USING ACOUSTIC TELEMETRY MONITORING TECHNIQUES TO QUANTIFY MOVEMENT PATTERNS AND SITE FIDELITY OF SHARKS AND GIANT TREVALLY AROUND FRENCH FRIGATE SHOALS AND MIDWAY ATOLL

BY

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ABSTRACT

The Northwestern Hawaiian Islands (NWHI) host a variety of large vertebrate animals including seabirds, green sea turtles (*Chelonia mydas*), Hawaiian monk seals (*Monanchus schauislandi*), and large teleost fish such as trevally (Family Carangidae) and several species of sharks. The air-breathing vertebrates have been the subjects of relatively continuous and well-funded research programs over the past several decades, and many aspects of their biology in the NWHI have been documented fairly well. However, studies directed at understanding the biology and ecology of large teleost fishes and sharks in the NWHI have lagged substantially behind research conducted on birds, turtles and seals. In the summer of 2000, an array of autonomous acoustic receivers was deployed at French Frigate Shoals (FFS) in the NWHI as part of a project investigating the movement patterns of tiger sharks (*Galeocerdo cuvier*) within the atoll, particularly in relation to the high seasonal abundance of potential prey (birds, turtles, seals). Shortly after the establishment of the initial array of monitors in 2000, additional monitors were deployed in an effort to monitor the movements of Galapagos sharks (*Carcharhinus galapagensis*) at FFS, particularly at locations where monk seal pups had been preyed upon by these sharks. The scope of the monitoring study was further expanded to Midway Atoll during summer of 2001 to monitor movements of Galapagos sharks near seal haul-out beaches and to examine survivorship and behavior of giant trevally (*Caranx ignobilis*) captured and released in a commercial sport fishing operation conducted within the Midway National Wildlife Refuge. For each study, experimental animals were captured and surgically fitted with long-life, individually-coded acoustic transmitters. During nearly 4 years of acoustic monitoring at FFS and 2 years of monitoring at Midway, a total of over 45,000 detections of sharks and fish with transmitters were recorded on acoustic monitors. These data enable an assessment of long-term movement patterns of these large predators within the NWHI. Each species investigated demonstrated somewhat repeated and predictable behavioral patterns that provide a basis for improved understanding of determinants of behavior and for enhanced management of these animals and prey (birds, seals, turtles) with which they may interact.

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INTRODUCTION

The Northwestern Hawaiian Islands (NWHI) support a wide variety of large marine vertebrates and are a well known breeding grounds for seabirds, green sea turtles (*Chelonia mydas*), and the endangered Hawaiian monk seal (*Monanchus schauislandi*) (Gerrodette and Gilmartin, 1990; Gilmartin and Eberhardt, 1995). The nearshore waters surrounding these islands are also home to several species of large, predatory fishes and sharks. Concern over negative human impacts on NWHI seabird, sea turtle, and monk seal populations has resulted in substantial efforts to monitor and rebuild populations of these animals (Gilmartin and Eberhardt, 1995). Establishment of NWHI field camps and permanent field stations has enabled long-term studies of these populations, and many aspects of the behavior, feeding, reproduction, and population dynamics of these species have been characterized (Rice and Kenyon, 1962; Harrison et al., 1984; Gilmartin and Eberhardt, 1995).

Despite their abundance (Friedlander and DeMartini, 2002), importance in trophic interactions as apex predators (Polovina, 1984), and possible impact on protected and endangered species populations (Balazs and Whittow, 1979; Alcorn and Kam, 1986; Lowe et al., 1996), studies on the biology and ecology of the large predatory fishes (sharks and trevally) of the NWHI have lagged considerably behind those of seabirds, turtles and seals. Much of the research that has been conducted on large marine fishes in the NWHI has been limited to islands with sufficient infrastructure (i.e., field stations, small boats, and ready access) to support seasonal or short-term field work (French Frigate Shoals and Midway), or has been conducted from research ships briefly visiting various islands within the NWHI (Tricas et al., 1981; Sudekum et al., 1991). Because of their solely aquatic nature, these fishes cannot be observed, captured, or monitored as easily as air-breathing vertebrates that spend periods of time either on land or at the surface.

Standard techniques typically used to assess and monitor fish populations in other locations are not effective in the NWHI for several reasons: 1) the remoteness of the NWHI adds greatly to the cost of fieldwork and transportation to study sites and reduces the effectiveness of methods that rely typically on local recreational or commercial fisheries; 2) the limited availability of suitable boating facilities within the NWHI and the often difficult sea conditions severely restrict use of small boats that are needed to access these fishes; 3) there are extensive fishing restrictions within the boundaries of the NWHI and Midway Atoll National Wildlife Refuge because of potential interactions with endangered monk seals; and 4) diver surveys are limited to only daytime observations and are often biased because divers tend to attract some of the large predatory fishes and may repel others.

Because of the limitations of various fishery techniques, telemetry has become increasingly popular for remote monitoring of fish populations (Voegeli et al., 2001; Simpfendorfer et al., 2002; Heupel et al., 2004; Lowe and Bray, 2006). Acoustic telemetry monitoring utilizes autonomous receivers to continuously "listen" for the presence or absence of organisms fitted with uniquely coded transmitters, and to store these data for long periods of time. Placement of autonomous receivers along a coastline, in channels, or in arrays can allow for relatively long-term (>1 year) monitoring of movement patterns and fidelity to an area. Unlike conventional tag and recapture methods, acoustic monitoring allows for repeated "electronic" recaptures without the need for continuous fishing efforts and in some instances may be a more effective tool for monitoring population dynamics of species such as sharks and trevally that are difficult to study (Voegeli et al., 2001).

We used an array of autonomous acoustic receivers to monitor the movement patterns and site fidelity of tiger sharks (*Galeocerdo cuvier*), Galapagos sharks (*Carcharhinus galapagensis*), and giant trevally (*Caranx ignobilis*) around specific islands at FFS and Midway Atoll from 2000 to 2004. The objectives of this paper are to demonstrate whether these large predatory fishes show any affinity to islands containing common semi-terrestrial prey (i.e., seabirds, sea turtles, and monk seals) and to illustrate the utility of acoustic monitoring for studying the movement patterns of large fishes in remote locations over varying spatial scales.

METHODS

Study Sites

This study was conducted at two atolls within the NWHI: French Frigate Shoals (FFS) from 2000 to 2004, located midway along the Hawaiian Archipelago (23° 52.3' N latitude, 166° 14.4' W longitude); and Midway Atoll from 2001 to 2003, near the northwestern end of the chain (28° 15' N latitude, 177° 20' W longitude). At FFS, our base of operation was the U.S. Fish and Wildlife Service (USFWS) field station on Tern Island, and at Midway operations were conducted in cooperation with USFWS and Midway Phoenix Corporation from Sand Island.

Fishing and Tagging

Sharks were caught using handlines baited with dead birds or fish. Handlines were monitored continuously during all fishing efforts. Our fishing methods used large hooks (14/0) and large baits in order to target larger sharks, although several species of smaller sharks (gray reef sharks – *Carcharhinus amblyrhynchos* and whitetip reef sharks (*Triaenodon obesus*) were occasionally caught at FFS. All tiger and Galapagos sharks caught were brought along side of the 6-m boat, and a rope was placed around their tail. Once sharks were restrained, they were inverted and placed in tonic immobility, at which point each was measured, sexed, tagged with an external identification tag (M-capsule tags or spaghetti type dart tags) in the dorsal musculature, and fitted with a coded acoustic transmitter.

At FFS the majority of fishing for tiger sharks was conducted near the center of the atoll at East Island, whereas Galapagos sharks were targeted primarily at Trig Island, along the perimeter of the atoll (Fig. 3). During the final 2 years of operations at FFS, we were not permitted to fish within 800 m of Trig Island or to use chum in attempts to attract sharks to baited hooks. The same methods used to fish for Galapagos and tiger sharks at FFS were employed at Midway Atoll; however, giant trevally were caught via trolling or by dunking fresh bait from a boat.

Transmitters and Autonomous Acoustic Receivers

To determine longer-term site fidelity of sharks and trevally to islets at FFS and Midway, individuals were fitted with coded acoustic transmitters (V16-R256 random coded, 69.0 kHz, Vemco). Sharks caught on handlines were brought along side the boat and placed in tonic immobility (Fig. 1a, b). Coded transmitters were implanted surgically into the body cavity of sharks through a small incision (4 cm), and the wound was closed with 4-5 interrupted sutures. Transmitters were coated with a combination of beeswax (30%) and paraffin wax (70%) to reduce immune response (Holland et al., 1999). Each transmitter emitted a uniquely coded acoustic signal at random intervals between 40-70 seconds and had battery lives of up to 4 years.

Giant trevally were anaesthetized with MS-222 (0.2 g/L, 30 to 45 s immersion time), placed on a foam pad and measured (fork length (FL) in cm). A coded transmitter (V16-R256 random coded, 69.0 kHz) coated with beeswax/paraffin was implanted surgically into the body cavity of each fish (Fig. 1c). Before surgery the scalpel blade and transmitter were immersed in iodine solution, and the incision site was swabbed with iodine solution. A small (20 mm) incision was made through the peritoneal wall into the posterior region of the body cavity. This site was chosen to avoid damage to internal organs from transmitter insertion. The transmitter was inserted into the body cavity through the incision, which then was sutured closed. Each fish was also tagged externally with a serially numbered, 10-cm plastic dart identification tag (Hallprint, South Australia), resuscitated by towing or swimming it alongside the boat until fully responsive, and then released (Fig. 2).

An array of autonomous acoustic receivers (VR1 model, Vemco) was placed at locations around various islands within FFS and Midway. These receivers are designed to listen for coded transmitters and to record the date and time of arrival and departure of individual sharks and trevally. At FFS, 10 receivers were placed around Tern, Trig, Round, East, Shark, and Gin Islands at depths easily reached by free diving (average depth of monitors was 2.5 m below the surface) (Fig. 3a). At Midway, five receivers were placed adjacent to Sand and Eastern Islands, in the main boat channel and on the outer reef at a dive site named "Fish Hole" (Fig. 3b). USFWS personnel recovered three of these receivers in summer 2004, but were unable to relocate the receiver from Fish Hole.

All receivers were secured to the benthos using sand screws and swiveling stainless steel rods. Foam floats were used to buoy acoustic receivers and attachment gear (Fig. 4). This design was chosen to reduce the risk of monk seal entanglement in the equipment arrays. The majority of receivers remained in place for many years with this design, although several floats were lost, and all floats that were still attached to monitors showed evidence of shark bites.

Acoustic range of each receiver varied depending on water depth, tide, and neighboring reef structure. Range tests at several sites indicated transmitter detection ranges of up to 400 m; however, at most locations the range was on the order of 20-50 m due to shallow depth and proximity of a reef or an island. Receivers were downloaded every 4 to 7 months by the research team or by USFWS personnel.

Site Fidelity and Movement Analysis

Degree of site fidelity and extent of use of a particular area was determined by the amount of time a fish spent in proximity to a particular receiver and by the number of detections at each location. Annual catch rates (CPUE) and recapture rates were determined for each island. Extent of movement within the acoustic receiver array at all islands was determined by measuring the linear distance between the two most distant receivers where tagged sharks or giant trevally were detected.

RESULTS

French Frigate Shoals

Catch Data. During four summers (2000-2003) and one fall (2002), a total of 477 h were spent fishing at East and Trig Islands, with 190.5 h spent fishing around East Island. A total of 34 sharks were caught at FFS, including tiger, Galapagos, whitetip reef, and grey reef sharks. Of the 34 sharks caught, 4 Galapagos and 13 tiger sharks were fitted with coded acoustic transmitters (Table 1). With the exception of a few whitetip reef and gray reef sharks, only tiger sharks were caught at East Island, whereas many of the sharks caught and observed at Trig Island were Galapagos sharks. The CPUE for tiger sharks in all fishing at East Island was 0.052 sharks h^{-1}. In 2002 and 2003, very little time was spent fishing at East Island (7.5 h), and no tiger sharks were caught. In previous years, tiger sharks were frequently observed preying on fledging albatross chicks in the mornings, when the winds appeared to provide the best opportunities for the young birds to fly. In 2003, we sighted very few tiger sharks at East Island, although this trip was conducted during August, when nearly all albatross have fledged from East Island. No Galapagos sharks were seen or caught at East Island.

During 2002-2003, the majority of fishing effort was focused in the vicinity of Trig Island in an attempt to target Galapagos sharks. A total of 274 h was spent fishing near Trig Island. Although tiger sharks were rarely seen at Trig Island, over all years we caught one small, one medium and two large-sized tiger sharks (178, 259, 394, and 397 cm TL), three of which were captured in October of 2002 (Table 1). A total of four Galapagos sharks were also captured at Trig Island. CPUEs for tiger sharks and Galapagos were identical (0.015 sharks h^{-1}). Galapagos sharks were the most common large sharks observed at Trig Island; however, their occurrence appeared to vary widely on both a daily and annual basis.

The total fishing effort in all years of this study resulted in the capture, tagging, and instrumentation with transmitters of 13 tiger sharks and 4 Galapagos sharks. Ten gray reef sharks were also caught during this time period but were only tagged with standard identification tags, and none of the whitetip reefs sharks caught were tagged. All tiger sharks caught were females, of which ~70% appeared notably rotund and may have been pregnant. The average total length of tiger sharks caught was 350 ± 7 cm (± sd), and, based on available reproductive data, it is likely that all except two sharks were mature (Wetherbee et al., 1994). The four Galapagos sharks captured at Trig were relatively large and had an average total length of 248 ± 2 cm (Table 1).

Acoustic Monitoring. All of the 13 tiger sharks tagged at FFS were detected by acoustic receivers. Tiger sharks were detected a total of 38,886 times during the course of this project. Two tiger sharks (ID tag #005 and #011) were not detected on receivers until 26 and 11 months, respectively, following tagging and release. Of the nine tiger sharks tagged at East Island, all were detected at East Island as well as at islands other than East Island (Trig, Gin, Round, Shark, and Tern Island) throughout the year at FFS. Based on the number of acoustic detections (hits) recorded by different receivers, the amount of time sharks spent in proximity to certain islands varied considerably. A vast majority of the hits from tiger sharks were recorded in June and July at East Island, whereas tiger sharks spent proportionally more time around Tern Island in the winter months (Fig. 5). With the exception of the monitors at East Island, detections were usually brief, suggesting that sharks were passing through an area when detected. Tiger sharks also showed distinct temporal patterns of visits to the various islands, particularly at East Island, where they were typically detected during summer months in the mornings. One tiger shark (#005) tagged at East Island, FFS in July 2000 was detected by an array of acoustic receivers off the Kona coast (approx. 1,190 km straight-line distance) from January-March 2003. Another tiger shark (#008) tagged at East Island, FFS in July 2000 was detected by our array of acoustic receivers off Midway (approx. 1,280 km straight-line distance) from September-December 2002 (Table 1).

Of the four Galapagos sharks tagged, three were detected by acoustic receivers at FFS, yielding a total of 2,891 detections during the entire study. These sharks were detected primarily by monitors at Trig Island, followed by Tern Island, and only a few brief detections at Shark and East Islands. The occurrence of Galapagos sharks at Trig Island varied seasonally, with fewest detections recorded between February and July, and an elevated number of detections between August and January (Fig. 6). Detections at Tern Island, as well as Shark and East Islands, also were highest between September and February (Fig. 6). The number of detections at different times of day for all Galapagos sharks pooled indicated that these sharks visited Trig throughout the day, but more frequently at night. At other islands (Tern and Shark), Galapagos sharks also were detected more frequently during nighttime hours (Fig. 6).

Midway

Acoustic Monitoring. The Midway Atoll Galapagos shark data are skewed by VR1 receiver coverage due to difficulties in getting to Midway Atoll in order to download and rebattery receivers. The batteries in several VR1 receivers deployed in summer 2001 failed in May 2002 and were not replaced until September 2002. Only three of five VR1 receivers deployed in September 2002 were recovered successfully by USFWS personnel. The two VR1s that were lost (Fish Hole, Main Channel) were historically the receivers with the most Galapagos shark detections. The combination of these events meant that no data were available for the heavily utilized Fish Hole and Channel locations after May 2002.

Six Galapagos sharks were detected by the array of underwater receivers at Midway Atoll over periods ranging from 55 to 749 days (Table 2). Based on detections at receivers spread across the atoll, sharks were detected at receivers ranging from 1 to 9 km apart. The movements of all six sharks overlapped, with each individual being most frequently detected at the Fish Hole and Channel locations (Fig. 7). Five sharks showed a day-night habitat shift, with four individuals occupying channel and forereef habitats by day and venturing up onto the shallow reef flats at night. One Galapagos shark showed the reverse pattern (arriving in the channel only at night), while the remaining individual did not show any obvious diel periodicity in movements (Fig. 7).

During September 2002, four giant trevally ranging in size from 100 to 146 cm FL were captured using hook and line (trolling and dunking from a boat) at Midway Atoll (Table 3). Three of the four giant trevally tagged at Midway were detected by the array of underwater receivers at Midway Atoll over periods ranging from 280 to 374 days (Table 3). Two of these fish had previously been tagged and released by the Midway sport fishery. Based on detections at receivers spread across the atoll, giant trevally were detected at receivers ranging from 5 to 9 km apart. The movements of these three fish overlapped, even though they were captured at different locations up to 9 km apart. The one receiver located on the outside edge of the atoll was lost (Fish Hole – Fig. 2b), but the four remaining receivers each detected at least two giant trevally on multiple occasions over a 12-month period (Fig. 8). The diel pattern of detections varied among the giant trevally, with one fish (U2792) showing a day-night habitat shift during 2002, whereas the other two lacked obvious diel periodicity (Fig. 8). There was also some seasonal variation in frequency of giant trevally detections, with fewest detections occurring during the winter months (Fig. 9).

DISCUSSION

Acoustic monitoring proved to be an effective method for studying site fidelity and movement patterns of large marine fishes at French Frigate Shoals and Midway Atoll. This technology yielded tens of thousands of detections of transmitter-equipped animals, which provided new insight into both general patterns of behavior and distinct behavioral differences among individuals and among species of large fishes at these locations. For example, previous anecdotal observations of tiger sharks at French Frigate Shoals suggested that tiger sharks dramatically increase in abundance during summer and were perhaps only seasonal visitors to this atoll (Tricas et al., 1981; Lowe et al., 1996). However, acoustic monitoring data from 13 tagged tiger sharks indicated that at least 70% of these sharks exhibited some degree of year-round residence at FFS over a 3-year period. Although some tiger sharks were detected at islands within FFS during every month of the year, many were not detected for as long as 2-month intervals. While it is possible that these individuals could have traveled to neighboring atolls or shoals during these periods, it is also possible that they simply moved to other areas in or around the atoll where there was no receiver coverage. Some of the individuals tagged at FFS were detected by acoustic receivers at Midway and off the Kona coast (on the Island of Hawaii), indicating that individual tiger shark movements can encompass the entire Archipelago.

Even though tiger sharks were detected at FFS throughout the year, there was a strong seasonal trend in area use through the atoll, with tiger sharks spending more time around East Island in the summer months, but more time around the northern islands (Tern, Trig, and Shark Islands) in winter months. The one tiger shark tagged at Midway Atoll (#019) in July 2001 was detected near the flats off Eastern Island and near the cargo pier only during summer months.

A total of 38,886 detections were recorded from all receivers placed near six islands at FFS. The estimated total acoustic detection area of all 10 acoustic receivers was approximately 0.031 km^2, which accounts for less than 0.004% of the shallow lagoon habitat at FFS. Considering the vast area of available habitat for tiger sharks at FFS and the small detection areas of acoustic receivers in these shallow reef areas, the high numbers of detections clearly indicate that tiger sharks regularly visit these islands, in response to concentration of important prey items at particular islands during summer months.

Compared to tiger sharks, there is a much smaller amount of data available for analysis of movement patterns of Galapagos sharks at FFS. Furthermore, the presence of these sharks at Trig Island varied within the diel cycle, within annual cycles, and among individual sharks. Although only four adult Galapagos sharks were caught and tagged at FFS, acoustic receiver data and visual observations by many researchers at FFS suggest that Galapagos sharks are most common at islands close to the outer reef of FFS (i.e., Tern, Trig, and Shark) and are not frequent visitors to the interior of the atoll. This contention is supported by previous studies which indicate that Galapagos sharks are typically found along outer reef drop-offs (DeCrosta et al., 1984; Wetherbee et al., 1996). Galapagos sharks were the most common species of large shark observed at Trig Island, possibly attracted by the recent increase in seasonal monk seal pupping at this site. Adult Galapagos sharks have been observed cruising very close to the shore (< 2 m) and occasionally preying on pre-weaned monk seal pups at this location (Baker and Johanos, 2004). Acoustic monitoring indicated high variability in Galapagos shark activity at Trig Island, but these data were primarily derived from only two individuals that each showed different patterns of activity around Trig. One shark was most commonly detected in the late afternoon during summer months, whereas the other was most commonly at Trig during early morning hours in winter. Clearly, more research is required to understand the behavior of adult Galapagos sharks at Trig Island, and to provide sufficient data for assessing the potential success of using shark culling to reduce seal predation. Nevertheless, it appears that Galapagos sharks do not exhibit the same island visitation patterns as tiger sharks.

The Galapagos sharks tagged at Midway exhibited different movement patterns from those tagged at FFS; however, this may be attributed to differences in size/age of sharks tracked. The lagoon and main channel at Midway contained large numbers of juvenile Galapagos sharks, which were not observed or caught at FFS. The juvenile Galapagos sharks at Midway tended to use the channel areas or forereef during the day, but would venture onto flats inside the atoll at night, and some of these small sharks moved at least 10 km between acoustic receivers. Considering the arbitrary positioning and limited number of acoustic receivers throughout the atoll, the number of detections and individual sharks detected suggest that these young Galapagos sharks move extensively throughout the lagoon habitat at Midway. The differences in Galapagos shark movements and habitat use at FFS and Midway may be related to the different size of sharks. For example, in some locations Galapagos sharks use shallow lagoons as nursery grounds (Kato and Carvallo, 1967) and in the Main Hawaiian Islands Galapagos sharks segregate by size and sex, but do not appear to use lagoon nurseries (Wetherbee et al., 1996).

Three of the four giant trevally equipped with acoustic transmitters at Midway Atoll were detected by four acoustic receivers spread across the southern portion of the atoll. Only one of the three giant trevally detected at Midway showed any diel pattern of area use; however, all three were found to span at least 10 km between the most distant receivers. Interestingly, the one trevally that exhibited a diel pattern of habitat use (U2792) exhibited that behavior only for the first few months. Fish were typically detected on the flats by Eastern Island or Frigate Point at night, sometimes for many hours. These observations suggest high plasticity in behavior. Other fish have been shown to exhibit diel-habitat shifts, including bluefin trevally (*Caranx melampygus*) and juvenile giant trevally in the Main Hawaiian Islands (Holland et al., 1996; Wetherbee et al., 2004; Meyer and Honebrink, 2005). Two of the giant trevally detected at Midway were most common during summer and fall months, but decreased substantially in the winter months. It is unclear whether these fish left the atoll during winter or moved to locations at Midway that lacked receiver coverage. This sort of seasonal shift in habitat use has not been seen in younger size classes studied in the Main Hawaiian Islands (Wetherbee et al., 2004). Nevertheless, seasonal differences in water temperature between the Main Hawaiian Islands and Midway may explain these possible seasonal area use patterns observed among the few giant trevally monitored.

We demonstrate that acoustic monitoring can provide an effective method for assessing long-term site fidelity and behavior of large fishes in remote areas. Obviously, more detailed information about movement patterns and habitat use could have been obtained if there were a greater number of receivers spread throughout each atoll; however, the main focus of the studies at FFS and Midway was to examine shark and trevally affinity to islands that hold large numbers of semi-terrestrial prey. Extensive fishing, tag and recapture, and visual observations conducted continuously over many years would have been required to answer this question, resulting in a much higher cost and impact to the environment. While acoustic monitoring provides a far less labor-intensive method for measuring site fidelity and movement patterns of large fishes in remote areas, it still requires a certain degree of maintenance to ensure successful retrieval of data. Autonomous acoustic receivers must be periodically downloaded, and batteries must be replaced. Securing ground tackle also needs to be maintained annually, particularly in areas exposed to high surf. Although this maintenance does not take long and can be done by small crews, the remoteness of the NWHI makes regular array maintenance challenging, as was seen at Midway Atoll where we were unable to place personnel to regularly maintain receivers. This resulted in loss of data and a receiver. In addition, autonomous acoustic receivers have the capacity to record and store large amounts of data, which, over time, requires extensive database management.

With a moderate fishing effort, hundreds of large marine apex predators (fishes, sharks, seals, and turtles) could be tagged, and acoustic receivers could be placed strategically around each of the major islands and shoals throughout the NWHI to assess long-term site fidelity, dispersal potential, and even species interactions. Receiver arrays can be maintained quickly and easily with moderate ship support. In fact, the newest form of autonomous acoustic receiver (VR3, Vemco Ltd.) now incorporates a tethered surface transmitter that can relay stored data to a satellite or via acoustic modem to a ship, eliminating the need to retrieve and manually download the receivers. Because of the logistical challenges of access to the NWHI, potential conflicts with endangered species, and difficulty in studying large marine fishes, acoustic monitoring coupled with satellite telemetry may provide the most cost-effective, environmentally sound means of studying the apex predators of the NWHI.

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Table 1. Summary of acoustic monitoring data for transmitter-equipped tiger and Galapagos sharks captured at French Frigate Shoals.

Species	ID Tag Number	Length (cm)			Sex	Date Deployed	Date First Detected	Date Last Detected	Days Between Deployment & First Detection	Overall Detection Period (days)	Max. Distance Spanned (km)
		PCL	FL	TL							
G. cuvier	002	255	284	330	F	25-Jun-00	30-Jun-00	16-Apr-03	5	1020	20
G. cuvier	001	294	320	389	F	27-Jun-00	18-Aug-00	27-Nov-02	52	831	12
G. cuvier	003	237	260	316	F	3-Jul-00	3-Jul-00	20-Dec-01	0	535	22
G. cuvier	004	127	138	178	F	10-Jul-00	6-Aug-00	10-Jan-04	27	1252	20
G. cuvier	005	320	354	392	F	11-Jul-00	11-Jul-00	19-Sep-02	0	989	1190
G. cuvier	007	295	318	372	F	11-Jul-00	22-Jul-00	28-Nov-03	11	1224	20
G. cuvier	008	302	333	364	F	12-Jul-00	12-Jul-00	26-Dec-02	0	897	1280
G. cuvier	009	301	328	392	F	19-Jun-01	25-Jun-01	16-Sep-03	6	813	18
G. cuvier	011	325	353	422	F	21-Jun-01	22-Jun-01	18-Nov-03	1	879	13
G. cuvier	001F	280	303	342	F	30-Jun-01	30-Jun-01	28-Dec-01	0	181	22
G. cuvier	006F	192	215	259	F	26-Oct-02	9-Nov-02	10-Jan-04	14	427	22
G. cuvier	305	306	334	394	F	28-Oct-02	17-Dec-02	22-Apr-03	50	126	20
G. cuvier	304	310	339	397	F	29-Oct-02	5-Nov-02	28-Nov-03	7	388	20
C. galapagensis	025	204	227	250	F	3-Jul-00	6-Aug-00	23-Oct-00	34	78	5
C. galapagensis	026	193	212	244	M	18-Jun-01	24-Jun-01	24-Jun-01	6	0	-
C. galapagensis	028	165	182	225	F	1-Jul-01	10-Jul-01	20-Oct-02	9	467	8
C. galapagensis	031	208	231	272	F	10-Jun-02	16-Jun-02	12-Feb-03	6	241	14

Table 2. Summary of acoustic monitoring data for transmitter-equipped Galapagos and tiger sharks captured at Midway Atoll.

Species	ID Tag Number	Length (cm)			Sex	Date Deployed	Date First Detected	Date Last Detected	Days Between Deployment & First Detection	Overall Detection Period (days)	Max. Distance Spanned (km)
		PCL	FL	TL							
G. cuvier	306	390	318	294	M	27-Jul-01	12-Aug-01	1-Sep-03	16	750	9
C. galapagensis	299	118	96	89	M	24-Jul-01	4-Aug-01	23-Aug-03	11	749	9
C. galapagensis	300	157	131	120	F	24-Jul-01	1-Aug-01	16-Apr-03	8	623	5
C. galapagensis	301	114	100	91	M	25-Jul-01	15-Nov-01	24-Jun-03	113	586	1
C. galapagensis	302	130	105	96	F	26-Jul-01	3-Aug-01	27-Sep-01	8	55	5
C. galapagensis	303	122	100	90	M	26-Jul-01	22-Aug-01	26-May-02	27	277	5
C. galapagensis	307	135	118	105	F	27-Jul-01	1-Aug-01	18-Oct-01	5	78	1

Table 3. Summary of acoustic monitoring data for four transmitter-equipped giant trevally (*Caranx ignobilis*) captured at Midway Atoll.

Species	ID Tag Number	Fork Length (cm)	Date Deployed	Date First Detected	Date Last Detected	Days Between Deployment & First Detection	Overall Detection Period (days)	Max. Distance Spanned (km)
C. ignobilis	U2795	100	8-Sep-02	20-Sep-02	27-Jun-03	12	280	5
C. ignobilis	U2793	116	8-Sep-02	Not Detected	-	-	-	-
C. ignobilis	U2791^{+}	109	10-Sep-02	13-Sep-02	5-Sep-03	3	357	9
C. ignobilis	U2792*	146	10-Sep-02	11-Sep-02	20-Sep-03	1	374	9

*Recapture (original tag # 0148)

$^{+}$Recapture (original tag # MAO 495)

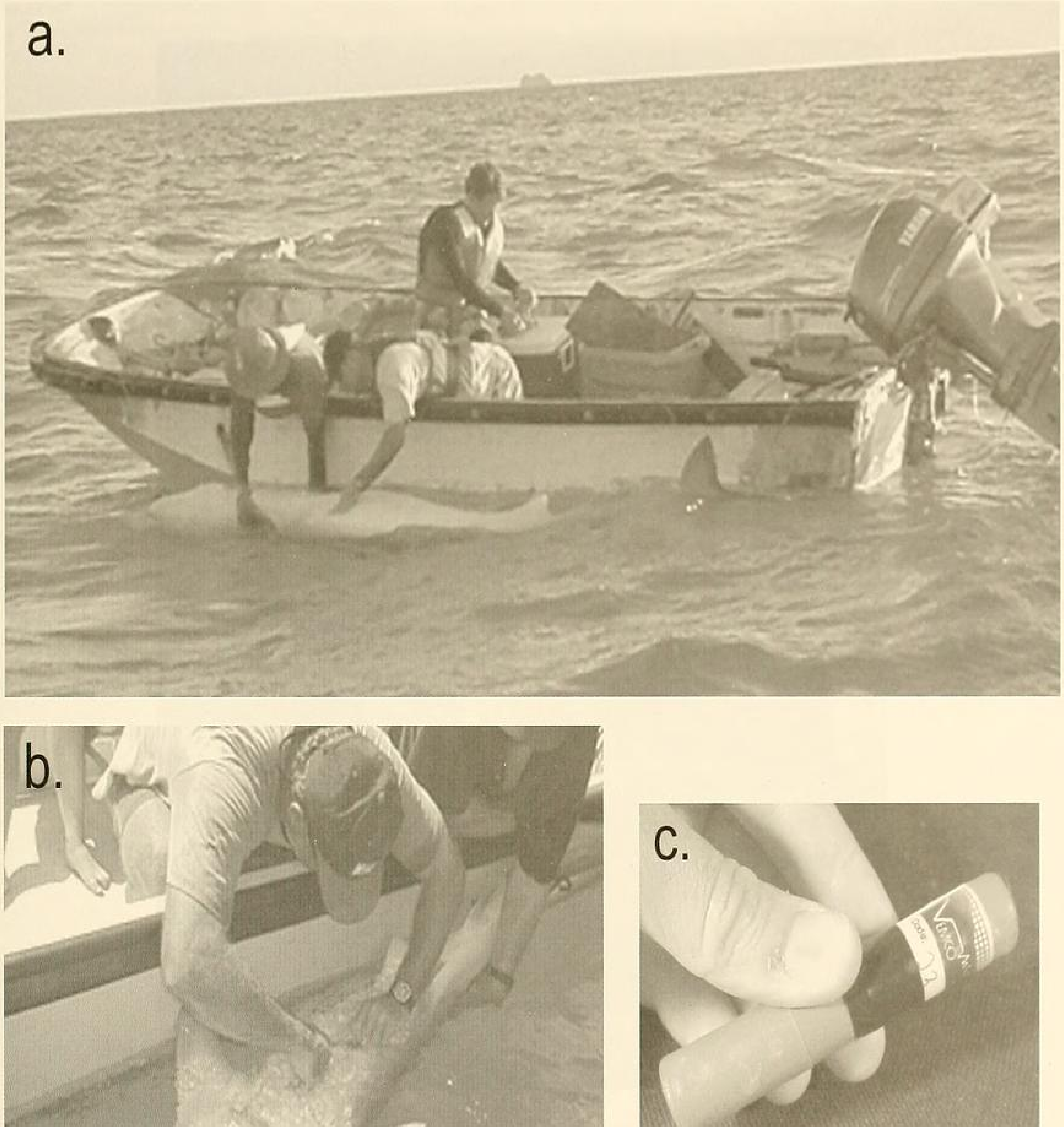

Figure 1 a. A 4 m tiger shark in tonic immobility along side a 5.2m Boston Whaler. La Perouse in the background. b. Field surgery on a 2.5 m tiger shark at Trig Island. c. A Vemco model V16 coded acoustic transmitter.

Figure 2. Surgical implantation of a V16 coded acoustic transmitter in an anaesthetized 1.3 m giant trevally.

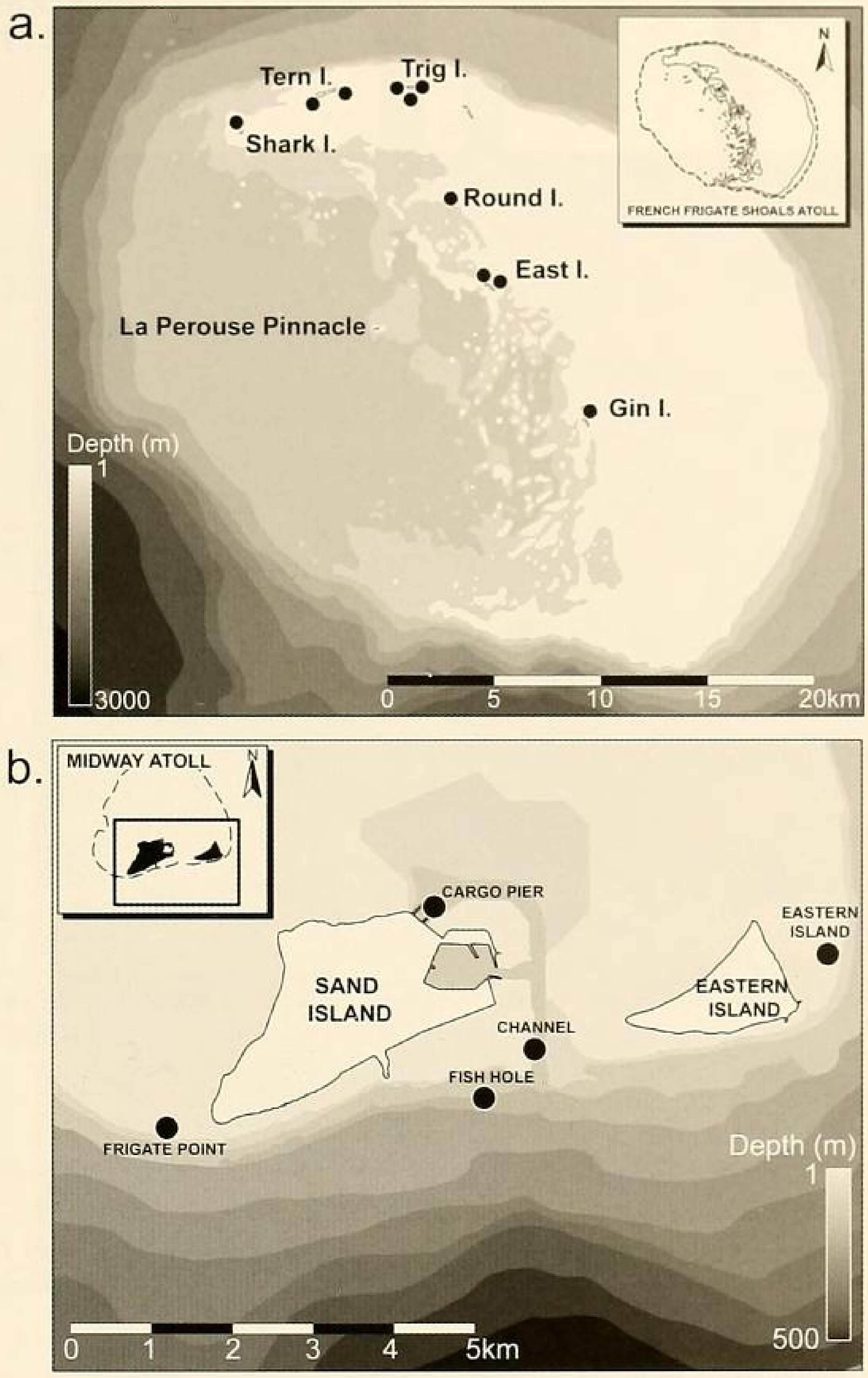

Figure 3 a. Location of automated acoustic receivers (VR1, Vemco Ltd.) (solid circles) at French Frigate Shoals. b. Locations of automated acoustic receivers (solid circles) at Midway Atoll.

Figure 4. Diver with a VR1 autonomous acoustic receiver anchored to the seafloor with sand screws.

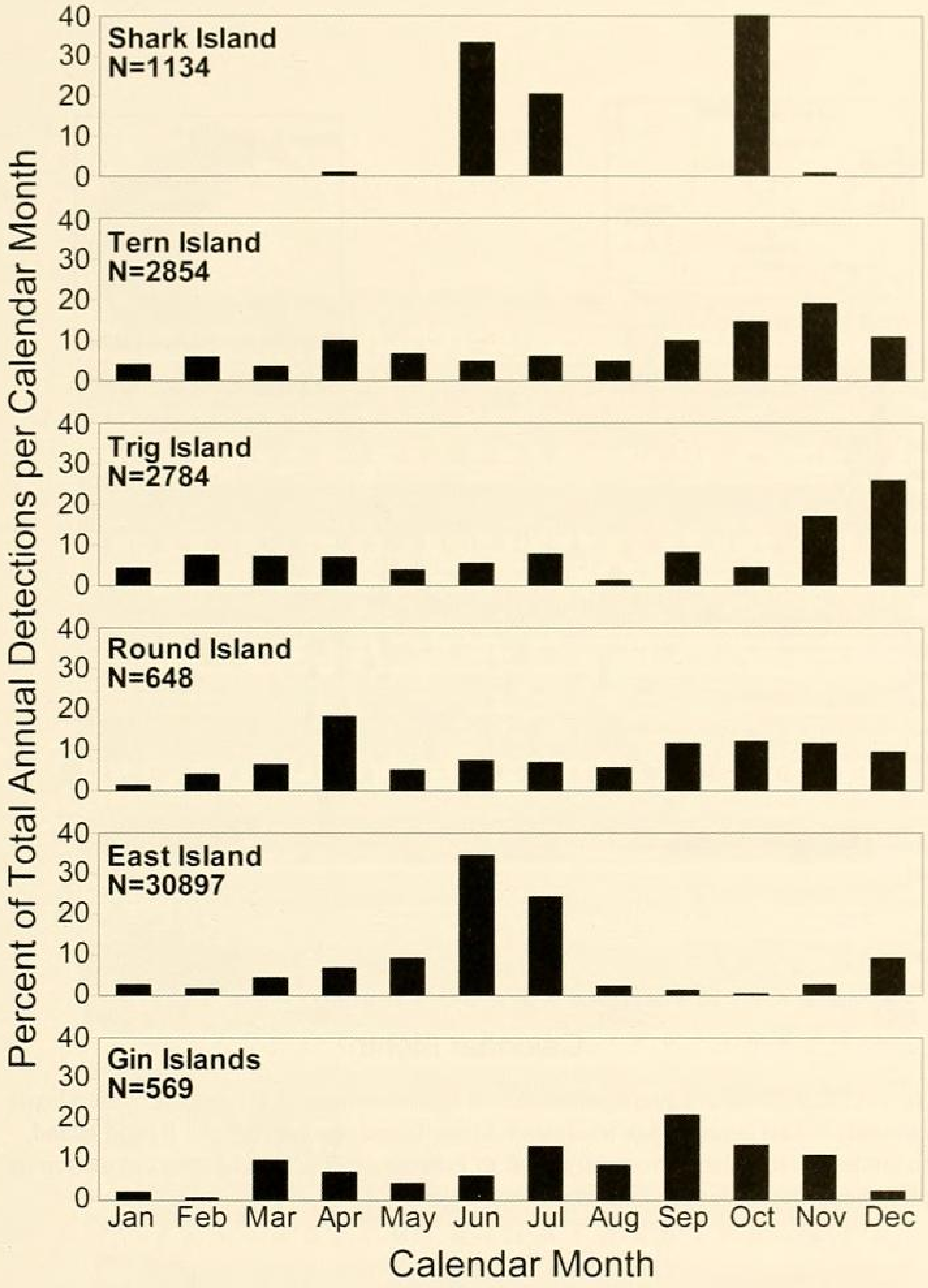

Figure 5. Percentage of all acoustic detections for all tiger sharks per month tagged at French Frigate Shoals at each island.

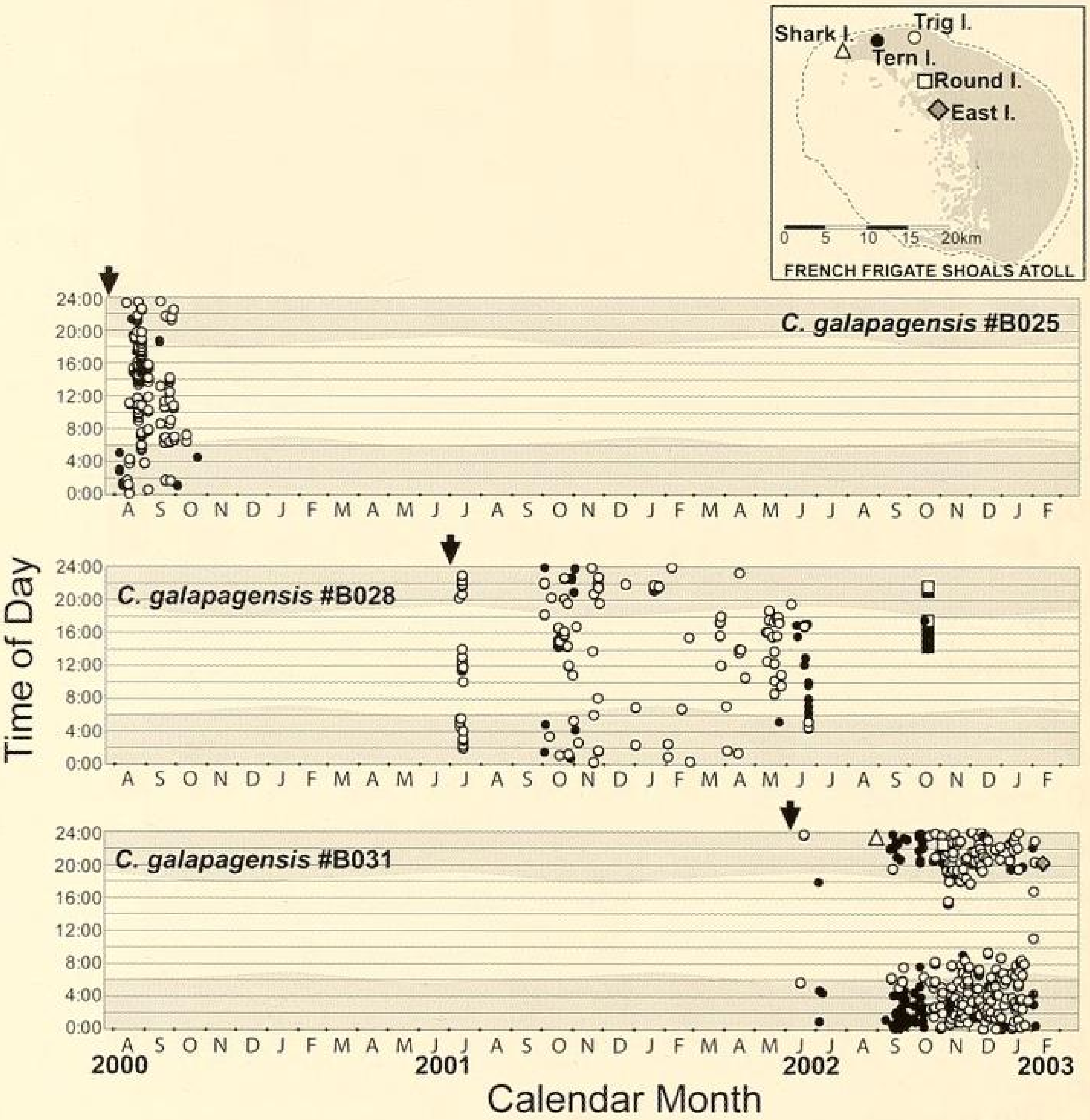

Figure 6. Diel detections of Galapagos sharks on receivers located at French Frigate Shoals (grey diamonds = East Island, open triangles = Shark Island, open squares = Round Island, and open circles = Trig Island) from July 2000 to February 2003. Black arrows at the top of the graph indicate the date when each shark was tagged.

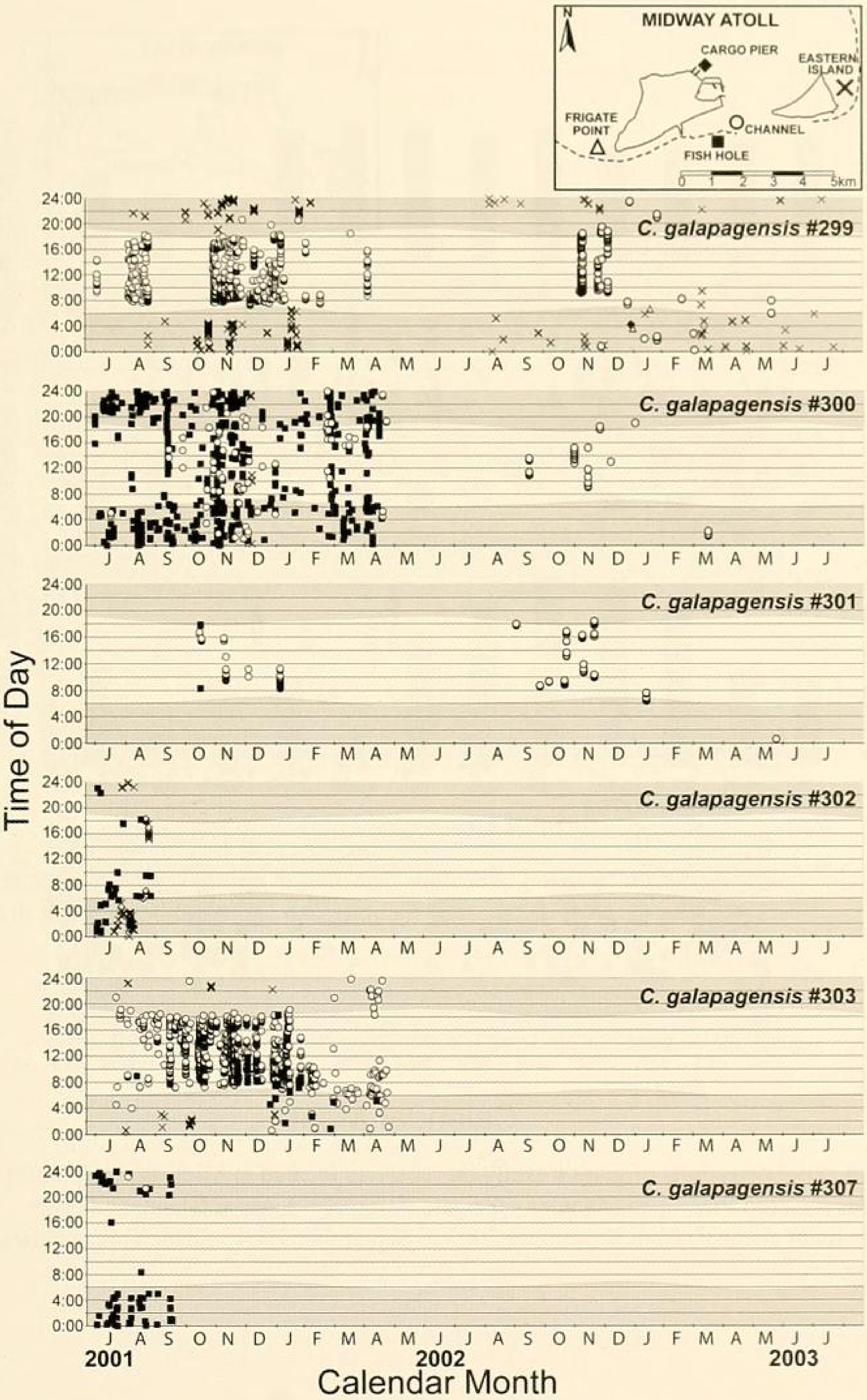

Figure 7. Diel detections of six Galapagos sharks on receivers located at Midway Atoll (solid diamonds = Cargo Pier, open triangles = Frigate Point, X = Eastern Island, and open circles = main channel) from July 2001 to September 2004.

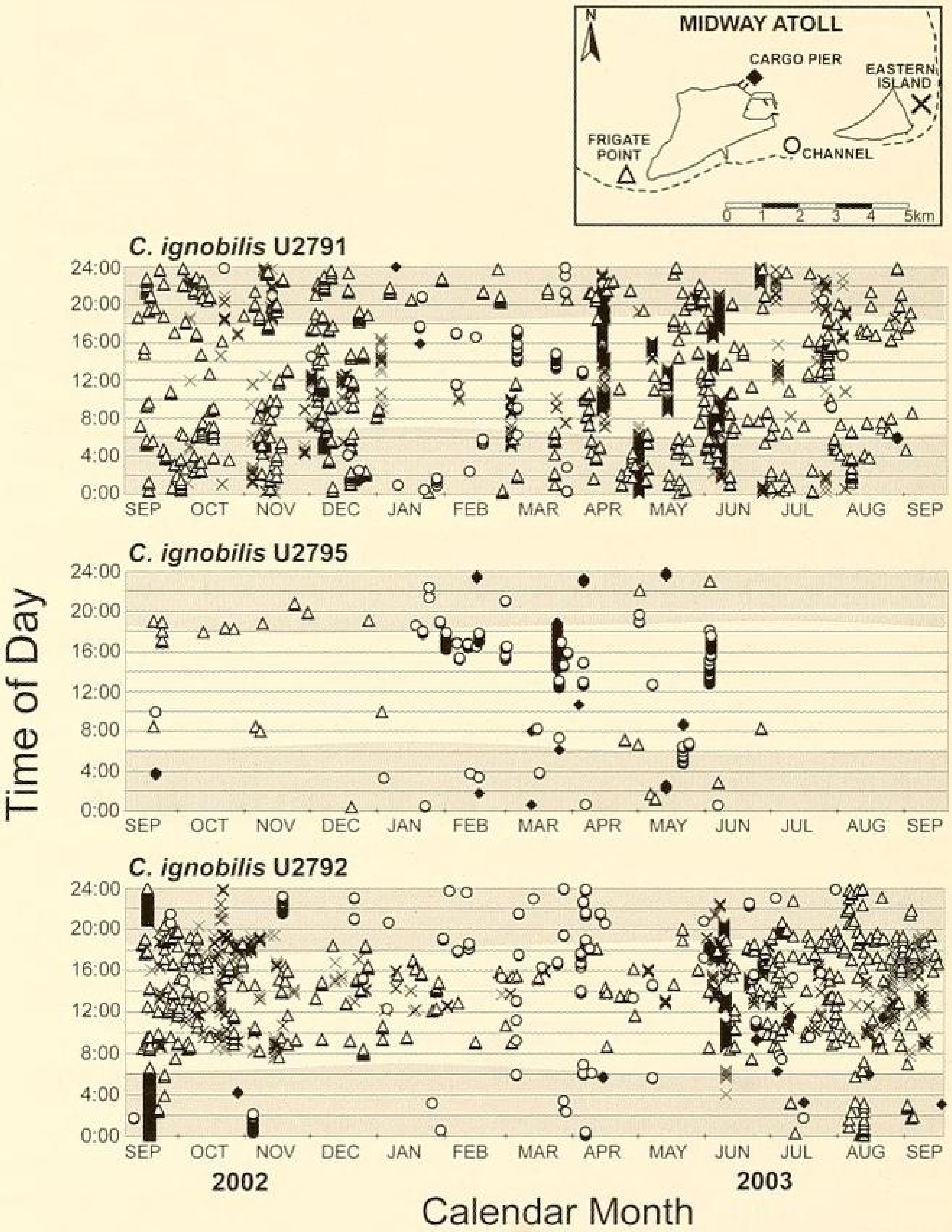

Figure 8. Diel detections of giant trevally on receivers located at Midway Atoll (solid diamonds = Cargo Pier, open triangles = Frigate Point, X = Eastern Island, and open circles = main channel) from September 2003 to September 2004. Shaded areas indicate nighttime.

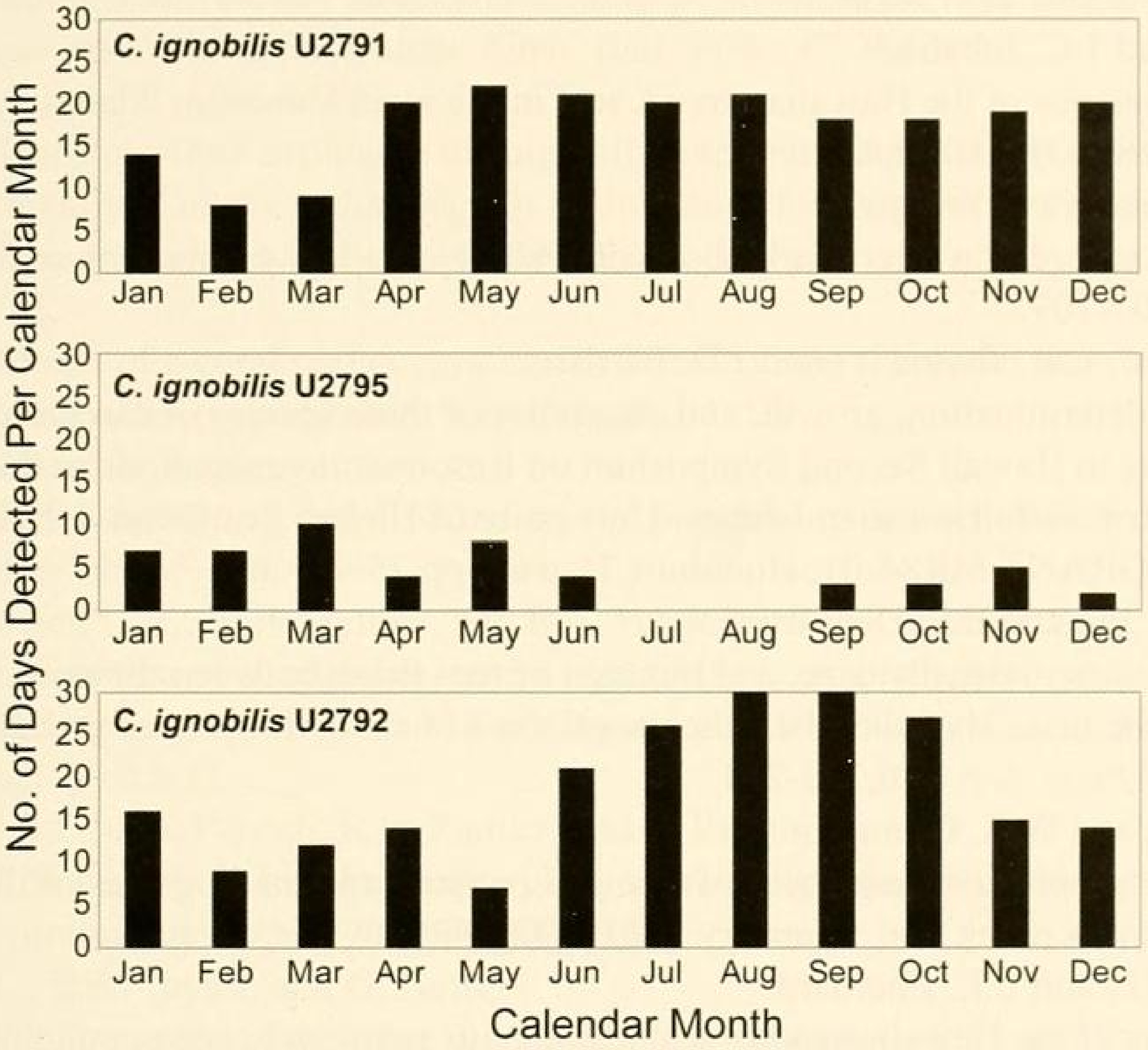

Figure 9. Seasonal variation in giant trevally detections at Midway Atoll, September 2002 to September 2003.

LITERATURE CITED

Alcorn, D.J., and A.K.H. Kam

1986. Fatal shark attack on a Hawaiian monk seal (*Monachus schauinslandi*). *Mar. Mamm. Sci.* 2:313-315.

Baker, J.D., and T.C. Johanos

2004. Abundance of the Hawaiian monk seal in the main Hawaiian Islands. *Biol. Conserv*. 116:103-110.

Balazs, G.H., and G.C. Whittow

1979. First record of a tiger shark observed feeding on a Hawaiian monk seal. *Elepaio* 39:107-109.

DeCrosta, M.A., L.R. Taylor Jr., and J.D. Parrish

1984. Age determination, growth, and energetics of three species of carcharhinid sharks in Hawaii Second Symposium on Resource Investigations of the Northwestern Hawaiian Islands. University of Hawaii Sea Grant, UNIHI-SEAGRANT-MR84-01, Honolulu, Hawaii, pp 75-95.

Friedlander, A.M., and E.E. DeMartini

2002. Contrasts in density, size, and biomass of reef fishes between the northwestern and the main Hawaiian Islands: the effects of fishing down apex predators. *Mar. Ecol. Prog. Ser*. 230:253-264.

Gerrodette, T., and W.G. Gilmartin

1990. Demographic consequences of changed pupping and hauling sites of the Hawaiian monk seal. *Conserv. Biol*. 4:423-430.

Gilmartin, W.G., and L.L. Eberhardt

1995. Status of the Hawaiian monk seal (*Monachus schauinslandi*) population. *Can. J. Zool.* 73:1185-1190.

Harrison, C.S., M.B. Naughton, and S.I. Fefer

1984. The status and conservation of seabirds in the Hawaiian Archipelago and Johnston Atoll. *In*: Croxall, J.P., P.G.H. Evans, R.W. Schreiber (eds.). *Status and conservation of the World's seabirds*. ICBP, Cambridge, U.K., pp 513-526.

Heupel, M.R., C.A. Simpfendorfer, and R.E. Hueter

2004. Estimation of shark home ranges using passive monitoring techniques. *Envir. Biol. Fish*. 71:135-142.

Holland, K.N., C.G. Lowe, and B.M. Wetherbee

1996. Movements and dispersal patterns of blue trevally (*Caranx melampygus*) in a fisheries conservation zone. *Fish. Res*. 25:279-292.

Holland, K.N., B.M. Wetherbee, C.G. Lowe, and C.G. Meyers

1999. Movements of tiger sharks (*Galeocerdo cuvier*) in coastal Hawaiian waters. *Mar. Biol*. 134:665-673.

Kato, S., and A.H. Carvallo

1967. Shark tagging in the eastern tropical Pacific Ocean, 1962-1965. *In*: Gilbert, P.W., R.F. Mathewson, J.P. Rall (eds.). *Sharks, skates, and rays*. Johns Hopkins Press, Baltimore, pp 93-109.

Lowe, C.G., and R.N. Bray
2006. Fish movement and activity patterns. *In*: Allen, L., D.P. Pondella, and M. Horn (eds.). *Ecology of California Fishes*. University of California Press, Berkeley.

Lowe, C.G., B.M. Wetherbee, G.L. Crow, and A.L. Tester
1996. Ontogenetic dietary shifts and feeding behavior of the tiger shark, *Galeocerdo cuvier*, in Hawaiian waters. *Envir. Biol. Fish.* 47:203-211.

Meyer, C.G., and R. Honebrink
2005. Transintestinal expulsion of surgically implanted dummy transmitters by bluefin trevally (*Caranx melampygus*): Implications for long-term movement studies. *Trans. Amer. Fish. Soc.* 134:602-606.

Polovina, J.J.
1984. Model of a coral reef ecosystem. I. The ECO-PATH model and its application to French Frigate Shoals. *Coral Reefs* 3:1-11.

Rice, D.W., and K.W. Kenyon
1962. Breeding history and distribution and populations of north Pacific albatrosses. *Auk* 79:365-386.

Simpfendorfer, C.A., M.R. Heupel, and R.E. Hueter
2002. Estimation of short-term centers of activity from an array of omnidirectional hydrophones and its use in studying animal movements. *Can. J. Fish. Aquatic Sci.* 59:23-32.

Sudekum, A.E., J.D. Parrish, R.L. Radtke, and S. Ralston
1991. Life history and ecology of large jacks in undisturbed, shallow, oceanic communities. *Fish. Bull.* 89:493-513.

Tricas, T.C., L.R. Taylor, and G. Naftel
1981. Diel behavior of the tiger sharks, *Galeocerdo cuvier*, at French Frigate Shoals, Hawaiian Islands. *Copeia* 1981:904-908.

Voegeli, F.A., M.J. Smale, D.M. Webber, Y. Andrade, and R.K. O' Dor
2001. Ultrasonic telemetry, tracking and automated monitoring technology for sharks. *Envir. Biol. Fish.* 60:267-281.

Wetherbee, B.M., G.L. Crow, and C.G. Lowe
1996. Biology of the Galapagos shark, *Carcharhinus galapagensis*, in Hawaii. *Envir Biol. Fish.* 45:299-310.

Wetherbee, B.M., K.N. Holland, C.G. Meyer, and C.G. Lowe
2004. Use of a marine reserve in Kaneohe Bay, Hawaii by the giant trevally, *Caranx ignobilis*. *Fish. Res.* 67:253-263.

Wetherbee, B.M., C.G. Lowe, and G.L. Crow
1994. A review of shark control in Hawaii with recommendations for future research. *Pac. Sci.* 48:95-115.