

BLUEFIN TUNA MIGRATORY BEHAVIOR IN THE WESTERN AND CENTRAL MEDITERRANEAN SEA REVEALED BY ELECTRONIC TAGS

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SUMMARY

During 2008 and 2009 several tagging expeditions were carried out in the Mediterranean in order to determine Atlantic bluefin tuna trajectories and behavior. Tagging activities during 2008 were concentrated in the Western Mediterranean. In 2009 the Adriatic Sea area, where tagging with pop-up tags on wild tuna had never taken place before, was also covered. Pop-up satellite archival tags and internal archival tags were used for adults and juveniles respectively. In total 4 pop-up and 21 archival tags were deployed in 2008, while 11 pop-up and 2 archival tags were used in 2009. Tagged bluefin tuna weights ranged from 12 to 200 kg. Data from all pop-up tags was successfully recovered and their retention rates ranged from 1 to 172 days. Additionally, a 2008 archival tag was recovered after 391 days at liberty. None of the tagged tunas left the Mediterranean Sea during the whole tracking period. Results suggest a residence pattern for large adults north of the Balearic Islands in late summer, and a link between the Gulf of Lions and the Tyrrhenian Sea, and between the Adriatic Sea and the Libyan coast.

KEYWORDS: *Thunnus thynnus*, pop-up tags, archival tags, tagging, Western Mediterranean, Adriatic, migration

1. Introduction

The Atlantic bluefin tuna inhabits the North Atlantic Ocean and its adjacent seas and has been fished since ancient times (Fromentin and Powers 2005, Rooker *et al.* 2007). Stocks of this species have been at critical levels in recent decades, leading to the likely collapse of the population in the western Atlantic and the high risk of collapse in the eastern Atlantic and the Mediterranean (Safina and Klinger, 2008; SCRS, 2008; MacKenzie *et al.*, 2008). Such figures urgently call for a clearer understanding of bluefin tuna biology to enable the implementation of the most effective management measures.

Few studies involving electronic bluefin tuna tagging have been carried out in the Mediterranean. De Metrio *et al.* (2004, 2005a, b) tagged bluefin tuna in fishing traps and tuna farms with Pop-up Archival Tags (PAT) providing incomplete results due to some technical problems. A study from fish tagged in a tuna farm in Croatia (Yamashita and Miyabe, 2000) focused on vertical movements of the fish. More recent studies, using Pop-up Satellite Archival Tags (PSAT), highlighted the importance of the Western Mediterranean not only for spawning but also as an ecological foraging or overwintering area (Fromentin 2009).

WWF in conjunction with Pesca Recreativa Responsable (an association of recreational anglers promoting the catch and release practice) and *C.N. Sambenedettese* in Italy deployed pop-up (PSAT) and archival tags on wild bluefin tuna in the Western Mediterranean and Adriatic Sea during 2008 and 2009. Here we report some preliminary results on the trajectories and vertical migration patterns for the fish tagged with pop-ups in 2008, on the trajectory of one fish tagged with an archival tag in 2008, and on trajectories of fish tagged with pop-up tags during 2009.

2. Methods

During 2008, two expeditions in August and September were carried out, while in 2009, a total of nine expeditions were carried out from May to September. Larger tuna were fished with rod and reel using the “brumeo” technique (chumming the water with sardines while anchored or drifting). When possible, the tunas were embarked and tagged on board, and the total length of each fish was measured to the nearest 0.5 cm. When it was not possible to lift the fish to

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the deck, the tags were fixed to the base of the second dorsal fin with a pole, and their weight was estimated by the tagging team. Two different darts were used for this type of tagging: Domeier (13) and Prince (2). Juveniles were captured by trawling lures and taken on-board to have an archival tag surgically-implanted (Wildlife Computers MK9). The tracks were estimated by CLS (Collecte Localisation Satellites), applying the Kalman filtering of the light-based geolocations and using satellite obtained sea surface temperature and bathymetry as constraints (Sibert *et al.* 2003, Royer *et al.* 2005, Nielsen *et al.* 2006, Nielsen *et al.* 2007). The geolocation error within the Mediterranean was estimated to be of one to two degrees (F. Royer pers. comm.).

Time at depth data for 2008 were provided as the percentage of time spent by each fish at the different depth layers during the 12 h intervals considered as day and night (i.e. 6:00 to 18:00 GMT and 18:00 to 6:00 GMT, respectively). The 2008 tags were programmed to register pressure, light level and water temperature at 60 second intervals. Depth layers were set at 0, 0-10, 10-20, 20-50, 50-100, 100-150, 150-200, then at 100 m intervals until 800, and over 800 m.

3. Results

All the pop-up tags transmitted their pop-off location to the satellite, and tracks were plotted for all those tunas that yielded information for over 30 days at liberty (Figures 1, 2 and 3). Nevertheless, since the initially programmed recording period was 12 months after the tagging date, premature release was detected in all the tags (Tables 1 and 2). Due to the transmission problems that are a big challenge in the Mediterranean, data were not always received with success. Tables 1 and 2 show the number of days during which light, depth and temperature data were successfully received, and the percentage and number of days for which at least one of the three set of data were received by the satellite.

Four wild adult tunas (estimated weight between 50 and 200 kg) were tagged with PSAT tags (Wildlife Computers Mk10) off the northern coast of Mallorca in August 2008 (**Table 1** and **Figure 1**), while 21 juvenile tunas (total average weight 14.9 ± 4.1 Kg) were tagged with archival tags, in the Gulf of Lions in September 2008 (**Figure 4**). In 2009, a total of 11 adult (**Table 2**) and two juvenile tunas were tagged. Two of the adult tunas, weighing between 70 and 130 kg were captured and tagged in Pollença (north of Mallorca); five tunas, ranging from 40 to 130 kg were tagged off the coast of Roses (Catalunya); and four tunas, weighing between 40 and 50 kg were tagged close to the Fosa di Pomo, a well known area for fishing adult tuna in the central Adriatic Sea. The two juveniles (17 kg on average) were tagged with archival tags off Roses, in the same area as the ones shown in **Figure 4** for the 2008 expedition.

All four pop-up tags deployed in mid-August 2008 detached from the fish and transmitted data via satellite after 60-125 days (**Table 1**). An accurate analysis of their tracks including the temporal dimension (not included here) showed that they all displayed a similar pattern, staying north of the Balearic Islands during at least the first 30 days (**Figure 1**). Then three of the fish migrated south-westwards from this region, with their tags detaching off the south-eastern coast of Spain and the north coast of Algeria between mid-October and mid-December 2008. The fourth tuna remained north of Mallorca for the entire 70 days before its tag detached at the end of October 2008.

One of the 21 archival tags deployed in a juvenile fish in 2008 was recovered after 391 days at liberty by a professional long liner, around 100 miles from the initial tagging position in the Western Mediterranean. This juvenile tuna tagged off the coast of Roses on August 31 2008 spent two months going around the Balearic Islands before traveling speedily eastwards in early November, and spending the following four months migrating slowly southwards between Corsica and Sicily, in the Tyrrhenian Sea. In early April 2009, when it was close to the eastern coast of Tunisia, it once again speedily migrated westwards, back to the Balearic Sea. It finally stayed there, circling the islands until its capture in late September 2009, a few miles away from the deployment point (**Table 3** and **Figure 5**). This last trajectory sheds a unique light onto the movements of juvenile tuna in the Mediterranean Sea throughout a 12-month period and a detailed analysis is currently on-going on the dataset recorded by the tag.

From the 11 pop-up tags deployed in 2009 (**Table 2**), five (three from the coast of Roses and two from the Adriatic Sea) detached from the fish within 20 days, providing little information about the behavior of the fish. The other six pop-ups, however, detached from the fish after 30 and up to 172 days (**Figures 2** and **3**). The two archival tags deployed in 2009 have not been retrieved yet.

The two adult tunas tagged in mid-August 2009 off the coast of Mallorca had a similar pattern to those tagged during the same month in 2008 (**Figure 2**), staying in the waters north of Mallorca for 30 and 70 days before their tags detached in mid-September and late October 2009, respectively (**Table 2**). The two tunas (which provided data for more than 30 days) tagged in late August and early September 2009 off Roses in the Gulf of Lions traveled south-eastwards (**Figure 2**), spending time in the waters between the Balearic Islands, and Sardinia and Corsica. When their tags popped-off in mid-December (after 102 and 104 days at liberty), one was still within these waters, while the other had traveled to the north of Sicily, in the Tyrrhenian Sea. This behavior was similar to the pattern observed for the juvenile tagged with the archival tag in 2008 (**Figure 5**).

Of the two pop-up tags deployed in the Adriatic Sea (off the coast of San Benedetto del Tronto, central-eastern Italy) that remained attached to the tuna for over 30 days (**Table 2**), one was attached for 103 days and showed that the fish had stayed in the Adriatic Sea for this entire period, seemingly spending more time in deeper areas (**Figure 3**). It was heading towards the northern Adriatic Sea when its tag detached in late December 2009. The second tuna showed a similar pattern during the first month, but afterwards it left the Adriatic Sea, traveling southwards and ending its registered track close to the Libyan coast after 172 days (**Figure 3**).

The analysis of the vertical movements of the four pop-up tags deployed in 2008 showed that for the period during which all tuna remained north of the Balearic Islands (**Figure 1**), they were largely confined to the first 50 m of depth both day and night (**Figure 6a**). The temperature profiles obtained from the tags (not shown here) revealed a strong thermocline between 20 and 50 m, as it would be expected in the Mediterranean for this time of the year. This pattern changed for the three large tunas (over 100 kg: TagIDs 86246, 86241 and 86239 in **Table 1**) which migrated to the southwest (**Figures 1** and **6b**). During their migration, and coinciding with a weakening of the thermocline, these tunas showed a clear preference for staying within the 0-10 m layer at night, and from 20 to 100 m depth during the day (nearly 70% of the time in both cases, **Figure 6b**). The 50-kg tuna, which did not migrate, did not show any change in its depth preference during its whole recorded trajectory.

4. Discussion

Our preliminary results revealed that none of the adult tuna left the Mediterranean during 30 to 391 days after being tagged. This finding is not consistent with a broad hypothesis that after spawning, Mediterranean bluefin tuna immediately initiate a trophic migration towards the Atlantic Ocean (De la Serna *et al.* 2004; De Metrio *et al.* 2005a, b). Previous electronic tagging results, which did not cover the Balearic Sea, concluded that after spawning, large bluefin tuna weighing over 150 kg migrated out the Mediterranean, though some individuals stayed to the west of the Strait of Gibraltar (De Metrio *et al.* 2005a).

The data from 2008 revealed a more complex pattern, with a phase of temporary residence during late summer in the north of the Balearic Islands, followed by a migration to the south-western Mediterranean at least until December (**Figure 1**). Moreover the 2009 PSAT tags together with the archival tag recovered in the Catalan Sea after 391 days, revealed an opposite migrating pattern. The resulting tracks showed that the archival tagged juvenile tuna (TagID 890138) did not leave the Mediterranean Sea; instead it moved south-eastwards crossing the Western Mediterranean and spending the winter in the Tyrrhenian Sea and in the south of Sicily. In spring, it then returned to the south of the Balearic Sea (**Figure 5**). This migration pattern was similar to that observed for one of the adult tunas tagged in the Gulf of Lions in 2009 (TagID 86247) (**Figure 2**). Overall, and until December, the four adult tunas tagged in 2009 in the Gulf of Lions remained in the Mediterranean Sea and stayed far away from the Strait of Gibraltar (**Figure 2**).

These results suggest that for some of the tuna associated to the Balearic Sea the Atlantic migration might either take place significantly later in the year or not happening at all in a given year. This is supported by another study (Fromentin 2009) that suggested a higher residency time in the Mediterranean than expected. The tunas tagged in the south of France during Fromentin's study were related to a possible foraging or overwintering area offshore the Gulf of Lions and one of them migrated to the central Mediterranean.

Regarding the vertical movements, a deeper analysis of the tuna tagged in 2008 off the island of Mallorca with pop-up tags showed two distinct behavioral patterns (**Fig.6a** and **b**). The first, "residential" pattern, included a continuous use

of the habitat from the surface down to the thermocline at 50 m depth in deep water areas, during day and night for more than a month in the aggregation area (north of the Balearic Islands). As suggested by Salat (1996), this region is dominated by mesoscale dynamic features characterized by a likely permanent and well-defined cyclonic gyre and a thermal front. Fromentin and Powers (2005) related these aggregations to foraging, which suggests that the aggregation to the north of the islands during 2008 was for feeding purposes and not for spawning as the area, time period and oceanographic conditions are not described as optimal for reproduction. Although the vertical movements of individuals tagged in the same place in 2009 have not been analyzed yet, trajectories were similar to those recorded in 2008.

The second, “migrational” pattern, which was only observed for the three larger tunas (≥ 150 kg) while travelling southwestwards, involved preference for surface waters during the night and frequent visits to deeper depths during the day. This change appeared to be related to the modification in prevailing hydrological conditions. On the other hand, the smaller tuna, which did not migrate, continued displaying the first, “residential” behavior until the tag detached (**Table 1**).

With the antecedents from 2008, it can be hypothesized that at least some of the bluefin tuna associated to the Balearic spawning ground engage in a trophic migration after spawning towards the southwestern Mediterranean (and possibly reaching the Atlantic). This migration follows a stepping stone pattern, whereby adult tunas spend considerable time foraging within waters north of the Balearic Islands first and occasionally in other appropriate areas later on. Additionally, a foraging or overwintering area seems to exist in the southern Tyrrhenian Sea, as suggested by the juvenile tagged in 2008 in the Gulf of Lions and the 2009 adults tagged with PSAT in the same area.

The Adriatic tags also suggest the preference of the fish for deeper areas there, probably linked to more biologically productive hydrological features. Besides, the longer lasting tag, attached for more than 5 months, showed a possible link between tunas that inhabit the Adriatic Sea and those aggregating off the Libyan coast. These results coincide with the description of the track of a juvenile tagged in a tuna farm in Croatia in 1999, which, after moving to the Adriatic, Ionian and Aegean Seas finished its track in waters off Libya (FAO, 2005), hence establishing a presumable link between the Adriatic demographic population and one of the main spawning areas for the species located off Libya.

The premature release detected in the pop-ups could be a combination of at least two factors: the use of a single anchor point (except in two tunas, see **Table 1**), affecting the integrity of the tag and the anchor; and the use of a pole to tag the tuna in the water resulting in a less accurate insertion of the dart. Another challenge is related to the transmission of data, where the lower percentage of data transmitted corresponds to the area close to Sicily.

Tagging activities are still on-going and will continue in the following years. More in-depth analysis on the data set gathered from 2008 and 2009 tags is also under way, and will integrate hydrological data to help understanding vertical and horizontal patterns.

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Table 1. Summary of the deployment and pop-off of the PSAT tags deployed in 2008 in the northern coast of Mallorca (Balearic Islands). 'Days with all data' refers to the successful transmission of the three data sets (depth, light and temperature). 'D/L/T' means days when only one or two of the three data sets were received.

Year	TagID	Area	Release position	Pop-off position	Size (kg)	Deployment	Pop-off	Days at liberty	Days with all data	Perc (%)	D/L/T	Perc (%)	Dart
2008	86241	Balearic Islands	40° 00' N 03° 09' E	38° 96' N 00° 21' E	150-200	17/08/2008	26/10/2008	70	20	28,6	39	55,7	Domeier
	86239	Balearic Islands	40° 00' N 03° 09' E	35° 88' N 00° 49' W	150-200	16/08/2008	19/12/2008	125	17	13,6	12	9,6	Domeier
	86246	Balearic Islands	40° 00' N 03° 09' E	37° 88' N 01° 74' E	100-150	16/08/2008	15/10/2008	60	32	53,3	5	8,3	Domeier
	86253	Balearic Islands	40° 00' N 03° 09' E	40° 26' N 04° 29' E	50	17/08/2008	29/10/2008	73	8	11,0	34	46,6	Domeier

Table 2. Summary of the deployment and pop-off of the PSAT tags deployed in the 2009 expeditions. Note: (*) Two darts were used to anchor the tag. 'Days with all data' refers to the successful transmission of the three data sets (depth, light and temperature). 'D/L/T' means days when only one or two of the three data sets were received.

Year	TagID	Area	Release position	Pop-off position	Size (kg)	Deployment	Pop-off	Days at liberty	Days with all data	Perc (%)	D/L/T	Perc (%)	Dart
2009	86245	Roses	42° 20' N 03° 20' E	39° 04' N 07° 09' E	80-90	03/09/2009	11/09/2009	8	-	-	-	-	Domeier
	86254	Roses	42° 18' N 03° 19' E	41° 39' N 04° 17' E	70-80	03/09/2009	23/09/2009	20	-	-	-	-	Domeier
	86248	Roses	42° 20' N 03° 20' E	41° 25' N 04° 03' E	60-70	04/09/2009	09/09/2009	5	-	-	-	-	Domeier
	86256	Roses	42° 23' N 03° 20' E	38° 58' N 05° 19' E	40-50	04/09/2009	17/12/2009	104	15	14,4	58	55,8	Prince
	86255	Balearic Island	40° 01' N 03° 01' E	39° 46' N 02° 40' E	90-130	14/08/2009	23/10/2009	70	42	60,0	5	7,1	Domeier
	86238	Balearic Island	40° 01' N 03° 01' E	39° 58' N 03° 37' E	60-70	15/08/2009	14/09/2009	30	15	50,0	1	3,3	Domeier
	86247	Roses	42° 20' N 03° 20' E	38° 09' N 14° 00' E	84	27/08/2009	07/12/2009	102	1	1,0	83	81,4	Domeier (*)
	86234	Adriatic	42° 48' N 14° 35' E	43° 46' N 13° 42' E	40- 50	13/09/2009	25/12/2009	103	4	3,9	68	66,0	Domeier
	86235	Adriatic	42° 47' N 14° 36' E	42° 57' N 14° 43' E	40- 50	13/09/2009	14/09/2009	1	-	-	-	-	Domeier
	86242	Adriatic	42° 49' N 14° 37' E	30° 38' N 19° 02' E	47	14/09/2009	05/03/2010	172	21	12,2	135	78,5	Domeier (*)
	86237	Adriatic	42° 48' N 14° 37' E	42° 37' N 15° 42' E	37	14/09/2009	19/09/2009	5	-	-	-	-	Prince

Table 3. Summary of the deployment and recapture of the archival tag deployed in 2008 in the Gulf of Lions.

Year	TagID	Area	Release position	Pop-off position	Size (kg)	Deployment	Recapture	Days at liberty
2008	890138	Roses	41° 56' N 03° 36' E	41° 01' N 02° 45' E	12,1	31/08/2008	26/09/2009	391

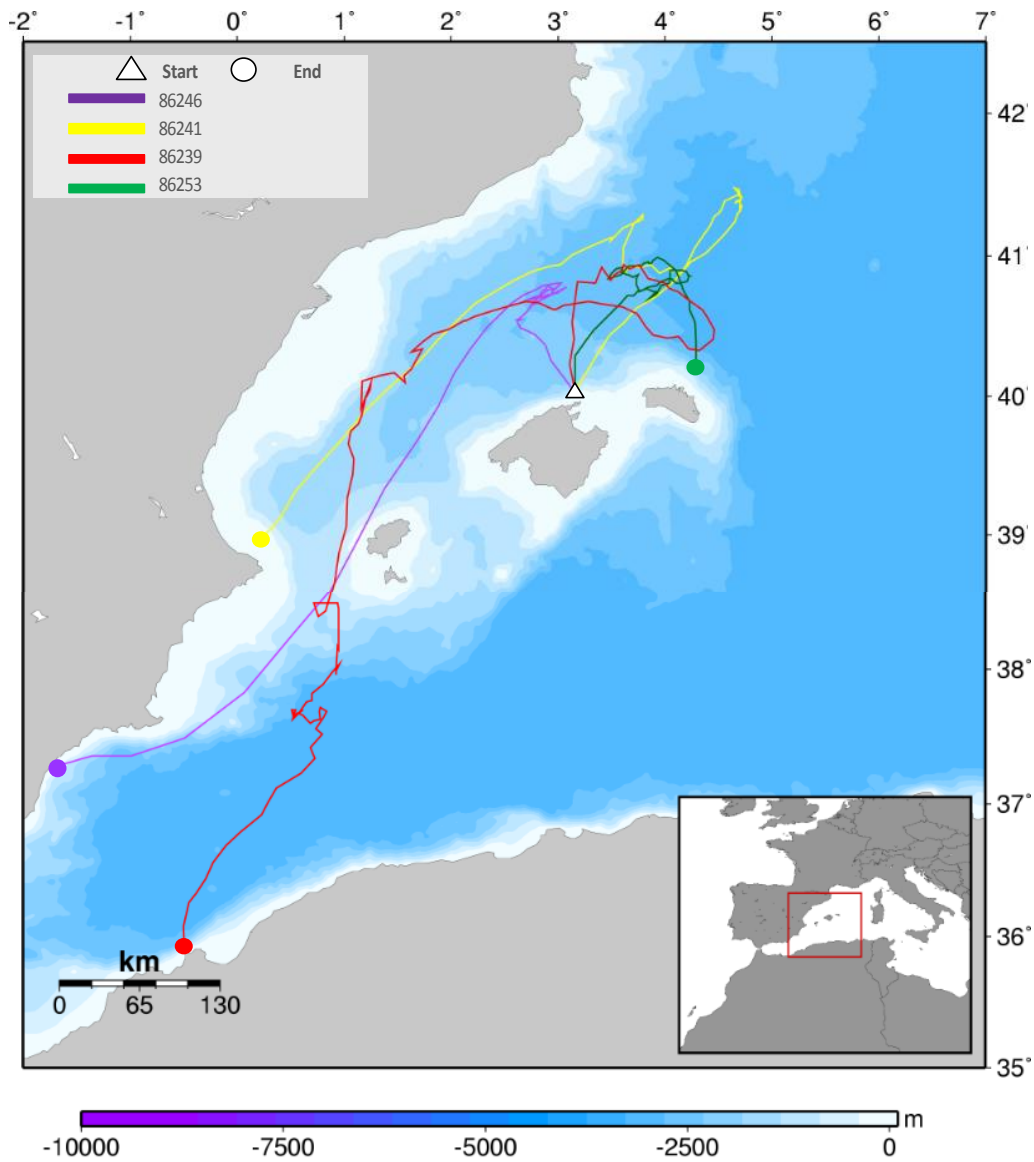


Figure 1. Estimated tracks for the four tunas tagged with PSAT tags in mid-August 2008 off Pollença (Mallorca Island).

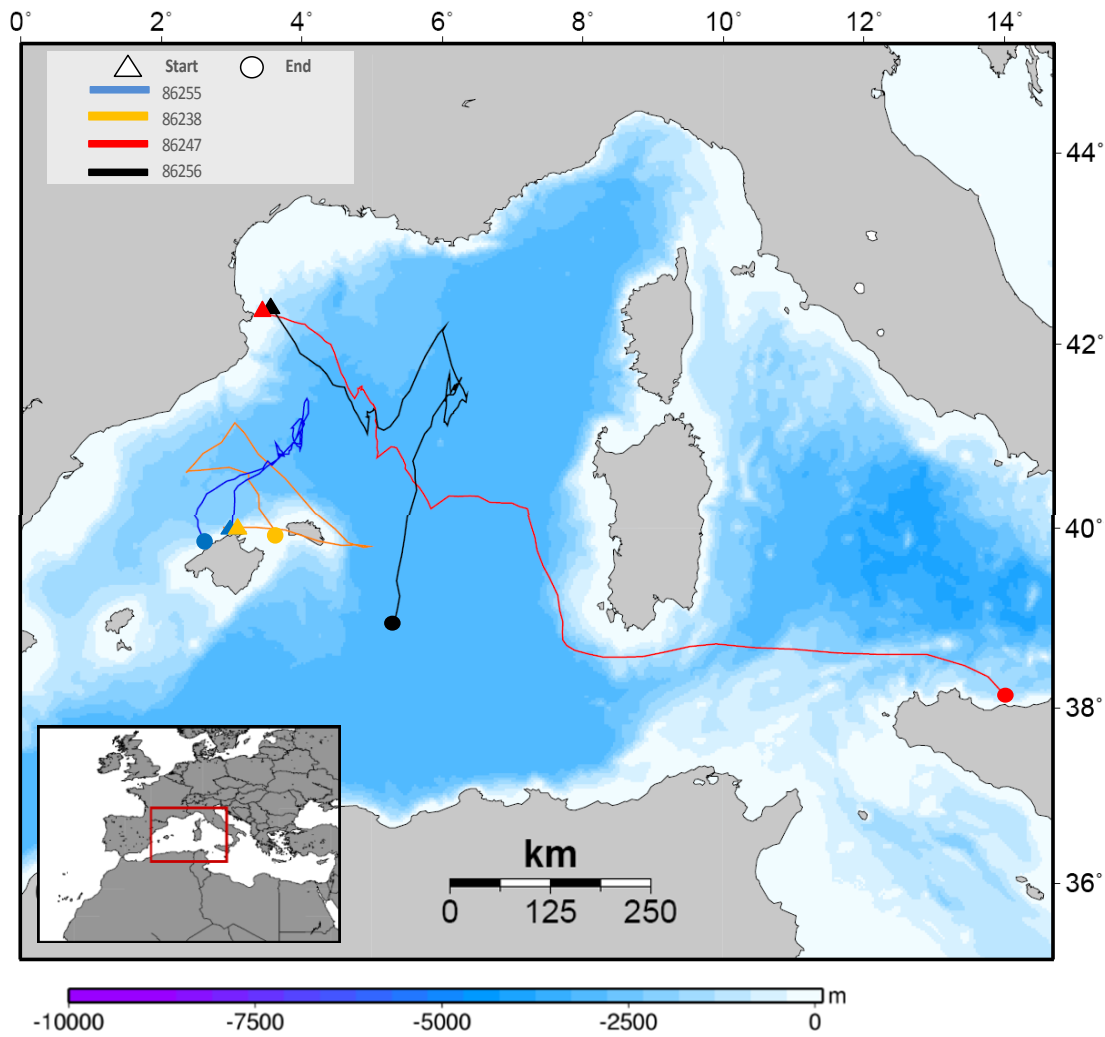


Figure 2. Estimated tracks for the four tunas tagged with PSAT tags (over 30 days) during 2009. Blue and Yellow: the two adult tunas tagged in mid-August off the coast of Mallorca; Red and Black: the two adult tunas tagged in early September off the coast of Roses in the Gulf of Lions.

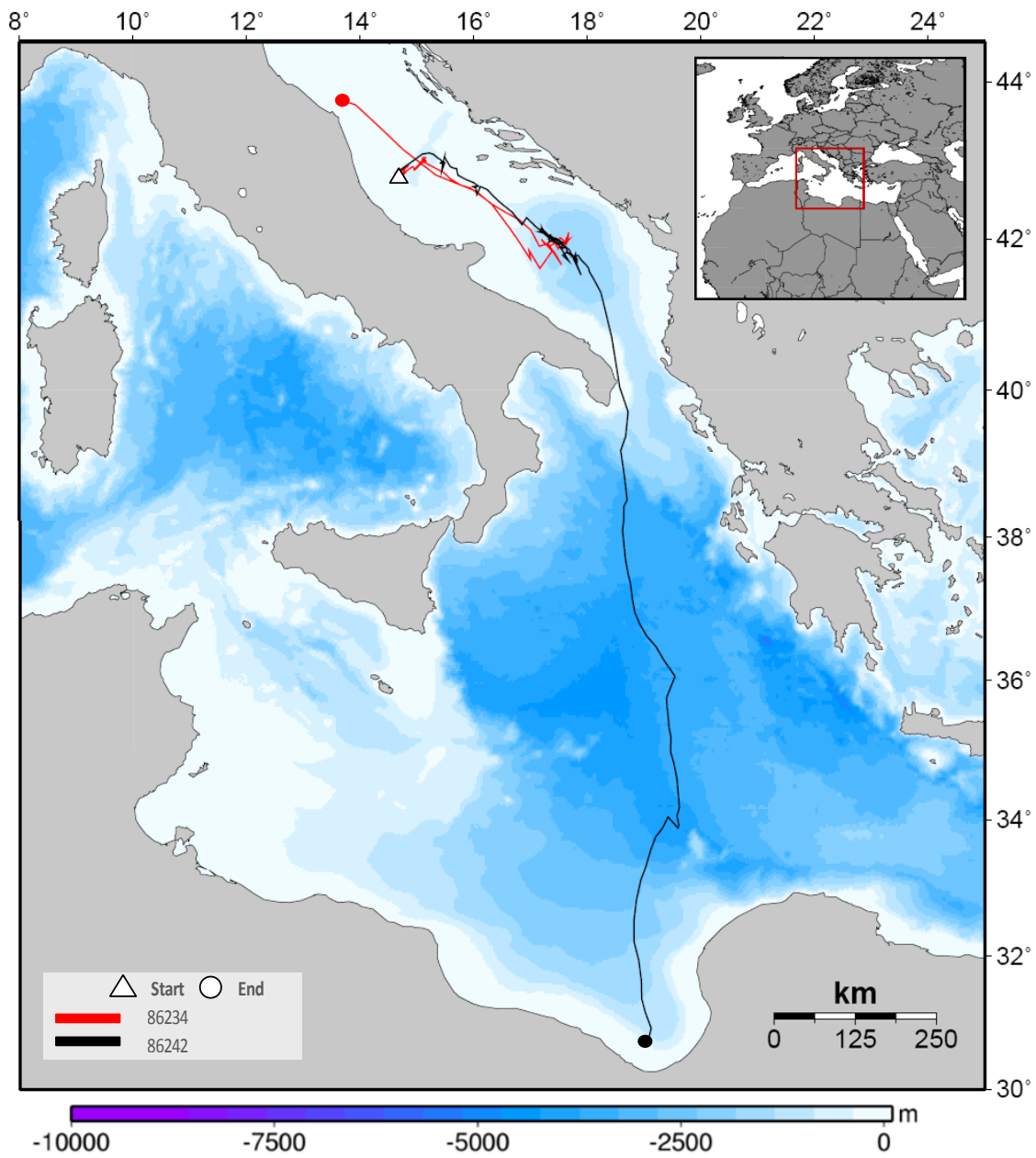


Figure 3. Estimated tracks of two of the four tunas tagged in the Adriatic Sea during 2009.

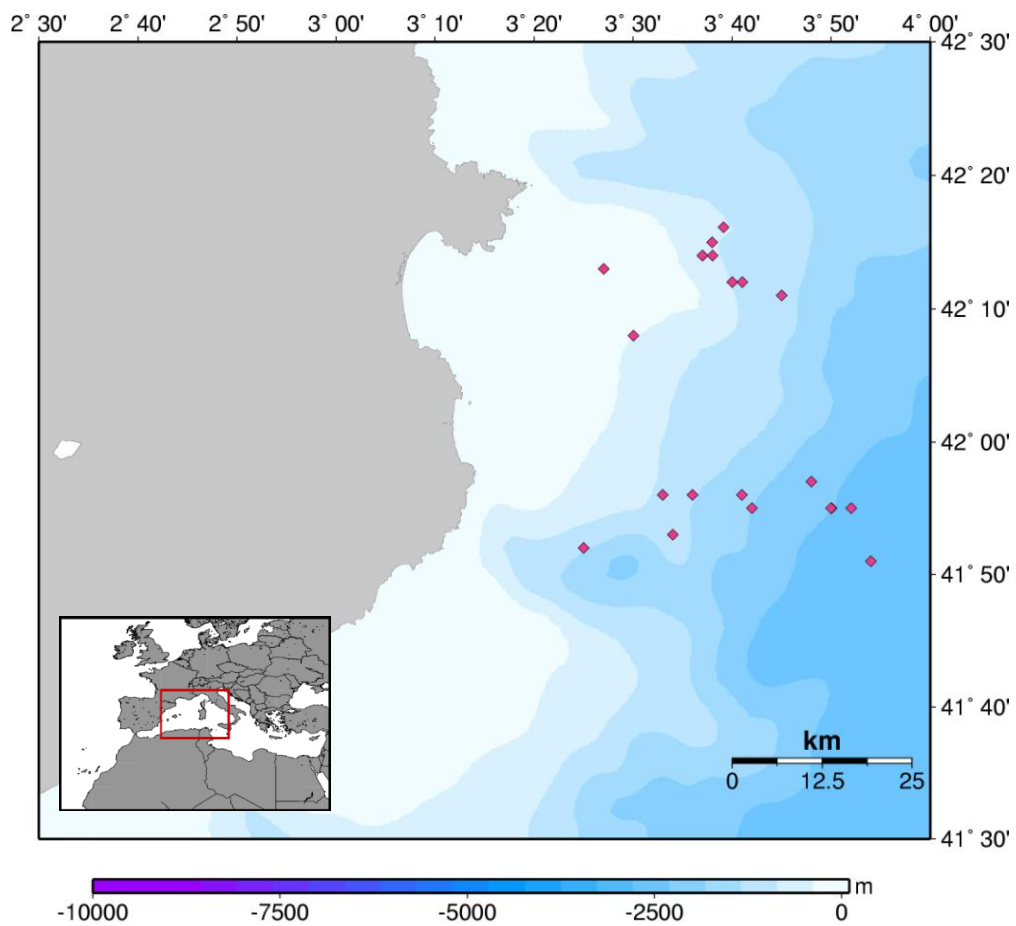


Figure 4. Distribution of the 21 juvenile tunas tagged with archival tags during 2008 off Roses (Catalunya).

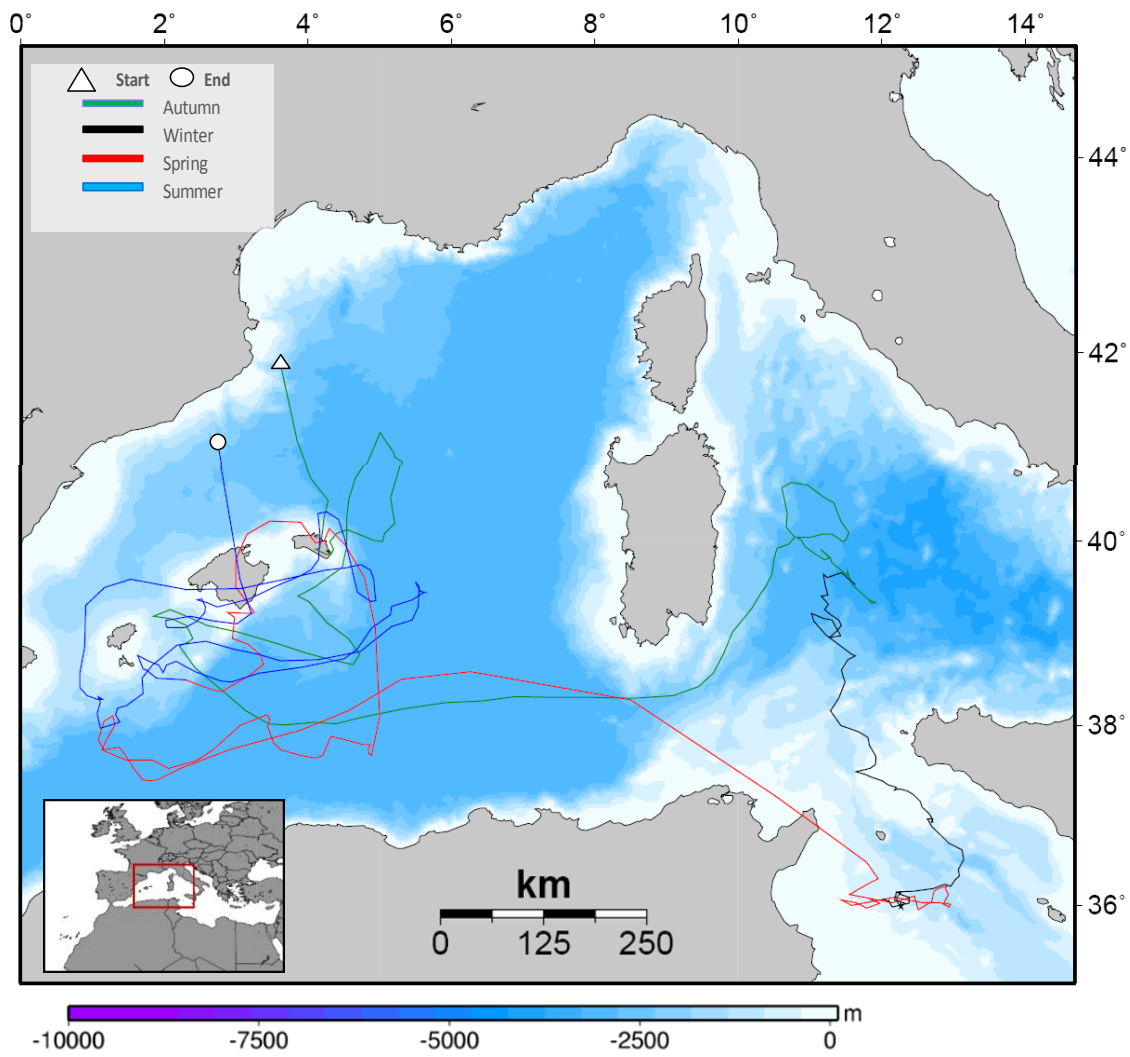


Figure 5. Estimated track of the juvenile tuna tagged with an archival tag on August 2008 in the Gulf of Lions and recovered close to the initial position after 391 days at liberty.

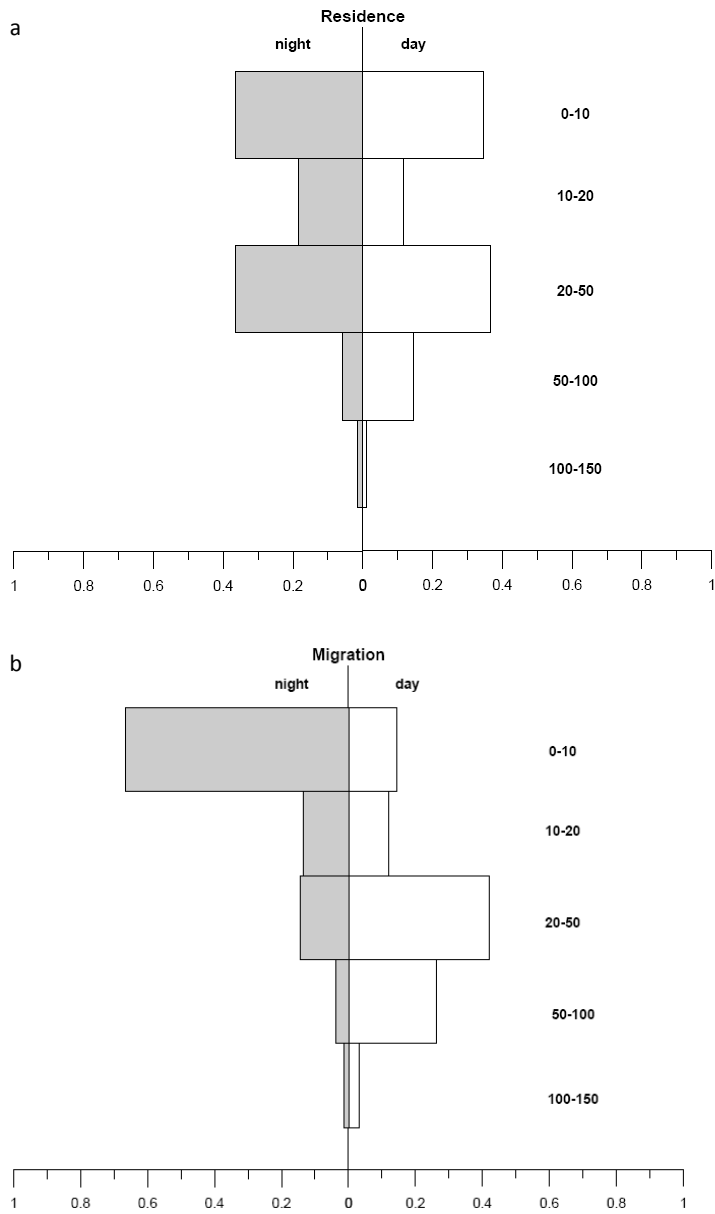


Figure 6. Percentage of time spent at the different depth layers during day and night in 2008, for (a) the four tunas during their aggregation north of Mallorca and Menorca, and for (b) the three larger tunas (TagID 86246, 86241 and 86239) during their migration south-westwards.