leeuwin, Western Australia. The otherwise diverse range of habitats used by the tagged white sharks in the Great Australian Bight was consistent with previous telemetry-based studies in Australian waters (Bruce *et al*. 2006; Sims *et al*. 2011), off New Zealand (Bonfil *et al*. 2010), and the North-eastern Pacific Ocean. In these other regions, tracked white sharks were observed to exhibit coastal and island movement and residency phases (Weng *et al*. 2007; Domeier and Nasby Lucas 2008), interspersed with oceanic migrations characterised by regular time spent at depths of 400–700+ m (Nasby Lucas *et al.* 2007). The observed diversity of movement patterns is hypothesised to relate to patterns of distribution and abundance of suitable prey, reproductive cycling and oceanographic cues, yet the relative importance of each of these drivers remains unresolved.

Analyses of mini-PAT data for the five white sharks reported here showed these large bodied endotherms inhabited diverse depth and thermal habitats. The depths ranged from those associated with the predominantly shallow areas in upper Spencer Gulf, to the reefs and gutters of the southern gulf approaches, and the lower shelf slope and oceanic habitats of the Great Australian Bight and south-east Indian Ocean. White sharks exhibited two movement modes we defined as 'gulf-approach' and 'migratory-shelf'. The prominent offshore preference we observed were consistent with previous movement and behavioural studies in the South-west Region (Bruce *et al.* 2006; McAuley *et al.* 2016). Two specimens that migrated considerable distances during autumn-winter, experienced high variability in thermal habitats of 4.7–18.3°C. These movements consisted of episodic surface swimming interspersed with regular deep dives of 600–700 m when migrating, and possibly foraging in offshore shelf slope habitats (Maximum

depth = 917 m) off southern Western Australia. This pattern was consistent with findings during a previous study of white sharks during migratory movements in the north-east Pacific Ocean (Weng *et al*. 2007).

Bigeye thresher

The bigeye thresher is a rare deep-water oceanic species, and like the Lamnidae (white sharks and shortfin makos) has specialised physiological features, including regional endothermy and rete meribile that heat the eyes and brain and are thought to allow extensive and rapid vertical migrations in thermally stratified oceanic and slope habitats (Weng and Block 2004). The bigeye thresher tagged during the survey spent ~84% of its time below the estimated mixed layer depth (MLD) of 103.5 ± 25.9 m, which is consistent with findings for bigeye threshers tagged in deep-water oceanic habitats of the eastern Pacific Ocean (Nakano *et al*. 2003) and off Hawaii and in the Gulf of Mexico (Weng and Block 2004). Minimum and maximum depths occupied by the bigeye thresher tagged in the present study ranged from the surface to 1096 m, which was considerably deeper than vertical maxima in other studies in the eastern Pacific Ocean (Maximum = 723 m, n = 2) (Nakano *et al*. 2003), northern Pacific (Kona, Hawaii) and the Gulf of Mexico (Maximum = 600–800 m, n = 2) (Weng and Block 2004), and the SW Pacific Ocean (Maximum = 600 m, temp range = 11.1–21.6° C, n = 1) (Stevens *et al*. 2010). The average minimum and maximum daily depths of the bigeye thresher we tagged in the Great Australian Bight were 13.7 ± 9.0, and 661.3 ± 152.9 m, respectively, showing this shark undertook brief yet regular forays into the surface and upper mixed layers above the thermocline. Two acoustically tagged bigeye threshers in the eastern tropical Pacific Ocean, WSW of the Galapagos Islands, were found to undertake crepuscular daily 'yo-yo style' movements whilst exploring large portions of the water column (Nakano *et al*. 2003). The bigeye thresher we tagged in the Great Australian Bight experienced low average thermal minima of 7.8 ± 1.8° C during deep dives off the shelf slope, compared to the relatively warm and stable average temperature minima and maxima in the upper mixed layer (20.5 ± 3.4 and 21.7 ± 3.3° C); further data analyses will assess relationships with crepuscular, diurnal, and nocturnal timing, throughout the entire spatial and temporal extent of the track.

Overlaps with spatially managed areas and petroleum leases

Time-spent-per-area analyses confirmed that areas where blue sharks exhibited highest residency were at and beyond the lower continental shelf slope, and north of the latitudinal band bounding the Sub-tropical Front region, south of the Great Australian Bight. Highest quantities of time spent in oil and gas lease areas by blue sharks ranged between 115–120 days, yet four individuals also spent <30 days inside the leases. By comparison, time spent in the central Great Australian Bight Marine Reserve by this species ranged between 0–38 days. Vertical habitat information suggest blue sharks exhibit fidelity in depth ranges between 100–300 m in the Great Australian Bight (M. Heard unpublished data). Whilst some blue sharks and the shortfin mako that were tracked during the survey subsequently migrated to the Indian Ocean, or the Tasman Sea via Bass Strait, these individuals spent minimal time in spatially discrete, oceanic 'patches' during these migrations, when compared to the time they spent to the south of the Great Australian Bight, thus reinforcing the relative importance of this ecosystem. We speculate that these oceanic patches may be less productive and have lower persistence times than the shelf slope regions where bentho-pelagic habitat complexity is generally higher.

The shortfin mako spent 32 days in the lease areas, however, time-spent-per-area for this individual should be considered in light of the sample size. Further assessment of habitat use by this species should refer to time-spent-per-area analyses of Rogers *et al.* (2015b), and meta-analyses to be conducted during Project 4.2 of the Great Australian Bight Research Program. By comparison, the areas of highest use by the shortfin mako, included the shelf-break and slope adjacent to the Lacepede Shelf, Murray Canyons the south of Kangaroo Island, and the outer continental shelf, and shelf break between the 100 and 300 m isobaths in the central and western Great Australian Bight. Similar patterns of habitat use were observed in our recent analyses of shortfin makos tagged in western Victoria during summer 2012–13, and state space model-based analyses of ten juveniles tagged in the Great Australian Bight in 2008–9, which showed important shared habitats included the central and eastern Great Australian Bight, the Bonney Upwelling, southern Western Australia, western Victoria, western and eastern Bass Strait, and the Sub-tropical Front (Rogers *et al*. 2015a, b; Rogers and Bailleul 2015).

Conclusions

We combined telemetry and survey methods to update existing information on the distributions, critical habitat use, and migration-mediated connectivity of highly migratory pelagic and oceanic shark species that inhabit the shelf-break, slope and oceanic ecosystems of the Great Australian Bight and eastern Indian Ocean. Knowledge of pelagic shark distributions and migration paths could be applied in the future to reduce operational interactions between sharks and vessels operating in the Great Australian Bight. The species we investigated have varying levels of international and national conservation and management significance, and some are listed and/or protected by the Australian Commonwealth Government *Environmental Protection Biodiversity and Conservation Act* (1999). The white shark, shortfin mako, common thresher and bigeye thresher are globally recognised and listed as threatened (Vulnerable) by the International Union for Conservation of Nature (IUCN) Red-list. They are each listed Highly Migratory Species (HMS) under the *Convention on Migratory Species*.

Research gaps and next steps

There remains a need to better resolve the shared habitats and migration pathways of listed pelagic sharks in the Great Australian Bight. Importantly, these highly migratory species have international conservation and management profiles, and are valued by community and regional economies of southern Australia and neighboring Pacific and Indian Ocean regions. Listed species for which significant data gaps remain include the white shark, shortfin mako, two Alopiidae spp., and porbeagle. Project 4.2 of the Great Australian Bight Research Program will address questions regarding shared areas of ecological significance for marine predator species. Gaps also remain in available dietary and foraging data for pelagic sharks in shelf slope, submarine canyons and near slope oceanic habitats. This information is required to understand the ecological functioning and dynamism in the upper trophic levels when applying ecosystem modelling approaches.

REFERENCES

Abascal, F. J., Quintans, M., Ramos-Cartelle, A., and Mejuto, J. (2011). Movements and environmental preferences of the shortfin mako, *Isurus oxyrinchus*, in the southeastern Pacific Ocean. *Marine Biology* 158, 1175–1184.

Allen, S. E., Vindeirinho, C., Thomson, R. E., Foreman, M. G. G., Mackas, D. L. (2001). Physical and biological processes over a submarine canyon during an upwelling event. *Canadian Journal of Fisheries and Aquatic Sciences* 58, 671–684.

Bakun A (2006). Fronts and eddies as key structures in the habitat of marine fish larvae: opportunity, adaptive response, and competitive advantage. Sci Mar 70(Suppl 2), 105–122.

Bernal, D., Donley, J. M., McGillivray, D. G., Aalbers, S. A., Syme, D. A., Sepulveda, C. (2010). Function of the medial red muscle during sustained swimming in common thresher sharks: Contrast and convergence with thunniform swimmers. *Comparative Biochemistry and Physiology*, Part A, 155, 454–463**.**

Bestley, S., Gunn, J. and Hindell, M. (2009). Plasticity in vertical behaviour of migrating juvenile southern bluefin tuna (*Thunnus maccoyii*) in relation to oceanography of the south Indian Ocean. *Fisheries Oceanography* (18), 237–245.

Bestley, S., Patterson, T., Hindell, M. and Gunn, J. (2008). Feeding ecology of wild migratory tunas revealed by archival tag records of visceral warming. *Journal of Animal Ecology* 77, 1223-1233.

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., and Costa, D. P. (2011). Tracking apex marine predator movements in a dynamic ocean. *Nature* 475 (7354), 86–90.

Bosley, K. L., Lavelle, J. W., Brodeur, R. D., Wakefield, W. W., Emmett, R. L., Baker, E. T., Rehmke, K. M. (2004). Biological and physical processes in and around Astoria submarine Canyon, Oregon, USA. *Journal of Marine Systems* 50, 21–37.

Bruce, B., Stevens, J. and Malcolm, H. (2006). Movements and swimming behaviour of white sharks (*Carcharodon carcharias*) in Australian waters. *Marine Biology* 150, 161–172.

Bruce B. D., and Bradford, R. (2015). Segregation or aggregation? Sex-specific patterns in the seasonal occurrence of white sharks *Carcharodon carcharias* at the Neptune Islands, South Australia. *Journal of Fish Biology* 87, 1355–1370.

Bruce B. D. (2014). Shark Futures: A synthesis of available data on mako and porbeagle sharks in Australasian waters - Current status and future directions. Final Report to the Fisheries Research and Development Corporation - FRDC 2011/045. CSIRO Marine & Atmospheric Research Hobart Tasmania. 159 pp.

Bunce. A., Norman, F. I., Brothers, N., and Gales. (2002). Long-term trends in the Australasian gannet (Morus serrator) popualtion in Australia: the effect of climate change and commercial fisheries. *Marine Biology* 141. 262–269.

Campana, S. E., Joyce,W., Fowler, M., and Showell, M. (2016). Discards, hooking, and post-release mortality of porbeagle (*Lamna nasus*), shortfin mako (*Isurus oxyrinchus*), and blue shark (*Prionace glauca*) in the Canadian pelagic longline fishery. *ICES Journal of Marine Science* 73, 520–528.

Campana, S. E., Dorey, A., Fowler, M., Joyce, W., Wang, Z., Wright, D., and Yashayaev, I. (2011) Migration pathways, behavioural thermoregulation and overwintering grounds of blue sharks in the Northwest Atlantic. *PLoS ONE* 6(2), e16854. doi:10.1371/journal.pone.0016854.

Currie, D.R.,Sorokin, S.J. (2014). Megabenthic biodiversity in two contrasting submarine canyons on Australia's southern continentalmargin. *Marine Biology Research* 10, 97–110.

Currie, D. R., McClatchie, S., Middleton, J. F. and Nayar, S. (2012). Biophysical factors affecting the distribution of demersal fish around the head of a submarine canyon off the Bonney coast, South Australia. *PlosOne* 7(1): e30138.

Daley, R. K., Williams, A., Green, M., Barker, B., and Brodie, P. (2014). Can marine reserves conserve vulnerable sharks in the deep sea? A case study of *Centrophorus zeehaani* (Centrophoridae), examined with acoustic telemetry. http://dx.doi.org/10.1016/j.dsr2.2014.05.017.

Domeier, M. L.., and Nasby-Lucas, N. (2008). Migration patterns of white sharks *Carcharodon carcharias* tagged at Guadalupe Island, Mexico, and identification of an eastern Pacific shared offshore foraging area. *Marine Ecology Progress Series* 370, 221–237.

Einoder, L. D. and Goldsworthy, S. D. (2005). Foraging flights of short-tailed shearwaters (*Puffinus tenuirostris*) from Althorpe Island: assessing their use of neritic waters. *Transactions of the Royal Society of South Australia* 129, 209–216.

Einoder, L. D., Page, B., Goldsworthy, S. C., DeLittle, S. C., and Bradshaw, C. J. A. (2011). Exploitation of distant Antarctic waters and close neritic waters by short-tailed shearwaters breeding in South Australia. *Austral Ecology* 36, 461–475.

Francis, M. P., and Duffy, C. (2005). Length at maturity in three pelagic sharks (*Lamna nasus, Isurus oxyrinchus,* and *Prionace glauca*) from New Zealand. *Fisheries Bulletin* 103, 489–500.

Genin, A. (2004). Bio-physical coupling in the formation of zooplankton and fish aggregations over abrupt topographies. *Journal of Marine Systems* 50, 3–20.

Gill, P. C., Morrice, M. G., Page, B., Pirzl, R., Levings, A. H. and Coyne, M. (2011). Blue whale habitat selection and within-season distribution in a regional upwelling system off southern Australia. *Marine Ecology Progress Series* 421, 243–263.

Goldsworthy, S. D., Page, B., Rogers, P. J., Bulman. C., Wiebkin. A., McLeay, L.J., Einoder, L., Alastair, M. M., Baylis, A. M. M., Braley, M., Caines, R., Daly, K., Huveneers, C., Peters, K., Lowther, A. D., and Ward, T. M. (2013). Trophodynamics of the eastern Great Australian Bight ecosystem: ecological change associated with the growth of Australia's largest fishery. *Ecological Modelling* 255, 38–57.

Greene, C.H., Wiebe, P.H., Burczynski, J., Youngbluth, M.J. (1988). Acoustical detection of high-density krill demersal layers in the submarine canyons off Georges Bank. *Science* 241, 359–361.

Hall, M. (1981) Measurement of acoustic volume backscattering in the Indian and Southern Oceans. *Australian Journal of Marine and Freshwater Research* 32, 855–876**.**

Heap, A.D., Harris, P.T. (2008). Geomorphology of the Australian margin and adjacent seafloor. *Australian Journal of Earth Science* 55, 555–585.

Huang, Z., Nichol, S. L., Harris, P. T., Caley, M. J. (2014). Classification of submarine canyons of the Australian continental margin. *Marine Geology* 357, 362–383.

IMOS Ocean currents and sea-surface temperatures (oceancurrent.imos.org.au**)**

Jonsen, I. D. with contributions from S. Luque, A. Winship and M.W. Pedersen (2014). bsam: Bayesian state-space models for animal movement. R package version 0.43-1. http://www.r-project.org.

Jonsen, I. D., Myers, R. A., & James, M. C. (2007). Identifying leatherback turtle foraging behaviour from satellite telemetry using a switching state-space model. *Marine Ecology Progress Series*, *337*, 255-264.

Jonsen, I. D., J. M. Flemming, and R. A. Myers. (2005). Robust state-space modeling of animal movement data. Ecology 86: 2874–2880.

Kaempf, J., Doubel, M., Griffin, D. A., Matthews, R. and Ward, T. M. (2004). Evidence of a large seasonal coastal upwelling system along the southern shelf of Australia. *Geophysical Research Letters* 31(L09310): doi:10.1029/2003GL019221.

Kaempf, J. (2007). On the magnitude of upwelling fluxes in submarine canyons. *Continental Shelf Research* 27, 2211–2223.

Last, P.R., Stevens, J.D. (2009). Sharks and Rays of Australia, second edition. CSIRO, Melbourne. 644 pp.

McAuley, R., Bruce, B., Keaya, I., Mountforda, S., and Pinnella, T. (2016). Evaluation of passive acoustic telemetry approaches for monitoring and mitigating shark hazards off the coast of Western Australia. Fisheries Research Report No. 273, Department of Fisheries, Western Australia. 84pp.

McClatchie, S., Middleton, J. F. and Ward, T. M. (2006). Water mass analysis and alongshore variation in upwelling intensity in the eastern Great Australian Bight. *Journal of Geophysical Research* 111(C08007): doi:10.1029/2004JC002699.

Middleton, J. F. and Bye, J. A. T. (2007). A review of the shelf slope circulation along Australia's southern shelves: Cape Leeuwin to Portland. *Progress in Oceanography* 75, 1–41.

Middleton, J. F. and Cirano, M. (2002). A northern boundary current along Australia's southern shelves: the Flinders current. *Journal of Geophysical Research-Oceans* 107(C9), 3129–3143.

Mulvaney, J., and Kamminga, J. (1999). Sahul: A Pleistocene Continent. In: *Prehistory of Australia.* Ch. 8. (pgs 113–119). 504 pp.

Nakano, H., Matsunaga, H., Hiroaki, O., Okazaki, M. (2003). Acoustic tracking of bigeye thresher shark *Alopias superciliosus* in the eastern Pacific Ocean. *Marne Ecology Progress Series* 265, 255–261.

Nasby-Lucas, N., Dewar, H., Lam, C. H., Goldman, K. J., Domeier, M. L., (2009). White shark offshore habitat: A behavioral and environmental characterization of the eastern Pacific shared offshore foraging area. *PLoS ONE* 4(12), e8163. doi:10.1371/journal.pone.0008163.

National Oceanic and Atmospheric Administration (2016). Northeast Fisheries Science Centre, Apex Predators Program Large Coastal Shark Survey: **http://nefsc.noaa.gov/nefsc/Narragansett/sharks/survey.html**

Page, B., McKenzie, J., Sumner, M. D., Coyne, M., Goldsworthy, S. D. (2006). Spatial separation of foraging habitats among New Zealand fur seals. *Marine Ecology Progress Series* 323, 263–279.

Patterson, T., Evans, K., Carter, T. and Gunn, J. (2008). Movement and behaviour of large southern bluefin tuna (*Thunnus maccoyii*) in the Australian region determined using pop-up satellite archival tags. *Fisheries Oceanography* 17, 352–367.

Rogers, P. J. (2011). Habitat use, movement and dietary dynamics of pelagic sharks in coastal and shelf ecosystems off southern Australia. PhD Thesis. Flinders University. South Australia. 217 pp.

Rogers, P. J., Huveneers, C., Page, B., Hamer, D. J., Goldsworthy, S. D., Mitchell, J. G., and Seuront, L. (2012). A quantitative comparison of the diets of sympatric pelagic sharks in gulf and shelf ecosystems off southern Australia. *ICES Journal of Marine Science*. doi: 10.1093/icesjms/fss100.

Rogers P. J., Ward T. M., van Ruth P. D., Williams A, Bruce B. D., Connell, S. D., Currie D. R., Davies C. R., Evans K, Gillanders B. M., Goldsworthy S. D., Griffin D. A., Hardman-Mountford N.J., Ivey A. R., Kloser R.J., Middleton J. K., Richardson A. E., Ross A, Tanner J. E., and Young J. (2013). Physical processes, biodiversity and ecology of the Great Australian Bight region: a literature review. CSIRO, Australia. 197 pp.

Rogers, P. J., Corrigan, S, and Lowther, A. (2014). Using satellite tagging and molecular techniques to improve the ecologically sustainable fisheries management of shortfin makos (*Isurus oxyrinchus*) in the Australasian region. SARDI Aquatic Sciences. Final Report to the FRDC. 84 pp.

Rogers, P. J., Huveneers, C., Page, B., Goldsworthy, S. D, Coyne, M., Lowther, A. D., Mitchell, J.G., and Seuront, L. (2015a). Life on the shelf edge: Habitat use of juvenile shortfin makos *Isurus oxyrinchus* in the Great Australian Bight, southern Australia. *Fisheries Oceanography*. 24 (3), 204–218.

Rogers, P. J., and Bailleul, F. (2015b). Innovative ways to ensure the future sustainability of the recreational fishery for shortfin makos (*Isurus oxyrinchus*) in Victoria. Final Report to the State of Victoria, Department of Environment and Primary Industries Recreational Fishing Grants Program. SARDI Research Report Series. No. 872. 69 pp.

Rogers, P. J., Corrigan, S, and Lowther, A. (2015c). Using satellite tagging and molecular techniques to improve the ecologically sustainable fisheries management of shortfin makos (*Isurus oxyrinchus*) in the Australasian region. SARDI Aquatic Sciences. Final Report to the FRDC. 84 pp.

Rogers, P. J., and Huveneers, C. (2016). Residency and photographic identification of white sharks *Carcharodon carcharias* in the Neptune Islands Group Marine Park between 2013 and 2015. Report to Department of Environment, Water and Natural Resources. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2015/000825-1. SARDI Research Report Series No. 893. 108 pp.

Simpfendorfer, C. A., Hueter, R. E., Bergman, U., and Connett, S. M. H. (2002). Results of a fishery independent survey for pelagic sharks in the western North Atlantic, 1977–1994. *Fisheries Research* 55, 175–192.

Smith, H. K. (1983). Fishery and biology of *Nototodarus gouldi* (McCoy, 1988) in western Bass Strait. *Memoirs of the National Museum Victoria*, 44. 285–290.

Sims, W. D., Humphries, N. E., Bradford, R. W. and Bruce, B. D. (2011). Levy flight and Brownian search patterns of a free-ranging predator reflect different prey field characteristics. *Journal of Animal Ecology* doi: 10.1111/j.1365-2656.2011.01914.x.

Stevens, J. D. (1984). Biological observations on sharks caught by sport fishermen off New South Wales. *Australian Journal of Marine and Freshwater Research* 35, 573–590.

Stevens, J. D. (1992). Blue and mako shark by-catch in the Japanese longline fishery off South-eastern Australia. *Australian Journal of Marine and Freshwater Research* 43, 227–236.

Stevens, J., Bradford, R., and West, G. J. (2010). Satellite tagging of blue sharks (*Prionace glauca*) and other pelagic sharks off eastern Australia: depth behaviour, temperature experience and movements. *Marine Biology* 157, 575–591.

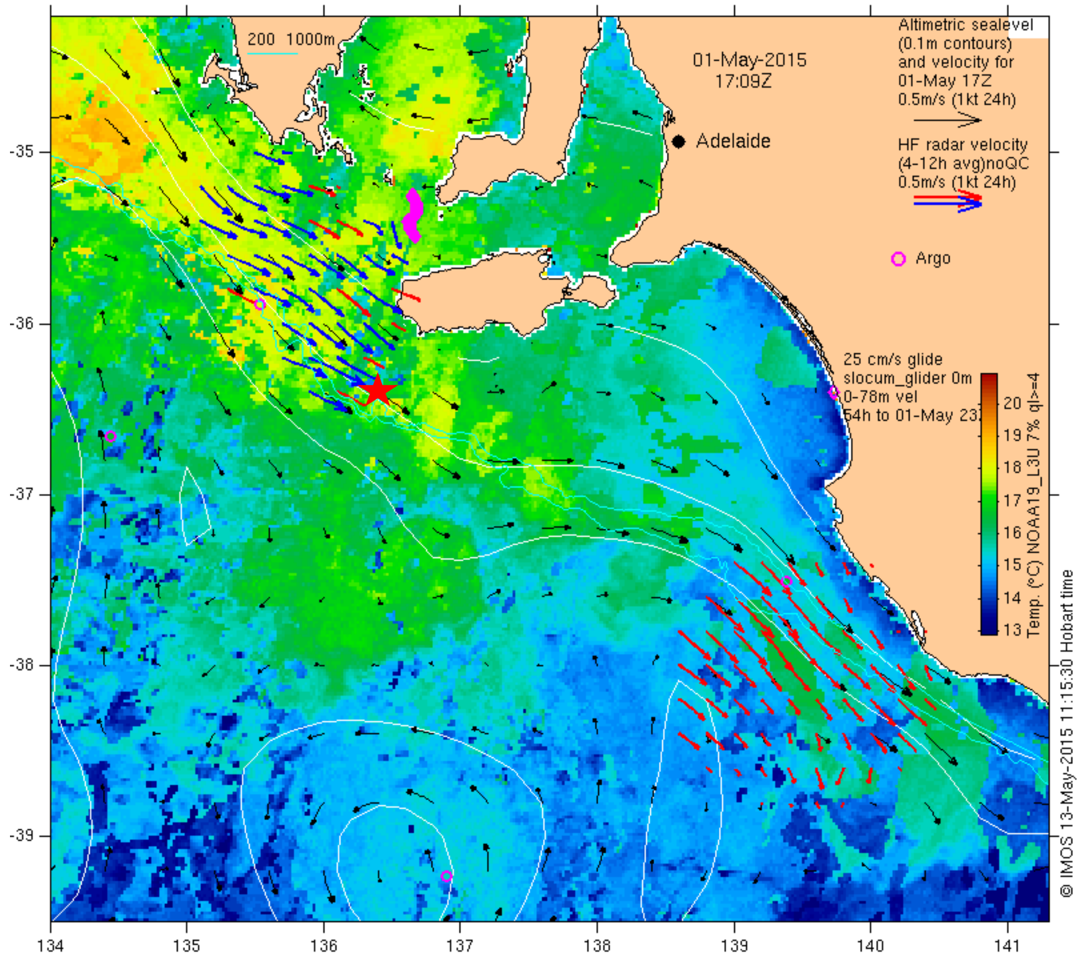
Vetter, R. Kohin, S., Preti, A., McClatchie, and Dewar, H., (2008). Predatory interactions and niche overlap between mako shark, *Isurus oxyrinchus*, and jumbo squid, *Dosidicus gigas*, in the California Current. *CalCOFI Rep*. 49, 142–156.

Weng, K C,. and Block, B. A. (2004). Diel vertical migration of the bigeye thresher shark (*Alopias superciliosus*), a species possessing orbital retia mirabilia. *Fisheries Bulletin* 102, 221–229.

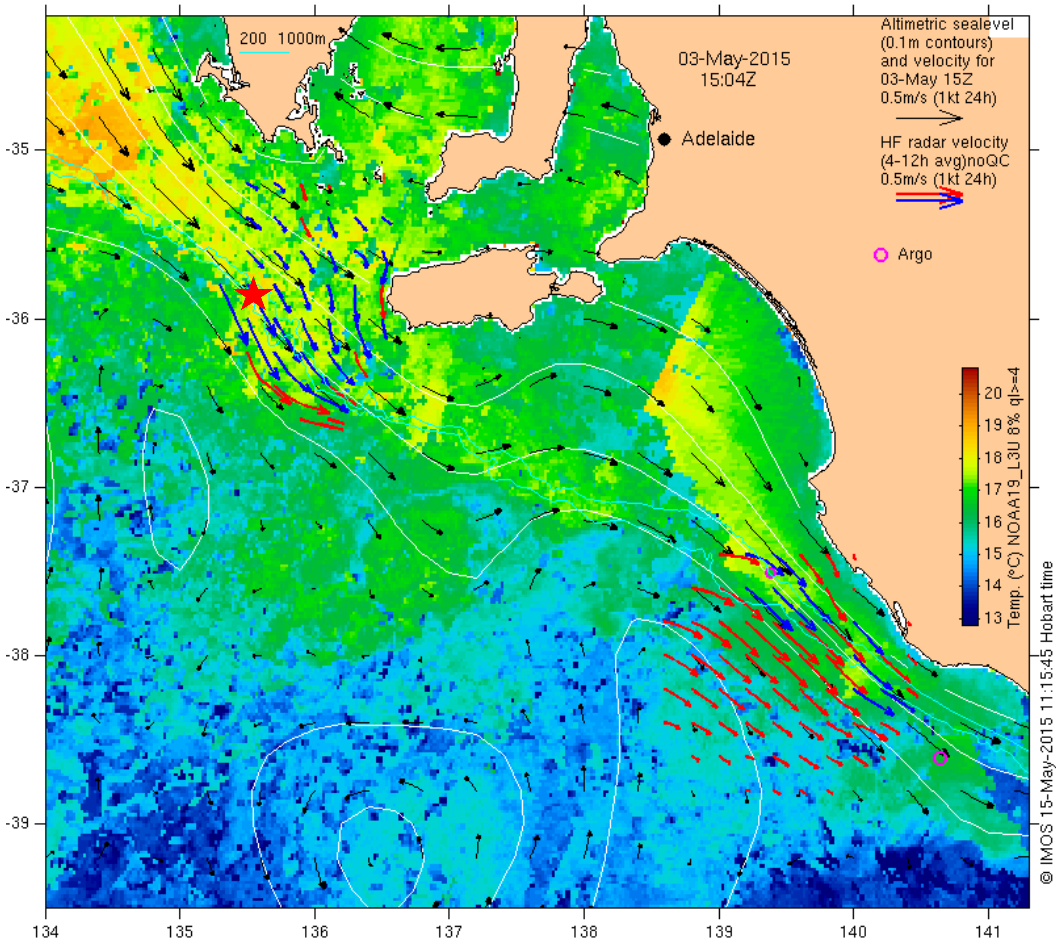
Weng, K. C., Boustany, A. M., Pyle, P., Anderson, S. D., Brown, A., and Block, B. A. (2007). Migration and habitat of white sharks (*Carcharodon carcharias*) in the eastern Pacific Ocean. *Marine Biology* 152, 877–894.

Williams, A., Daley, R., Green, M, Barker, B., and Knuckey, I. (2012). Mapping the distribution and movement of gulper sharks, and developing a non-extractive monitoring technique, to mitigate the risk to the species within a multi-sector fishery region off southern and eastern Australia. FRDC Final Report Project 2009/024. Fisheries Research and Development Corporation, Australia. pp 320.

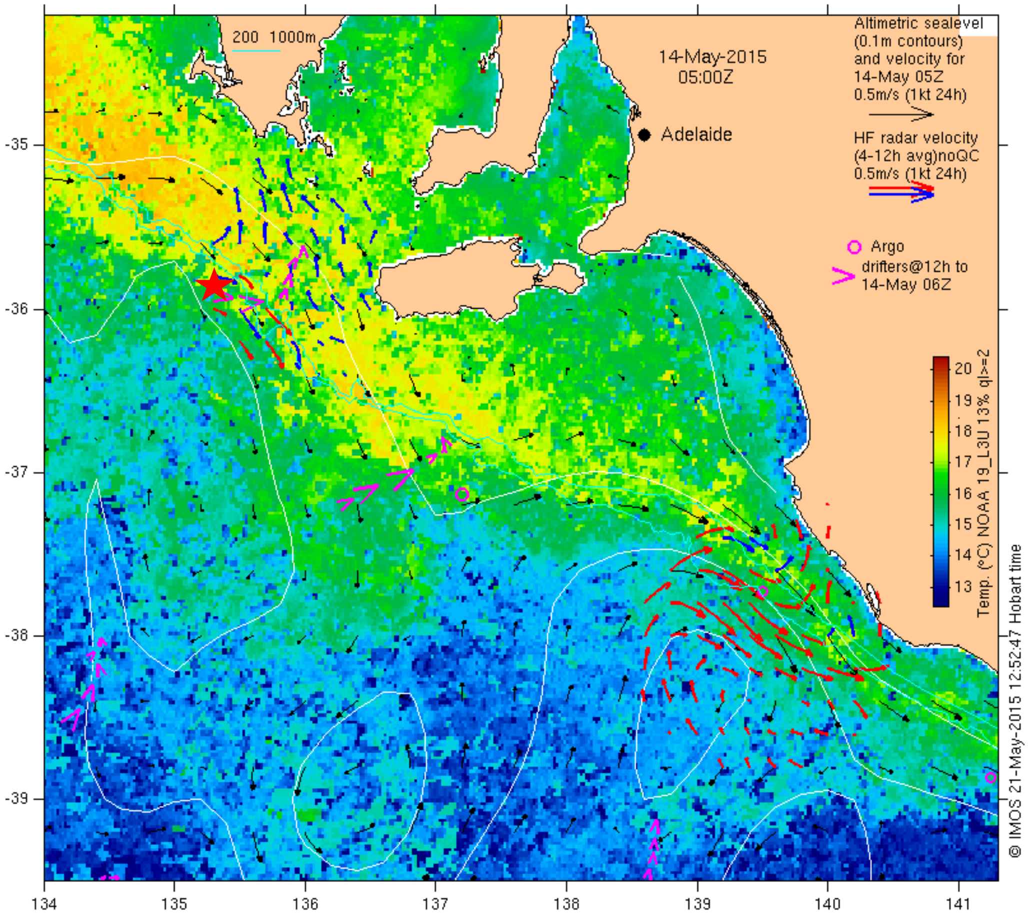
Appendix 1. Patterns in currents and sea-surface temperatures during the survey (imos.org.au)



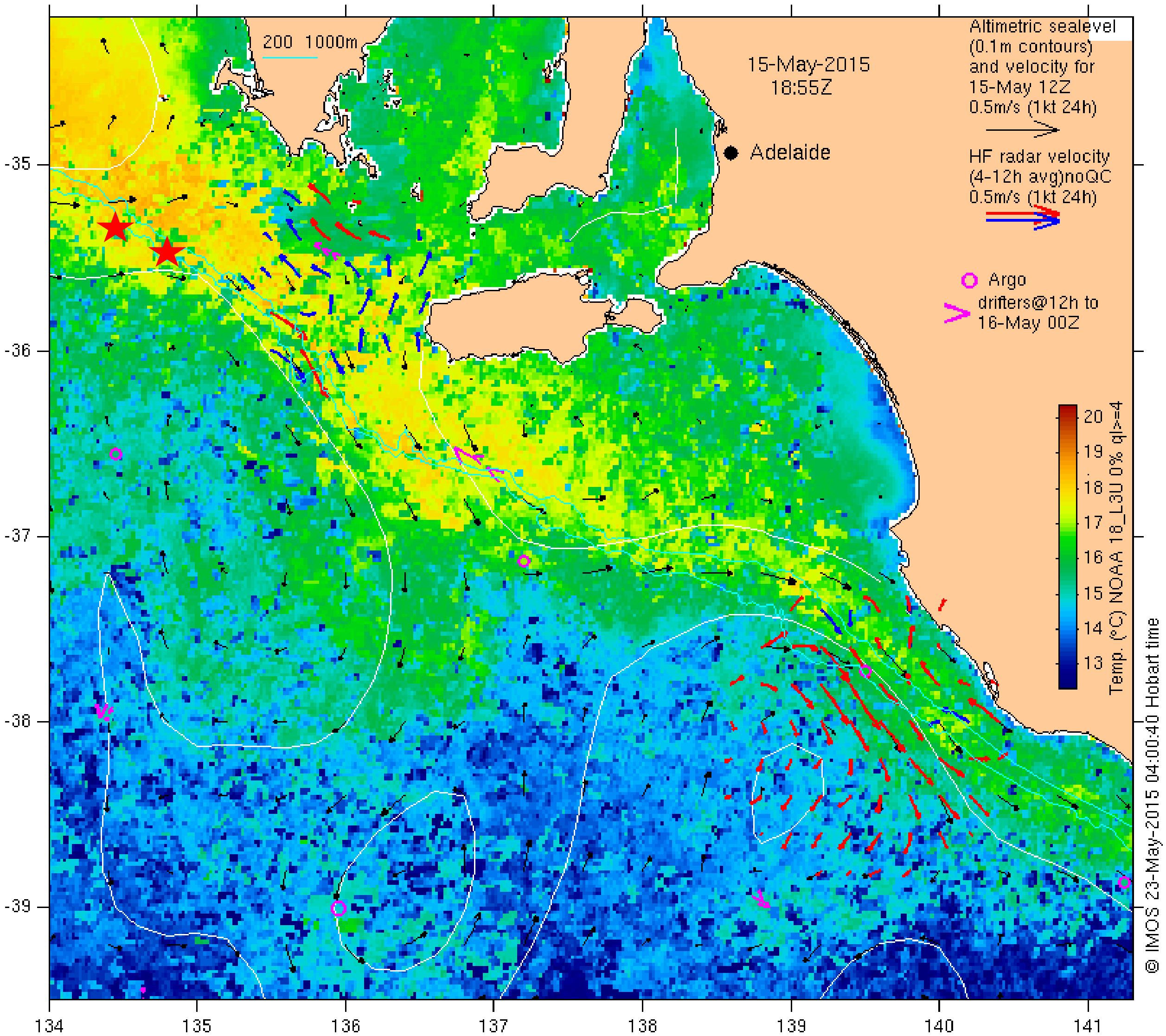
Sea-surface temperature during S1 (red star) at du Couedic Canyon on 1 May 2015. Source: http://oceancurrent.imos.org.au



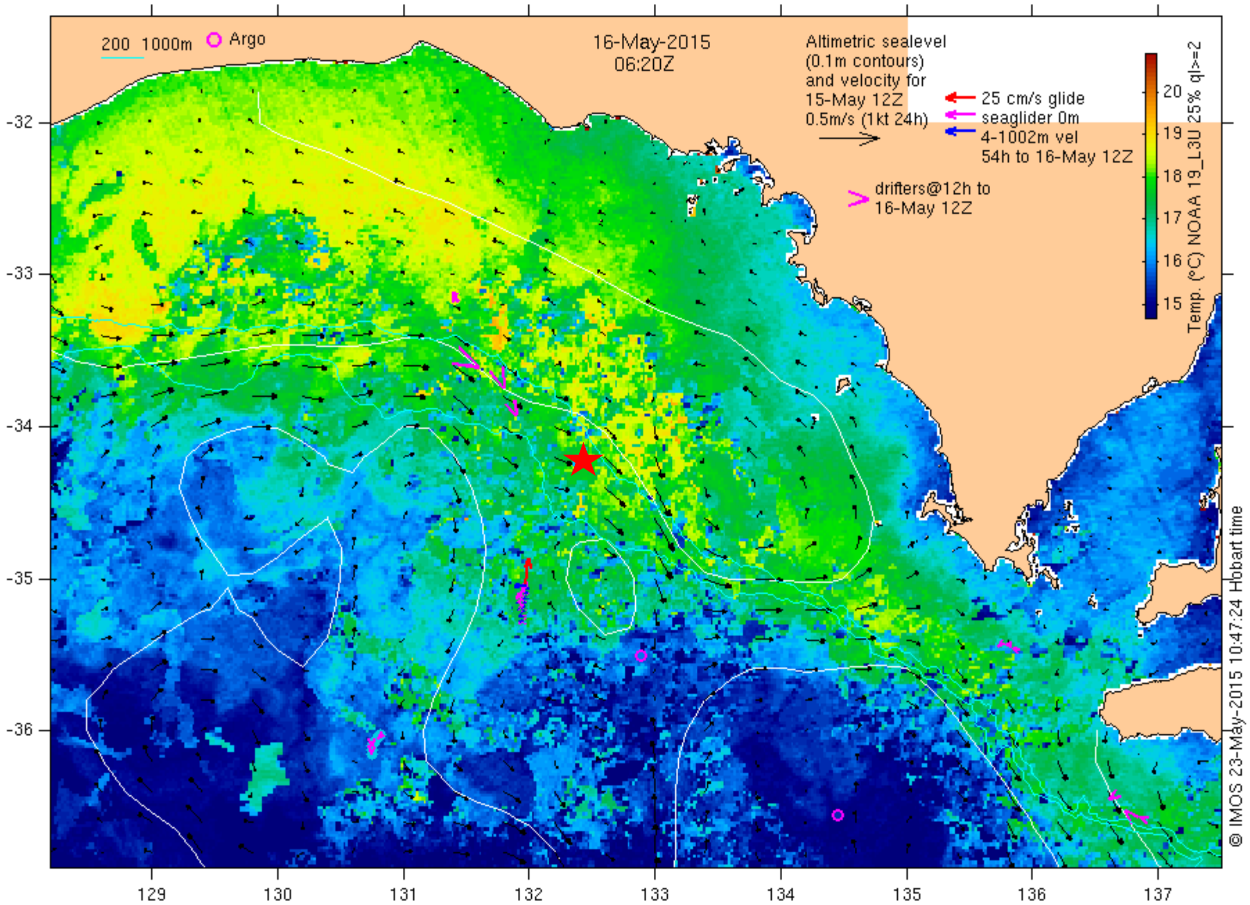
Sea-surface temperature during S2 (red star) at Topgallant Canyon on 3 May 2015. Source: http://oceancurrent.imos.org.au



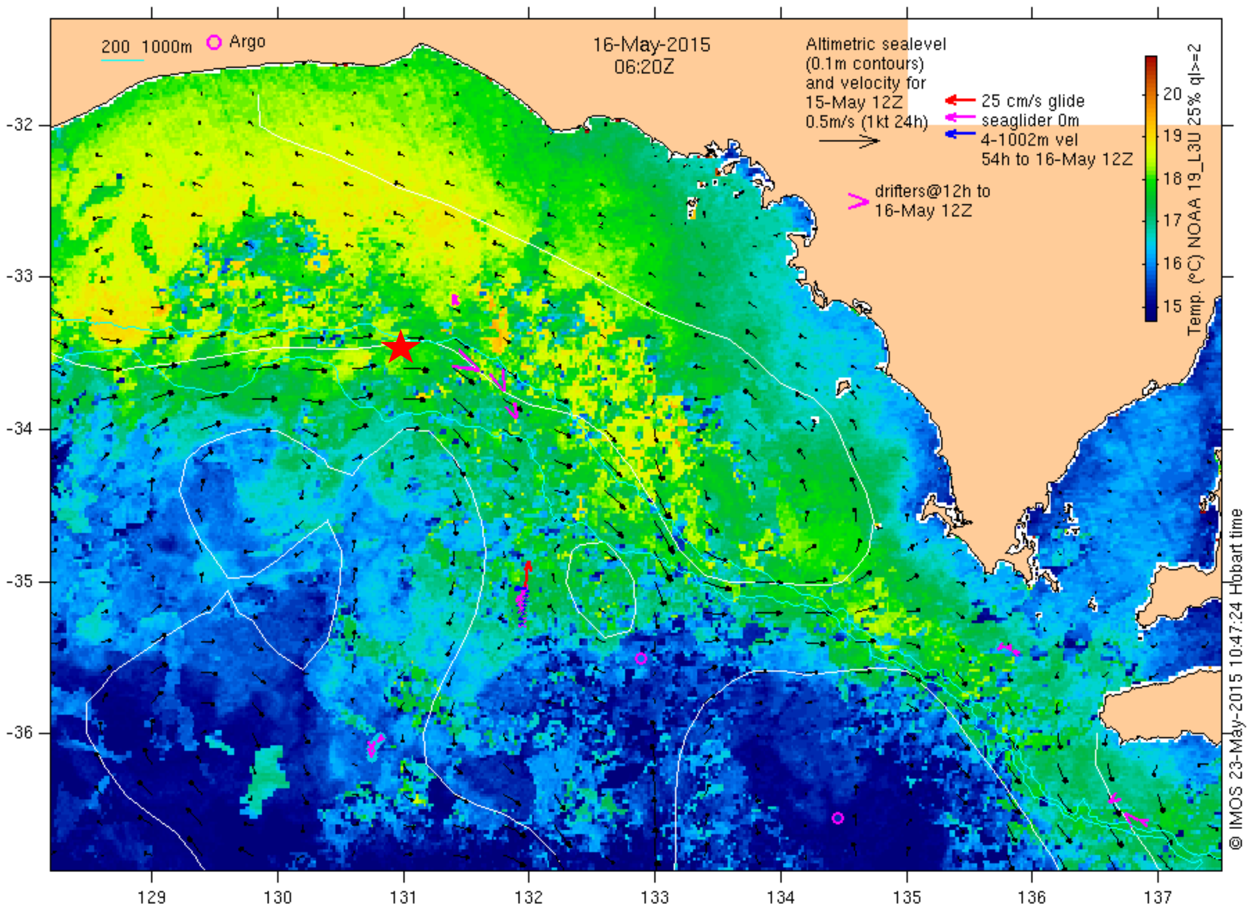
Sea-surface temperature during S3 (red star) at Topgallant Canyon on 14 May 2015. Source: http://oceancurrent.imos.org.au



Sea-surface temperature during S4 and S5 South-west of Rocky Island on 15 May 2015. Source: http://oceancurrent.imos.org.au



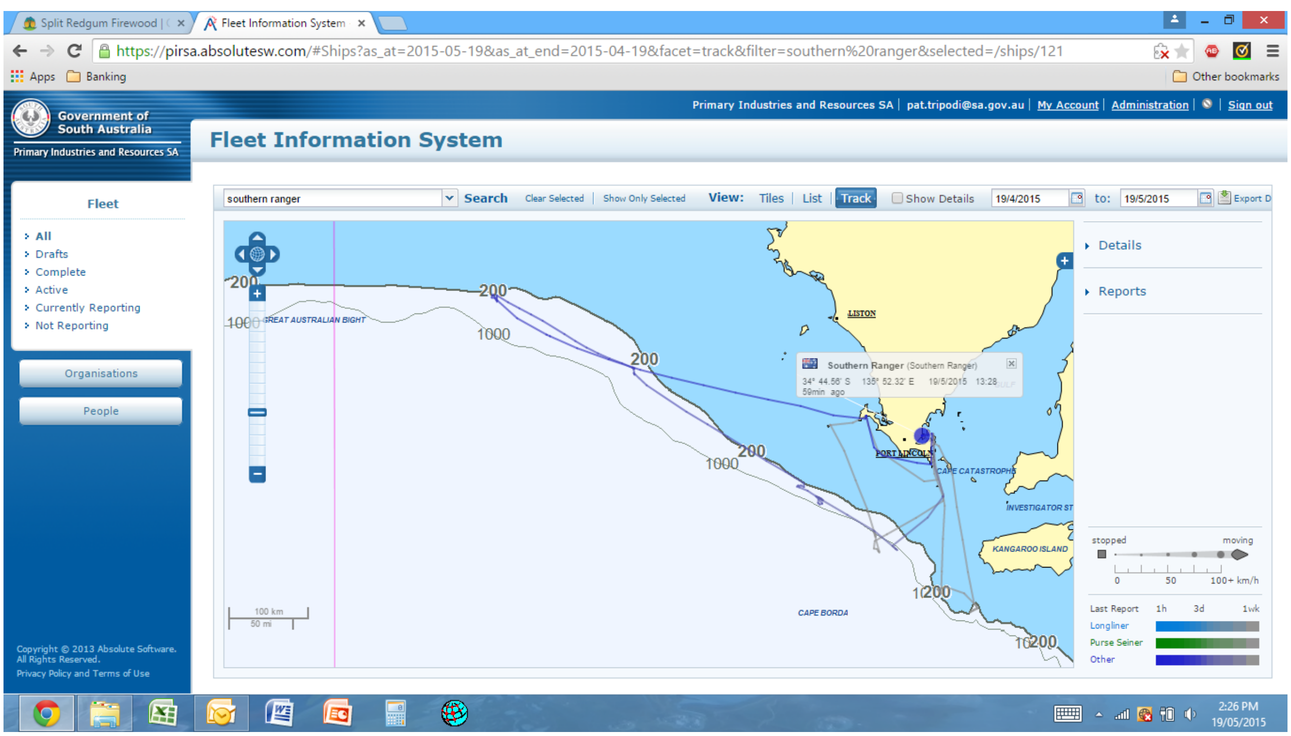
Sea-surface temperature during S6 south of Fowlers Bay on 15 May 2015. Source: http://oceancurrent.imos.org.au



Sea-surface temperature during S7 south of Head of Bight on 16 May 2015. Source: http://oceancurrent.imos.org.au

Appendix 2. Locations, activities, weather conditions and vessel track during the survey.

Day	Date	Location	Wind direction and speed (knots)
1	30 Apr 2015	Port Lincoln (steamed to S1 at mid-night)	N 12–18
2	1 May 2015	S1	NW to W 12–17
3	2 May 2015	South Neptune Island	SW to W 25–30
4	3 May 2015	South Neptune Island to S2	Var-NE 5, W 20–30
5	4 May 2015	Greenly Island and Avoid Bay anchorages	NW to SW 30–60
6	5 May 2015	Avoid Bay anchorage	SW 30
7	6 May 2015	South Neptune Island	SW 20–25
8	7 May 2015	Returned to Port Lincoln	SW 20–25
1	13 May 2015	Port Lincoln to South Neptune Island	S to SW 20–25
2	14 May 2015	S3	S to SW 15
3	15 May 2015	S4 and S5	S to SE 10–15
4	16 May 2015	S6	E 8–12
5	17 May 2015	S7, travelled to Avoid Bay anchorage	NE to N 20-30 then variable to 5-12
6	18 May 2015	Avoid Bay to Port Lincoln	



Appendix 3. Seabird bycatch mitigation techniques adopted during the pelagic survey.

- Side-setting - the mainline was deployed on the starboard side and the baited hooks and leaders were lowered down the darkened side of the vessel, whilst giving each baited hook sufficient time to sink under the vessel wake.
- Minimal deck-lighting was used during the sets to reduce the chance of seabirds making visual contact with baits.
- Leaders included weighted swivels to increase the sink-rate of baits during the set, and hooks were painted black to reduce the potential to attract birds.
- Constant visual contact was maintained with individual seabirds during the setting processes.
- No bait scraps or wheelhouse food scraps were disposed of from the vessel near set locations. Where possible, scraps were retained in bio-degradable hessian bags for disposal.
- The setting rates were modified or stopped if a seabird was present near the stern of the vessel.
- Deep-bait setting equipment and a tori line was on-board for deployment if seabird density increased during sets.

Appendix 4. Observation data. Marine predator species observations at set locations in the Great Australian Bight.

Location	Date	Common name	Species	Estimate (~) or count
S1	1 May 2015	Australian fur seal	*Arctocephalus pusillus*	?
S1	1 May 2015	Common dolphin	*Delphinus delphis*	~500
S1	1 May 2015	Yellownose Albatross	*Thalassarche chlororhynchos*	10
S1	1 May 2015	Shy Albatross	*Thalassarche carteri*	1
S1	1 May 2015	Wandering Albatross	*Diomedea exulans*	1
S1	1 May 2015	Black-browed Albatross	*Thalassarche melanophris*	20
S1	1 May 2015	White faced storm petrel	*Pelagodroma marina*	15
S1	1 May 2015	Wilsons storm petrel	*Oceanites oceanicus*	5
S1	1 May 2015	Southern giant petrel	*Macronectes giganteus*	1
Inside S2	3 May 2015	Yellownose Albatross	*Thalassarche chlororhynchos*	2
Inside S2	3 May 2015	Shy Albatross	*Thalassarche carteri*	2
Inside S2	3 May 2015	Black-browed Albatross	*D. impavidan* = 1, *D. melanophris*	13
Inside S2	3 May 2015	Fleshfoot shearwater	*Puffinus carneipes*	3
Inside S2	3 May 2015	Wilsons storm petrel	*Oceanites oceanicus*	1
Inside S2	3 May 2015	Southern giant petrel	*Macronectes giganteus*	?
S2	3 May 2015	Wandering Albatross	*Diomedea exulans*	2
S2	3 May 2015	Black-browed Albatross	*Thalassarche melanophris*	12
S2	3 May 2015	White faced storm petrel	*Pelagodroma marina*	5
S2	3 May 2015	Wilsons storm petrel	*Oceanites oceanicus*	1
S2	3 May 2015	Yellownose Albatross	*Thalassarche chlororhynchos*	5
S2	3 May 2015	Fleshfoot shearwater	*Puffinus carneipes*	1
S2	3 May 2015	Southern giant petrel	*Macronectes giganteus*	1
S3	14 May 2015	Common dolphin	*Delphinus delphis*	5
S3	14 May 2015	Blackbrow Albatross	*Thalassarche melanophris*	5
S4	14 May 2015	Common dolphin	*Delphinus delphis*	5
S4	14 May 2015	Black-browed Albatross	*Thalassarche melanophris*	10
S4	14 May 2015	Yellownose Albatross	*Thalassarche chlororhynchos*	2
S4	14 May 2015	Shy Albatross	*Thalassarche carteri*	2
S4	14 May 2015	Kerguelen petrel	*Lugensa brevirostris*	1
S4	14 May 2015	Wilsons storm petrel	*Oceanites oceanicus*	5
S5	14 May 2015	Slender-billed prion	*Pachyptila belcheri*	15
S5	15 May 2015	Black-browed Albatross	*Thalassarche melanophris*	10
S5	15 May 2015	Light mantled sooty albatross	*Phoebetria palpebrata*	1
S5	15 May 2015	Kerguelen petrel	*Lugensa brevirostris*	1
S5	15 May 2015	Wilsons storm petrel	*Oceanites oceanicus*	4
S5	15 May 2015	Cape Petrel	*Daption capense*	2
S5	15 May 2015	Giant Petrel spp.	Unid.	1
S7	17 May 2015	Black-browed Albatross	*Thalassarche melanophris*	~400
S7	17 May 2015	Wilsons storm petrel	*Oceanites oceanicus*	2

Appendix 5. Statistics describing remote-sensed habitat variables correlating with the satellite tracks for pelagic sharks B1–B7 and S1 during 2015–16.

		Shark ID							
Parameter	**Statistic**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**S1**
	N records	1889	1764	1785	126	1670	1249	1412	1784
Depth	Mean	4528	3914	3767	1552	3049	3706	2517	755
	SD	1402	1708	1483	336	1746	1707	1864	1344
	Median	5179	4677	4286	1504	2625	4590	1730	206
	Max	5912	6250	5904	2162	5736	5208	5831	5845
	Min	97	-	67	932	42	-	**-x**	-
Bath grad	Mean	2.11	2.44	2.31	1.08	1.62	1.68	1.62	2.10
	SD	2.14	2.46	2.11	0.54	1.47	2.08	1.14	2.84
	Median	1.53	1.61	1.64	0.98	1.20	0.97	1.39	1.04
	Min	0.05	0.01	0.02	0.06	0.02	0.01	0.04	0.00
	Max	15.36	15.69	14.00	2.16	13.56	15.86	13.14	16.50
SST	Mean	15.25	18.96	19.31	17.34	16.80	16.29	16.20	18.06
	SD	1.60	3.78	5.69	0.69	1.81	1.37	1.66	2.16
	Median	15.20	17.51	16.49	17.20	16.53	16.19	15.86	18.37
	Min	12.11	14.42	13.36	16.16	14.23	13.51	13.63	13.61
	Max	18.48	27.58	30.10	18.36	20.91	20.30	20.45	24.24
SST grad	Mean	0.00064	0.00058	0.00062	0.00070	0.00038	0.00080	0.00042	0.00047
	SD	0.00040	0.00038	0.00036	0.00019	0.00025	0.00057	0.00024	0.00032
	Median	0.00055	0.00049	0.00060	0.00065	0.00032	0.00068	0.00039	0.00041
	Min	0.00005	0.00002	0.00003	0.00016	0.00001	0.00001	0.00001	0.00003
	Max	0.00201	0.00202	0.00181	0.0012	0.00152	0.00303	0.00113	0.00186
SSH	Mean	0.55	0.66	0.66	0.55	0.58	0.67	0.56	0.57
	SD	0.05	0.17	0.18	0.02	0.05	0.12	0.05	0.12
	Median	0.54	0.61	0.57	0.55	0.57	0.66	0.56	0.55
	Min.	0.36	0.28	0.35		0.48	0.43	0.44	0.38
	Max	0.73	1.07	1.05	0.61	0.68	1.26	0.68	0.95
SSH grad	Mean	0.000047	0.000075	0.000049	0.000048	0.000048	0.000092	0.000042	0.000049
	SD	0.000029	0.000059	0.000040	0.000019	0.000022	0.000070	0.000023	0.000035
	Median	0.000042	0.000056	0.000036	0.000053	0.000040	0.000075	0.000038	0.000041
	Min	0.000002	0.000002	0.000003	0.000011	0.000000	0.000008	0.000003	0.000002
	Max	0.000202	0.000335	0.000218	0.000070	0.000122	0.000658	0.000106	0.000245

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