Broad-scale coastal movements of white sharks off Western Australia described by passive acoustic telemetry data

R. B. McAuley[a], B. D. Bruce[b], I. S. Keay[a], S. Mountford[a], T. Pinnell[a] , F. G. Whoriskey[c]

[a] Department of Fisheries, Government of Western Australia WA Fisheries and Marine Research Laboratories. 30 Northside Drive Hillarys, WA. PO Box 20 North Beach, WA 6920;

[b] CSIRO Oceans and Atmosphere Research, Hobart, Tasmania.

[c] Ocean Tracking Network Dalhousie University, 1355 Oxford Road. POB 15,000, Halifax, NS, B3H 4R2. Canada

Abstract

Movements of 89 acoustically-tagged sub-adult and adult white sharks (*Carcharodon carcharias*) were monitored off the South and West coasts of Western Australia (WA) between December 2008 and May 2016 by a network of up to 343 passive acoustic receivers. A total of 290 inter-regional movements, totalling 185,092km were recorded for 73 of these sharks. Estimated rates of movement in excess of 3 km per hour (mean=1.7 kmh^{-1}; max=5.6 kmh^{-1}) were common, even over distances of thousands of kilometres. Detections indicated that white sharks may be present off most of the South and lower West coasts of WA coast throughout the year, although they are more likely to be encountered during spring and early summer and are least likely to be present during late summer and autumn. There was limited evidence of predictable return behaviour; seasonal movement patterns or coordination of the direction and timing of individual sharks' movements. Nevertheless, the data suggested that further analyses of movements in relation to ecological factors might be useful predictors of shark activity at local scales. It is hoped that these data may be useful for informing public safety initiatives aimed at mitigating the risks associated with human encounters with white sharks off the WA coast.

Introduction

White sharks (*Carcharodon carcharias*) have a circum-global distribution in temperate to tropical latitudes (Compagno, 2001; Last and Stevens, 2009), where they are most commonly found in temperate continental shelf waters and around oceanic islands, although in some regions they may spend considerable periods in the open ocean (Weng et al., 2007; Bruce, 2008; Domier and Nasby-Lucas, 2008). The species is most frequently encountered off South Africa (Cliff et al., 1996; Kock et al., 2013), southern Australia (Bruce et al., 2006), New Zealand (Duffy et al., 2012), northern California (Boustany et al., 2012), Mexico (Domier and Nasby-Lucas, 2012; Santana-Morales et al., 2012) and the north eastern United States (Casey and Pratt, 1985; Skomal et al., 2012). In regions where *C. carcharias* is relatively common, individuals are widely but not evenly distributed and occur in low abundance, although in some areas they may be more locally-abundant around pinniped colonies (Bruce 1992; Bruce and Bradford, 2015; Francis et al., 2015; Klimley, 1985; Kock et al., 2013; Malcolm et al., 2001; Robbins and Booth, 2012; Skomal et al., 2012). Satellite-tagged white sharks have repeatedly been shown to travel thousands of kilometres through continental shelf and oceanic waters (Bruce et al., 2006; Weng et al., 2007; Domier and Nasby-Lucas, 2008; Duffy et al, 2012) and trans-oceanic return movements have been documented for the species between South Africa and North-West Australia (Bonfil et al. 2005). A common feature of previous studies has been seasonal or, in some cases, more frequent returns to tagging sites (Bonfil et al., 2005; Boustany et al., 2002; Domier and Nasby-Lucas, 2008; Weng and Honebrink, 2013).

In Australia, white sharks most commonly occur across the southern half of the continent, from central Queensland on the East coast to North-West Cape in Western Australia but may occasionally occur further north on both coasts (Paterson, 1990; Bruce et al., 2006; Last and Stevens 2009). Adult and sub-adult white sharks appear to occur particularly frequently around some fur seal and sea lion colonies off the south coast of the continent, including the Neptune Islands in South Australia (SA), areas of the Great Australian Bight and the Recherche Archipelago in Western Australia (Malcolm et al., 2001). Based on observations of temporal changes in the size and sex of sharks around the Neptune Islands (Robbins, 2007; Robbins and Booth, 2012; Bruce and Bradford, 2015), acoustic telemetry data (Bruce et al., 2005a; Bruce and Bradford, 2011; Rogers and Huveneers, 2016) and satellite tracking (Bruce et al., 2005b; Bruce and Stevens, 2006), it is apparent that individual sharks do not, however, permanently reside at these locations and actually spend the majority of their time away from them. Satellite-tracking has shown sharks from the Neptune Islands undertake extensive coastal movements to North West Cape in WA and return movements to Rockhampton in Queensland (Bruce et al., 2006). Long-distance movements have also been documented between eastern Tasmania and the southern Great Barrier Reef (Bruce and Bradford, 2012). However, no individuals have been observed to travel up both west and east coasts of Australia and, genetic evidence suggests that sharks off the eastern and western coasts effectively form two functionally-separate populations in Australian waters (Blower et al., 2012).

Despite their perceived association with pinniped prey, white sharks are versatile predators that feed on teleosts and other elasmobranchs throughout life (Bruce, 1992), adding larger prey items to their diet as sub-adults (Malcolm et al., 2001). White sharks first commonly appear at fur seal (*Arctocephalus pusillus doriferus* and *Arctocephalus forsteri*) and Australian sea lion (*Neophoca cinerea*) colonies in Australia by about 3.0m Total Length (TL), which probably indicates the size at which marine mammals are added to their diet. The smallest examined white shark from Australian waters to contain pinniped remains in its stomach was 2.7m TL (Malcolm et al., 2001). These observations are consistent with vertebral isotope analyses which indicate a dietary shift to include marine mammals by approximately 3.4 m (Estrada et al., 2006). Adult, sub-adult and juvenile white sharks are also frequently observed scavenging on whale carcasses (Carey et al., 1985; Curtis et al., 2006; Dicken, 2008) and may be particularly active around whale stranding sites (Bruce and Stevens, 2004). The species has also been recorded to feed on sunfish, tuna, birds, sea otters and turtles (Ames et al. 1996; Fergusson et al., 2000; Kim et al., 2013). Due to their large size, generally coastal distribution, dietary versatility and variety of predatory behaviours, white sharks can pose a threat to human safety and have been responsible for numerous injurious and fatal encounters with people throughout their range but especially in Australian waters (West, 1993; 2011).

Although human encounters with sharks, including white sharks, very rarely result in injuries, shark bites can have traumatic consequences for those involved, their families, friends and affected communities. Furthermore, shark bites often receive disproportionately high levels of media attention and may have flow-on economic effects for tourism and other marine-related industries (Francis, 2011; Neff, 2012; Neff and Yang, 2012). Bites from white sharks can be especially traumatic and in the 50 years between 1966 and 2015, inclusive, this species has reportedly been responsible for twice as many fatalities in Australia (n=42) than all other shark species combined (n=21; ASAF, 2015). In WA waters, a total of 95 injurious and 26 fatal shark attacks have been recorded between March 1803 and December 2015, inclusive (ASAF, 2015). Although the annual frequency of those incidents has been highly variable, there has been an increasing trend since the 1970s (West, 2011; Anon., 2012). Notwithstanding under-estimation of historical shark bite records due to a lack of organised data collection programs before the late 1980s, approximately half of all recorded shark attacks (n=65) and fatalities (n=12) in WA have occurred during the two decades between 1 January 1996 and 31 December 2015. The last ten fatalities, all of which involved white sharks, took place over an approximately 6 year period between August 2010 and June 2016.

In response to the increasing frequency of white shark bites and encounters around the WA coast, a number of initiatives to monitor potential shark hazards and study white sharks' local ecology have been introduced. The research reported here was undertaken to describe when, where and why this species occurs off the most populated parts of the WA coastline, to help in understanding the complex and dynamic interactions between sharks' and humans' abundance, distributions and behaviours that contribute to white shark bites. Specifically, the objectives of the study were to investigate (i) patterns of white sharks' occurrence and movements off WA's south-west and lower-west coasts; (ii) their large-scale movements between South and Western Australia and (iii) whether individual sharks repeatedly visit or are resident at particular locations off the WA coast. It is intended that results from this study of the species' coastal movements might be useful for developing effective, evidence-based strategies for mitigating the risks associated with human encounters with this species in Western Australia and internationally where white shark bites are an issue of concern.

Materials and methods

Tagging

A total of 234 *C. carcharias* were 'tagged' with Vemco V16-6H, V16-6L and V16-5L acoustic transmitters with random transmission intervals of between 50 and 130 seconds (V16-6H, V16-6L) or 70 to 150 seconds (V16-5L). Transmitters were fitted to sharks between 20 December 2007 and 30 December 2015, off South Australia (n=177) and Western Australia (n=57), during cage diving tourism operations at the Neptune Islands, targeted research activities in both States and opportunistically in WA, usually when sharks were encountered scavenging whale carcasses (Figure 1). Transmitters were externally-fitted to all of the sharks tagged in SA and to 48 of the WA-tagged sharks, via 1.6mm diameter 316-grade stainless steel wire rope tethers attached to sharpened stainless steel anchors. These external ‘tags’ were embedded in sharks’ dorsal musculature using applicator needles mounted on fiberglass hand-spears as they swam past tagging vessels. Between October 2012 and September 2015, 37 sharks were caught off the lower west and South coasts of WA during targeted research fishing with individual baited setlines. Captured sharks (which included 28 of the 48 fitted with external tags in WA) were secured in an inverted position alongside tagging vessels and V16-5L and V16-6L transmitters were surgically-implanted in their abdominal cavities according to standard techniques (eg. Heupel and Hueter, 2001). Internally-tagged sharks were also tagged with uniquely-numbered Jumbo Rototags (Dalton ID Systems Ltd., Henley on Thames, Oxon. UK) in their first dorsal fins for future visual recognition before being revived and released. Two of the dual-acoustically sharks tagged with both internal and external transmitters, were recaptured and re-tagged with new internal and external transmitters after 347 and 372 days at liberty. A third shark which had previously been fitted with an external tag at the Neptune Islands, was also re-tagged with new internal and external transmitters, when captured off Albany (35.03^{0}S 117.90^{0}E) after 510 days at liberty. Sharks were sexed and either measured to the nearest centimetre Fork Length (FL) when captured for internal tagging; or Total Length (TL) was visually-estimated to the nearest 10cm when free-swimming sharks were externally-tagged (Figure 2). As data were not collected to convert estimated and measured lengths, these length units are reported separately below.

Monitoring

Tagged sharks were monitored by 13 arrays of up to 334 passive (Vemco VR2W and VR4G) acoustic receivers off the WA coast between North-West Cape and Cape Le Grand and in Gulf St. Vincent and at the Neptune Islands in South Australia (Figure 3A). Receiver arrays were deployed in seven (7) different regions: Ningaloo Reef (n=42) [1], metropolitan Perth (n=134-143)[2], South-West WA (n=52), Chatham Island (n=44),

---

[1] Integrated Marine Observing System’s (IMOS) Animal Tracking Facility (http://imos.org.au/animaltracking)

[2] Including 53 Ocean Tracking Network receivers (http://oceantrackingnetwork.org/)

Albany-Bald Island (n=35 plus 6 temporary receivers at Two Peoples Bay), the Recherche Archipelago (n=5-18; Figure 3B-3F, respectively) and South Australia (n=3)[3]. The locations of arrays to the south of Ningaloo Reef were chosen for logistical reasons and to reflect the presumed area of greatest overlap between shark and human population abundance. Because receivers were operated by four different organisations for six separate projects, the numbers, configurations and operational periods of each array varied over the course of this study (Table 1). As the occurrence and movements of sharks outside of WA are largely beyond the scope of these analyses, only sharks' first and last detections by SA-located receivers (ie. start and end points of each inter-state movement) are referred to below.

Figure 3.

Table 1.

Data were generally retrieved annually from VR2W receivers (bi-annually from IMOS Animal Tracking receivers at Ningaloo in some years) and weekly (until 31 May 2016) from satellite-linked VR4G receivers. All the detection data reported below were collected prior to May 31 2016.

Movement estimation

Distances of tagged sharks' movements between acoustic receiver arrays and/or release and recapture[4] locations ($\Delta\sigma$), were calculated as least-possible distance vectors between successive points, according to the great-circle (or orthodromic) equation:

$$distance = arccos[sin\emptyset_1 . sin\emptyset_2 + cos\emptyset_1 . cos\emptyset_2 . \cos(\lambda_1 - \lambda_2)] . r$$

Where $\emptyset_1$, λ_1 and $\emptyset_2$, λ_2 are the latitude and longitude of receivers 1 and 2 and *r* is the radius of the earth (in radians).

[3] Operated by Commonwealth Scientific and Industrial Research Organisation (CSIRO) at the Neptune Islands (Bradford et al., 2013) and IMOS in Gulf St. Vincent (Huveneers et al., 2014)

[4] Including the location at which a 3.86m FL male shark beached itself.

To avoid unrealistically estimating movements across land, vectors were forced around arbitrary turning points where necessary. Turning point locations were the same for all sharks and defined as the following points off:

> Dirk Hartog Island (25.5^{0}S 118.0^{0}E); Cape Naturaliste (33.5^{0}S 115.0^{0}E); Cape Leeuwin (34.4^{0}S 114.9^{0}E); Black Point (35.0^{0}S 116.0^{0}E); Albany (35.2^{0}S 118.0^{0}E) and Cape Arid (34.1^{0}S 123.3^{0}E)

As movement vectors assume constant straight-line travel between points, they represent the minimum possible distances travelled and by derivation, associated Rates of Movement (RoM) are minimum constant speeds over those distances.

Results

Including release and recapture events, 89 acoustically-tagged white sharks were detected a total of 29,171 times between December 2008 and May 2016, within the area monitored by combined WA receiver arrays (Figure 4). The largest number of sharks (n=52) and majority of detections (n=21,199) were recorded in the Perth metropolitan region, where the largest number of receivers were located over the longest period. The next-largest number of sharks (n=43) was detected over approximately 4 years by the Bald Island array, followed by the Chatham Island (n=31 sharks) and Cape Leeuwin (n=24 sharks) arrays, from which 3 years of data were available. Due to receivers' variable periods of operation, detection data were standardised by the number of days receivers were in operation. Three receivers in a temporary 6-receiver array, deployed between 24 July and 17 November 2011at the site of a whale carcass stranding in Two People's Bay (25km East of Albany; Figure 4D), were the most active in the network, with detection rates of 383-732 detections per 100 days of operation ($100d^{-1}$). These rates were 3.6 - 6.8 times higher than the next highest detection rate by a receiver at Salisbury Island, in the Recherche Archipelago (Figure 4E, right panel) and more than 80 times the mean rate of all other WA-located receivers (4.5 $100d^{-1}$, S.D.= 8.6).

Figure 4.

Excluding the temporary receivers in Two Peoples Bay, the Recherche Archipelago array was the most active in the network, with a mean detection rate of 18.6 detections $100d^{-1}$ (S.D.=23.4). The two VR4G receivers in King George Sound off Albany recorded the next highest mean rate of 8.5 detections $100d^{-1}$, followed by the combined metropolitan arrays (6.1 detections $100d^{-1}$, S.D.=10.5), the Geographe Bay/Cape Naturaliste VR4G array (4.2 detections $100d^{-1}$, S.D.=7.1), Bald Island (3.0 detections $100d^{-1}$, S.D.=2.4), Cape Leeuwin (2.3 detections $100d^{-1}$, S.D.=2.2) and Chatham Island (1.7 detections $100d^{-1}$, S.D.=1.4) arrays. Unsurprisingly for a species with a primarily temperate distribution, receivers in tropical waters of the IMOS Ningaloo array recorded the lowest mean rate of 0.1 detections $100d^{-1}$. Caution should be used in interpreting detection rates at these regional levels however, as data were strongly influenced by extended detection periods of small numbers of sharks. For example, 146 of the 153 *C. carcharias* detections by the Albany receivers were of a single 5.04m FL female shark that was detected on 15 days between 26 March and 30 April 2014. In the Recherche array, two sharks accounted for 81% of detections and in the combined Perth arrays, 78% of detections were from just six sharks (9% and 12% of sharks detected in those regions, respectively).

Detection data from the cross-shelf arrays off metropolitan Perth, Cape Leeuwin, Chatham Island and Bald Island, were characterised by discrete offshore peaks in detection rates by receivers located in 70m to 120m depths (Figure 4B-D). Similarly, higher numbers of individual sharks were detected in offshore waters off the Perth Metropolitan coast, Cape Leeuwin, Chatham Island and Bald Island (Figure 5). Conversely, although the Recherche array spanned a smaller extent of the continental shelf, detection rates were higher inshore of Mondrain Island than offshore. However, in the most-thoroughly monitored region off metropolitan Perth, tagged sharks were most-frequently but unevenly detected by receivers within seven kilometres of the mainland coast. In the southern metropolitan region, sharks were detected in and across the mouth of Cockburn Sound (17.0 $100d^{-1}$, S.D.=18.9) at nearly 10 times the rate of receivers along the northern metropolitan coast (1.9 $100d^{-1}$, S.D.=2.4; Figure 4B). Although the configuration and numbers of receivers differed between northern and southern metropolitan waters, comparison of detection rates by receivers located similar distances from shore, showed similar levels of disparity in detection rates between north and south. In addition, Cockburn Sound receivers detected nearly twice as many different sharks (max.=12, mean=6.6, S.D.=3.8) than receivers off the northern coast (max.=7, mean=3.8, S.D.=2.0) and 19 of the 25 sharks tagged in the metropolitan region were also located inside Cockburn Sound or adjacent waters.

Figure 5.

Pooled multi-year detection data indicated that *C. carcharias* may be present off the lower-West and South coasts of WA throughout the year, although the number of sharks detected and mean detection periods differed seasonally (Figure 6). Sharks were sporadically detected at Ningaloo Reef in winter (June-August) and late spring (November) to summer (December- January) but too few sharks were detected to suggest these detections might represent a consistent pattern of occurrence in the region. Off metropolitan Perth, the numbers of recorded sharks and detection rate increased through winter, before peaking in spring (October). While relatively high numbers of sharks were also detected off Perth in November and December, the steep decline in detection rates over those months indicated that the amount of time sharks spent within monitored areas in the region was much lower. To the South, the mode of detected shark frequency in Geographe Bay and Cape Leeuwin was December, although the peak in monthly detection rates was slightly earlier in October. The number of sharks detected off the western South coast (Chatham and Bald Islands) was slightly more consistent throughout most months, although there were distinct troughs in the numbers of sharks detected by these arrays between April and July and February to June, respectively. Although pooled monthly detection rates also suggested relatively low levels of shark activity in the Recherche Archipelago between December and February, detections were highly variable and monthly monitoring effort was uneven due to the 18 month data collection period (Nov 2014 - Apr 2016, Table 1). Thus, seasonal patterns of shark activity remain unclear in this region.

Including data from first and last detections by South Australian receivers and sharks' known release and recapture locations, a total of 293 inter-array and inter-regional movement vectors were estimated for 73 individual sharks. Cumulatively, all estimated movement vectors totalled 186,387km. The maximum individual movement distance (between the Neptune Islands and Ningaloo Reef before arrays were installed off the South and South-West coasts of WA) was estimated to be 3,375 km. However, nearly half of the estimated individual movements (n=145) were between adjacent receiver arrays or release and recapture locations, over distances of less than 300km (Figure 7A). Of the other 148 movements, 67 exceeded 1,000km, 18 were over 2,000km and 6 were over distances of more than 3,000km. Multiple inter-regional movements were recorded for most tagged sharks (n=47) and individuals were recorded travelling cumulative distances of up to 6,986km (mean=2,553km; S.D.=1,733km, Figure 7B). Four South Australian-tagged sharks made return trips between the Neptune Islands and WA (two to Perth, one to Ningaloo and one made two trips to Cape Leeuwin). Following removal of the CSIRO VR4G at the Neptune Islands, an additional 11 SA-tagged sharks were detected at Ningaloo (n=3), Perth (n=7) and Cape Leeuwin (n=1) before being detected travelling back towards SA by Bald Island and Recherche arrays. However, due to the lack of consistent receiver coverage in SA and cryptic tag-shedding issues, it is impossible to determine whether those sharks eventually returned to SA. Only one WA-tagged shark was detected (by IMOS receivers in Gulf St. Vincent, Figure 3A), before being recaptured in the Recherche Archipelago.

The maximum Rate of Movement (RoM) was estimated at 5.6kmh^{-1} for a 1.8m estimated TL male shark that travelled between receivers off Bald and Chatham Islands (orthodromic distance of 193km) in less than 35h (Figure 7C). Twenty five other sharks were estimated to have maintained ROMs in excess of 3kmh^{-1} over distances of between 103 and 3,362km (Figure 7D), suggesting that rapid and possibly direct, long-distance movements are relatively common for this species.

There was very limited evidence that white sharks regularly returned to the same WA locations. One of the four sharks that undertook return movements into WA from the Neptune Islands (an 5.0m estimated TL male) apparently travelled briefly to the South-West corner of WA (between Cape Leeuwin and metropolitan Perth arrays) in August to September 2012 and again in August 2013. In the most intensively-monitored region off metropolitan Perth, seven white sharks (five males and 2 females, 2.42m-3.92m FL) were re-detected in the region more than one year after their first detection (or tagging). Two of these (a 3.86m FL female and 3.5m estimated TL male) were redetected after more than 2 years. Five of the seven sharks were tagged in metropolitan region, one was tagged 30km east of Albany and one at the Neptune Islands. All seven of these sharks were detected in the region at least once during spring but also at other times of year.

Apart from six sharks detected off Perth as they travelled south after detection at Ningaloo Reef, all of the inter-regional movements into the metropolitan arrays were from the South. Movements into the region occurred from the South in all months and from the North in January, March, July and December (Figure 8A), without any clear seasonal patterns.

South of Perth (Figure 8B-E), shark movements were generally bi-directional in most months and there were also no clear indications of seasonal patterns in movement directions. While there were general increases in the frequency of detected movements between the South-West (Cape Leeuwin and Geographe Bay) and South coast (Chatham Island, Bald Island and Recherche Archipelago) arrays, during winter and spring months, directions of those movements were approximately equal. The only suggestion of distinct seasonal travel was from eight of the 11 sharks that travelled to Ningaloo, which were first detected there between November and January. However, those detections were composed of separate detections of two groups of three sharks that were tagged within a month of each other at the Neptune Islands and off Perth and then within days to weeks of each other at Ningaloo. It is unclear whether these unusually coordinated or coincidental movements are representative of all of the sharks that travel as far North as Ningaloo.

Discussion

Understanding the ecological factors influencing encounters with *C. carcharias* in Western Australia has previously been hampered by the paucity of data describing the species' apparently sporadic occurrence around the extensive Western Australian coastline (Anon. 2004). Satellite telemetry data from four sharks (Bruce and Stevens, 2004; Bruce et al., 2006) and occasional but inconsistent records of white shark captures, sightings and bites (McAuley et al., 2016) were of little value in explaining how the probability of human encounters with this species changes with time and location. In lieu of reliable empirical data to explain these rare and unpredictable events, there has been considerable speculation about the reasons for apparent increases in white shark encounters and bites and many theories and opinions have instead gained popular acceptance (Anon., 2012).

Tag detection data collected since 2009 have revealed that white sharks may be encountered off the lower West and South coasts of WA at any time of year. Apart from brief reductions in tagged sharks' abundance off Cape Leeuwin and Chatham Island in winter, Albany/Bald Island in autumn and the Recherche Archipelago in late summer-early autumn, the data indicate that *C. carcharias* abundance is more seasonally consistent off the South coast of WA than off the lower West coast. As suggested by the number of sharks detected off Perth and concurrent peak in mean duration of detection periods, it appears that the probability of encountering the species off the metropolitan coast is highest between September and December and lowest (but never zero) between February and May. This peak detection period in metropolitan and SW regions, corresponds to a relative increase in the frequency of *C. carcharias* bites to people in spring and early summer, with 43% of incidents having occurred in these regions between October and December (ASAF, 2015). However, because the probability of human-shark encounters is confounded with peoples' participation rates in aquatic activities, which increase with improving weather and ocean conditions during spring, the disproportionately high rate of shark bite incidents in the region at this time of year cannot solely be attributed to changes in white shark abundance.

Despite the seasonal patterns in their occurrence, the direction and timing of individual sharks' movements were found to be highly variable throughout the study area. Apart from the specific examples of concurrent movements to Ningaloo Reef and in some of those cases, back to Perth and the South-West WA, *C. carcharias* were recorded travelling past each monitored region in both directions at most times of the year. Such asynchronous movements do not support one popular theory (Sprivulis, 2014) that white sharks follow humpback whales (*Megaptera novaeangliae*) as they predictably migrate northwards along the WA coast during winter (June-August) and southwards in spring (August-November; Jenner et al., 2001; Kent et al., 2012). Given the extent of tagged sharks' movements off the WA coast, however, it is apparent that they co-occur along much of the *M. novaeangliae* migration route. Although *C. carcharias* is not known to actively predate great whales, they have frequently been observed scavenging carcasses (Bruce and Stevens, 2004) and eleven of the WA-tagged sharks, including all nine tagged in 2009-10 were located in vicinity of humpback, southern right (*Eubalaena australis*) and sperm (*Physeter macrocephalus*) whale carcasses. This association was opportunistically investigated when five sharks were monitored at the site of a beached humpback carcass in Two Peoples Bay (25km East of Albany) between June and September 2010. Detections by a temporary 6-receiver array deployed in the area, revealed that tagged sharks continued to visit the bay for up to 17 days (mean=6.6d) after the carcass had come ashore. However, their visits were typically brief (mean detection periods of 7h per day) and declined in frequency and duration, presumably, as sharks' interest diminished after repeated unsuccessful scavenging attempts and/or scent from the carcass dissipated.

Another popular theory for explaining the increasing rate of *C. carcharias* bites in WA is that sharks have been attracted to the increasing number and densities of long-nosed fur seal (*Arctocephalus forsteri*) colonies off the South and lower West coasts of the State (Campbell et al., 2014). Although receiver arrays were not designed to monitor sharks' behaviour around pinniped colonies, detection rates from receivers in close proximity to WA seal colony and haul-out sites, were noticeably lower than those of receivers further offshore of those locations. As nearshore patrolling is a consistent feature of white sharks' predatory behaviour at pinniped colonies in South Australia and California (Strong et al., 1992; Goldman and Anderson, 1999; Bruce et al., 2005a; Domier et al., 2012), higher detection rates close to WA colonies would logically be expected if sharks were actively targeting seals at those locations. However, detection rates of white sharks by receivers within 2km of a large new *A. forsteri* colony at Chatham Island were between 0.00-1.35 detections $100d^{-1}$, compared to an average rate of 11.41 detections $100d^{-1}$ (S.D.=16.42) by receivers further off Chatham Island. Similarly, detection rates by OTN receivers within 2km of the West End of Rottnest Island, where an expanding fur seal colony has been blamed for perceived increases in shark activity in the metropolitan area and a fatal bite near the colony in October 2011, were also an order of magnitude lower (0.00-0.27 detections $100d^{-1}$) than the average detection rate of OTN receivers further offshore (2.33 detections $100d^{-1}$, S.D.=1.88).

Given the asynchrony observed in sharks' movements throughout the study region, the two instances of coordinated or coincidental movements to north-western WA were unusual and the ecological or social drivers for them, if any, remain uncertain. When reporting a tagged 380cm TL female's return migration between South Africa and North West Cape, Bonfil et al. (2005) suggested that this region might be an area of inter-breeding between geographically-separated African and Australian populations. However, as all of the white sharks detected at Ningaloo during the current study were juveniles and sub-adults (2.0-3.5m estimated TL), reproductive migration is an unlikely reason for these sharks to visit the region. As there are multiple relatively abundant sources of prey between Ningaloo Reef and the Neptune Islands, where most (n=8) of these sharks were tagged, prey availability also does not seem to be a likely explanation. As yet undescribed features of *C. carcharias* foraging behaviour, therefore, provide the most likely explanation for these movements.

The lack of receivers between metropolitan Perth and Ningaloo Reef and between monitored sites in South Australia and off Esperance resulted in obvious gaps in the data recorded from large portions of tagged sharks' ranges. Although sharks' movements and behaviour may have differed in those areas from the patterns observed in the more-intensively monitored region between Perth and Albany, the primary focus of this study was to investigate movements along the most heavily-populated part of the Western Australian coastline. With the exception of Geraldton on the mid-West coast (28.79^{0}S 114.60^{0}E, population *c*. 40,000), monitoring arrays were situated close to all of the major coastal population centres around white sharks' known Western Australian distribution (Last and Stevens, 2009). Thus, these data gaps are not thought to have compromised our interpretation of shark movements in the most heavily-populated part of the State or at a broader scale and how these dynamics might relate to the risks of shark bites.

Movements of SA-tagged sharks into WA (n=46) waters were relatively common and their visits were sometimes prolonged. By contrast, only two WA-tagged sharks were detected in SA: a 2.7m (FL) female shark that was detected by AATAMS receivers in Gulf St. Vincent in February-March 2014 and an as yet unidentified WA-tagged shark that was photographed at the Neptune Islands in June 2015. Despite the small number of acoustic receivers installed at the Neptune Islands, these have been in nearly-continuous operation around the Islands since 2008 (Bradford et al., 2011; Rogers et al., 2014). Given that identical external tagging methods were employed in South and Western Australia and that an increasing number of sharks were tagged with internal transmitters in WA since 2012, avoiding uncertainties caused by uncertain rates of external tag shedding, the paucity of detections at the Neptune Islands suggests that WA-tagged sharks may not be frequent visitors to this specific location. Although there are several other possible explanations for the lack of WA-tagged shark detections in SA (e.g. low levels of receiver coverage, tag shedding, cryptic mortality, etc.), previous studies have noted fine-scale spatial sexual and ontogenetic segregation of sharks over relatively small geographic areas (Anderson and Pyle, 2003; Robbins and Booth, 2012; Kock et al., 2013). It may therefore be that movements of WA-tagged sharks into South Australian waters were more common than indicated by detections by Neptune Islands and IMOS Gulf St. Vincent receivers.

In WA, detections by cross-shelf receiver arrays were characterised by short detection periods, punctuated by relatively rapid movements between adjacent arrays, suggesting that sharks generally only occurred within and between monitored areas for brief periods. However, data from the more thoroughly monitored metropolitan region, included examples of more prolonged localised detection periods, with 10 of the 52 sharks recorded in the region, detected in three or more consecutive months, five of them twice. Eleven of these sharks' 15 extended metropolitan detection periods included detections in either October or November, implying that ecologically-favourable local conditions might have existed during those months. Although four of these sharks were disproportionately responsible for the majority (94%) of detections by receivers in and around Cockburn Sound, where the highest regional detection rates were recorded, extended occurrences of seven other sharks in southern metropolitan waters suggest that the area is particularly attractive to *C. carcharias* at that time of year. In addition to the high detection rates recorded by receivers in southern Perth waters, relatively large numbers of different sharks were detected in the southern part of the region. For example, on average nearly twice as many sharks (9-12, mean=10 receiver^{-1}) were detected by receivers around north-eastern Cockburn Sound than at beachside locations (2-7, mean=4.2 receiver^{-1}).

The high abundance and persistence of tagged sharks in southern metropolitan waters during spring and early summer coincided with the seasonal formation of locally-significant spawning aggregations of snapper (*Chrysophrys auratus*) in Cockburn Sound, which nearly half (n=9) of the 21 *C. carcharias* tagged in the metropolitan region were caught in close proximity to. Extensive commercial and recreational fishery management actions have been introduced over the last decade to rebuild previously over-exploited demersal teleost stocks in the metropolitan region and recent assessments now indicate that these stocks are recovering (Fairclough et al., 2014). Snapper are thought to be a relatively important component of white sharks' diets across southern Australia and tagged sharks have previously been associated with pre-spawning and spawning schools of *C. auratus* in various areas including Spencer Gulf (SA) and off eastern Victoria (Bruce et al., 2006; Sims et al., 2012). Thus, the regular seasonal occurrence of spawning aggregations of demersal teleost species off the metropolitan coast provides at least a circumstantial explanation for the observed increase in seasonal abundance of tagged white sharks and their prolonged detection periods at this time of year.

Observed occurrences of *C. carcharias* off the metropolitan coast were not, however, restricted to those predictable seasonal prey availability events. For example, four male and female sharks (3.0-4.5m estimated TL) were tagged whilst scavenging whale carcasses in May and July 2009. Another three males and three females (2.1–3.9m FL) were caught around a highly unseasonal school of Australian salmon (*Arrips truttaceus*) 8km North of Cockburn Sound during 3 (non-consecutive) days in August 2015. Even sharks that were tagged around *C. auratus* schools in Cockburn Sound were detected away from Cockburn Sound for periods of over several days. For example, during their extended periods of detection in Cockburn Sound during October and November 2012, two female sharks (2.6m and 3.0m FL) were concurrently detected over consecutive 3-5 day periods by receivers in the central and northern-most extents of the metropolitan arrays, respectively. Real-time investigations of local ecological conditions during those detection periods revealed large schools of unidentified baitfish and in the latter case, skipjack tuna (*Katsuwonis pelamis*), Australian sea lions (*Neophoca cinerea*), bottlenose dolphins (*Tursiops aduncus*) and various seabirds were also present. Once these transient conditions subsided, one of the sharks returned to Cockburn Sound for a month before departing to Ningaloo Reef where the other shark was also next detected.

Although accurately predicting when and where individual white sharks might occur off any particular part of the WA coast remains an unrealistic aspiration at this time, the data collected during these ambitious continental-scale international collaborative projects have rapidly and substantially improved understanding of white sharks' movement ecology in south-western Australian waters. Although data suggest that the abundance, distribution and movements of white sharks around WA vary between southern Australian government jurisdictions from one year to another, they have identified periods and locations where white sharks are more likely to occur and have begun to identify the range of ecological factors that may influence the probability of encountering this species off the WA coast. More detailed analyses of these data in relation to specific local environmental variables (e.g. ocean temperatures, circulation patterns, Southern Oscillation Indices, etc.), may provide additional explanations of the patterns observed in this study.

Notwithstanding further analyses, the observed patterns of tagged sharks' occurrence and movements provide useful insights into how *C. carcharias* abundance and movements influence probabilities of human encounters with the species. In particular these results indicated that although white shark movements appear asynchronous and uncoordinated, peak activity periods differed around the WA coast. It is hoped that results from this study might offer an important empirical basis for developing effective and defensible methods for identifying and responding to locally-important white shark hazards (eg. seasonal and transient fish schools and whale carcasses). As such, the authors hope that the results of this study might provide a useful basis for reducing risks of human encounters with white sharks in WA and other regions where such interactions are an issue of concern.

Acknowledgements

This project was primarily funded through a series of grants from the Western Australian State Government. The authors are indebted to Charlie Huveneers, Paul Rogers and Andrew Fox for data sharing and field assistanceand to the following for their considerable assistance: Russ Bradford, Chris Dowling, Dani Waltrick de Souza, Mark Kleeman, Mark Davidson, Lisa West, Carly Bruce, Rick Allison, Gabby Mitsopoulos, Craig Skepper, Brett Crisafulli, Rod O'Halloran, skippers and crews of the RV Naturaliste, PVs Hamelin, Houtman and Walcott, Mike Simmons (Simtron), David Whillas (Seabotix, Australia), Nick Stampone (Transfield Services) and Dave Wilson (Fendercare, Australia). Additional acoustic tag detection data were sourced from the CFI (Canada Foundation for Innovation)-supported Ocean Tracking Network (OTN) project and the Integrated Marine Observing System (IMOS), which is supported by the Australian Government through the National Collaborative Research Infrastructure Strategy and the Super Science Initiative. The tagging of sharks was approved under a Section 115 exemption (South Australian [SA] Fisheries Management Act 2007), permits MR00025-1 and U26255 from the Department of Environment, Water and Natural Resources SA (and previous derivations) and Tasmanian Department of Primary Industries, Parks, Water and the Environment (DPIPWE) Animal Care and Ethics Project 1/2013-14 (and previous derivations). Barry Bruce's time on this project was supported by the Marine Biodiversity Hub, a collaborative partnership supported through funding from the Australian Government's National Environmental Science Programme NESP). NESP Marine Biodiversity Hub partners include the Institute for Marine and Antarctic Studies, University of Tasmania; CSIRO, Geoscience Australia, Australian Institute of Marine Science, Museum Victoria, Charles Darwin University, University of Western Australia, NSW Office of Environment and Heritage, NSW Department of Primary Industries and the Integrated Marine Observing System. We are also grateful for Malcolm Francis' comments, which greatly improved this manuscript.

References

Ames, J. A., Geibel, J. J., Wendell, F. E. and Pattison, C. A. (1996). White shark-inflicted wounds on sea otters in California, 1968–1992. In Great white sharks: the biology of *Carcharadon carcharias* (Eds A. P. Klimley and D. G. Ainley) pp. 309–316. (Academic Press, San Diego, CA.).

Anderson, S. D. and Pyle, P. (2003). A temporal, sex specific occurrence pattern among white sharks at the South Farallon Islands, California. California Fish and Game **89**: 96–101.

Anon. (2004). Review and Recommendations on Shark Hazard Mitigation Activities in Western Australia. Shark Hazard Committee. August 2004. Unpublished report, Department of Fisheries, Perth Western Australia.

Anon. (2012). A correlation study of the potential risk factors associated with white shark attacks in Western Australian waters. November 2012. Fisheries Occasional Publication No. 109, 2012. Department of fisheries, Perth. Western Australia.

ASAF (2015). Australian Shark Attack File Annual Report Summary for 2015. https://taronga.org.au/conservation/conservation-science-research/australian-shark-attack-file/2015.

Blower, D. C., Pandolfi, J. M., Bruce, B. D., Gomez-Cabrera, M. D. and Ovenden, J. R. (2012). Population genetics of Australian white sharks reveals fine-scale spatial structure, transoceanic dispersal events and low effective population sizes. Marine Ecology Progress Series **455**: 229–244.

Bonfil, R., M., Meÿer, M., Scholl, M. C., Johnson, R., O'Brien, S., Oosthuizen, H., Swanson, S., Kotze D. and Paterson, M. (2005). Transoceanic migration, spatial dynamics, and population linkages of white sharks. Science (New York, N.Y.) **310**: 100–3.

Boustany, A. M., Davis, S. F., Pyle, P., Anderson, S. D., Le Boeuf, B. J. and Block, B. A. (2002). Expanded niche for white sharks. Nature **415**: 35–36.

Bradford, R.W., Bruce, B.D., McAuley, R.B. and Robinson, G. (2011). An Evaluation of Passive Acoustic Monitoring Using Satellite Communication Technology for Near Real-Time Detection of Tagged Animals in a Marine Setting. The Open Fish Science Journal, **4**: 10-20.

Bradford, R. W., Bruce, B. D. and Hobday, A.. (2012). Identifying juvenile white shark behaviour from electronic tag data. In Global perspectives on the biology and life history of the white shark. (Ed. M. Domeier) pp. 255–270. (CRC Press, Boca Raton, FL.).

Bruce, B. D. (1992). Preliminary observations on the biology of the White Shark, *Carcharodon carcharias*, in South Australian waters. Australian Journal of Marine and Freshwater Research **43**:1-11.

Bruce, B. D. (2008). White sharks: the biology and ecology of *Carcharodon carcharias*. In Sharks of the Open Ocean. (Eds. E. Pikitch and M. Camhi) pp. 69–81. (Blackwell Scientific).

Bruce, B. and Stevens, J. (2004). Tracking the movement patterns of large white sharks in Australian waters. Final report to: AQWA – the Aquarium of Western Australia and the AQWA Research Foundation. CSIRO Marine Research, Hobart. May 2004. 25pp.

Bruce, B.D. and Bradford, R.W. (2012). Habitat use and spatial dynamics of juvenile white sharks, *Carcharodon carcharias*. In Global perspectives on the biology and life history of the white shark. (Ed. M. Domeier) pp. 225–254. (CRC Press, Taylor & Francis Group, Boca Raton, FL.).

Bruce, B.D. and Bradford, R.W. (2013). The effects of shark cage-diving operations on the behaviour and movements of white sharks, *Carcharodon carcharias*, at the Neptune Islands, South Australia. Marine Biology **160**: 889–907.

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

Bruce, B.D., Stevens, J.D. and Bradford, R.W. (2005a). Identifying movements and habitats of white sharks and grey nurse sharks. Final report to Department of Environment and Heritage. CSIRO Hobart.

Bruce, B. D., Stevens, J. D. and Bradford, R. W. (2005b). Site fidelity, residence times and home range patterns of white sharks around pinniped colonies. Final report to Department of Environment and Heritage. CSIRO Hobart.

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

Campbell, R. Holley, D.A, Collins, P. and Armstrong, S. (2014). Changes in the abundance and distribution of the New Zealand fur seal (*Arctocephalus forsteri*) in Western Australia: are they approaching carrying capacity? Australian Journal of Zoology, **62**: 261–267.

Carey, F. G., Casey, J. G., Pratt H. L. Jr., Urquhart, D. and McCosker, J. E. (1985). Temperature, heat production and heat exchange in lamnid sharks. Memoirs of the Southern California Academy of Sciences **9**: 92–108.

Casey, J.G. and Pratt, H.L. Jr. (1985). Distribution of the white shark, *Carcharodon carcharias*, in the western North Atlantic. Memoirs of the Southern California Academy of Sciences **9**: 2–14.

Cliff, G., Dudley, S.F.J. and Fry, M.R. (1996). Catches of white sharks in KwaZulu-Natal, South Africa and environmental influences. In Great white sharks: the biology of *Carcharadon carcharias*. (Eds A. P. Klimley and D. G. Ainley) pp. 351–362. (Academic Press, San Diego, CA).

Compagno, L. J. V. (2001). Sharks of the World. An annotated and illustrated guide of the shark species known to date. Volume 2. Bullhead, mackerel and carpet sharks

(Heterodontiformes, Lamniformes and Orectolobiformes). FAO species catalogue for fishery purposes. FAO Rome.

Curtis, T., Kelly, J. T., Menard, K. L., Laroche, R. K., Jones, R. E. and Klimley, A. P. (2006). Observations on the behaviour of white sharks scavenging from a whale carcass at Point Reyes, California. California Fish and Game **92**: 113–124.

Dicken, M. L. (2008). First observations of young of the year and juvenile great white sharks (*Carcharodon carcharias*) scavenging from a whale carcass. Marine and Freshwater Research **59**: 596–602.

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.

Domeier, M. L., Nasby-Lucas, N. and Lam, C. H. (2012). Fine-scale habitat use by white sharks at Guadalupe Island, Mexico. In Global perspectives on the biology and life history of the white shark. (Ed. M. Domeier) pp 121–132. (CRC Press, Boca Raton, FL.).

Duffy, C., Francis, M. Manning, M. and Bonfil., R. (2012). Regional population connectivity, oceanic habitat, and return migration revealed by satellite tagging of white sharks, *Carcharodon carcharias*, at New Zealand aggregation sites. In Global perspectives on the biology and life history of the white shark. (Ed. M. Domeier) pp 301–318. (CRC Press, Boca Raton, FL.).

Estrada, J. A., Rice, A. N., Natanson, L. J. and Skomal, G. B.. (2006). Use of isotopic analysis of vertebrae in reconstructing ontogenetic feeding ecology in white sharks. Ecology **87**:829–834.

Fairclough, D.V., Molony, B.W., Crisafulli, B.M., Keay, I.S., Hesp, S.A., Marriott, R.J. (2014). Status of demersal finfish stocks on the west coast of Australia. Fisheries Research Report No. **253**. Department of Fisheries, Western Australia. 96 pp.

Fergusson, I. K., Compagno, L. J. V. and Marks, M. A.. (2000). Predation by white sharks *Carcharodon carcharias* (Chondrichthyes: Lamnidae) upon chelonians, with new records from the Mediterranean Sea and a first record of the ocean sunfish *Mola mola* (Osteichthyes: Molidae) as stomach contents. Environmental Biology of Fishes **58** :447–453.

Francis, B. (2011). Before and after Jaws: changing representations of shark attacks. Honours thesis, Murdoch University, Western Australia.

Francis, M. P., Duffy, C. and Lyon, W. (2015). Spatial and temporal habitat use by white sharks (*Carcharodon carcharias*) at an aggregation site in southern New Zealand. Marine and Freshwater Research **66**: 900–918.

Goldman, K. J. and Anderson, S. D. (1999). Space utilization and swimming depth of white sharks, *Carcharodon carcharias*, at the South Farallon Islands, central California. Environmental Biology of Fishes. **56**: 351-364.

Heupel, M. R. and Hueter, R. E. (2001). Use of a remote acoustic telemetry system to monitor shark movements in a coastal nursery area. In Electronic Tagging and Tracking in Marine Fisheries. (Eds J.R. Sibert and J.L. Nielsen) pp. 217–236. (Dordrecht: Kluwer Academic Publishers).

Huveneers, C., Rogers, P. J., Drew, M. (2014). Monitoring shark species of conservation concern within the Adelaide metropolitan and Gulf St Vincent regions. Final Report to the Adelaide & Mount Lofty Ranges Natural Resources Management Board. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2013/000716-1. SARDI Research Report Series No. **754**. 89 pp.

Jenner, K. C. S., Jenner M-N. M. and McCabe, K. A. (2001). Geographical and temporal movements of humpback whales in Western Australian waters. Appea Journal 2001: 749-765.

Kent, C. S., Jenner, C., Jenner, M., Bouchet, P. and Rexstad, E. (2012). Southern hemisphere breeding stock D humpback whale population estimates from North West Cape, Western Australia. Journal of Cetacean Research and management. **12**: 29–38.

Rogers, P. J., Huveneers, C, and Beckmann, C. (2014). Monitoring residency of white sharks, *Carcharodon carcharias* in relation to the cage-diving industry in the Neptune Islands Group Marine Park. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2014/000800-1. SARDI Research Report Series No. **818**. 75 pp.

Kim, S. L., Tinker, M. T., Estes, J. A. and Koch, P. L. (2013). Ontogenetic and among-individual variation in foraging strategies of northeast Pacific white sharks based on stable isotope analysis. Plos One **7**.

Klimley, A. P. (1985). The areal distribution and autoecology of the white shark, *Carcharodon carcharias*, off the west coast of North America. Memoirs of the Southern California Academy of Sciences **9**: 15–40.

Kock, A., O'Riain, M. J., Mauff, K., Meÿer, M., Kotze, D. and Griffiths, C.. (2013). Residency, habitat use and sexual segregation of white sharks, *Carcharodon carcharias* in False Bay, South Africa. PloS One **8**.

Last, P. R. and Stevens, J. D. (2009). Sharks and Rays of Australia. Second edition. CSIRO Publishing. Collingwood, Victoria.

Malcolm, H., Bruce, B. D. and Stevens, J. D. (2001). A review of the biology and status of white sharks in Australian waters. Page 113. CSIRO Marine Research, Hobart.

Neff, C. (2012). Australian beach safety and the politics of shark attacks. Coastal Management **40**: 88–106.

Neff, C. L., and Yang, J. Y. H. (2013). Shark bites and public attitudes: Policy implications from the first before and after shark bite survey. Marine Policy **38**: 545–547

Paterson, R. A. (1990). Effects of long-term anti-shark measures on target and non-target species in Queensland, Australia. Biological Conservation **52**: 147–159

Robbins, R., and Booth, D.. (2012). Seasonal, sexual and size segregation of white sharks, *Carcharodon carcharias*, at the Neptune Islands, South Australia. In Global perspectives on the biology and life history of the white shark. (Ed M. Domeier) pp. 287–299. (CRC Press, Boca Raton, FL.).

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 the 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**. 109pp.

Santana-Morales, O., Sosa-Nishizaki, O., Escobedo-Olvera, M., Onate-Gonzalez, E., O'Sullivan, J. and Cartamil, D.. (2012). Incidental catch and ecological observations of juvenile white sharks, *Carcharadon carcharias*, in Western Baja california, Mexico. Conservation implications. In Global perspectives on the biology and life history of the white shark. (Ed M. Domeier) pp. 187–198. (CRC Press, Boca Raton, FL.).

Sims, D. W., Humphries, N. E., Bradford, R. W. and Bruce, B. D. (2012). Levy flight and brownian search patterns of white sharks in response to different prey fields. Journal of Animal Ecology 81: 432-442.

Skomal, G. B., J. Chisholm, and S. Correai. (2012). Implications of increasing pinniped populations on the diet and abundance of white sharks off the coast of Massachusetts. In Global perspectives on the biology and life history of the white shark. (Ed M. Domeier) pp. 405–418. (CRC Press, Boca Raton, FL.).

Sprivulis, P. C. (2014). Western Australia coastal shark bites: a risk assessment. Australasian Medical Journal. **7**: 137-142.

Strong, W. R., Murphy, R. C., Bruce, B.D., and Nelson, D.R. (1992). Movements and associated observations of bait-attracted white sharks, *Carcharodon carcharias*: a preliminary report. pp 13–20. *In:* Sharks: Biology and Fisheries. (Ed.). J. G. Pepperell. Australian Journal of Marine and Freshwater Research **43**: 349 pp.

Weng, K., and Honebrink, R. 2013. Occurrence of white sharks (*Carcharodon carcharias*) in Hawaiian waters. Journal of Marine Biology 2013: 7pp.

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.

West, J. G. (1993). The Australian Shark Attack File with notes on preliminary analysis of data from Australian waters. In Shark Conservation (Eds J. Pepperell, P. Woon and J. West) pp. 93-101. (Taronga Zoo, Sydney.).

West, J. G. (2011). Changing patterns of shark attacks in Australian waters. Marine and Freshwater Research **62**: 744–754.

Table 1. Summary of WA-located acoustic receiver arrays characteristics. Modifications to arrays' configuration are indicated by: [a] reduced to 17 in 2011; [b] reduced to 27 in 2015; [c] inshore section of cross-shelf array was moved from mainland-Rottnest Is. to mainland-Garden Is.-Rottnest Is. in February 2014; [d]5 receivers were installed in 2013-2014 before being removed and replaced by a partial cross-shelf line between Nov 2014 and April 2016.

Array	Configuration	Receivers	No.	Data collection period
IMOS Ningaloo	Cross-shelf (partial)	VR2W	42	Jan 2008 – Mar 2016
SMN Perth	Along-shore/gate	VR2W	19[a]	Jan 2009 – Feb 2016
	Location-specific	VR4G	19	Jan 2009 – May 2016
DoF snapper	Mixed (gate/cluster)	VR2W	52[b]	Jan 2009 – Feb 2016
OTN	Cross-shelf	VR2W	53[c]	Jan 2009 – Feb 2016
SMN SW/Albany	Location-specific	VR4G	6	Oct 2013 – May 2016
SMN Cape Leeuwin	Cross-shelf	VR2W	48	Apr 2012 – Jun 2015
SMN Chatham Is.	Cross-shelf	VR2W	44	Apr 2012 – Jun 2015
Two Peoples Bay	Along-shore	VR2W	6	Jul 2010 – Nov 2010
SMN Bald Is.	Cross-shelf	VR2W	33	Apr 2012 – Apr 2016
SMN Recherche	Cross-shelf (partial)	VR2W	17[c]	Feb 2013 – Apr 2016

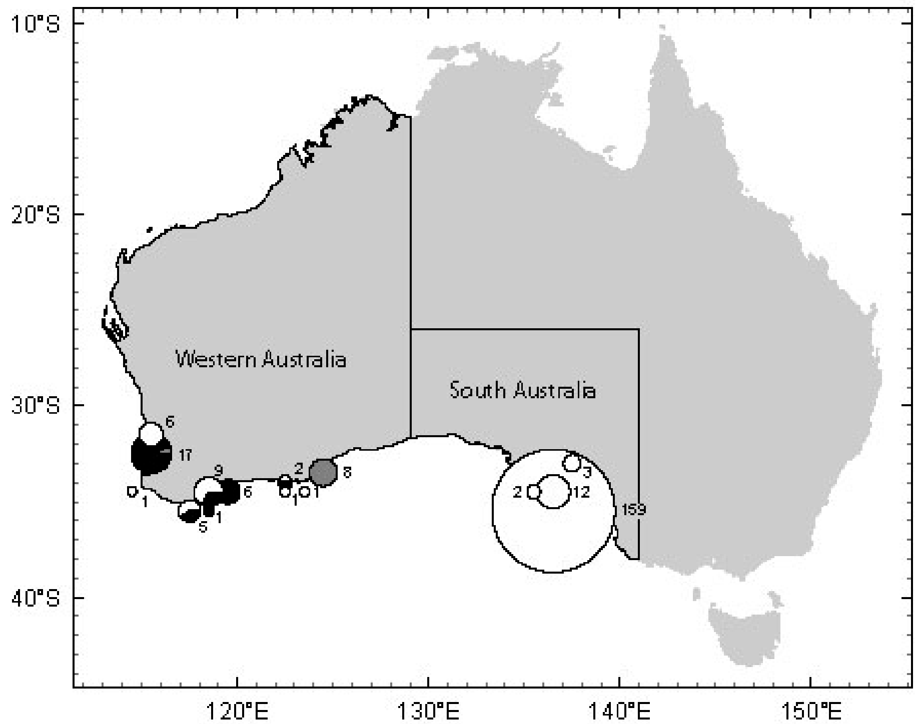

Figure 1. Spatial distribution of acoustic transmitters (tags) deployed on 234 *C. carcharias*, between December 2007 and December 2015. Pie charts illustrate the numbers of sharks tagged externally (white segments), internally (grey segments) and with dual internal and external transmitters (black segments) by 1 degree latitude and longitude blocks. Numbers indicate the total number of sharks tagged in each block.

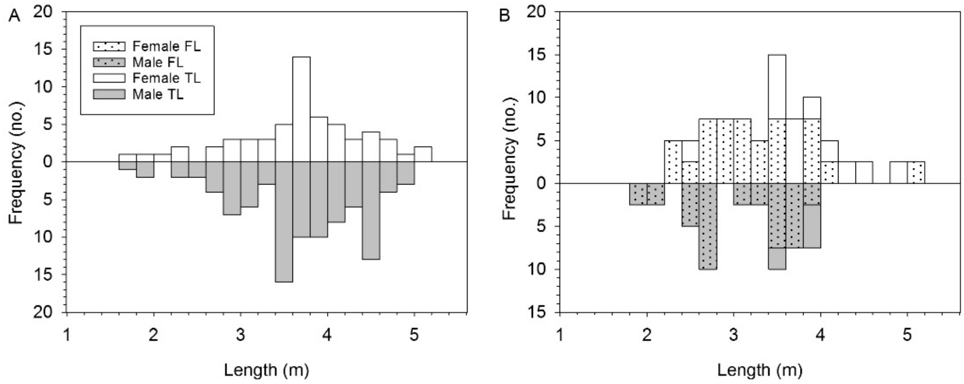

Figure 2. Size frequencies of *C. carcharias* tagged in (A) South Australia (n=156) and (B) Western Australia (n=54). Plain bars show estimated Total Lengths (TL) of externally-tagged sharks; dotted bars show measured Fork Lengths (FL) of internally-tagged sharks. N.B. size or sex was not recorded for 24 sharks.

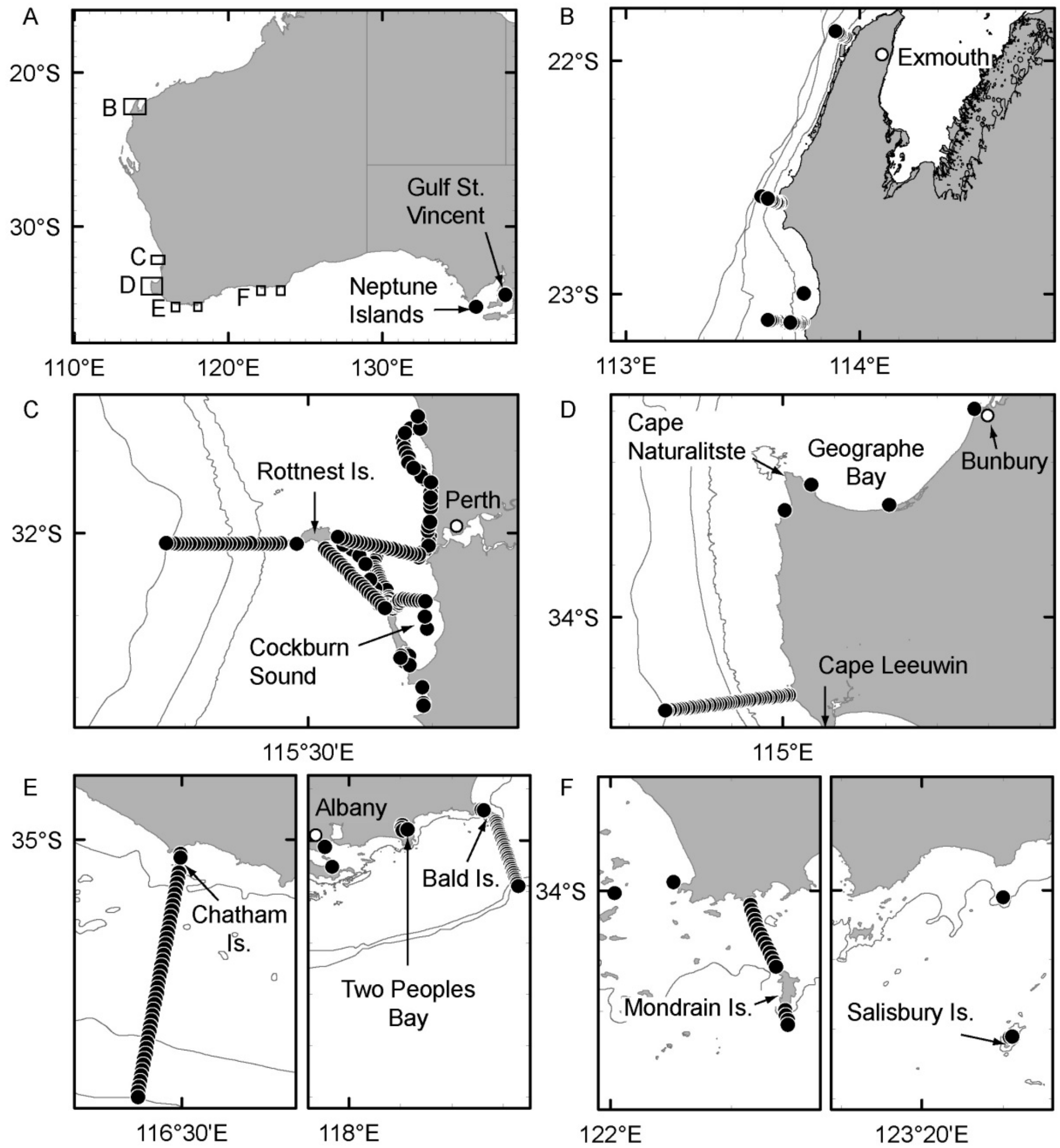

Figure 3. (A) Distribution of acoustic receiver arrays that provided data for this study and individual receiver locations (filled black circles) in the (B) IMOS Ningaloo array; (C) combined metropolitan Perth arrays; (D) South-West arrays; (E) Chatham Island (left panel) and Albany, Two Peoples Bay and Bald Island arrays (right panel) arrays and (F) Recherche Archipelago array. Locations include all permanent, temporary and re-located receiver stations between December 2008 and May 2016. Isobaths are shown at 50m, 100m and 200m intervals.

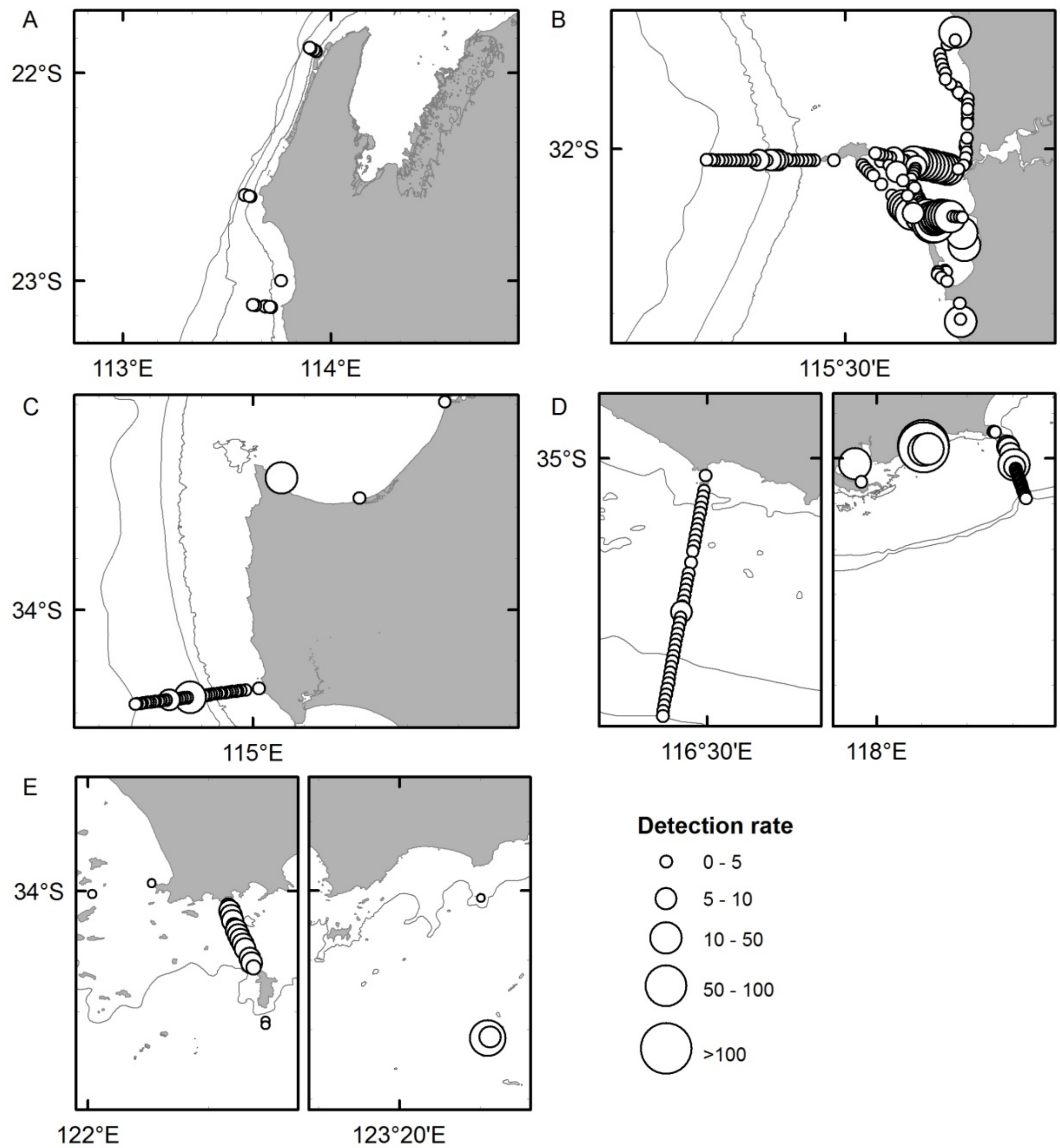

Figure 4. Individual receivers' detection rates (detections 100d^{-1}) of tagged *C. carcharias* in the (A) Ningaloo; (B) metropolitan Perth arrays; (C) South-West; (D) Chatham Island, Albany and (E) Recherche Archipelago regions. Isobaths are shown at 50m, 100m and 200m depths.

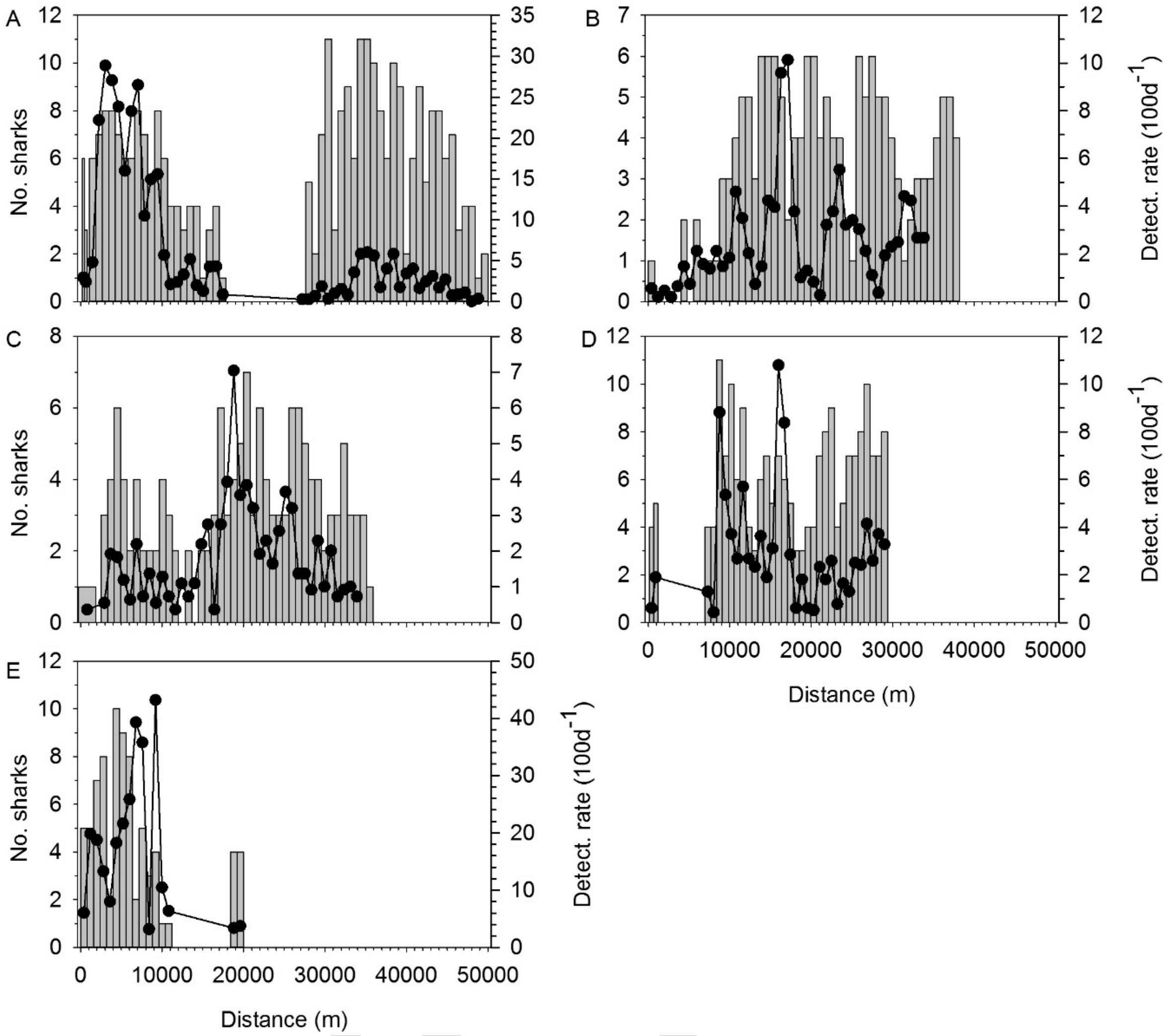

Figure 5. Frequency of tagged *C. carcharias* (grey bars) detected and tag detection rates (detections $100d^{-1}$; black line) by cross-shelf receiver arrays off (A) metropolitan Perth (Ocean Tracking Network); (B) Cape Leeuwin; (C) Chatham Island; (D) Bald Island and (E) Recherche Archipelago.

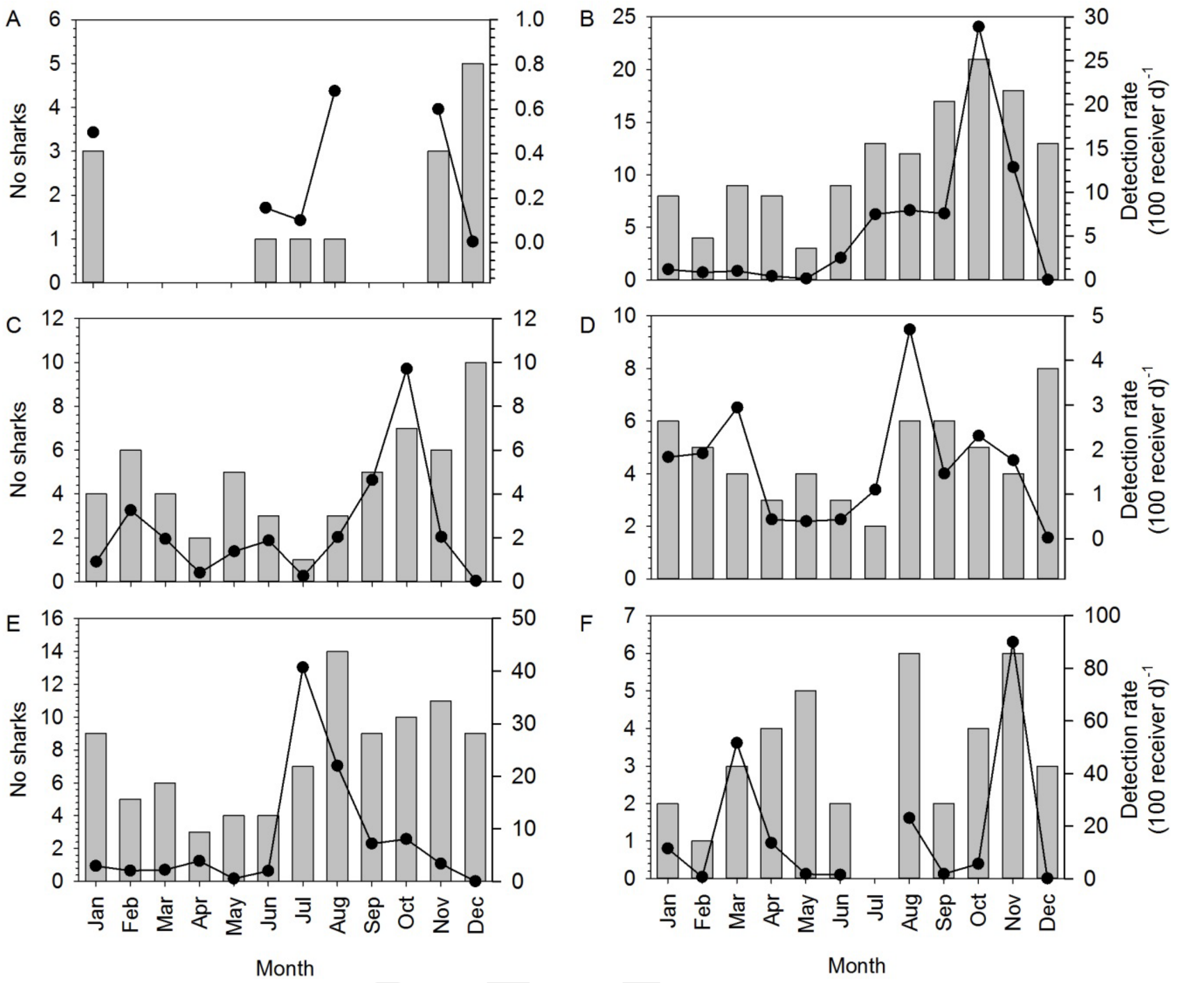

Figure 6. Monthly detections of tagged *C. carcharias.* Grey bars are the number of sharks detected (left axes) and black lines indicate the number of detections (right axes) by pooled calendar months in: (A) Ningaloo, (B) combined metropolitan, (C) South-West; (D) Chatham Island; (E) Albany and (F) Recherche Archipelago arrays.

Figure 7. Frequency distributions of estimated (A) movement distances (n=293) and (B) individual sharks' cumulative movement distances (n=73); (C) Rate of Movement (ROM) vs. distance and (D) frequency distribution of estimated ROM.

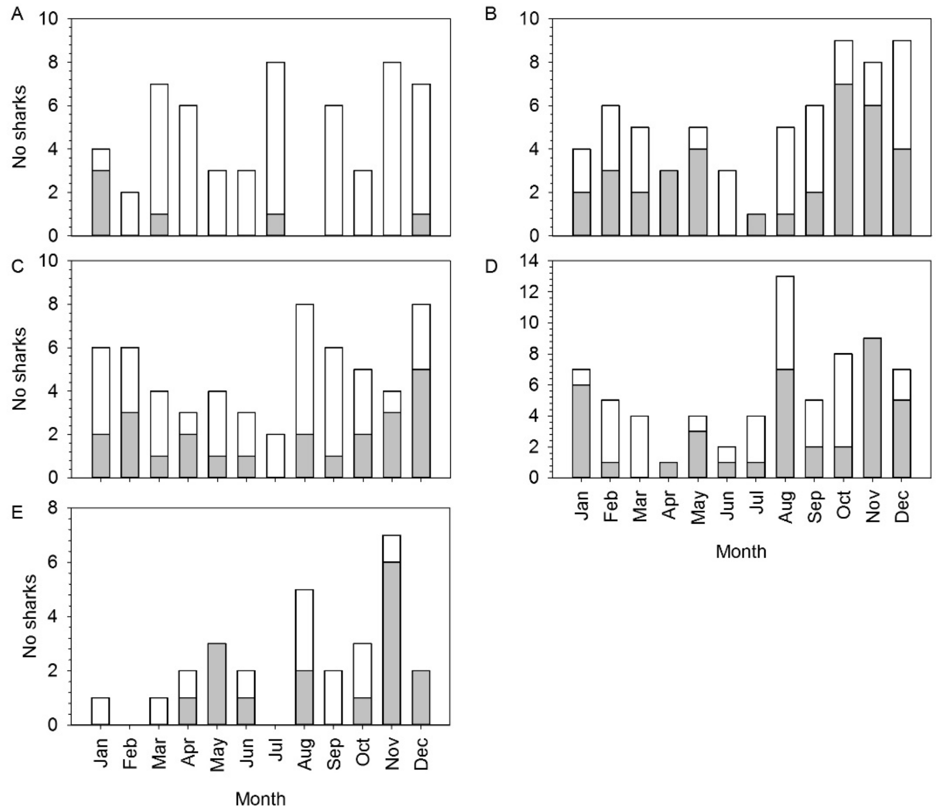

Figure 8. Pooled monthly movements of *C. carcharias* into the (A) metropolitan, (B) South-West; (C) Chatham Island; (D) Albany and (E) Recherche Archipelago regions. Grey bars indicate eastward/southward movements and white bars indicate westward/northward movements.