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Vertical behavior and habitat preferences of yellowfin and bigeye tuna in the South West Indian Ocean inferred from PSAT tagging data

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ABSTRACT

We present here preliminary results of PSAT tagging experiments conducted on bigeye tuna *Thunnus obesus* and yellowfin tuna *Thunnus albacares* in the South West Indian Ocean. We analyzed in this paper the vertical behavior and habitat preferences of the two tuna species. We found that bigeye and yellowfin tuna use distinct habitats during the day and night. At night, yellowfin tuna remains within the mixed layer while bigeye tuna is just below or moves around the thermocline. During the day, bigeye tuna reach colder and deeper layers between 300 and 600 m while yellowfin tuna stay around the thermocline.

KEYWORDS

PSAT tagging | Vertical movements | Habitat preferences | Thermocline | Yellowfin tuna | Bigeye tuna | South West Indian Ocean

1. Introduction

Bigeye tuna *Thunnus obesus* and yellowfin tuna *Thunnus albacares* are common tuna species in tropical regions where they are targeted by various fishing gears, mainly purse-seine and longline.

The regional ecology of yellowfin and bigeye tuna in the Indian Ocean: vertical behavior, habitat preferences, and migrations, is still poorly known despite previous attempts to deploy pop-up satellite archival tags (PSATs) on yellowfin tuna at least (in the BIOT: Schallert et al., 2013; in the Arabian Sea and Bay of Bengal: Premchand et al., 2014; off Zanzibar and Maldives, IOTC unpublished data).

Between November 2014 and July 2015, we tagged 32 yellowfin and 15 bigeye tuna with PSATs in the South West Indian Ocean (Reunion Island waters, east coast of Madagascar and Saya de Malha Bank) in order to study the vertical movements, behavior, habitat preferences and horizontal migrations of these two tuna species within framework of IRD – CAP RUN research project PROSPER (PROSpection and habitat of large PElagic fish in the EEZ of Réunion Island).

In the present paper, we first assess the performance of tag deployment and transmissions, and then we investigate the magnitude of diel migrations for the two tuna species and the potential relation with the mixed layer depth (MLD).

2. Material and Methods

2.1. Tags

Two types of PSATs were used in our tagging experiments: *miniPAT* by *Wildlife Computers Inc.* (Seattle, USA) and *LAT3400* by *Lotek Wireless Inc.* (St. John's, Newfoundland, Canada). Each type of tags collects data in different manner. Data cannot therefore be combined and were analyzed separately. In this paper, we present a preliminary analysis of data collected by *miniPAT* tags that already popped-up and finished transmitting their data (N = 27; Tab. 1).

MiniPAT tags were programmed to record depth, temperature and light, mostly for 90 days period, and for 180 days in a few cases (see Tab. 1). Time series for depth (5-min interval for 90 days deployments, 10-min interval for 180 days) was programmed to be always transmitted by satellite, as well as light levels recorded during twilight periods (used for geolocation), and summarized data such as histograms of binned depth (0-10; 10-30; 50 30; 50-100; 100-150; 150-200; 200-250; 250-300; 300-500; 500-800; >800 m) and binned temperature (0-3; 3-6; 6-9; 9-12; 12-15; 15-18; 18-21; 21-24; 24-27; 27-30; 30-33; >33°C) histograms (4-hour interval), and profiles of depth and temperature (PDT; 4-hour interval) (Wildlife Computers, 2013). Tags were fitted with *Wilton* and *Domeier* anchors (attached to the tag with a stainless steel tether).

2.2. Tuna tagging

Among the 27 *miniPATs* that already transmitted data, 17 were deployed on yellowfin tuna (91-164 cm FL) and 10 on bigeye tuna (101-141 cm FL) at the occasion of 3 tagging cruises carried out by IRD and CAP RUN (PROSPER research project) in the southwest Indian Ocean (Saya de Malha Bank, east coast of Madagascar and Reunion Island waters) in 2015 onboard French commercial longline vessel *Le Bigouden* (21.4 m LOA) (Fig. 1). Tuna were caught using short longline gear (average 313 hooks, range 278-479 hooks) with squid-baited hooks (in 5 sets we used a mix of squid and mackerel bait). The longline was deployed in surface layers during crepuscular periods: dusk and dawn. Very short drifting (period between end of setting and start of hauling, average 3.1 hours, range 1.9-4.0) and soaking time (average 7.5 hours, range 5.9-10.5) were used to maximize the chance of catching tuna alive. Also, branchlines were equipped with circle hooks in order to reduce potential hooking injury. We realized 36 fishing operations over 39 days at sea.

Tuna candidates for tagging were brought onto the deck of the boat using a lifting flexible cradle. To keep the tuna calm inside the cradle while on vessel deck, the eyes of the fish were covered with wet chamois synthetic cloth. In most cases a hose with running seawater was immediately placed in the tuna's mouth to ensure gills oxygenation. After removing the hook and ensuring the tuna was in good condition (active fish, with no gill, mouth or gut bleeding, no serious external or eyes injury, etc.), we inserted the tag anchor below the base second dorsal fin through the pterygiophores using an applicator provided by the tag manufacturer. In addition, an IOTC spaghetti tag was placed below the base of the first dorsal fin. The tagged tuna was then measured and carefully released into the ocean using the lifting cradle.

2.3. Tag retention and performance

Tag performance is assessed in terms of retention on the fish and data transmission through satellite based on metrics from Musyl et al. (2011). Retention in number of days (= days at liberty) is presented by individual (Tab. 1) and by species (Fig. 3), as well as considering the type of anchor used: *Wilton* vs. *Domeier* (Fig. 4). Data transmission is assessed by looking at (i) the global rate of tag reporting, (ii) the rate of successful transmissions (RST) for each tag, and (iii) the data density in transmitted data (DD):

(i) $RTR = T_{reported} / T_{total}$

where RTR: rate of tag reporting; T: number of tags

(ii) $RST = M_{received} / M_{sent}$

where RST: rate of successful transmission; M: number of messages

(iii) $DD = 1/2 * (D_{depth} + D_{light}) / D_{at\ liberty}$

where DD: data density; D: number of days

Also we propose a fault tree that summarizes PSATs deployments (Fig. 2).

2.4. Horizontal movements

Light-based geolocation data were not processed for this study. We only present horizontal movements based on straight distances between tagging and tag pop-up locations to appreciate the dispersion over the deployment period (Fig. 1; Tab. 1).

2.5. Vertical behavior and habitat

First of all, tags that were suspected to have spent a period in a predator's stomachs were excluded from the following analyses (tags #142811, #142812, #142821, #150815).

For both tuna species, we provide day versus night distributions of time-at-depth inferred from 5-min (or 10-min) resolution time series (Fig. 5). Dawn/dusk observations were excluded from day and night periods which correspond to 08:00-17:00 local time and 20:00-05:00 respectively.

The corresponding time-at-temperature distributions were directly taken from binned temperature histogram data summarized over 4-hour intervals (Fig. 6). As for depth time series, we excluded dawn/dusk observations.

As examples, we also provide characteristic mean daily depth profiles for a bigeye tuna (#142831) and a yellowfin tuna (#142826) to illustrate the general pattern of vertical movements, including the timing of descent and ascent (Fig. 7).

Figure 8 illustrates an individual tag deployment (#142826) including the depth profile time series, the interpolated temperature time series, and light measurements during twilight phases (Fig. 8). Temperature time series (that is not transmitted) was reconstructed by interpolation using PDT data (Profile of Depth and Temperature provided for 4-hour intervals) and depth time series (5-min interval).

PDT was also used to display the vertical thermal structure of the water column and to calculate the isothermal layer depth (ILD = thermocline; Kara et al., 2000) (Figs. 9 and 10). Figure 11 shows the thermocline along with the day and night positions (daily average and 95% confidence interval) of a bigeye tuna (#142831) and a yellowfin tuna (#142826).

3. Results

3.1. Tag retention and performance

Most tags (except three) transmitted data (RTR = 89%). Two of the tags that failed to transmit data were attached to bigeye tuna and one tag to a yellowfin. Among non-faulty tags, 13% met the programmed pop-up date. The other 87% corresponding to prematurely released tags can be divided in two categories: (i) cases of mortality in which the emergency release mechanism was triggered and mortality by predation (33%), and (ii) cases of attachment failure: faulty anchor, tether or attachment of tether to the tag (67%) (Fig. 2). Since none of the tags were recovered, the causes of attachment failure cases could not be identified.

Tag retention curves show that tags held better on bigeye than yellowfin tuna (Figs. 3 and 4). Also, *Domeier* anchors maintained tags on the fish for a longer period compared to *Wilton* anchors (Fig. 4). The longest tag deployment observed for bigeye tuna was 104 days using a *Domeier* anchor (originally prorammed for 180 days) while the longest yellowfin tuna deployment was 55 days with a *Wilton* anchor.

The rate of successful transmission (RST) was 15±3%, and data density (DD) was generally above 90% (expect for predated tags #142811 and #142812), even for the longest deployments (Tab. 1).

3.2. Horizontal movements

Tag pop-up locations demonstrate wide tuna dispersion in the western Indian Ocean: from limited displacements within tagging areas to long-distance migrations towards South Africa, Mauritius and Seychelles (Fig. 1). The longest distance traveled was observed for a yellowfin tuna (#142826): 1044 nmi in 54 days, i.e., an average speed of about 19 nmi per day. Comparable speeds were recorded for several other yellowfin tuna tracked for shorter periods. Bigeye tuna also demonstrated several long-distant movements: 798 nmi and 686 nmi with average speeds of 7.7 and 8.5 nmi per day respectively. In general, migratory activity of yellowfin tuna was more pronounced than for bigeye tuna. Most pop-up locations for bigeye tuna were close to tagging/release locations even for tags that achieved the full 90-day deployment period (Table 1).

3.3. Vertical behavior and habitat

Bigeye tuna visited deep layers between 300 and 600 m (median 450 m) during the day with occasional visits to the surface, and remained between 0 and 200 m (median 80 m) at night. Yellowfin tuna rarely went deeper than 250 m during the day (median 100 m) and rather stayed very close to the surface at night (Fig. 5). The range of temperature experienced by bigeye tuna was therefore greater since they visited deeper layers (6-33°C) with most of their time spent in waters between 9 and 15°C during the day and mostly between 21 and 30°C in upper layers at night. Yellowfin tuna remained above 300 m (9-33°C) and spent most of their time in waters between 21 and 30°C (Fig. 6). Daily mean depth profiles provided for one individual of each species confirmed the general patterns described above (Fig. 7). Figure 7 also shows the variability that exists in daily depth profiles for individual tuna and confirms that bigeye tuna undertake occasional visits to the surface during the day period. For both species, descent and ascent are timed on dawn and dusk phases respectively.

Data collected by certain tags show examples of environmental variability during tracking periods. Yellowfin tuna #142826 experienced a global temperature decrease as (i) it traveled southwards, and as (ii) austral winter is setting in (Fig. 8). Also, it appears that this tuna crossed thermal fronts at several occasions which corresponds to the sharp breaks in the interpolated temperature time series (Fig. 8). Figures 9 and 10 show the thermal structure of the water column encountered by this tuna. The thermocline (at 50 m on average) displays sharp variations (up to 100 m) that indicate that the tuna crossed thermal fronts moving across water masses. There is evidence of at least two clusters of temperature-depth profiles suggesting distinct water masses (Figure 10).

The relation between day/night positions (averaged over 4-hour intervals) and the thermocline of yellowfin tuna #142826 and bigeye tuna #142931 suggest that yellowfin tuna stay in the upper layer above the thermocline at night and exploit the thermocline during the day, while bigeye tuna take advantage of the thermocline at night (Fig. 11).

4. Discussion

4.1. Tag retention and performance

Data collected and transmitted by *miniPAT* tags provided a large amount of useful information to study tuna vertical behavior and habitat preferences. The proportion of messages received by satellite was above 10% and therefore very satisfying, which in turn led to high data density retrieved by satellite, with very limited holes in times series, even for the longer deployments. Only few tags did not report data, which may be due to tag failure or external causes of damage on the tag (see examples in Musyl et al., 2011).

Tags held better on bigeye than yellowfin tuna, which is consistent with major findings reported in the literature (e.g., Evans et al., 2011; Musyl et al., 2011; Lam et al., 2014). High swimming speeds and accelerations of yellowfin tuna might be an explanation for that pattern. We actually anticipated that issue and tagged almost twice more yellowfin tuna than bigeye tuna. In turn, we ended up with a comparable number of cumulated days of data for bigeye tuna (530) and yellowfin tuna (449).

Anchors play a key role in tag retention on the fish. It appears that we got better results with *Domeier* than *Wilton* anchors. However, conclusions on anchor performance should be considered with caution due to small sample size, and the potential effect of tagging person experience (not considered in this analysis). In practice, settling a tag with a *Domeier* anchor through the pterygiophores is simpler and need less caution and experience.

4.2. Vertical behavior and habitat preferences

Our tagging experiments on bigeye tuna and yellowfin tuna in the South West Indian Ocean show that similarly to other oceans, both tuna species undertake diel migrations. Ascent and descent are triggered by the dusk and dawn phases respectively. This study also demonstrates that bigeye and yellowfin tuna use distinct day and night habitat in the Indian Ocean. Bigeye tuna reaches depths between 300 and 600 m during the day with occasional visits to the surface comparably to other oceans (e.g., Coral Sea: Evans et al., 2008; tropical Pacific: Schaefer and Fuller, 2002; Gulf of Mexico: Hoolihan et al., 2014) where it experiences colder waters and low light conditions to which it is adapted. Yellowfin tuna does not have the same capabilities and remains near the thermocline during the day. At night, the separation is less clear but the bigeye tuna seems to stay below or oscillates around the thermocline while the yellowfin tuna is usually found above, and often in the first 20 m layer, comparably to the western and eastern Pacific (Evans et al. 2011; Shaefer et al., 2011).

Information collected by the tags on temperature clearly show that some tuna crossed fronts moving across water masses with distinct thermal signatures. This is the case for yellowfin tuna #142826 that was tagged off the east coast of Madagascar and traveled south and west towards South Africa for 54 days. This tuna probably went in and out the warm Agulhas Current that runs down the east coast of Africa (Whittle et al., 2008) as suggest the drastic changes in the vertical structure of water masses it encountered.

4.3. Perspectives

Next, we will focus on the estimation of fine-scale horizontal movements using light-based geolocation. This will allow us to analyze the detailed interaction and/or use oceanographic structures such as fronts, eddies, etc. by bigeye and yellowfin tuna species, as well as with the mixed layer depth, and potential effect of dissolved oxygen concentration.

5. Acknowledgements

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6. References

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Tables

#	Serial number	Species	FL (cm)	Program	Anchor	Tagging date	Tagging lat	Tagging lon	Pop-up date	Pop-up lat	Pop-up lon	Days at liberty	Distance (nmi)	RST (%)	DD (%)
142807	14P0458	YFT	162	90d	Wilton	18/02/2015	-10,953	60,236	24/02/2015	-10,557	59,203	6	65	16	95
142808	14P0417	BET	101	90d	Wilton	02/04/2015	-24,105	47,979	-	-	-	-	-	-	-
142809	14P0418	YFT	126	180d	Wilton	18/02/2015	-11,044	60,294	23/02/2015	-11,267	59,703	5	37	14	94
142810	14P0443	BET	141	90d	Wilton	16/02/2015	-11,214	60,386	20/02/2015	-11,138	60,423	4	5	14	93
142811	14P0444	YFT	140	180d	Wilton	21/02/2015	-11,137	60,338	09/04/2015	-9,920	60,335	47	73	15	52
142812	14P0445	YFT	92	90d	Wilton	18/02/2015	-11,011	60,274	25/02/2015	-11,108	60,222	7	7	15	88
142813	14P0447	YFT	148	90d	Wilton	21/02/2015	-11,185	60,368	03/03/2015	-10,700	60,373	10	29	15	97
142814	14P0454	YFT	91	90d	Wilton	21/02/2015	-11,197	60,377	17/04/2015	-10,902	60,530	55	20	16	99
142815	14P0455	YFT	160	90d	Wilton	18/02/2015	-10,951	60,238	-	-	-	-	-	-	-
142816	14P0456	YFT	131	90d	Wilton	17/02/2015	-11,091	60,303	05/03/2015	-16,185	58,573	16	322	15	98
142817	14P0569	YFT	118	90d	Wilton	29/03/2015	-22,504	48,658	08/06/2015	-8,268	49,207	71	855	13	95
142818	14P0571	YFT	107	90d	Wilton	31/03/2015	-23,328	48,276	10/05/2015	-24,540	47,650	40	81	16	88
142819	14P0574	YFT	164	90d	Wilton	28/03/2015	-20,970	50,294	05/04/2015	-19,033	50,992	8	123	16	96
142820	14P0578	BET	126	90d	Wilton	31/03/2015	-23,388	48,289	-	-	-	-	-	-	-
142821	14P0581	YFT	95	180d	Wilton	31/03/2015	-23,322	48,271	08/04/2015	-26,022	48,408	8	162	18	96
142822	14P0583	BET	107	90d	Wilton	02/04/2015	-24,163	48,008	01/07/2015	-21,622	49,735	90	180	16	93
142823	14P0584	YFT	154	90d	Wilton	30/03/2015	-23,215	48,308	30/04/2015	-29,175	48,758	31	359	18	98
142824	14P0585	BET	104	90d	Domeier	29/03/2015	-22,576	48,660	27/06/2015	-19,688	49,557	90	180	16	95
142825	14P0586	BET	119	90d	Wilton	30/03/2015	-23,227	48,323	07/06/2015	-21,957	49,007	69	85	16	95
142826	14P0587	YFT	158	180d	Wilton	30/03/2015	-23,084	48,345	23/05/2015	-31,852	31,258	54	1044	16	99
142827	14P0590	BET	118	90d	Wilton	29/03/2015	-22,575	48,345	02/06/2015	-22,887	50,990	65	115	16	97
142828	14P0591	YFT	119	90d	Wilton	29/03/2015	-22,576	48,939	19/05/2015	-23,133	48,923	21	37	16	98
142829	14P0598	YFT	151	180d	Domeier	30/03/2015	-23,291	48,367	20/05/2015	-23,488	49,117	21	43	15	99
142830	14P0600	BET	141	180d	Domeier	02/04/2015	-24,180	48,013	15/07/2015	-10,883	48,040	104	798	13	95
142831	14P0604	BET	122	90d	Wilton	02/04/2015	-24,177	48,013	01/07/2015	-27,090	46,072	90	204	15	91
142832	14P0606	YFT	156	90d	Domeier	29/03/2015	-22,576	48,660	04/05/2015	-22,890	57,557	36	492	16	97
150815	14P0797	BET	119	90d	Domeier	16/07/2015	-21,626	53,432	03/08/2015	-18,522	55,936	18	234	17	98

Table 1. Summary table of tag deployments. FL: fork length, RST: rate of successful transmissions, DD: data density, Distance: straight distance between tagging and pop-up locations.

8. Figures

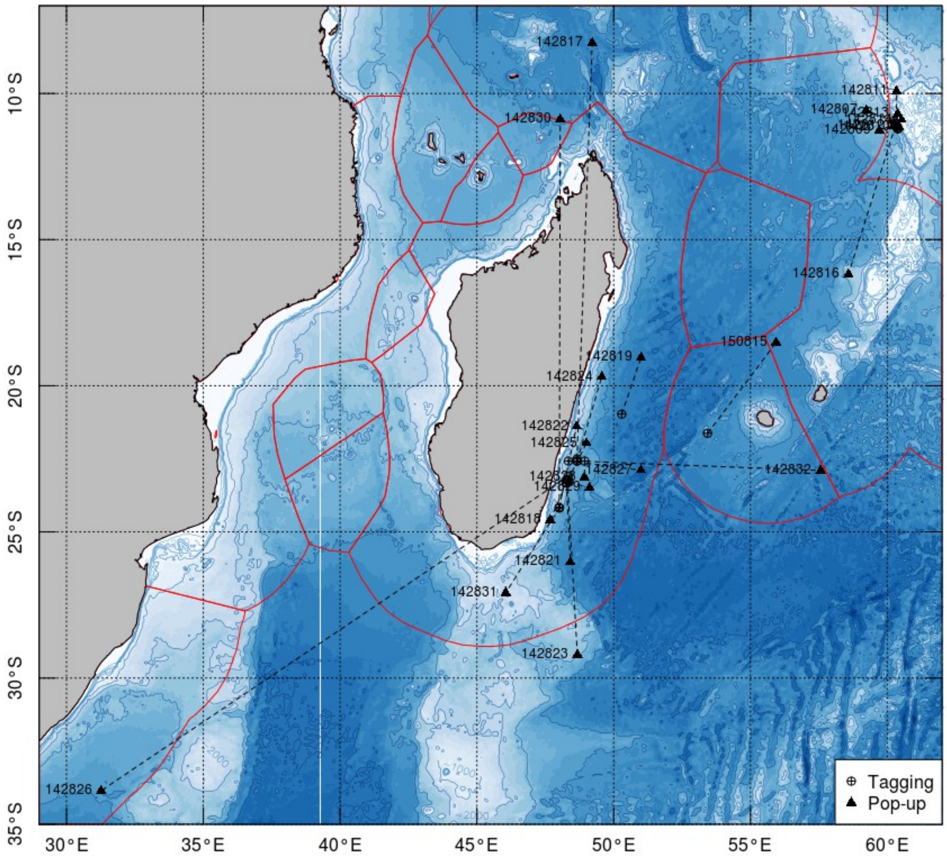

Figure 1. Tagging and pop-up locations.

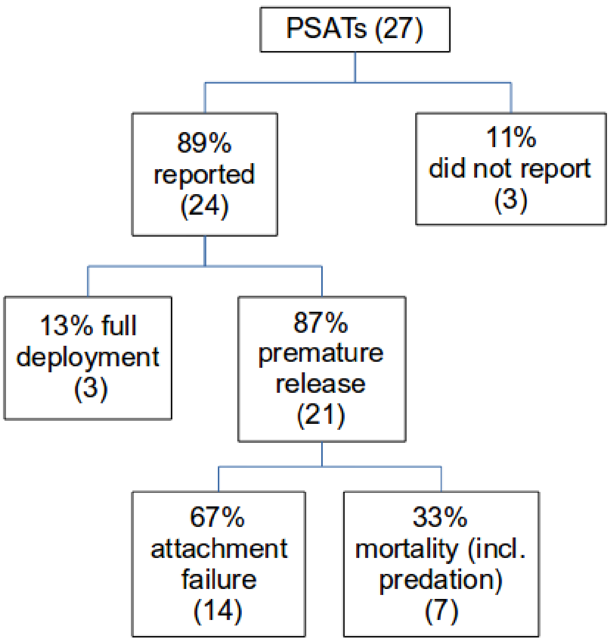

Figure 2. Fault tree summarizing PSAT deployments. The number of tags is given in the brackets.

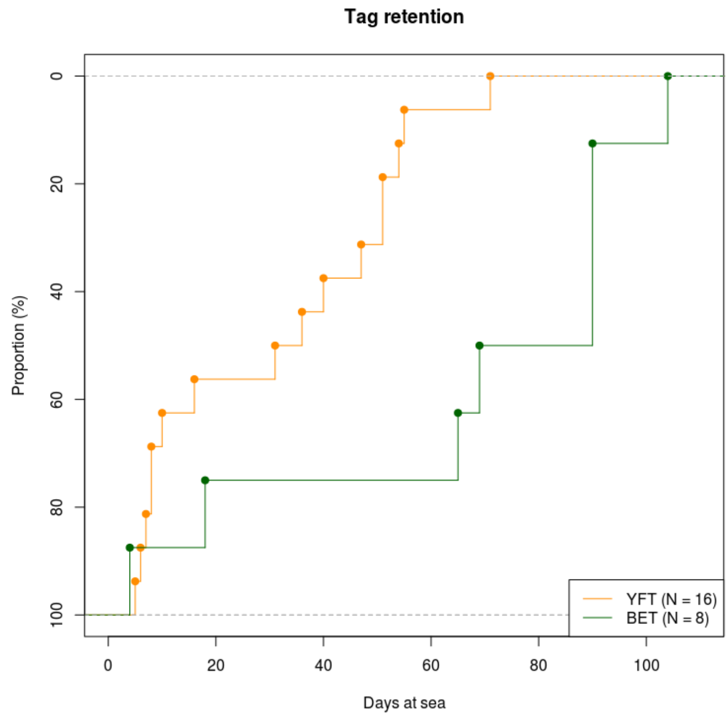

Figure 3. Tag retention on bigeye and yellowfin tuna.

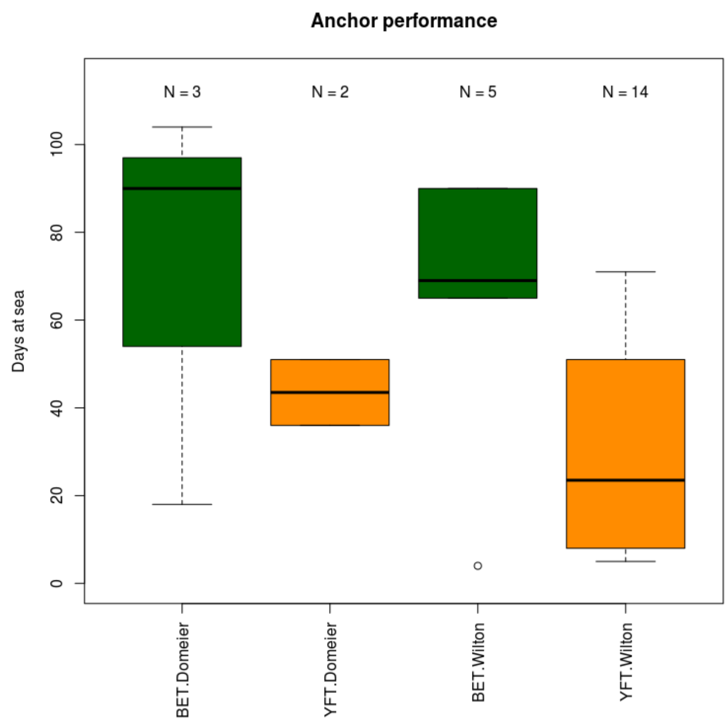

Figure 4. Anchor performance: *Domeier* anchor vs. *Wilton*, including the species effect.

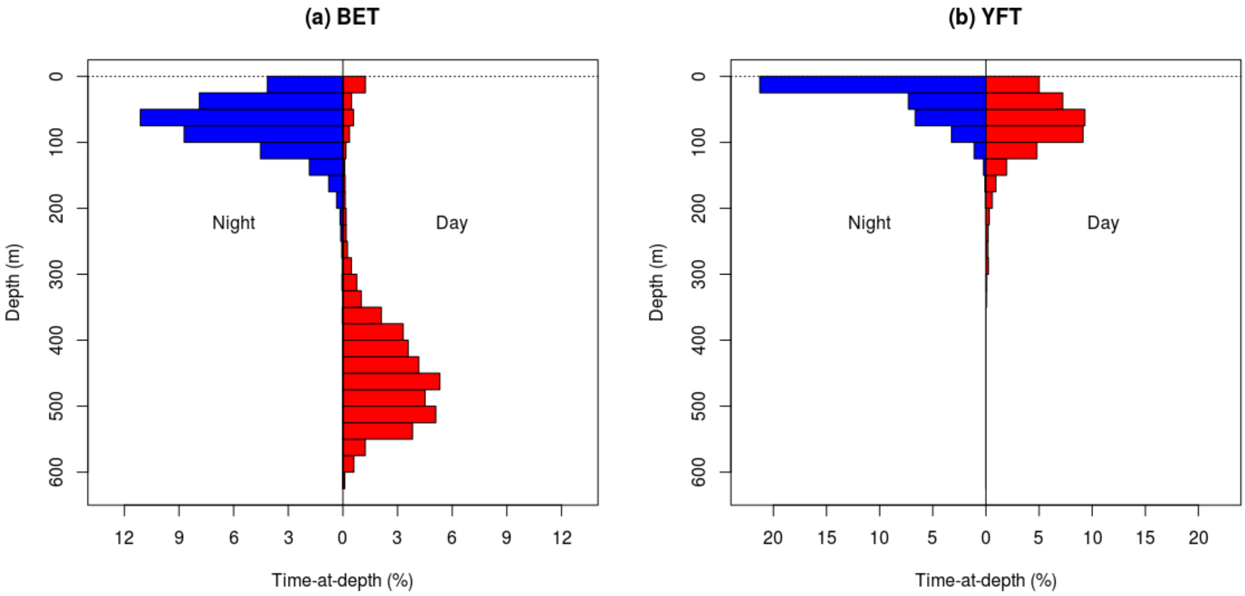

Figure 5. Percent of time-at-depth for (a) all bigeye tuna and (b) all yellowfin tuna derived from 5-min interval time series.

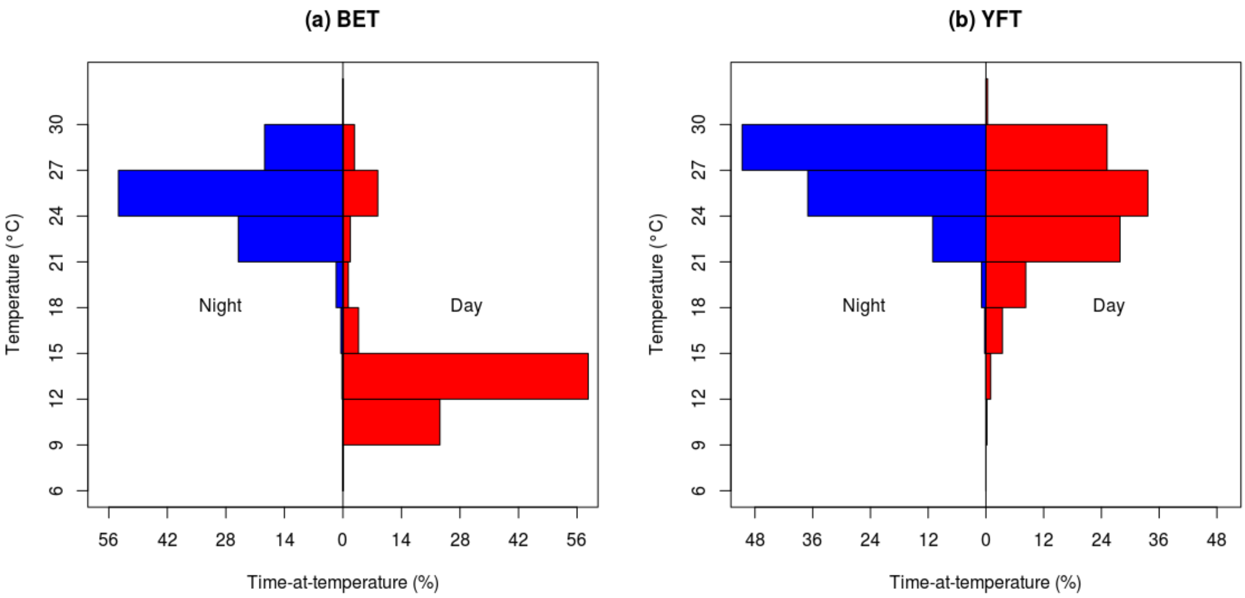

Figure 6. Percent of time-at-temperature for (a) all bigeye tuna and (b) all yellowfin tuna from 4-hours interval 3°C-binned data.

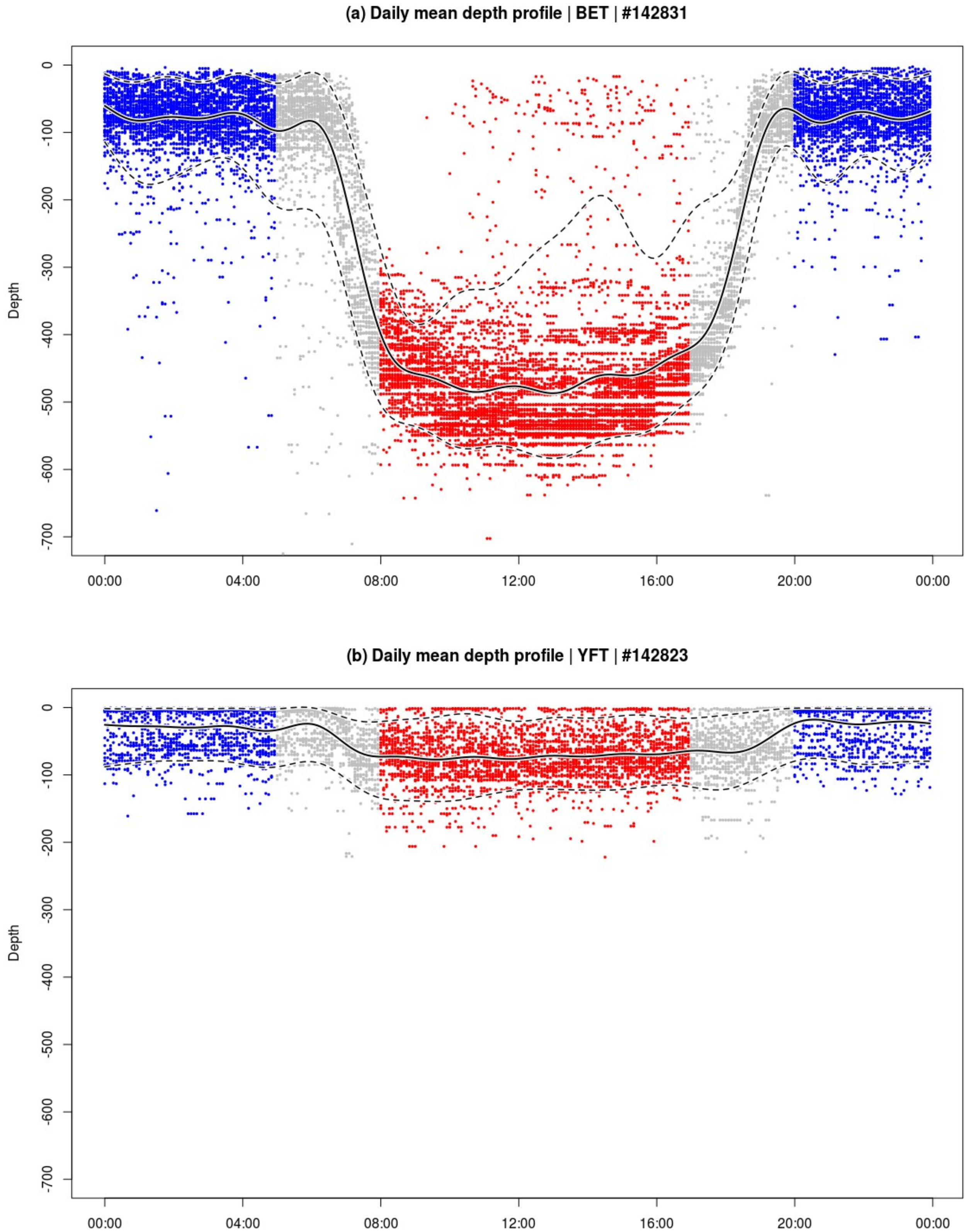

Figure 7. Mean daily depth profile for (a) a bigeye tuna (tag #142831) and (b) a yellowfin tuna (tag #142823). Blue, red, and grey dots receptively correspond to night, day and twilight observations.

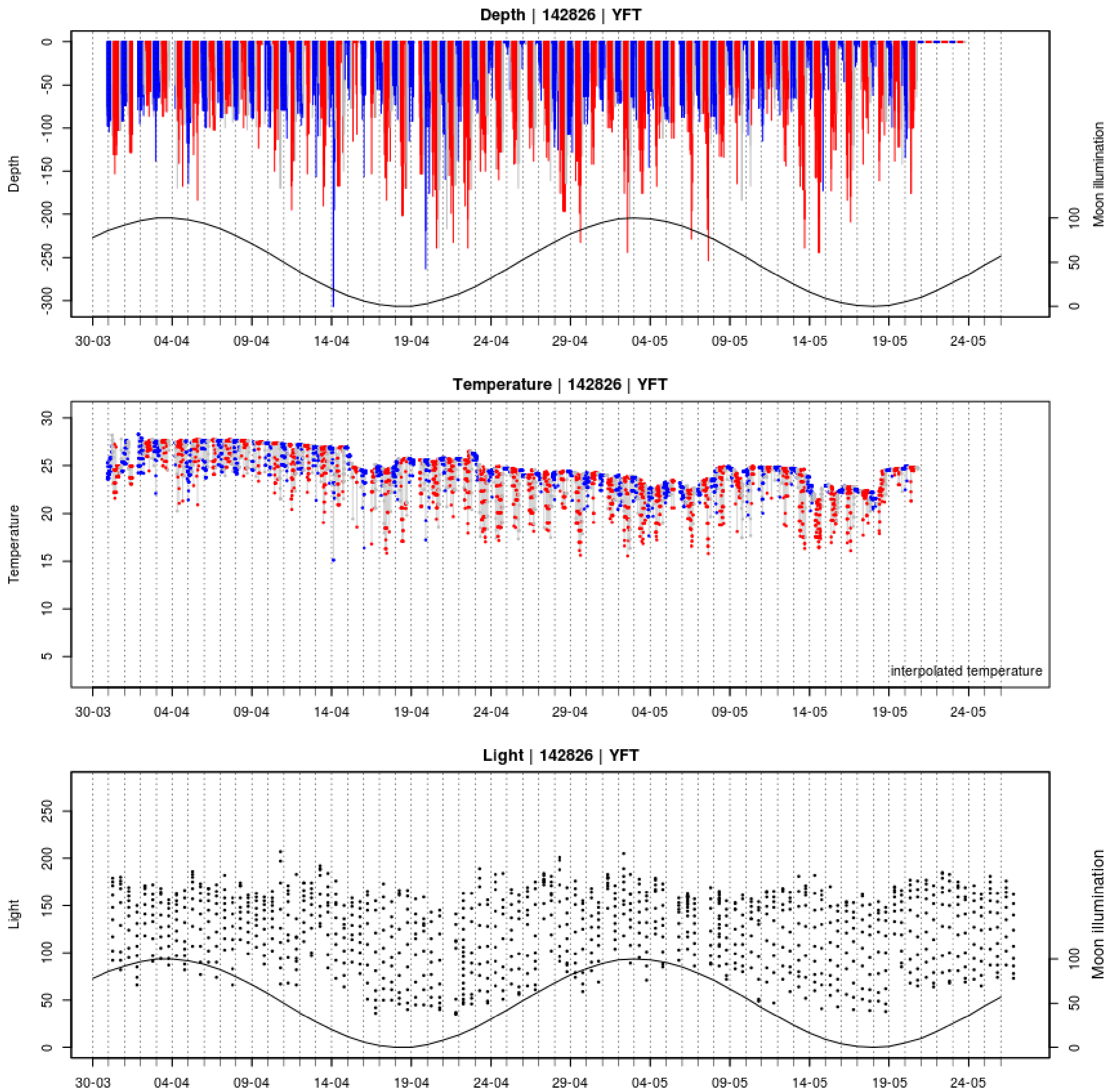

Figure 8. Depth, temperature and light time series for tag #142826 fitted on a 158 cm (FL) yellowfin tuna tagged on the east coast of Madagascar. Blue, red, grey bars and dots receptively correspond to night, day and twilight observations.

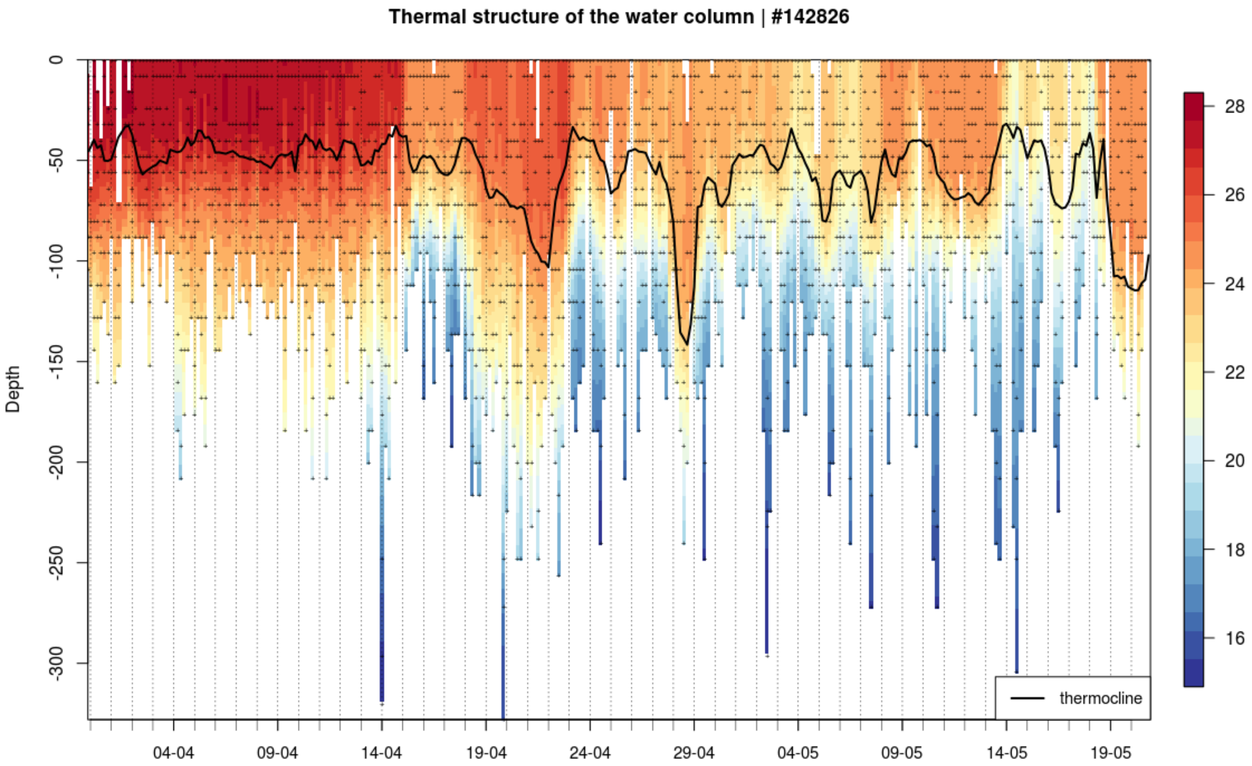

Figure 9. Thermal structure of the water column structure as sampled by a 158 cm (FL) yellowfin tuna (tag #142826). Crosses represent the original data points in the PDT file. Colorbar in °C.

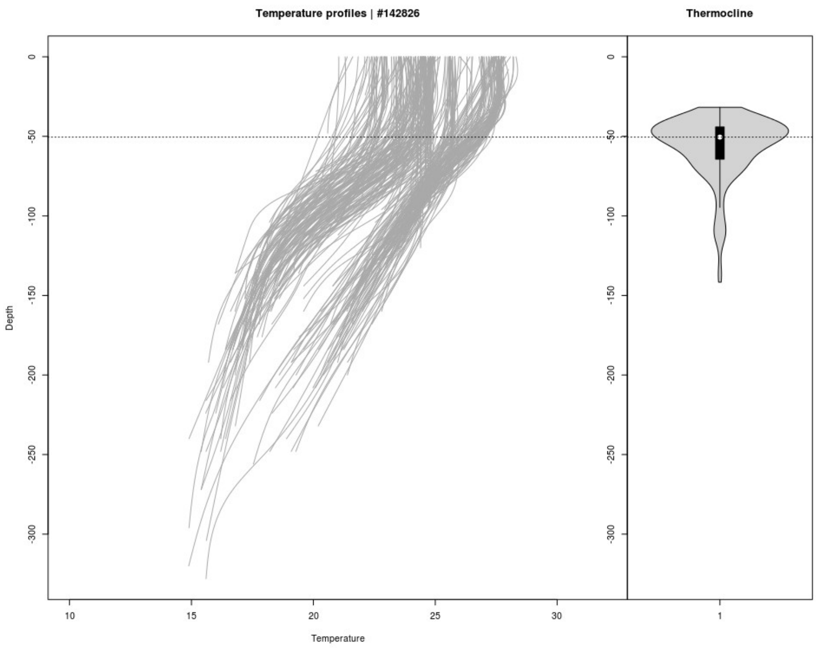

Figure 10. Temperature profiles and thermocline of tag #142826.

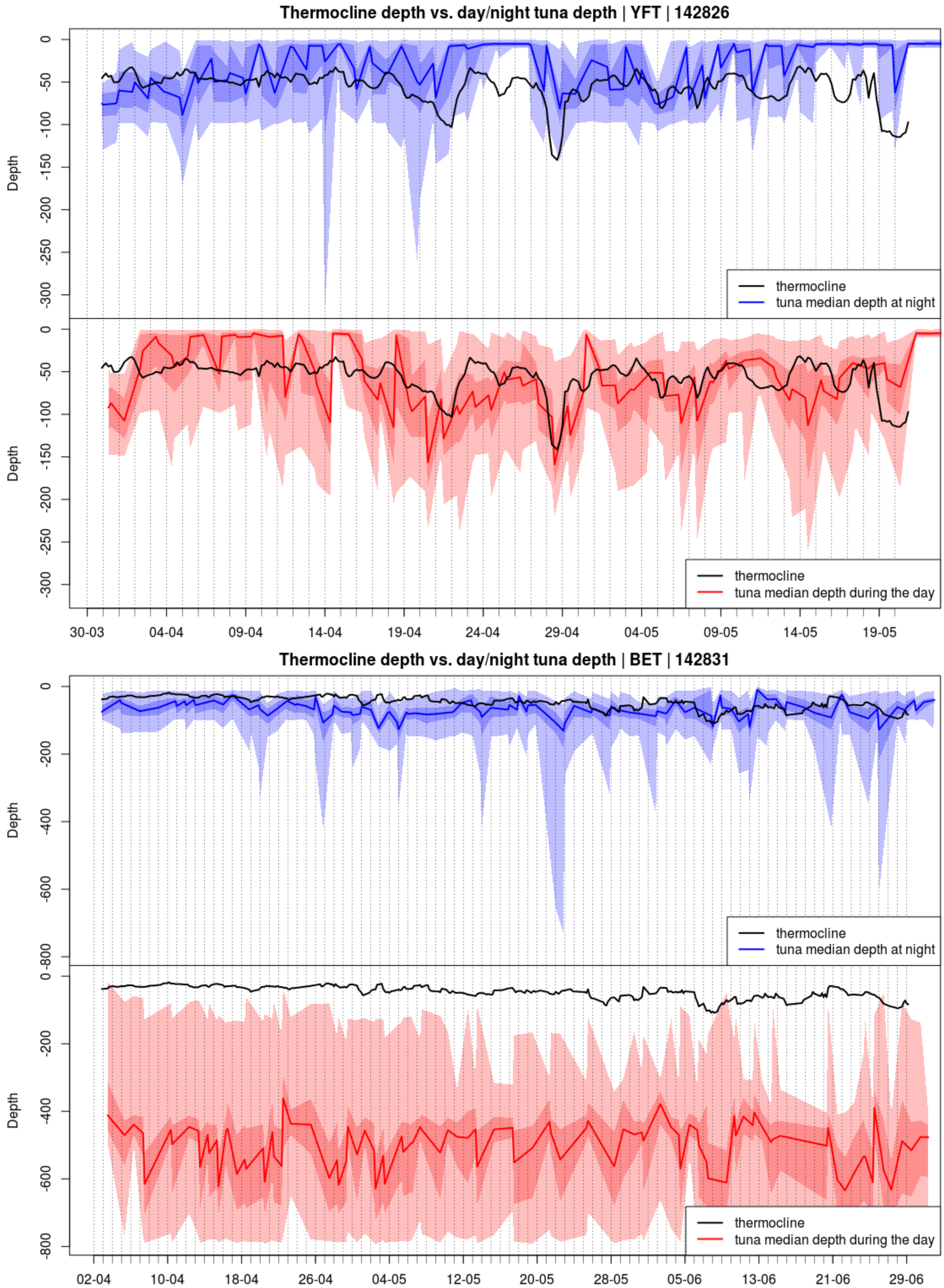

Figure 11. Average day/night positions (red/blue lines) of yellowfin tuna #142826 and bigeye tuna #142831 versus thermocline (black line). Shaded areas represent 50% and 95% CI.