# Behaviour of Tuna associated with Drifting Fish Aggregating Devices (FADs) in the Mozambique Channel

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**Abstract**

To study the behaviour of yellowfin (*Thunnus albacores*), skipjack (*Katsuwonus pelamis*) and bigeye tuna (*Thunnus obesus*) around Drifting Fish Aggregating Devices (DFADs), we tagged individuals with long-lived, coded sonic transmitters and attached automated sonic receivers to DFADs in the Mozambique Chanel, Western Indian Ocean. Two different methods were used to estimate residency times of tunas associated with DFADs; the continuous residence time (CRT) and fine-scale residence time (FCRT). The median CRTs of yellowfin, skipjack and bigeye tuna were 9.98, 4.47 and 3.89 days respectively with no inter-specific differences observed. However, for all species combined the median CRTs at DFAD34 were significantly higher than those at DFAD31, indicating that the tunas were more resident at DFAD34. In contrast, the median FCRT of yellowfin, skipjack and bigeye tuna were 0.59, 0.12 and 0.10 days respectively. There was a significant difference between the FCRT of yellowfin and skipjack tuna whilst, there was no differences in FCRTs between bigeye and yellowfin and skipjack tuna. Moreover, the FCRT of yellowfin tuna was significantly higher than the sum of its absence time (AT), whilst that of skipjack was not significant. This indicates that yellowfin tuna were more associated to DFAD than the two other species. The arrival and departure events were significantly higher during nightime compared to daytime for all three species of tuna. For both DFAD combined, the median number of excursions per day of skipjack tuna (2.13) was significantly higher than that of yellowfin tuna (1.08). However, the median total time of excursions of skipjack (2.30) and yellowfin tuna (1.80) was not significantly different. This shows that skipjack tuna made more excursions of more than one hour away from the DFAD than yellowfin tuna but spent almost the same amount of time away from the DFAD as yellowfin tunas. All three species of tuna exhibited diel patterns in their vertical distribution, with deeper median depths encountered during the day than during the night. The median depth of bigeye tuna was significantly deeper than that of yellowfin and skipjack tuna during daytime and nightime. In addition, that of skipjack tuna was significantly deeper than that of yellowfin tuna. More studies of this nature on DFADs are needed to establish if there are any temporal and spatial effects on the behaviour of tunas.

## Introduction

It is well documented that pelagic fishes such as yellowfin tuna (*Thunnus albacares*), skipjack tuna (*Katsuwonus pelamis*) and bigeye tuna (*Thunnus obesus*) are found associated with floating objects (Gooding and Magnuson 1967; Parin and Fedoryako 1992; Castro et al. 2002). Around the world fishers are using this knowledge to target pelagic fish by either deploying purposefully built structures known as fish aggregating devices (FADs) or using natural floating objects such as large logs to concentrate their fishing effort (Frusher 1986; Higashi 1994). In the western Indian Ocean (WIO), catches of tuna associated with drifting fish aggregating devices (DFADs) accounts for 50% to 70% of the total purse seine catch which is the highest FAD-derived percentage observed worldwide (Fonteneau 2003).

Most of the scientific studies on the behaviour of fishes around FADs have been conducted on anchored fish aggregating devices (AFADs) (review: Dempster and Taquet 2004). However, very few studies have looked at the behaviour of fishes around DFADs. This is mostly due to the fact that DFADs are less accessible, thus such research is more expensive and requires considerable planning to be successful. Scientific knowledge on fish behaviour around DFADs is so scarce that Moreno et al. 2007 carried out an interview based study of purse seine fishers to gather their knowledge on the attraction, retention and departure behaviour of tuna associated with DFADs. Such knowledge was used to help prepare future in situ studies on fish behaviour around DFADs (See Dagorn et al 2007 and Taquet et al 2007 for examples).

In this study we examined the behaviour of yellowfin, skipjack and bigeye tuna around DFADs in the Mozambique Channel by monitoring tagged fish using satellite linked acoustic receivers deployed on the DFAD. The main aims of our study were to (1) quantify the long-term residence times of tunas at DFADs, (2) investigate their fine-scale behaviour in order to see if there is any pattern in association and excursion during the 24-h cycle and (3) examine the vertical behaviour of associated tunas.

## Methods

In order to address the specific questions of this study, yellowfin, skipjack and bigeye tunas were equipped with surgically implanted individually coded sonic transmitters around two DFADs used by European purse seiners in the Mozambique Channel. The DFADs were equipped with automated acoutsic receivers.

### *DFAD selection and receiver deployment*

A research cruise onboard a 42-foot Catamaran (Inventive) was conducted in March 2010 in the Mozambique Channel. Positions of DFADs were relayed to the scientists onboard via email or satellite phone communication from collaborating French and Spanish purse seine captains. Upon arrival at a DFAD a short underwater visual census (UVC) was conducted by snorkelling or scuba diving to assess the assemblage of species at the DFAD. The presence of seabirds in the vicinity was also used as a criterion to assess if tunas were present at the DFAD. If the DFAD was deemed suitable for fishing and tagging, a prototype VEMCO VR4 Global satellite (Iridium) receiver was attached to the DFAD using a piece of rope. The VR4 receiver consists of a submerged omni-directional receiver which is attached to a surface satellite buoy via a cable. The receiver was weighted down using a couple of 1 kg weights at a depth of approximately 5 meters.

*Capture and Tag implantation*

Tunas were caught by trolling around the DFAD using artificial barbless lures to minimize injury to the fish. The fish to be tagged was carefully transferred into a "V" shaped tagging table where a hose supplying sea water was placed at the mouth of the fish to provide oxygen to the gills and the hook was carefully removed. The eyes of the fish were covered using a wet artificial chamois cloth. Only healthy fish with no apparent injury or significant bleeding were tagged. The fork length of each fish was measured to the nearest cm using callipers.

The tunas were surgically implanted with individually coded VEMCO V13P transmitters (V13P-1L-R64K, 69kHz, 50-130 s delay, estimated battery life 879 days) using standard fish tag implantation techniques (e.g., Meyer and Holland 2000; Schaefer and Fuller 2002). A scalpel was used to make a 1- 1.5 cm incision in the muscle of the abdomen about 2- 3 cm from the anus, on the ventral line. A tag was then inserted into the peritoneal cavity and the incision was closed with two independent monofilament nylon nonabsorbable sutures. To facilitate identification of the fish in the case of recaptures by the purse seiners, all fish were also tagged with an external spaghetti tag inserted through the pterygiophores of the second dorsal fin. All fish were released within 300 meters from the DFAD of capture. The maximum detection range of the V13 tags is estimated to be between 335 and 385 m (see Girard et al. 2007).

*Tagging and data collection*

Tagging was conducted at the first DFAD named DFAD34 on the 8$^{th}$ and 9$^{th}$ of March 2010 and on the 15$^{th}$ and 16$^{th}$ of March 2010 at the second DFAD named DFAD31. A total of 12 yellowfin tuna (29-60 cm FL), 13 skipjack tuna (47-57 cm FL) and 4 bigeye tuna (54-56 cm FL) equipped with internal sonic tags were released at the DFADs (Fig. 1) (Table 1). On DFAD34, the satellite receiver was operational for 66 days before a technical problem occurred. On DFAD31, the receiver was only operational 11 days before the receiver stopped working, likely because it was fished. However, all tunas had left the DFADs prior to the commencement of fishing. Of the 14 fish released at DFAD31, one skipjack and bigeye tuna were never detected and one yellowfin and bigeye tuna were detected only once. It is worthy to note, however, that these two bigeye tuna (also equipped with archival tags) were recaptured about a month after tagging. In contrast, at DFAD34 one skipjack tuna was never detected and one yellowfin tuna was detected only once. Therefore the analysis was conducted on a total of 12 yellowfin, 11 skipjack, and 3 bigeye tuna.

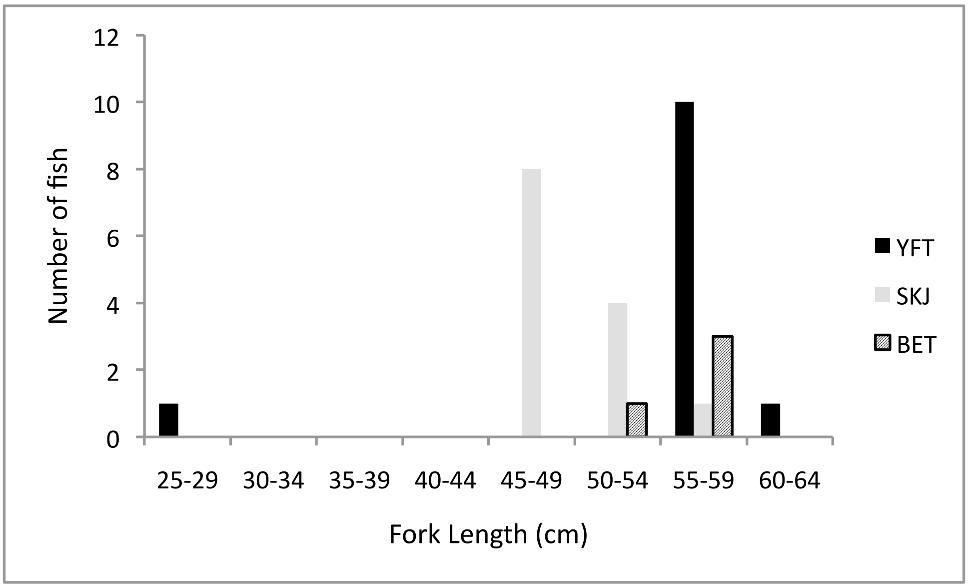


**Fig. 1** Length frequency of tagged yellowfin, skipjack and bigeye tuna

**Table 1** Tagging summary: DFAD of release, tagging periods and number of tuna tagged

| DFAD of release | Periods of tagging | Number of yellowfin-skipjack-bigeye tuna tagged |
|---|---|---|
| DFAD31 | 15-16 Mar 10 | 6-6-2 |
| DFAD34 | 8-9 Mar 10 | 6-7-2 |

*Data analysis*

The median total time of association (TTA), defined as the time between the first and last detection was computed for each individual. The continuous residency time (CRT) defined by Ohta and Kakuma (2005) as "the duration in which a tagged tuna was continuously monitored without day-scale (>24 h) absences" was calculated for each fish. We also calculated the fine-scale residence time (FCRT) which is defined as the duration for which a tagged tuna was monitored without a one hour absence, in order to study fine-scale behavior. For the FCRT, the absence time (AT) which was the amount of time a fish spent away from the DFAD (or total duration of the excursion away from the FAD) was also calculated. Mann-Whitney *U* tests were carried out to compare CRTs and FCRTs between species. In addition it was used to compare the sum of FCRT and AT for fishes of the same species.

The percentage of detections for each species in each hour of the 24 hour cycle was calculated over the entire monitoring period. To investigate diel patterns in the number of detections, we compared the number of detections during daytime and during the night using the Mann-Whitney *U* tests.

For the FCRT data, the average number of excursions per day and the total time of excursions by each fish at each DFAD were computed. Mann-Whitney *U* tests were carried out to investigate any inter-specific differences in the average number of excursions per day and total time of excursions at each DFAD and for both DFADs combined.

To investigate any patterns in the arrival and departure time of fish at the DFADs, we calculated the percentage of arrivals and departures in each hour of the day, for each species for all DFADs combined, using the FCRT data. Diel differences in the arrival and departure events were investigated by comparing the number of daytime and nigh time arrivals and departures using the Mann-Whitney *U* tests.

The depth distribution of each species during daytime and during the night was compared using the Mann-Whitney *U* tests. The same test was used to investigate any inter-specific differences in depth distribution during daytime and nightime. The average hourly depth distribution of each species at each DFAD was calculated over a period where the maximum numbers of fish were present.

All statistical tests carried out were two tailed and a significance level of $\alpha$=0.05 was used throughout the analysis.

## Results

*Long-term residence times (CRT)*

The median (range) total time of association of yellowfin, skipjack and bigeye tuna was 11.28 (0.00-26.78), 7.17 (0.18-19.73) and 3.89 (0.00-6.56) days respectively. A total of 32 CRTs were measured (14 CRTs from the 12 yellowfin tuna, 15 CRTs from the 11 skipjack tuna and 3 CRTs from the 3 bigeye tuna). Of the 12 yellowfin tuna tagged, only 2 made day-scale excursions away from the DFAD and returning to it. Similarly, only 3 skipjack tuna made day-scale excursions away from the DFAD (Fig. 2) and returning to it. The average (range) time out of FADs calculated from CRTs (minimum gap of 24 hours between 2 detections) of yellowfin tuna was 2.75 (1.43-4.07) days whilst that of skipjack was 1.58 (1.10-2.27) days. The median (range) CRT of yellowfin, skipjack and bigeye tuna for both DFADs combined was 9.98 (0.00-26.72), 4.47 (0.09-18.33) and 3.89 (0.00-6.56) days respectively. There were no inter-specific differences between the CRTs of yellowfin and skipjack tuna (Mann-Whitney *U* test: $U$ = 77, $N_{\mathrm{YFT}}$ =14, $N_{\mathrm{SKJ}}$ = 15, $P$ = 0.230). Similarly, there were no differences in the CRT of bigeye tuna compared to that of yellowfin and skipjack tuna (Mann-Whitney *U* test: $U$ = 10.5, $N_{\mathrm{BET}}$ = 3, $N_{\mathrm{SKJ}}$ = 14, $P$ = 0.207) (Mann-Whitney *U* test: $U$ = 17, $N_{\mathrm{BET}}$ = 3, $N_{\mathrm{SKJ}}$ = 15, $P$ = 0.554). A difference was observed between the CRTs of yellowfin tuna between the two DFADs. The median CRT of yellowfin tuna at DFAD34 (13.19 days) was significantly higher than those at DFAD31 (0.25 days) (Mann-Whitney *U* test: $U$ = 5, $N_{\mathrm{FAD34}}$ =7, $N_{\mathrm{FAD31}}$ = 7, $P$ = 0.015). In contrast, there was no significant difference between the median CRT of skipjack tunas at DFAD34 (5.62 days) and DFAD31 ( 1.71 days) (Mann-Whitney *U* test: $U$ = 15, $N_{\mathrm{FAD34}}$ =9, $N_{\mathrm{FAD31}}$ = 6, $P$ = 0.175).

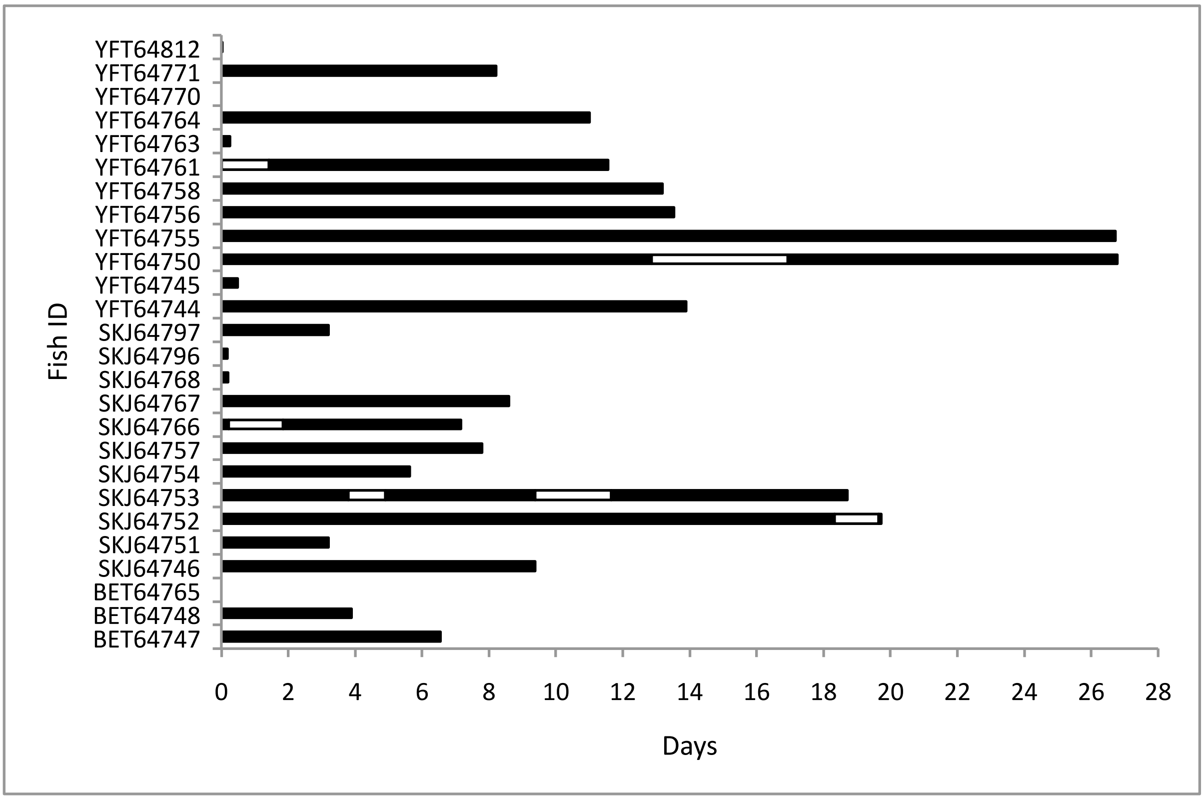


**Fig. 2** Continuous residency times of yellowfin, skipjack and bigeye tuna at the DFADs. Black bars corresponds to the CRTs and white bars represent the absences. Origin corresponds to tagging date and time of each fish

Short-term residence times (FCRT)

A total of 381 FCRTs were measured (157 FCRTs from the 12 yellowfin tuna, 202 FCRTs from the 11 skipjack tuna and 21 FCRTs from the 3 bigeye tuna). Of the 11 skipjack tuna tagged only 2 fish did not make any small-scale excursions of more than one hour away from the DFAD. Similarly, 4 of the 12 tagged yellowfin tuna did not make any short-term excursions away from the DFAD (Fig. 3). The median (range) FCRT of yellowfin, skipjack and bigeye tuna for both DFADs combined was 0.59 (0.00-6.65), 0.12 (0.00-1.6) and 0.10 (0.00-0.98) days respectively. There was a significant difference between the FCRT of yellowfin and skipjack tuna (Mann-Whitney $U$ test: $U$ = 10 620, $N_{\mathrm{YFT}}$ = 157, $N_{\mathrm{SKJ}}$ = 202, $P$ = < 0.0001). In contrast, there was no difference in FCRTs between bigeye and yellowfin and skipjack tuna (Mann-Whitney $U$ test: $U$ = 1881, $N_{\mathrm{BET}}$ = 21, $N_{\mathrm{SKJ}}$ = 202, $P$ = 0.394) (Mann-Whitney $U$ test: $U$ = 1267, $N_{\mathrm{BET}}$ = 21, $N_{\mathrm{YFT}}$ = 157, $P$ = 0.086). Moreover, there was a significant difference between the sum of FCRT and AT of yellowfin tuna (Mann-Whitney $U$ test: $U$ = 25, $N_{\mathrm{FCRT}}$ = $N_{\mathrm{AT}}$ = 11, $P$ = 0.021). However, there was no significant difference between the sum of FCRT and AT of skipjack tuna (Mann-Whitney $U$ test: $U$ = 24, $N_{\mathrm{FCRT}}$ = $N_{\mathrm{AT}}$ = 9, $P$ = 0.162). The median (range) of the sum of AT for yellowfin and skipjack tuna were 1.87 (0.00-7.18) and 2.885 (0.95-10.19) respectively.

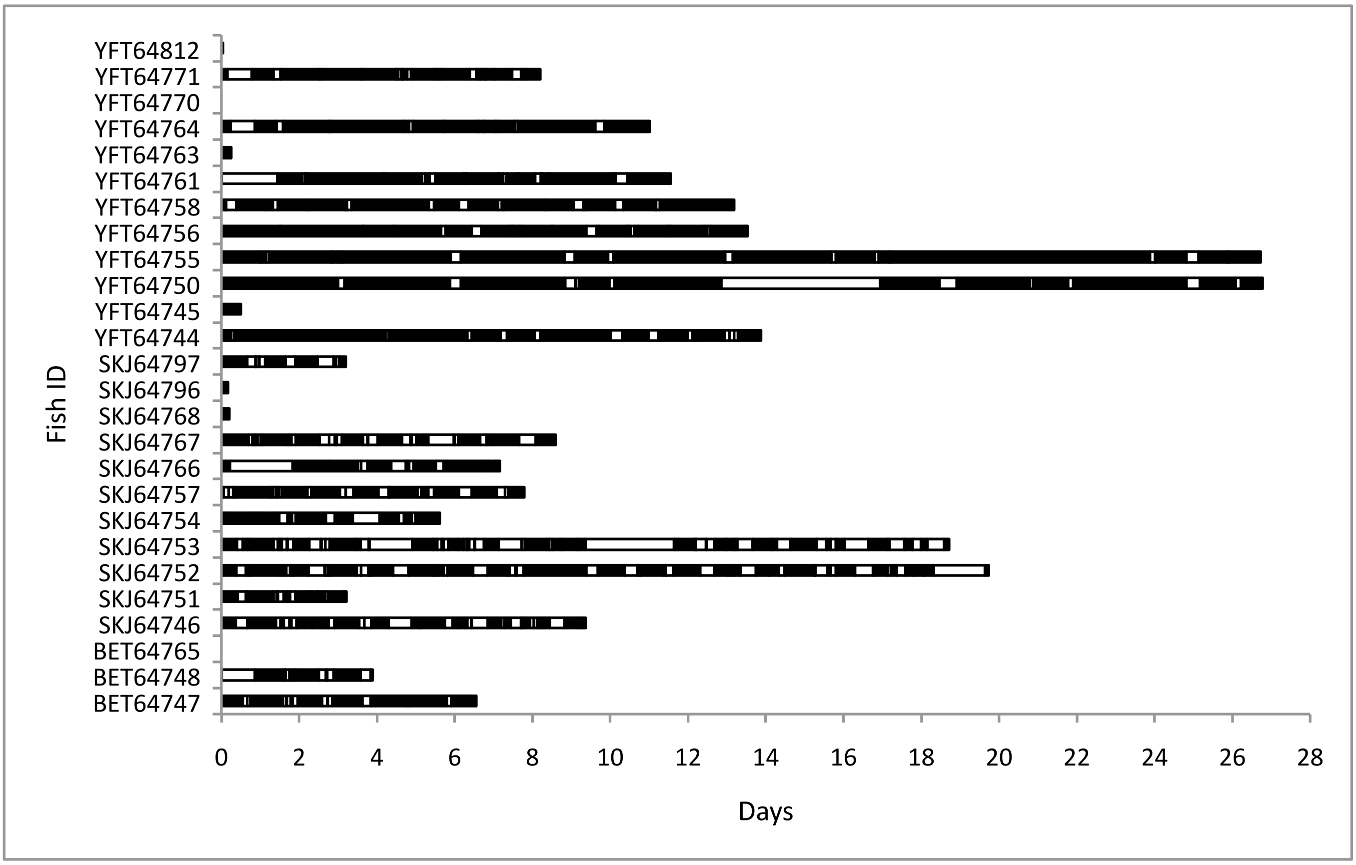


**Fig. 3** Fine-scale residency times of yellowfin, skipjack and bigeye tuna at the DFADs. Black bars corresponds to the CRTs and white bars represent the absences

The percentage of detections of the three species in each hour bin is shown in figure 4. All three species showed similar patterns of increasing number of detections from 0200 hours till 0700 hours, followed by a stable period between 0700 hours and 1600 hrs except for bigeye tuna where the number of detections decreased around midday. The number of detections then decreased gradually until it reached similar levels to those at 0200 hours. For all three species the number of detections was significantly higher during the day compared to the night (Table 2).

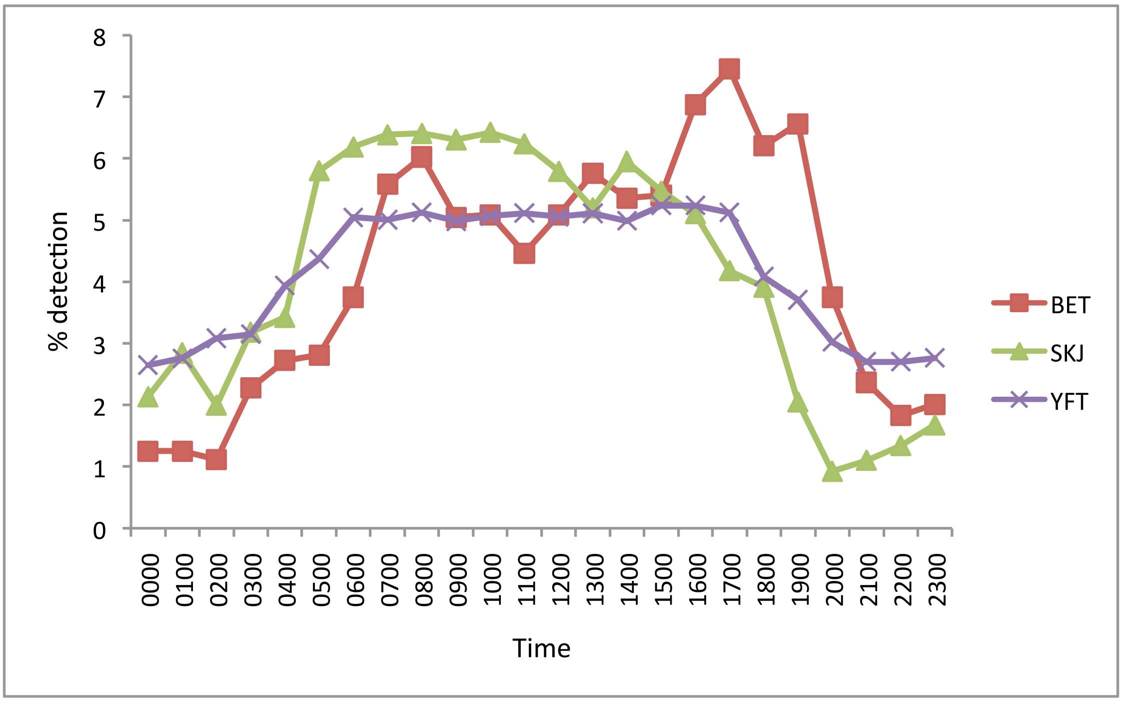


**Fig. 4** Percentage number of detections of yellowfin, skipjack and bigeye tuna in each hour bin

**Table 2** Summary of Mann-Whitney *U* test comparing the number of detections during daytime and nightime.

| | YFT | SKJ | BET |
|---|---|---|---|
| $N_{NIGHT}$ | 12 | 12 | 12 |
| $N_{DAY}$ | 12 | 12 | 12 |
| *U* | 0 | 5 | 20.5 |
| *P* | <0.0001 | <0.0001 | 0.0017 |

The average (range) number of excursions of more than one hour duration by skipjack and yellowfin tuna at DFAD31 was 1.15 (0.00-2.21) and 0.74 (0.00-2.07) per day respectively (Table 3). In contrast at DFAD34, the average number of excursions by bigeye, skipjack and yellowfin tuna were 1.74 (1.68-1.80), 2.56 (2.03-2.99) and 0.96 (0.00-1.63) per day respectively (Table 4).

**Table 3** Average number of excursions per day and the total excursion times for each fish at FAD 31.

| Fish ID | Average number of excursions per day | Total time of excursion in days |
|---|---|---|
| BET64765 | 0.00 | 0.00 |
| SKJ64766 | 1.67 | 2.88 |
| SKJ64767 | 2.21 | 3.10 |

| | | |
|---|---|---|
| SKJ64768 | 0.00 | 0.00 |
| SKJ64796 | 0.00 | 0.00 |
| SKJ64797 | 1.88 | 1.18 |
| YFT64761 | 1.38 | 2.67 |
| YFT64763 | 0.00 | 0.00 |
| YFT64764 | 1.00 | 1.51 |
| YFT64770 | 0.00 | 0.00 |
| YFT64771 | 2.07 | 1.96 |
| YFT64812 | 0.00 | 0.00 |

**Table 4** Average number of excursions per day and the total excursion times for each fish at FAD 34.

| Fish ID | Average number of excursions per day | Total time of excursion in days |
|---|---|---|
| BET64747 | 1.68 | 1.23 |
| BET64748 | 1.80 | 1.67 |
| SKJ64746 | 2.99 | 4.01 |
| SKJ64751 | 3.43 | 0.95 |
| SKJ64752 | 2.03 | 7.54 |
| SKJ64753 | 2.35 | 10.19 |
| SKJ64754 | 2.13 | 1.87 |
| SKJ64757 | 2.44 | 2.30 |
| YFT64744 | 1.15 | 1.86 |
| YFT64745 | 0.00 | 0.00 |
| YFT64750 | 1.16 | 7.19 |
| YFT64755 | 0.56 | 1.91 |
| YFT64756 | 1.63 | 1.74 |
| YFT64758 | 1.29 | 1.97 |

There were no inter-specific differences in the median number of excursions per day between skipjack (1.67) and yellowfin tuna (0.50) at DFAD31 (Mann-Whitney $U$ test: $U = 11$, $N_{SKJ} = 5$, $N_{YFT} = 6$, $P = 0.503$). In contrast, at DFAD34 there was a significant difference in the median number of excursions per day between skipjack (2.39) and yellowfin tuna (1.16) (Mann-Whitney $U$ test: $U = 0$, $N_{SKJ} = 6$, $N_{YFT} = 6$, $P = 0.005$). For both DFADs combined, the median number of excursions per day of skipjack tuna (2.13) was significantly higher than that of yellowfin tuna (1.08) (Mann-Whitney $U$ test: $U = 23$, $N_{SKJ} = 11$, $N_{YFT} = 12$, $P = 0.008$). In contrast, there was no significant differences between the median number of excursions per day of bigeye tuna (1.74) and skipjack and yellowfin tuna (Mann-Whitney $U$ test: $U = 6$, $N_{SKJ} = 11$, $N_{BET} = 2$, $P = 0.374$) (Mann-Whitney $U$ test: $U = 2$, $N_{YFT} = 12$, $N_{BET} = 2$, $P = 0.079$).

The average (range) total time of excursions of skipjack and yellowfin tuna at DFAD31 was 1.43 (0.00-3.10) and 1.02 (0.00-2.67) days respectively (Table 3). In contrast at DFAD34, the total time of excursions of bigeye, skipjack and yellowfin tuna were 1.45 (1.23-1.67), 4.48 (0.95-10.19) and 2.44 (0.00-7.19) days respectively (Table 4). There were no inter-specific differences in the median total time of excursions between skipjack (1.18) and yellowfin tuna (0.75) at DFAD31 (Mann-Whitney $U$ test: $U = 12$, $N_{SKJ} = 5$, $N_{YFT} = 6$, $P = 0.632$). Similarly, at DFAD34 there was no significant difference in the median total time of excursions between skipjack (3.16) and yellowfin tuna (1.89) (Mann-Whitney $U$ test: $U = 10$, $N_{SKJ} = 6$, $N_{YFT} = 6$, $P = 0.230$). Moreover, for both DFAD combined, the median total time of excursions of skipjack (2.30) and yellowfin tuna (1.80) was not significantly different (Mann-Whitney $U$ test: $U = 46$, $N_{SKJ} = 11$, $N_{YFT} = 12$, $P = 0.226$). In addition, there was no significant differences between the total time of excursions of bigeye tuna (1.23) and skipjack and yellowfin tuna (Mann-Whitney $U$ test: $U = 6$, $N_{SKJ} = 9$, $N_{BET} = 3$, $P = 0.274$) (Mann-Whitney $U$ test: $U = 2$, $N_{YFT} = 11$, $N_{BET} = 3$, $P = 0.339$).

The percentage number of departure and arrival events of bigeye tuna in each hour bin based on the FCRT, is shown in Figure 5. All of the arrival events occurred between the hours of 2200 and 0600. In contrast the departure events occurred between the hours of 1900 and 0400. No arrival and departure events were recorded between 0700 hours and 1800 hours. Therefore, the number of arrivals and departure events were significantly higher during the night compared to during daytime (Mann-Whitney $U$ test: $U = 30.5$, $N_{DAY} = 12$, $N_{NIGHT} = 12$, $P = 0.0059$) (Mann-Whitney $U$ test: $U = 12$, $N_{DAY} = 12$, $N_{NIGHT} = 12$, $P = 0.0001$).

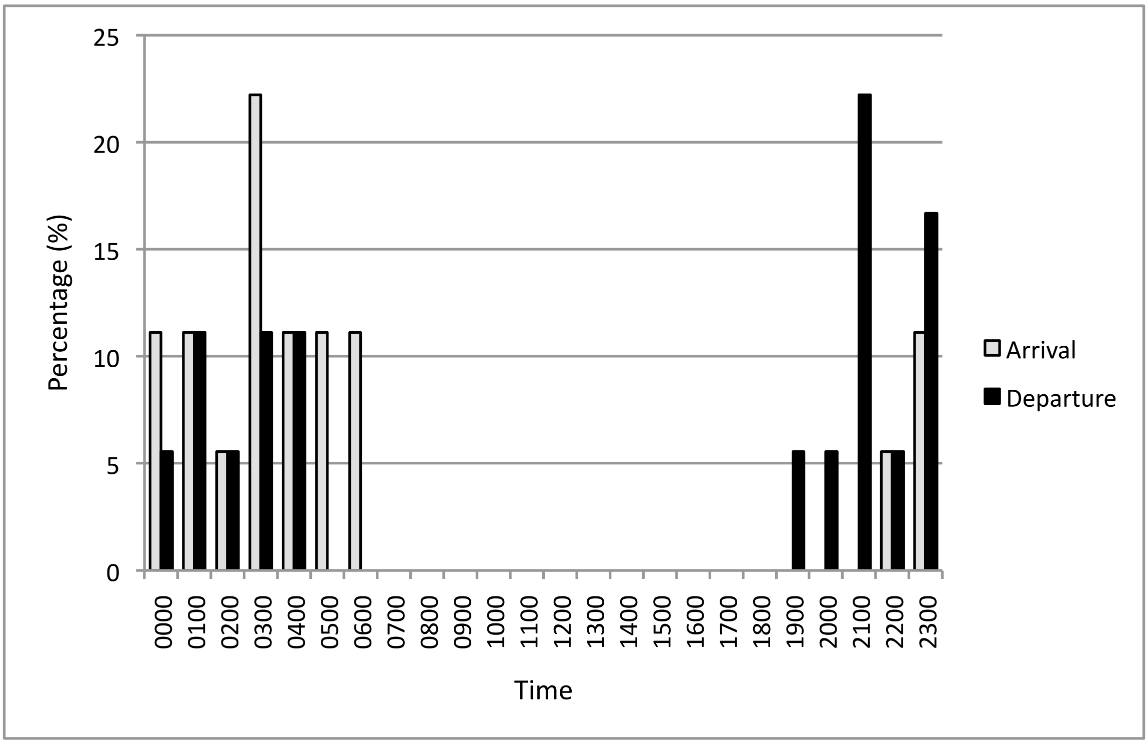


**Fig. 5** Percentage number of arrivals and departures of bigeye tuna in each hour bin

Similarly to bigeye tuna, the number of arrival and departure events for yellowfin tuna was significantly higher during the night compared to during daytime (Mann-Whitney $U$ test: $U = 7.5$, $N_{DAY} = 12$, $N_{NIGHT} = 12$, $P = 0.0001$) (Mann-Whitney $U$ test: $U = 24$, $N_{DAY} = 12$, $N_{NIGHT} = 12$, $P = 0.0057$). Approximately 96% of the arrival events took place between the hours of 1800 and 0500, whilst approximately 86% of the departure events took pace during the same time period.

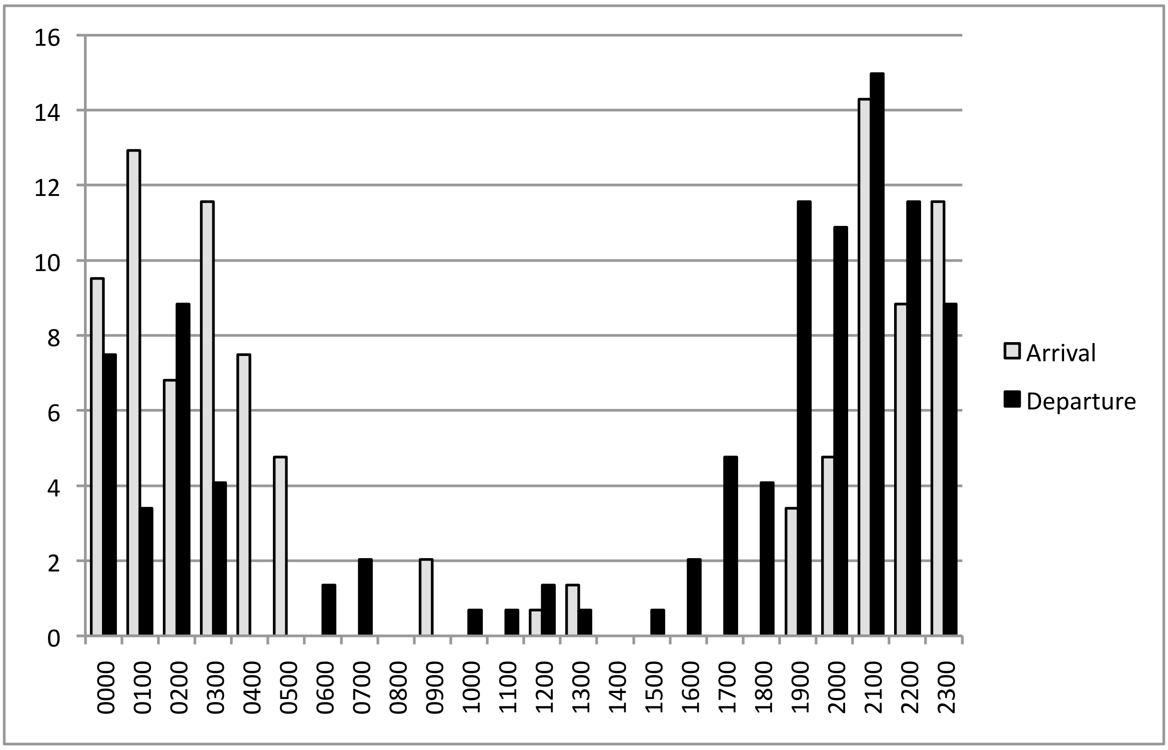


**Fig. 6** Percentage number of arrivals and departures of yellowfin tuna in each hour bin

Similarly, for skipjack tuna, there was a significant difference between the numbers of arrival and departure events during the night compared to during daytime (Mann-Whitney $U$ test: $U = 15$, $N_{DAY} = 12$, $N_{NIGHT} = 12$, $P = 0.001$) (Mann-Whitney $U$ test: $U = 33$, $N_{DAY} = 12$, $N_{NIGHT} = 12$, $P = 0.020$). In contrast to the arrival and departure event patterns of bigeye and yellowfin tuna, for skipjack tuna, arrival and departure events occurs throughout the whole day. Approximately 72% of arrival events occur between the hours of 2100 and 0500. The highest percentage number of departure events occurs during 0100 hours after which the number of departure events gradually decreases till 0500 hours. The number of departures then gradually increases throughout daytime from 0700 hours till 1900 hours after which it decreases till 0000 hours.

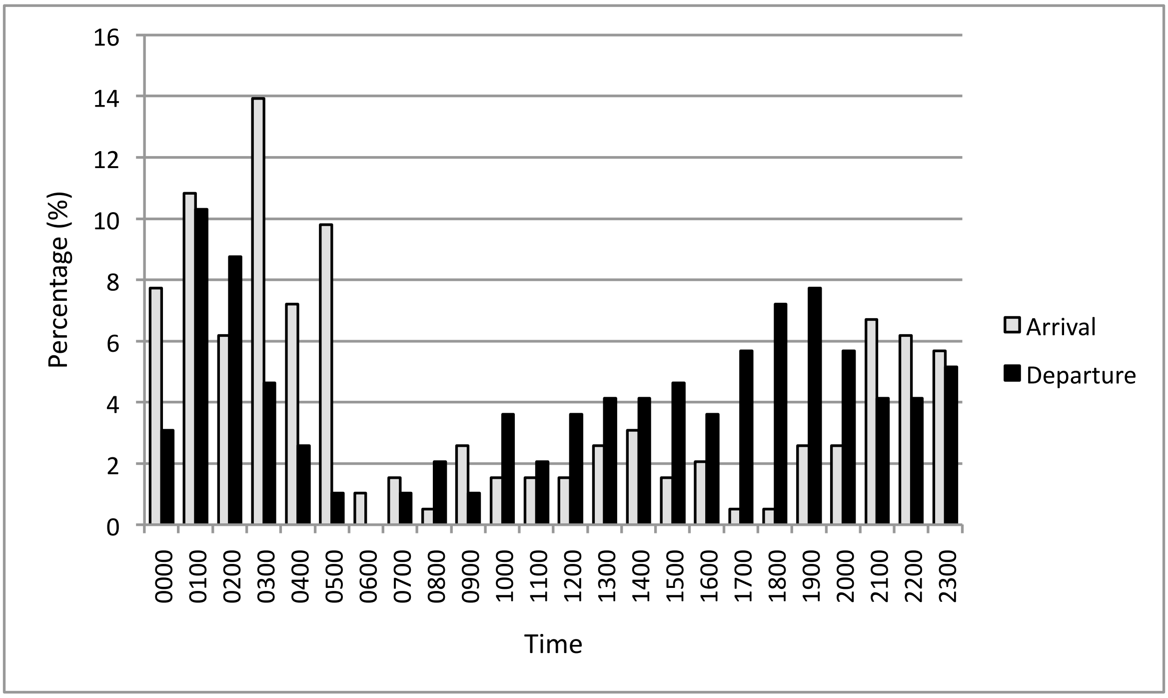


**Fig. 7** Percentage number of arrivals and departures of skipjack tuna in each hour bin

*Vertical behaviour*

The median (range) depth of yellowfin tuna during the day was 49.54 (0.00-310.86) m compared to 38.39 (0.00-156.05) m during the night (Fig. 8). There was a significant difference in the median depth of yellowfin tuna during the day compared to during the night (Mann-Whitney *U* test: $U$ = 3.90E+07, $N_{\text{Day}}$ = 12679, $N_{\text{Night}}$ = 8046, $P$ = < 0.0001).

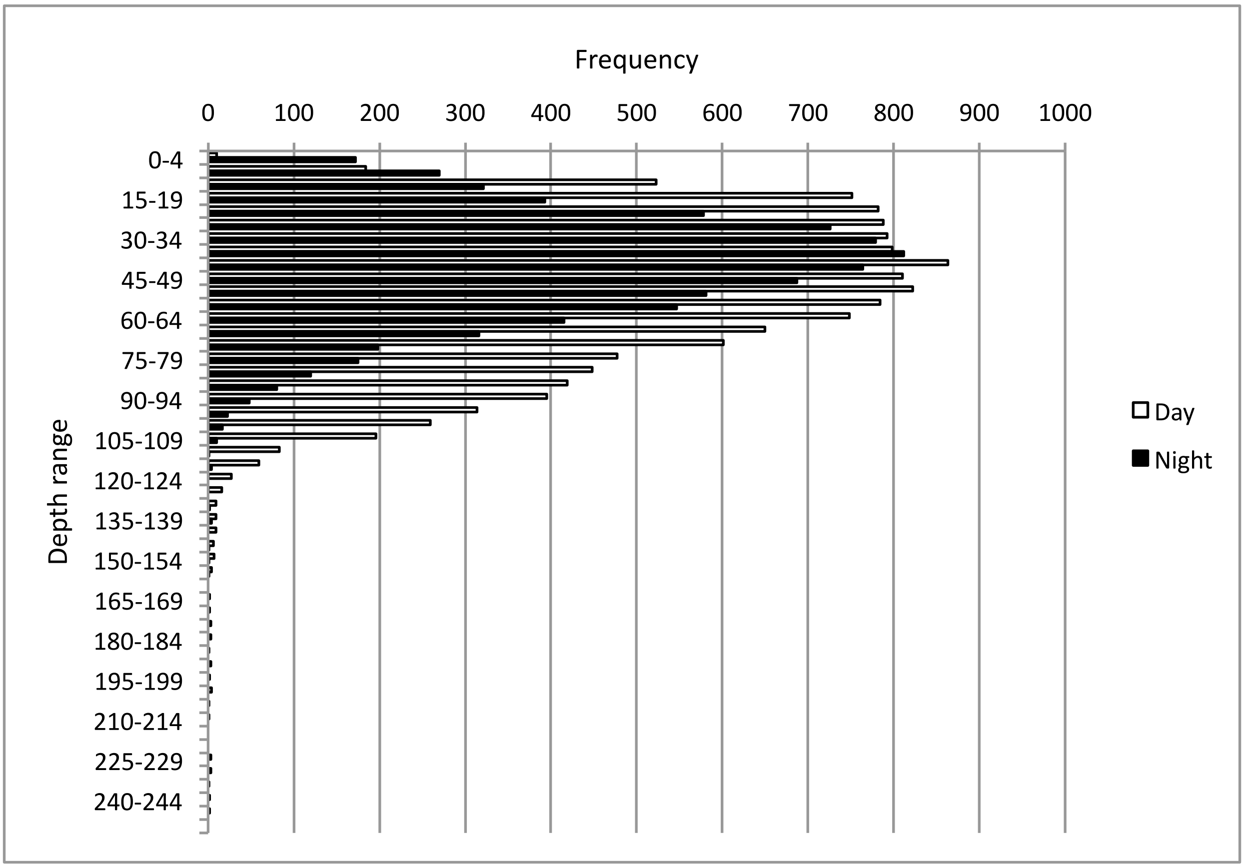


**Fig. 8** Depth distribution of yellowfin tuna during the monitoring period

Similarly, the median depth of skipjack tuna was significantly deeper during the day compared to during the night (Mann-Whitney $U$ test: $U$ = 3.65E+06, $N_{\text{Day}}$ = 4860, $N_{\text{Night}}$ = 2075, $P$ = < 0.0001). The median depth of skipjack tuna during the day was 54.49 (0.00-235.32) m compared to 40.87 (0.00-194.44) m during the night (Fig. 9).

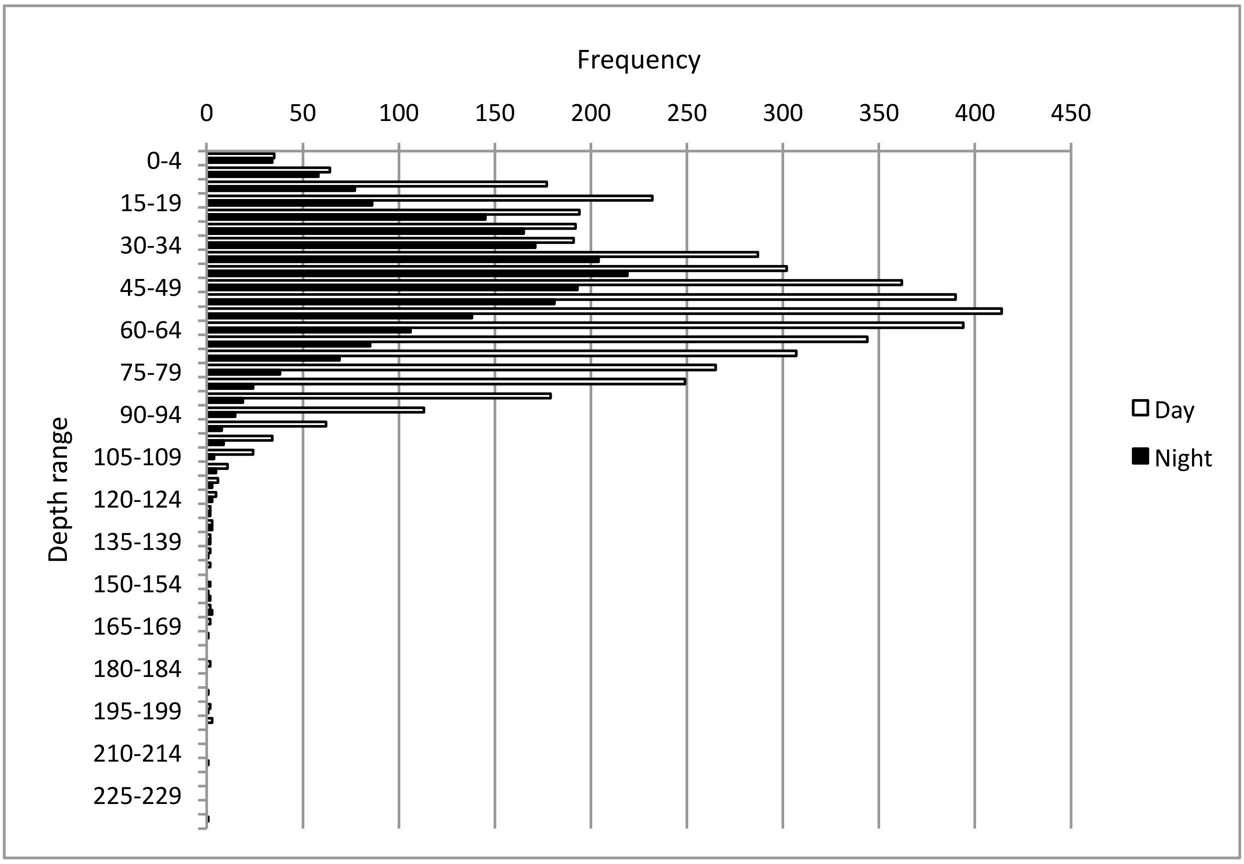


**Fig. 9** Depth distribution of skipjack tuna during the monitoring period

Similarly, there was a significant difference between the median depth of bigeye tuna during the night and day (Mann-Whitney $U$ test: $U$ = 1.04E+05, $N_{\mathrm{Day}}$ = 741, $N_{\mathrm{Night}}$ = 381, $P$ = < 0.0001). During the day the median depth was 70.59 (11.15-257.61) m compared to 60.69 (6.19-107.75) m during the night (Fig. 10).

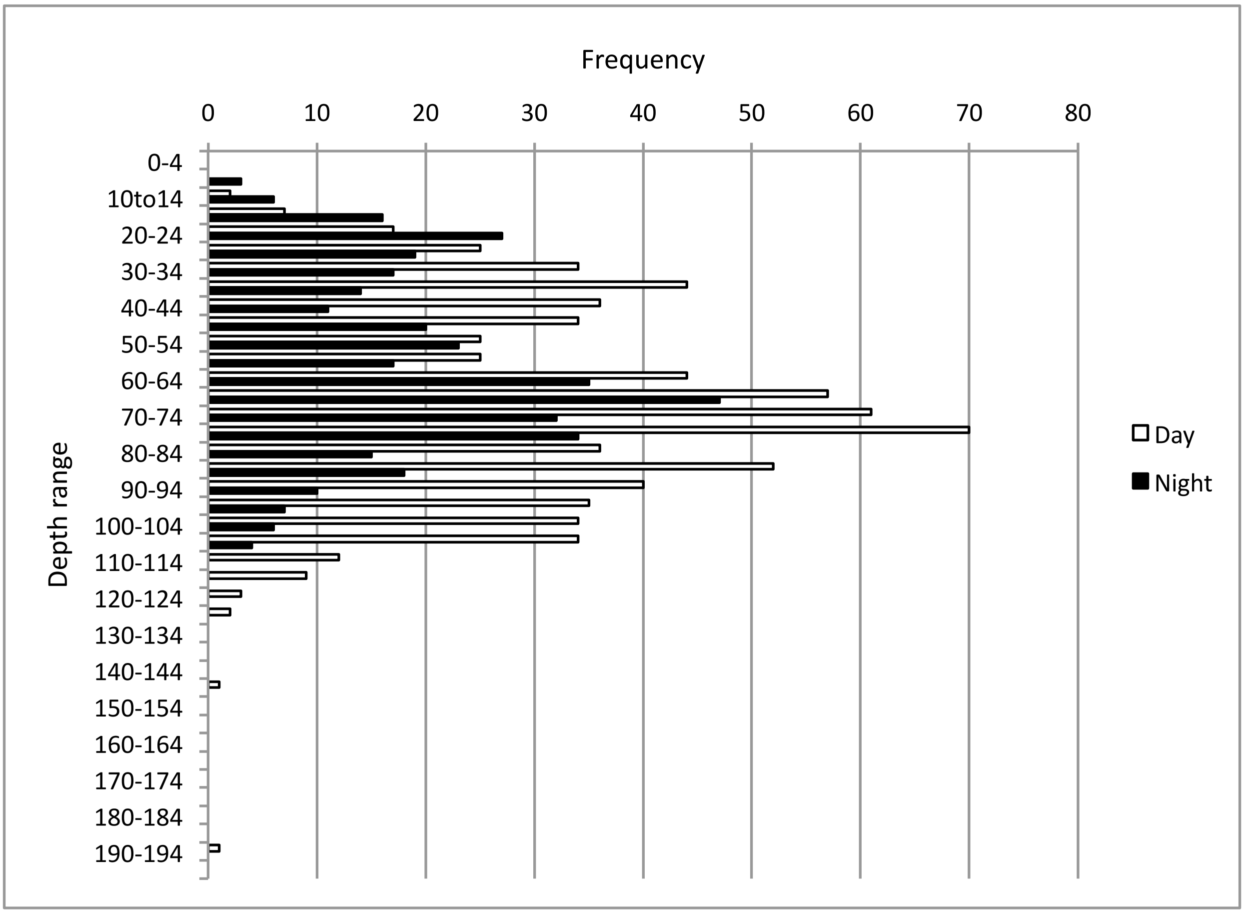


**Fig. 10** Depth distribution of bigeye tuna during the monitoring period

The median depth of bigeye tuna during the night was significantly deeper than that of yellowfin and skipjack tuna during the same period (Mann-Whitney *U* test: $U$ = 9.23E+05, $N_{BET}$ = 381, $N_{YFT}$ = 8046, $P$ = < 0.0001) (Mann-Whitney *U* test: $U$ = 2.54E+05, $N_{BET}$ = 381, $N_{SKJ}$= 2075, $P$ = < 0.0001). Moreover, there was a significant difference between the median depths of yellowfin and skipjack tuna during the night (Mann-Whitney *U* test: $U$ = 7.90E+06, $N_{YFT}$ = 8046, $N_{SKJ}$ = 2075, $P$ = 0.0002). During the daytime, the median depth of bigeye tuna was significantly deeper than that of yellowfin and skipjack tuna (Mann-Whitney *U* test: $U$ = 3.05E+06, $N_{YFT}$ = 12679, $N_{BET}$ = 741, $P$ = < 0.0001) (Mann-Whitney *U* test: $U$ = 1.20E+06, $N_{SKJ}$ = 4860, $N_{BET}$ = 741, $P$ = <0.0001). Moreover, there was a significant differences between the median depth of yellowfin and skipjack tuna during daytime (Mann-Whitney *U* test: $U$ = 2.92E+07, $N_{YFT}$ = 12679, $N_{BET}$ = 4860, $P$ = < 0.0001)

The average hourly depth distribution of yellowfin and skipjack tunas at DFAD31 is shown in Figure 11. Generally, for both species the average depth was deeper during daytime compared to nightime. Moreover, the daytime depths of yellowfin tuna were deeper than that of skipjack.

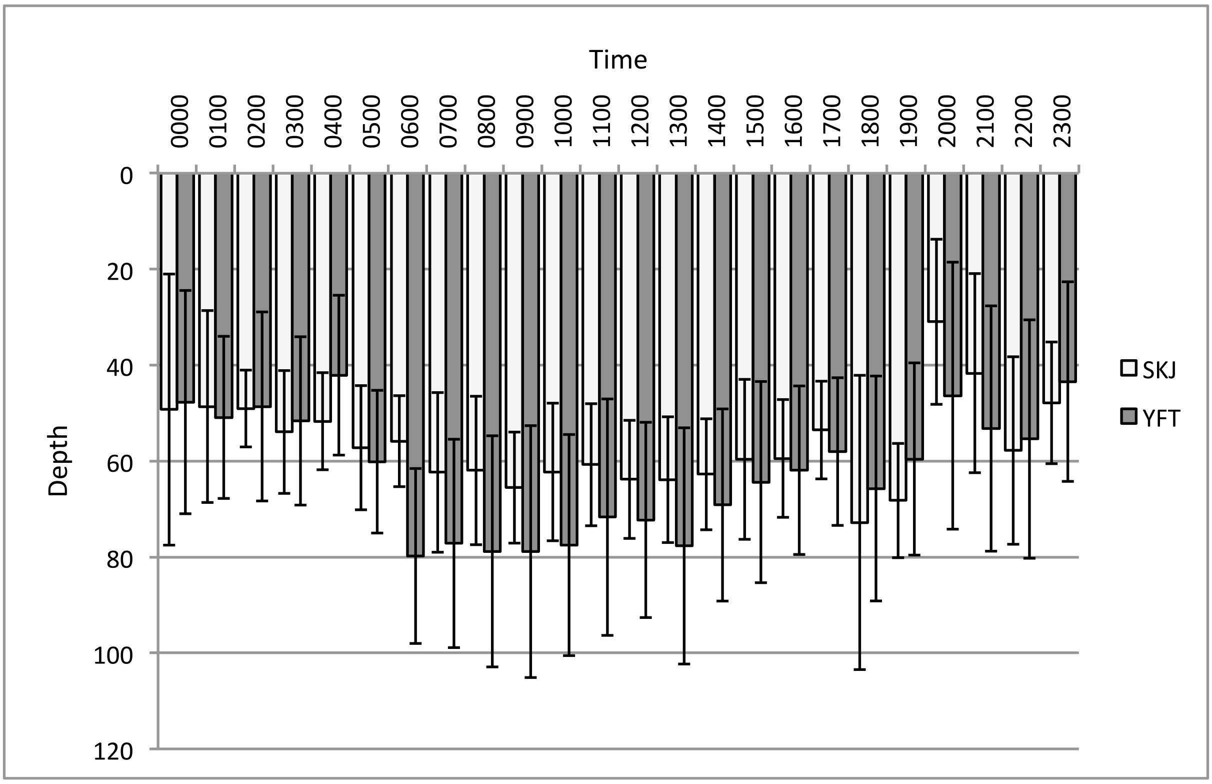


**Fig. 11** Average hourly depths of yellowfin and skipjack tuna at DFAD31

At DFAD34 the average hourly depth distribution of bigeye tuna was deeper that that of yellowfin and skipjack tuna (Fig. 12). Generally, the average depths of the three species increased between the hours of 0600 to 0900 and decreased gradually till noon where it stayed almost constant till 1900 hours, after which the average depths got shallower.

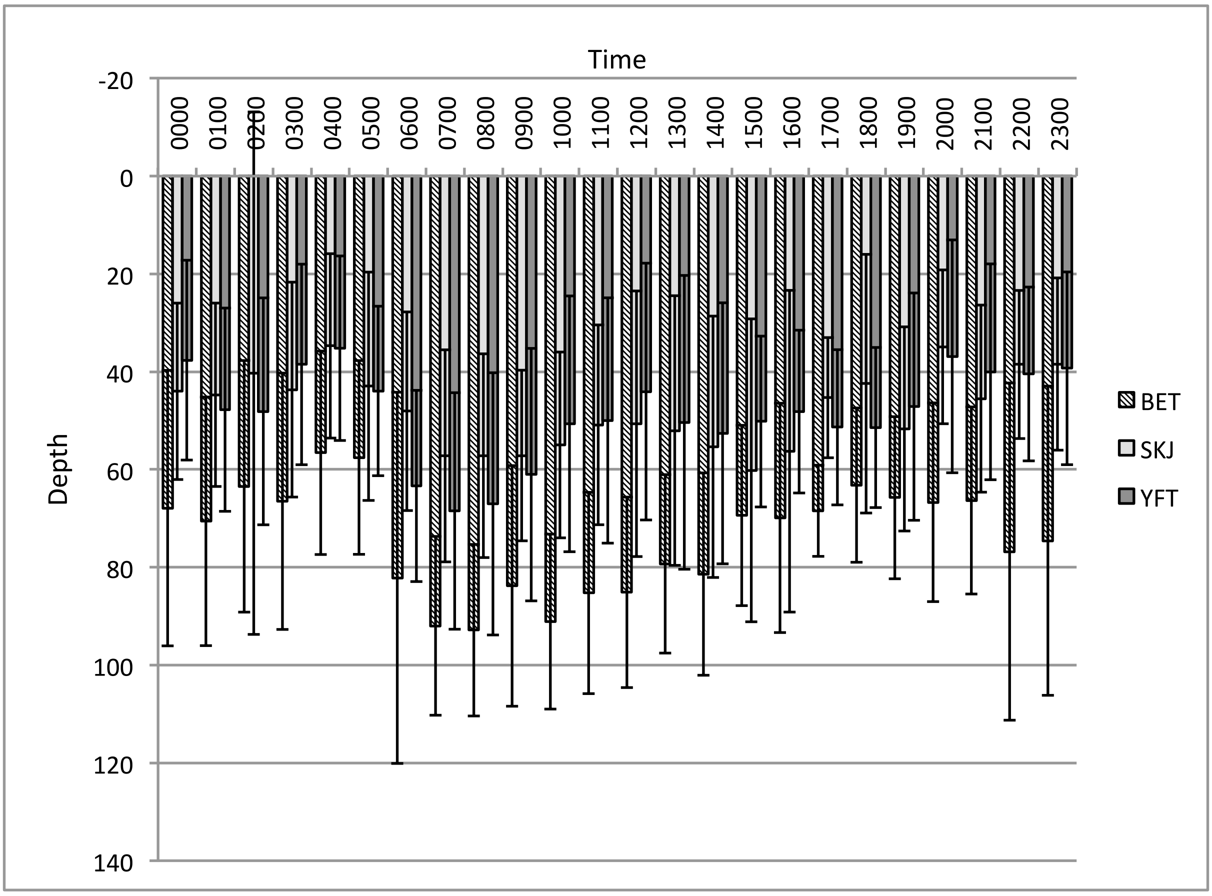


**Fig. 12** Average hourly depths of yellowfin, skipjack and bigeye tuna at DFAD34

## Discussion

*CRT and FCRT*

In this study we found that the use of the two different methods to calculate residency times gave different impressions of the association rate of tuna species at DFADs. The use of the CRT method showed that there were no differences in the residency times of yellowfin and skipjack tuna. In contrast, the use of the FCRT method showed that there were clear differences in the residency times of the two species. Moreover, by examining the difference between the sum of FCRTs and AT, we found that the FCRT of yellowfin tuna was significantly higher compared to the ATs. In contrast, there were no differences in the sum of FCRTs and ATs of skipjack tuna. This indicates that yellowfin tuna have a stronger association to DFADs than skipjack tuna. Yellowfin tuna remained associated with the DFADs for longer periods making short excursions of more the 1 hour. On the contrary, skipjack tuna remained associated to the DFADs for shorter periods of times whilst making regular excursions of more than 1 hour that did not differ from the amount of time they spent associated with the DFADs. However, the amount of time spent away from the DFAD did not differ between the two species. To date, there are no studies which have looked at inter-specific differences in residency times of tunas associated with DFADs. Most of the studies have focused on the behaviour of tuna around anchored FADs. Similarly to our study, Ohta and Kakuma (2005) observed that the majority of yellowfin and bigeye tunas tagged around the Okinawa Islands in Japan showed strong association with anchored FADs, staying continuously at the FADs where they were tagged without making any day-scale excursions until they left the FAD completely. They estimated the median CRT of yellowfin and skipjack tuna to be 7.9 and 7.0 days respectively. In addition, Dagorn et al. (2007) in Hawaii estimated the residency time of yellowfin and bigeye tuna at a single FAD to be 5 to 8 days. In both studies, there were no inter-specific differences in CRT. In the present study, the maximum time a tuna remained associated without day-scale absences was 26 days. This is shorter than the maximum association periods found around anchored FADs by Ohta and Kakuma (2005) and Dagorn et al. (2007) where the maximum stay at FADs was 55 and 64.7 days respectively, but could be considered as of the same order (several weeks). Collating residence times of the different tuna species at FADs is key to the better assessment of the impacts of FADs on their behaviour. The amount of data on residence times at drifting FADs collected thus far is currently too low, with the exception of data on bigeye tuna (Schaefer and Fuller 2010), to develop models on the behaviour of fish at FADs. Such models are key to predicting the impacts of different densities of FADs on tuna behaviour.

In our study we found that the number of arrival and departure events was significantly higher during the night than during the day. In other studies, Ohta and Kakuma (2005), who characterized the detection rates of yellowfin and bigeye tuna around anchored FADs into four distinct patterns, observed that except for one of the patterns, fish left the FAD at around sunset from 1747 to 1924 hours. They also observed that fish revisited the FAD frequently at around 2100 hours. In other species of fish, for example the bigeye scad, *Selar crumenophthalmus*, Soria et al. (2009) observed that 56 % of arrivals occurred between 0500 and 0700 hours whilst only 32 % of departure occurred between 1700 and 1900 hours.

Detailed information on the excursions away from FADs by the different species clearly shows that the three species do not share the same dependence on the FAD. Skipjack tuna seem to be very mobile and dynamic, with excursions occurring throughout the day, while yellowfin and bigeye tuna mainly leave and come back to the FAD during night hours. This could be due to different foraging behaviour as excursions away from FADs have generally been attributed to this behaviour (Holland et al. 1990, Cayré 1991, Dagorn et al 2000b). Moreover, such differences could be used to develop some mitigation measures. For instance, in areas such as the Pacific Ocean where catches of small bigeye tuna around FADs is an issue, the fact that certain species (e.g. skipjack tuna) leave while others (e.g. bigeye tuna) close to the FAD could be used to catch monospecific schools.

*Vertical behaviour*

The vertical behaviour of yellowfin, skipjack and bigeye tuna showed diel changes in depth resulting in significantly greater median depths during daytime than during the night. Similarly, previous studies examining diel patterns of vertical movements of yellowfin and skipjack tuna using ultrasonic telemetry indicated that the vertical depth distributions were significantly shallower at night than during the day (Dizon et al. 1978; Cayré and Chabanne 1986; Holland et al. 1990; Cayré 1991; Brill et al. 1999). In contrast, Schaefer and Fuller (2005) observed that skipjack tunas associated with a moored buoy and a drifting vessel exhibited the reverse diel pattern with greater mean depths at night than during the day. Furthermore, Cayré (1991) who tracked 2 skipjack tuna in the Comoros Islands observed that the time spent swimming in the upper layer (0-20 m) during daytime was higher than at night.

Previous studies have shown that bigeye tuna show similar diel patterns to yellowfin and skipjack tuna when associated with a FAD. Similarly to our study, Holland et.al (1990) observed that bigeye tuna swam at significantly greater depths during the daytime than yellowfin tuna. In addition, they showed greater shifts between daytime and nighttime distributions. Furthermore, Dagorn et al. (2000a), Musyl et al. (2003) and Schaefer and Fuller (2002, 2010) observed similar diel patterns. Conversely, Schaefer and Fuller (2005) observed that bigeye exhibited the reverse diel pattern with greater mean depths at night than during the day.

Not surprisingly, bigeye tuna were swimming deeper than the other two tuna species, for individuals of roughly same sizes. If such vertical segregations are not enough for developing further potential mitigation techniques targeting skipjack and not bigeye tuna, this information is very useful for better interpretation of data from echosounder buoys (see Lopez et al. 2010).

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## References

Brill RW, Block BA, Boggs CH, Bigelow KA, Freund EV, Marcinek DJ (1999) Horizontal movements and depth distribution of large adult yellowfin tuna (Thunnus albacares) near the Hawaiian Islands, recorded using ultrasonic telemetry: implications for the physiological ecology of pelagic fishes. Mar Biol 133:395–408

Castro JJ, Santiago JA, Santana-Ortega AT (2002) A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis. Rev Fish Biol Fish 11:255–277

Cayré PJ, Chabanne (1986) Marquage acoustique et comportement de thons tropicaux (albacore; *Tlzuiznus albacares,* et listao: *Katsuwonus pelamis)* au voisinage d'un dispositif concentrateur de poissons. *Océanogr. trop.* 21:167:183

Cayré P (1991) Behaviour of yellowfin tuna (Thunnus albacares) and skipjack tuna (Katsuwonus pelamis) around fish aggregating devices (FADs) in the Comoros Islands as determined by ultrasonic tagging. Aquat Living Resour 4:1–12

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

Dagorn L., Josse E., Bach P. 2000b. Individual differences in horizontal movements of yellowfin tuna (*Thunnus albacares*) in nearshore areas in French Polynesia, determined using ultrasonic telemetry. Aquatic Living Resources, 13: 193-202.

Dagorn L, Holland KN, Itano DG (2007) Behavior of yellowfin (Thunnus albacares) and bigeye (T. obesus) tuna in a network of fish aggregating devices (FAD). Marine Biology 151:595–606

Dempster T, Taquet M (2004) Fish aggregation device (FAD) research: gaps in current knowledge and future directions for ecological studies. Rev Fish Biol Fish 14(1):21–42

Dizon AR, Brill HS, Yuen (1978) Correlations between environment, physiology and activity and the effects of thermoregulation in skipjack tuna. *In:* The Physiology Ecology of Tunas. G. D. Sharp, A. E. Dizon ed., Academic Press, New York, 233-259

Fonteneau A (2003) Prospects for the management of FAD fisheries in the Indian Ocean In: Report of the Fifth Session of the IOTC Working Party on Tropical Tunas, Victoria, Seychelles, 3-12 June 2003. Indian Ocean Tuna Commission Document No. WPTT-03-04

Fréon P, Dagorn L (2000) Review of fish associative behaviour: towards a generalisation of the meeting point hypothesis. Rev. Fish. Biol. Fish 10:183–207

Frusher SD (1986) Utilization of small-scale fish aggregation devices by Papua New Guinea's artisanal fishermen In: The First Asian Fisheries Forum, edited by J.L. Maclean, L.B. Dizon and L.V. Hosillos. *Asian Fish.Soc., Manila*, pp371–4

Girard C, Dagorn L, Taquet M, Aumeeruddy R, Peignon C, Benhamou S (2007) Homing abilities of dolphinfish (Coryphaena hippurus) displaced from fish aggregating devices (FAD) determined using acoustic telemetry. Aquatic Living Resources, 20:313–321

Gooding RM, Magnusson JJ (1967) Ecological significance of a drifting object to pelagic fishes. Pacific Science, 21:486–497

Higashi GR (1994) Ten years of fish aggregation device (FAD) design development In: Hawaii. Bull. Mar. Sci. 55(2–3), pp 651–666

Holland KN, Brill RW, Chang RK (1990) Horizontal and vertical movements of yellowfin and bigeye tuna associated with fish aggregating devices. Fish Bull 88:493–507

Klimley AP, Holloway CF (1999) School fidelity and homing synchronicity of yellowfin tuna, Thunnus albacares. Mar Biol 133:307–317

Meyer CG, Holland KN (2000) Movement patterns, habitat utilization, home range size and site fidelity in the whitesaddle goatfish, Parupeneus porphyreus, in a marine reserve. Env Biol Fish 59(3):235–242

Moreno G, Dagorn L, Sancho G, Itano D (2007) Fish behaviour from fishers' knowledge: the case study of tropical tuna around drifting fish aggregating devices (DFADs). Can J Fish Aquat Sci 64:1517-1528

Musyl MK, Brill RW, Boggs CH, Curran DS, Kazama TK, Seki MP (2003) Vertical movements of bigeye tuna (Thunnus obesus) associated with islands, buoys, and seamounts near the main Hawaiian Islands from archival tagging data. Fish Oceanogr 12:152–169

Ohta I, Kakuma S (2005) Periodic behavior and residence time of yellowfin and bigeye tuna associated with fish aggregating devices around Okinawa Islands, as identified with automated listening stations. Mar Biol 146:581–594

Parin NV, Fedoryako BI (1992) Pelagic fish communities around floating objects in the open ocean In: Fishing for Tunas Associated with Floating Objects, International workshop. Inter-American Topical Tuna Commission, San Diego, California. pp 447-458

Schaefer KM, Fuller DW (2002) Movements, behavior, and habitat selection of bigeye tuna (Thunnus obesus) in the eastern equatorial pacific, ascertained through archival tags. Fish Bull 100:765–788

Schaefer KM, Fuller DW (2005) Behavior of bigeye (Thunnus obesus) and skipjack (Katsuwonus pelamis) tunas within aggregations associated with floating objects in the equatorial eastern Pacific. Mar Biol 146:781–792

Schaefer KM, Fuller DW (2010) Vertical movements, behavior, and habitat of bigeye tuna (Thunnus obesus) in the equatorial eastern Pacific Ocean, ascertained from archival tag data. Mar Biol

Taquet M, Dagorn L, Gaertner JC, Girard C, Aumerruddy R, Sancho G, Itano D (2007) Behavior of dolphinfish (Coryphaena hippurus) around drifting FAD as observed from automated acoustic receivers. Aquatic Living Resources, 20: 323–330