UPDATE ON THE SATELLITE TAGGING OF ATLANTIC AND MEDITERRANEAN SWORDFISH

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SUMMARY

This paper provides an update of the study on habitat use for swordfish, developed within the working plan of the Swordfish Species Group of ICCAT. A total of 26 miniPAT tags have been deployed so far in the North (n=13) and South Atlantic (n=9) and the Mediterranean (n=4). Data from eight tags was analysed for horizontal and vertical habitat use. These preliminary results showed swordfish moved in several directions, travelling considerable distances in both the North and South stocks. Swordfish spent most of the daytime in deeper waters with a mean of 540.8 m, being closer to the surface during nighttime (mean=78.3 m). The deepest dive recorded was of 1480 m. Regarding temperature, swordfish inhabited waters with temperatures ranging from 3.9ºC to 30.5ºC with a mean of 11.3ºC during daytime and 21.7ºC during nighttime. The main plan for the next phase of the project is to continue the tag deployment during 2022 in several regions of the Atlantic Ocean and Mediterranean Sea. Currently 11 tags are with the participating CPCs and nine tags are still to be attributed.

KEYWORDS: Satellite tagging; Xiphias gladius; habitat use; movement patterns; Atlantic; Mediterranean.

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1. Background

Swordfish (*Xiphias gladius*) is an epi- and mesopelagic oceanic species with a wide geographical range within tropical and temperate waters of all oceans (Nakamura, 1985). Globally, it is one of the most important target species in longline fisheries (Ward et al., 2002).

Even though it is one of the most important species for longline fleets, there are still important knowledge gaps regarding the biology, distribution and habitat use of swordfish that affect the assessments and management options. In ICCAT (International Commission for the Conservation of Atlantic Tunas), the Standing Committee on Research and Statistics (SCRS) has requested the revision of life history parameters, such as age and growth, the implementation of a tagging program for improved information on movements, habitat preferences and stock delimitation, and a detailed study on size and sex distribution of swordfish (ICCAT, 2017).

In 2018, the Swordfish Species Group initiated a collaborative tagging program to study the habitat use and migration patterns of swordfish, and to help delimitate the stock boundaries and mixing rate of swordfish between the Mediterranean Sea, North and South Atlantic. This working document presents an update on the satellite tagging work.

2. Methods

2.1 Tag acquisition

MiniPAT tags built by Wildlife Computers (WC) were used in this study. **Table 1** describes the numbers of tags acquired by ICCAT during the last four years and their allocation for deployment as well as the current deployment status. A tag from 2017 was available and is included in this study. Furthermore, 10 tags from NOAA have been included (**Table 2**).

2.2 Tagging procedure

Tagging took place across a wide area of the Atlantic Ocean, including the Mediterranean Sea, from 2017 to 2021 and was conducted in the Portuguese and Spanish pelagic longline fleet, the Italian harpoon fishery and the Uruguayan research vessel (**Figure 1**). The tag deployment was opportunistic when swordfish were captured during the regular fishing operations. Swordfish were either hoisted alongside the vessel or brought on board for tagging. A Domeier's dart (a nylon umbrella-type dart) was used to insert the tag laterally to the dorsal musculature below the dorsal finbase. For the harpoon fishery, the fish were tagged directly into the water with a modified harpoon, using one Domeier's dart and three small titanium darts. Before tag attachment, tags were tested for accurate data collection, and were programmed to record information for periods of 180 or 240 days in case of ICCAT tags and 240 days in the case of NOAA tags. In addition, the animals were measured for lower jaw fork length (LJFL). Date and time were recorded, and the geographic tagging location (latitude and longitude) was determined by Global Positioning System (GPS).

2.3 Data analysis

Geographic positions at tagging were determined by GPS, while the pop-up locations of transmitting tags were established as the first point of transmission with an Argos satellite. In order to investigate movement patterns, the most probable tracks between tagging and pop-up locations were calculated from miniPATs light level data using astronomical algorithms provided by the tag manufacturer. To improve the geolocation accuracy, a state-space model incorporating a sea surface temperature field was applied using the Wildlife Computers GPE3 software (Wildlife Computers, 2018). Vertical habitat use was investigated by summarizing the depth and temperature profiles of the tagged swordfish and analysing the depth and temperature profile plots from the 10-min interval transmitted data for six tags, and the 6 hour binned data for two tags. All statistical analyses were carried out with the R language (R Core Team, 2021). Analysis for the binned data was conducted in package "RchivalTag" (Bauer, 2021). Other plots were created using package "ggplot2" (Wickham, 2009).

3. Results

3.1 Tag reporting

Twenty-six MiniPAT tags were deployed so far during this study (**Figure 1**). Of the deployed tags, eight individuals suffered post-release mortality (PRM), one was fished after one day, three did not transmit, three tags had premature releases (popping up before the expected date) with less than 30 days, four had premature releases with more than 30 days, six tags reached full term, and one individuals tag pop-up date has not occurred yet (**Table 2**). Post-release mortality occurred in 50% of the cases (8 tags out of 16), when excluding samples that did not transmit or had less than 30 deployment days.

Data from the eight tags that reported and had deployment durations over 30-days were used for analysis. Six of these tags had an identified battery issue and many data gaps exist in the depth and temperature time-series (**Figure 2**).

Despite several tagging studies that have been implemented in the Atlantic Ocean, the current study is complementing previous studies by tagging swordfish mostly in the Northeast Atlantic, Equatorial South Atlantic and Mediterranean Sea, where few or no tags have been deployed so far (**Figure 3**).

3.2 Horizontal movements

Of the five swordfish tagged in the North Atlantic, two individuals moved north, and three individuals moved south (**Figure 1 and 4**). Of the three specimens that moved south, one was tagged in June (tag ID 179711) and moved south until the tag detached in September. The second one was tagged in October (tag ID 176685) and moved south up to December, before returning to the Madeira Islands area where it remained up to February, and finally moved south through the remaining time until the tag detached in March. Lastly, a swordfish tagged in August (tag ID 132158) close to the Cabo Verde Islands remained close to the archipelago up to January, when it started moving south up to the end of the tagging duration in April. Both fish that moved north were tagged in June. Fish with tag ID 179708 remained in the tagging area and started moving north in July and keeping that trend up to the detachment (August). The other tagged fish (tag ID 179709) had a similar trajectory but started by moving east and remained in that area up to September, and then moved north up to early December.

In the South Atlantic, one fish moved south and two remained in similar latitudes to the tagging location (**Figure 1 and 4**). Fish with tag ID 132157 popped-up in a southern location regarding the tagging location, from August to January, but no large directional displacement was observed. Fish with tag ID 176688 moved east, returning to the tagging area in September, and in December started moving west relative to the tagging position up to early January. A swordfish tagged in May (tag ID 176686) moved east from the tagging location and in November/December migrated approximately 13 degrees south up to January.

3.3 Vertical movements

Swordfish follow a daily vertical migration pattern, being in the surface during the nighttime and diving to deeper waters during the daytime. **Figure 5** presents the vertical movement of tag ID 179708 as an example. It occupies a wide depth range from the surface down to 1480 m, with mean depth of 327m. Water temperatures ranged between 3.9 and 30.5 ºC with a mean of 15.8ºC. Swordfish spent most of the nighttime in depths above 100 m, with a mean of 78.3 m, and preferred a range of water temperatures from 20 to 26 ºC, with a mean of 21.7ºC. During daytime, swordfish preferred deeper depths below 400 m with a mean of 540.8 m, and temperatures of 10 to 12ºC with a mean of 11.3ºC (**Figure 6**). Histogram reported data for two individual swordfish present slightly different distribution of time at depth and temperature, with one individual spending more time at deeper waters and going deeper than the other (**Figure 7**).

4. Discussion

Reporting rate of tags was high, with only 3 tags (out of 26) failing to report any data, however due to a known battery issue, data reported by a specific batch of tags was very limited. Regarding post-release mortality, in swordfish tagged opportunistically abord commercial longline vessels Abascal et al. (2010) in the Pacific Ocean and Abascal et al. (2015) found possible PRM events could happen in around 40% of the tag deployment, in the present study the PRM was around 50% of the cases. PRM tended to occur in the first few days after tagging. Most fish died within the first day, and the maximum of days after tagging that mortality occurred in the present study was 10 days.

Swordfish occur worldwide having a wide geographic distribution, both horizontally and vertically. With the limited data set so far, tagged swordfish usually travelled long distances moving in multiple directions. These extensive movements are consistent with previous studies that also demonstrated the highly migratory nature of this species (Abascal et al., 2015; Braun et al., 2019; Dewar et al., 2011; Neilson et al., 2009, 2014). Using satellite tagging, studies in the Northwestern Atlantic have shown directional movements to the north in the spring, spending the summer in the foraging grounds in the far north, while in autumn the opposite migration is made to the reproduction grounds in tropical and subtropical waters (Neilson et al., 2009, 2014). Braun et al. (2019) found this migration pattern particularly for adult individuals in the northwest Atlantic, while juveniles tagged in the Azores area had more regional movements. The same authors suggest that the variable movements compared to the north-south migration of adults might be related to the foraging needs of juveniles, changing to larger-scale movements related to spawning when adults. In the central Atlantic, Abascal et al. (2015) found that tagged individuals had a similar north-south migration pattern overall, with fish moving south in late fall and returning north to the feeding grounds in central Atlantic in early spring. The same authors could not infer any patterns in movements for fish tagged in Southeastern Atlantic as the sample size was low, however a large displacement between this area and the northeastern area was noted. A similar observation occurred in the present study with a fish tagged off the coast of Portugal moving south when the tagged pop-off south of the Canary Islands close to the African coast. In the current study, where fish are likely juveniles given the size, large displacements are still observed for these fish although more variable than the north-south migrations.

Swordfish are known for their strong daily vertical migrations (Abascal et al., 2015; Braun et al., 2019; Canese et al., 2008; Dewar et al., 2011; Koutsikopoulos, 2012) which are also corroborated by the present study, with fish spending the daytime in deeper colder waters and the nighttime in shallower-warmer waters. The deepest dives and minimum temperatures observed in this study (1480 m and 3.9ºC) agree with previous observations, where swordfish were recorded in waters as deep as 1664 m (Braun et al., 2019) and temperatures as low as 2ºC (Takahashi et al., 2003). Several factors have been suggested to influence the vertical habitat use by swordfish. Body size has been suggested to influence the vertical distribution of swordfish, with smaller swordfish spending less time-at-depth (Braun et al., 2019), this could be influenced by the ongoing development of the cardiac and vascular systems to withstand the daily vertical migrations and the ability to pursue and capture prey at depth (Braun et al., 2019).

The pattern in vertical distribution has also been shown to be different between different areas. Abascal et al. (2015) found fish in the Cape Verde Islands to spend more time in shallower depths during nighttime than fish tagged in the central Atlantic, suggesting these differences could be due to the thermal structure of the water or variations in the distribution of prey. Dewar et al. (2011) also found differences between the north-central Pacific Ocean and the Western North Atlantic-Caribbean, with fish in the Atlantic having a wider range of depths during nighttime than in the Pacific. Nighttime depths have also been shown to be influenced by the lunar cycle (Loefer et al., 2007; Dewar et al., 2011; Lerner et al., 2013; Abascal et al., 2015;), with fish being deeper in the full moon. Abascal et al. (2015) also found that the quarter of the year and the sea surface temperature influenced the nighttime distribution, with fish being deeper in the last quarter of the year and shallower at cooler temperatures. Dewar et al. (2010) also indicated that sea surface temperature can influence the nighttime depths, as fish in cooler waters tended to spend more time in the surface mixed layer, while fish in warmer areas moved into waters deeper than the thermocline, suggesting this could be to behaviourally thermoregulate. Braun et al. (2019) also noted a tendency for fish to be deeper at night in warmer regimes but evidenced that fish were still found near the surface even with sea surface temperatures above 25ºC, however these authors relate this tendency primarily to prey distribution instead of a thermoregulation behaviour, given the extreme plasticity of thermal habitat use shown by swordfish.

During daytime, Dewar et al. (2011) suggest also that swordfish depth can also be influenced by the solar illumination, as swordfish forages in the deep scattering layer during daytime and the depth of this layer is influenced by solar illumination (being deeper as light penetrates deeper), meaning that in areas or times of higher solar illumination the swordfish distribution would also be deeper following the prey distribution.

The vertical dial behaviour is sometimes interrupted by daytime basking, Dewar et al. (2011) defined basking events as a "rapid ascent from depth, a surface period ranging from minutes to hours, then followed by a rapid descent". This behaviour has been reported to occur in several electronic tagging studies (Canese et al., 2008; Dewar et al., 2011; Sepulveda et al., 2010; Takahashi et al., 2003) and makes swordfish available to harpoon fisheries during daytime (Canese et al., 2008; Neilson et al., 2009). Dewar et al. (2011) refers that basking events occur more frequently in cooler coastal waters and decrease as fish move offshore. A difference between sizes was also found by Lerner et al. (2013), with larger fish showing more basking events than smaller fish. Basking in swordfish has been associated with the need to thermoregulate, the need to recover from oxygen depths after foraging at depth or to foraging success where swordfish come to the surface to accelerate digestion (Dewar et al., 2011; Takahashi et al., 2003).

This document presents preliminary analysis of acquired PSAT data so far, the tagging program will continue during 2022 with the deployment of tags acquired up to now and analysis will continue as more data becomes available.

5. Acknowledgments

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Table 1. List with the distribution of ICCAT miniPATs by the participating Institutes, for the 4 project phases. Current deployment status and additional notes are also provided.

	Institute	Tag quantity	Deployment status
2017	DINARA (Uruguay)	1	Deployed
2018	IEO (Spain)	6	1 tag deployed
	IFREMER (France)	4	No tags deployed.
	UNIGE (Italy)	4	All deployed
	IPMA (Portugal)	1	Deployed
2019	IPMA (Portugal)	14	6 tags deployed
2020			
2021	IPMA (Portugal)	6	3 tags deployed
	To be distributed	9	

Table 2. Information on deployed tags.

Tag ID	Deployment date	Size (LJFL, cm)	Tracking days	Tag duration	Comments
132157*	03/08/2015	115	118	240	Premature release; possible mortality at 118 days
132158*	19/08/2015	115	240	240	
132165*	02/07/2015	145	0	240	Mortality
132168*	13/02/2016	140	10	240	Mortality
132169*	24/06/2016	120	1	240	Mortality
167200ϕ	05/06/2017	135	1	180	Mortality
176684*	24/10/2018	115		240	Malfunction, never transmitted
176685*	25/10/2018	113	153	240	Premature release
176686*	16/05/2019	114	240	240	Popped-up on the expected date, but transmitted data has many intervals
176688*	06/05/2019	140	240	240	Popped-up on the expected date, but transmitted data has many intervals
176689*	14/04/2019	120	4	240	Premature release, although the track has few days does not look like it died
62424ϕ	15/03/2019	120	0	180	Mortality
62603ϕ	26/03/2019	96	8	180	Premature release, although the track has few days does not look like it died
179708ϕ	29/05/2019	109	67	180	Premature release
179709ϕ	08/06/2019	110	180	180	Popped-up on the expected date, but transmitted data has many intervals
179710ϕ	13/06/2019	110	0	180	Mortality
179711ϕ	08/06/2019	105	86	180	Premature release
181044ϕ	27/10/2019	117		180	Malfunction, never transmitted
181046ϕ	15/06/2019	91	0	180	Mortality

62541ᶲ	16/07/2021	135	240	240	Pop-up on date; Transmitting
62542ᶲ	16/07/2021	125	1	240	Fished after 1 day
62543ᶲ	14/07/2021	125	240	240	Pop-up on date; Transmitting
62544ᶲ	16/07/2021	135		240	Malfunction, never transmitted
215421ᶲ	06/12/2021	107		180	In the water, expected pop-up date 04/06/2022
215426ᶲ	03/11/2021	112	1	180	Mortality
215427ᶲ	21/11/2021	98	11	180	Premature release, although the track has few days does not look like it died

Funding *NOAA; ᶲ ICCAT

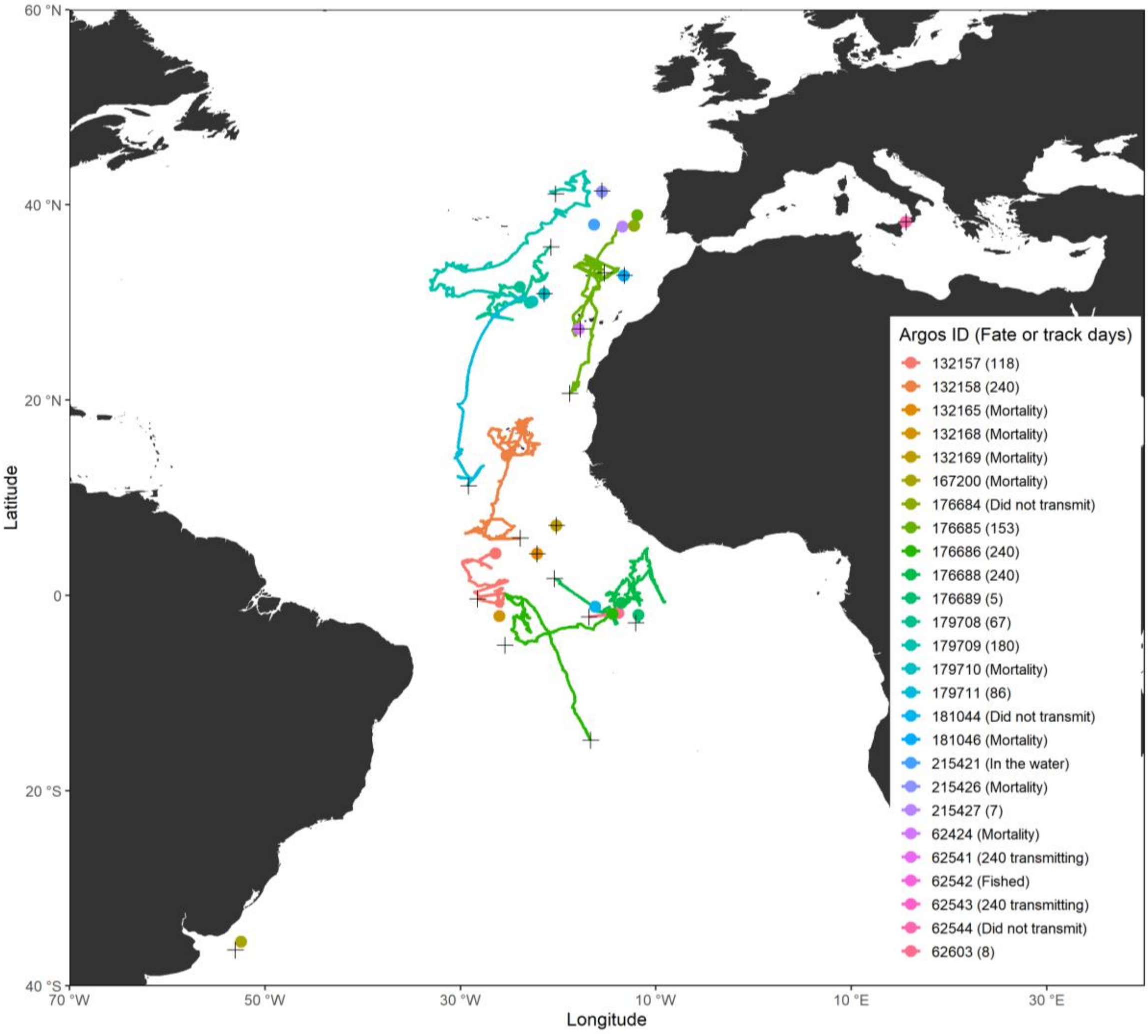

Figure 1. Map with the location of the swordfish (*Xiphias gladius*) tag deployments, and most likely tracks of individuals that did not suffer from post-release mortality. The colored point identifies the tagging location and the colored lines the individual tracks, the black cross indicates the location of the pop-up.

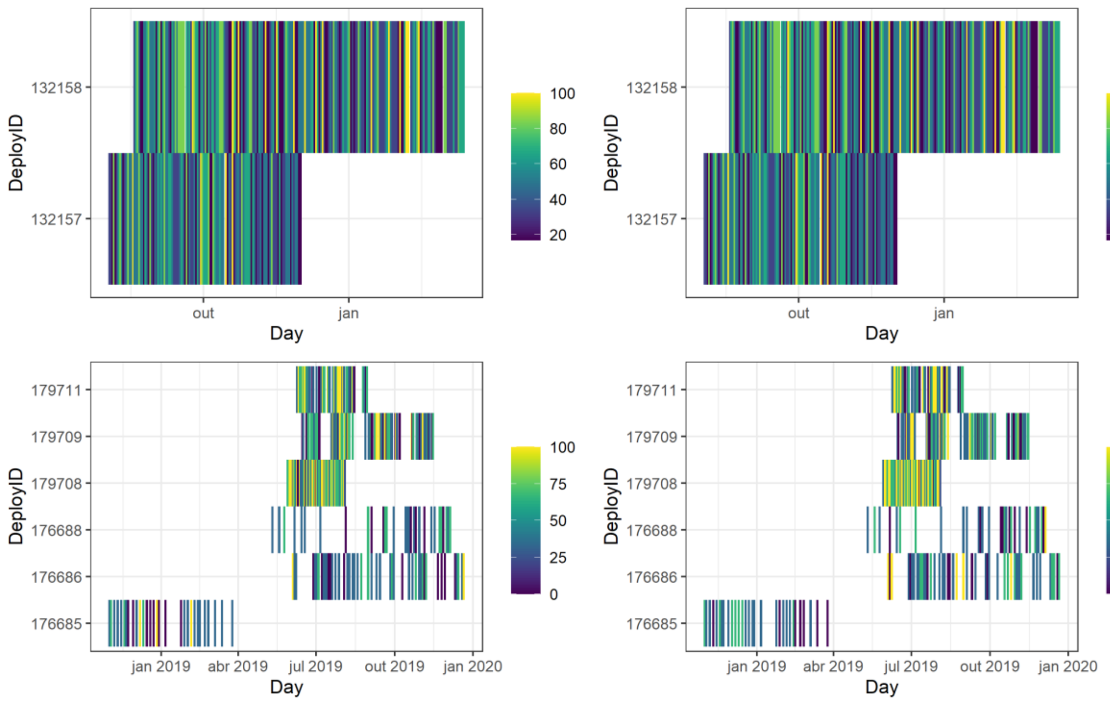

Figure 2. Data coverage (%) by day of data collection of swordfish tags with more than 30-day tracks. Top panels estimates were from histogram reported data and bottom panels are from tag reported time-series. Left panels represent the coverage of depth records and right panels the coverage of temperature records. Blank spaces represent days where no data was transmitted.

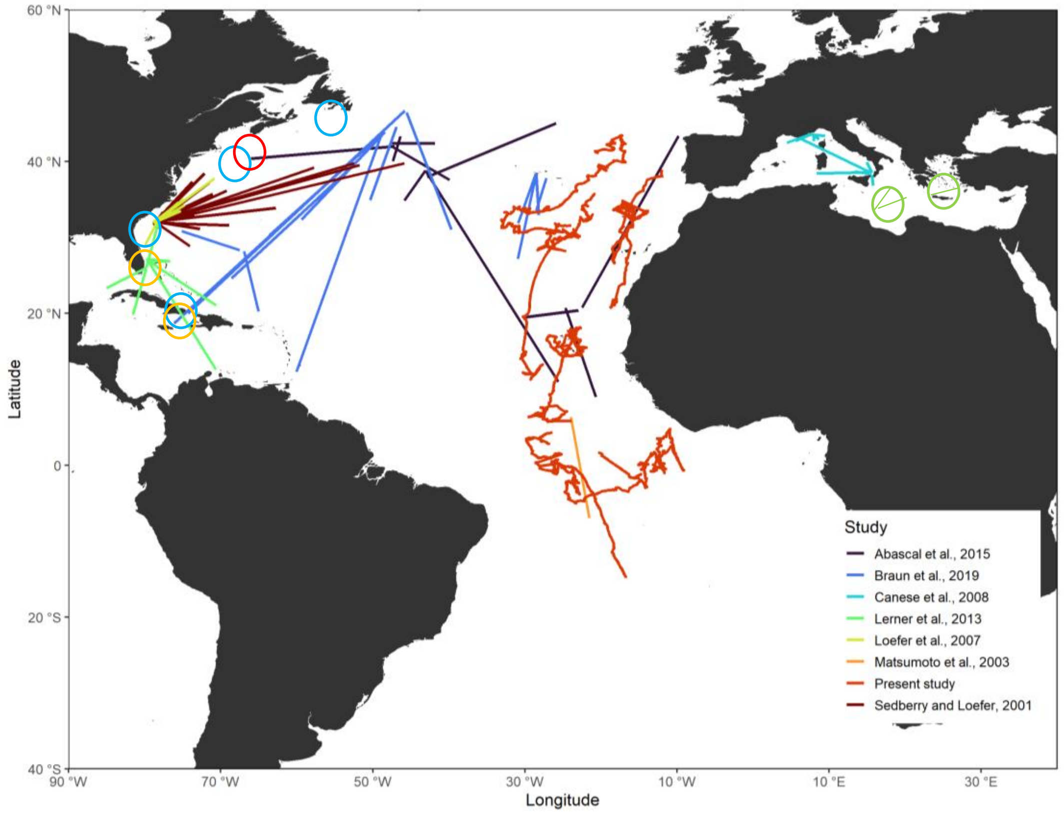

Figure 3. Map with the location of the swordfish (*Xiphias gladius*) tag deployments for the present study and previous studies in the Atlantic Ocean. Lines represent displacements between the tagging and pop-up location. Circles represent approximate tagging locations (◯Dewar et al. 2011;◯ Neilson et al., 2009; ◯ Neilson et al., 2014;◯ Koutsikopoulos et al., 2012)

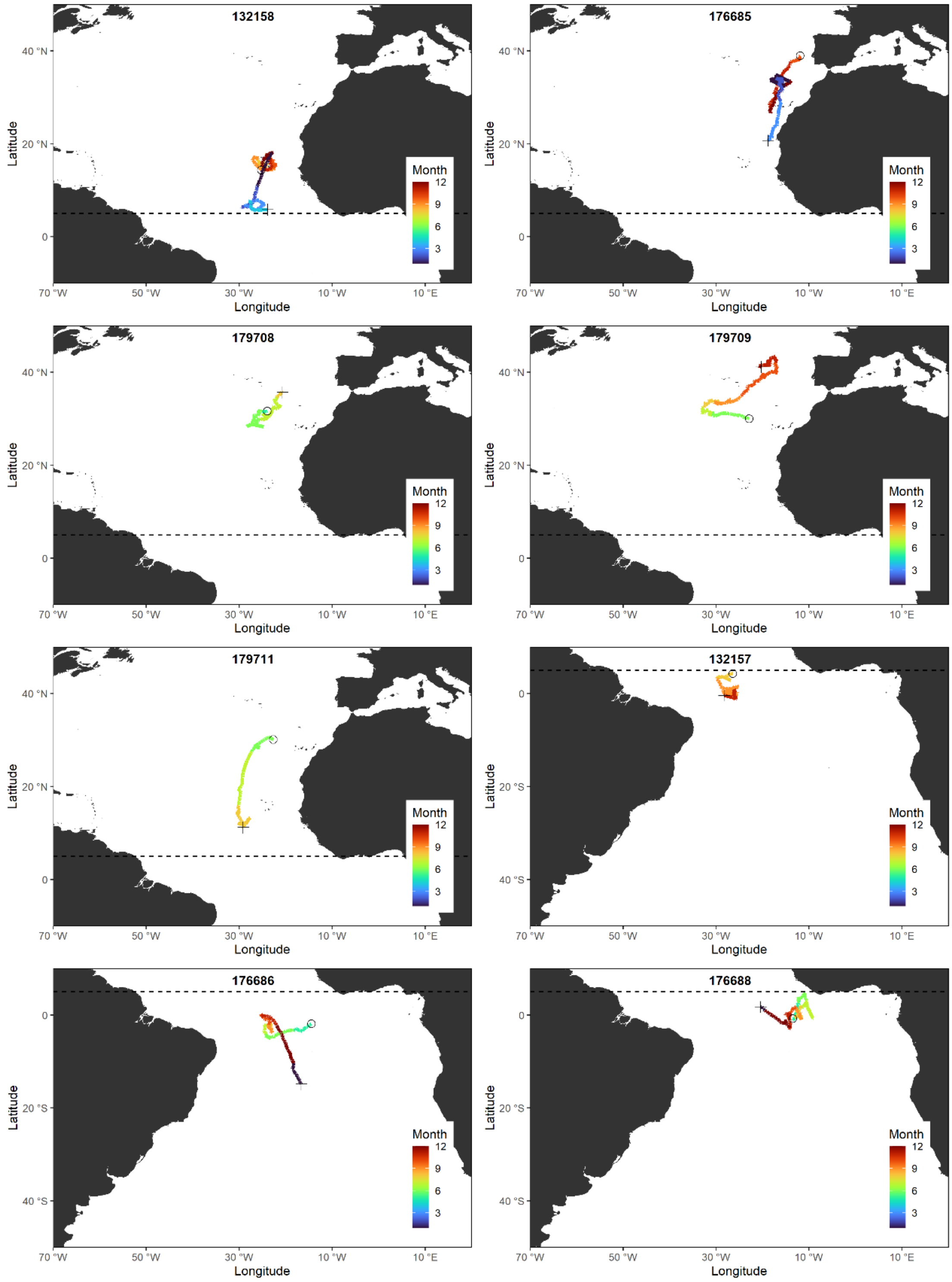

Figure 4. Individual tracks of swordfish tagged in the North and South Atlantic. Open circles represent tag locations and crosses the pop-up location. Most likely tracks are coloured acording to the month.

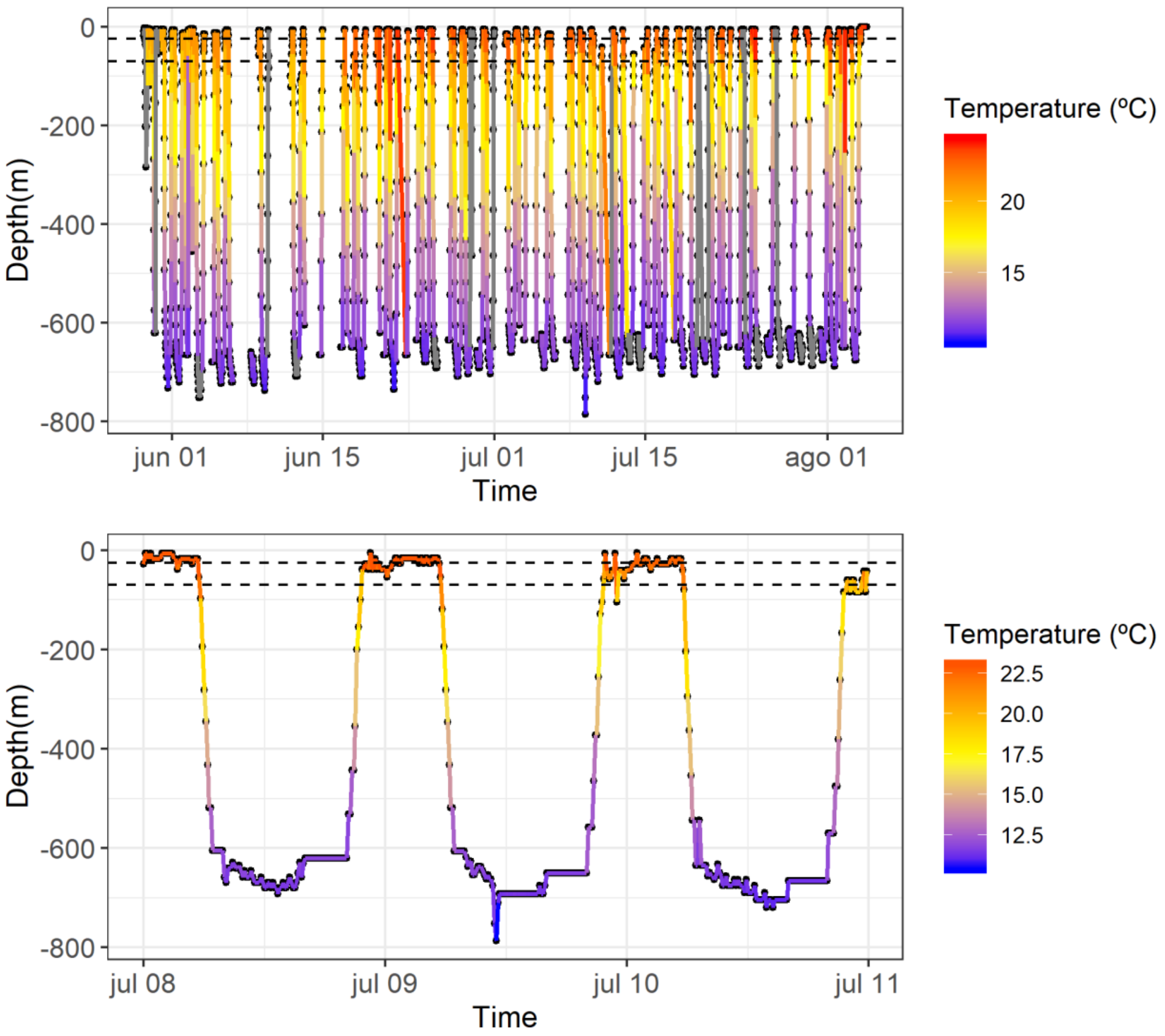

Figure 5. Depth and temperature profiles of an individual swordfish with 109 cm lower jaw fork length. Top panel represents 67 days tracking days; bottom panel represents a 3-day snapshot. Horizontal dashed lines represent the longline depth.

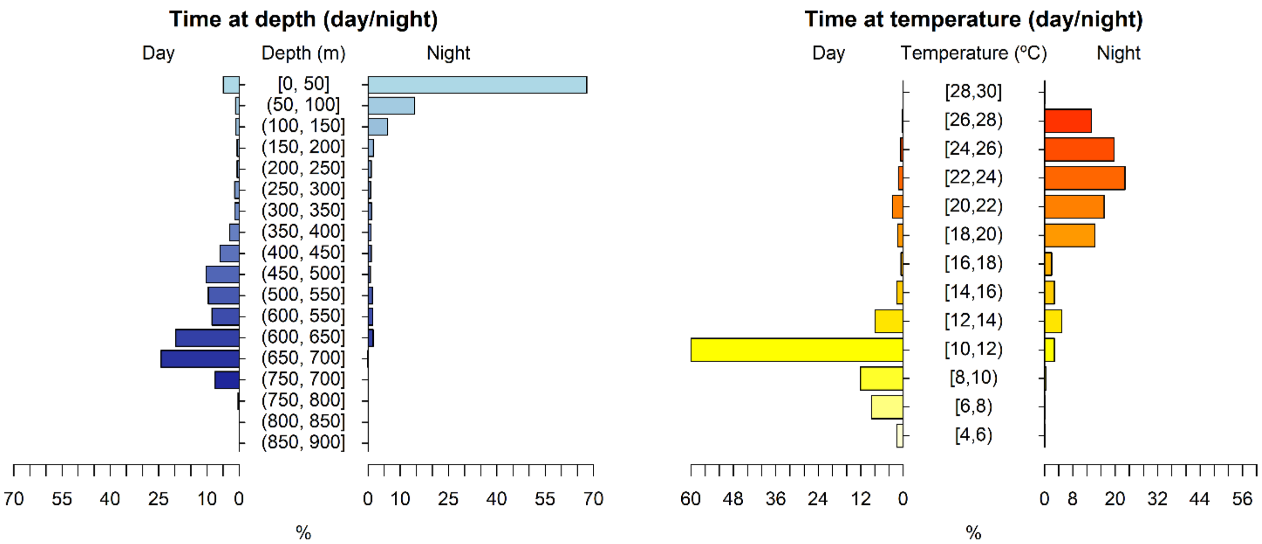

Figure 6. Vertical habitat use of swordfish (n=6) for daytime and night-time in terms of depth and temperature. Depth classes are categorized in 50 m intervals and temperature classes in 2ºC intervals.

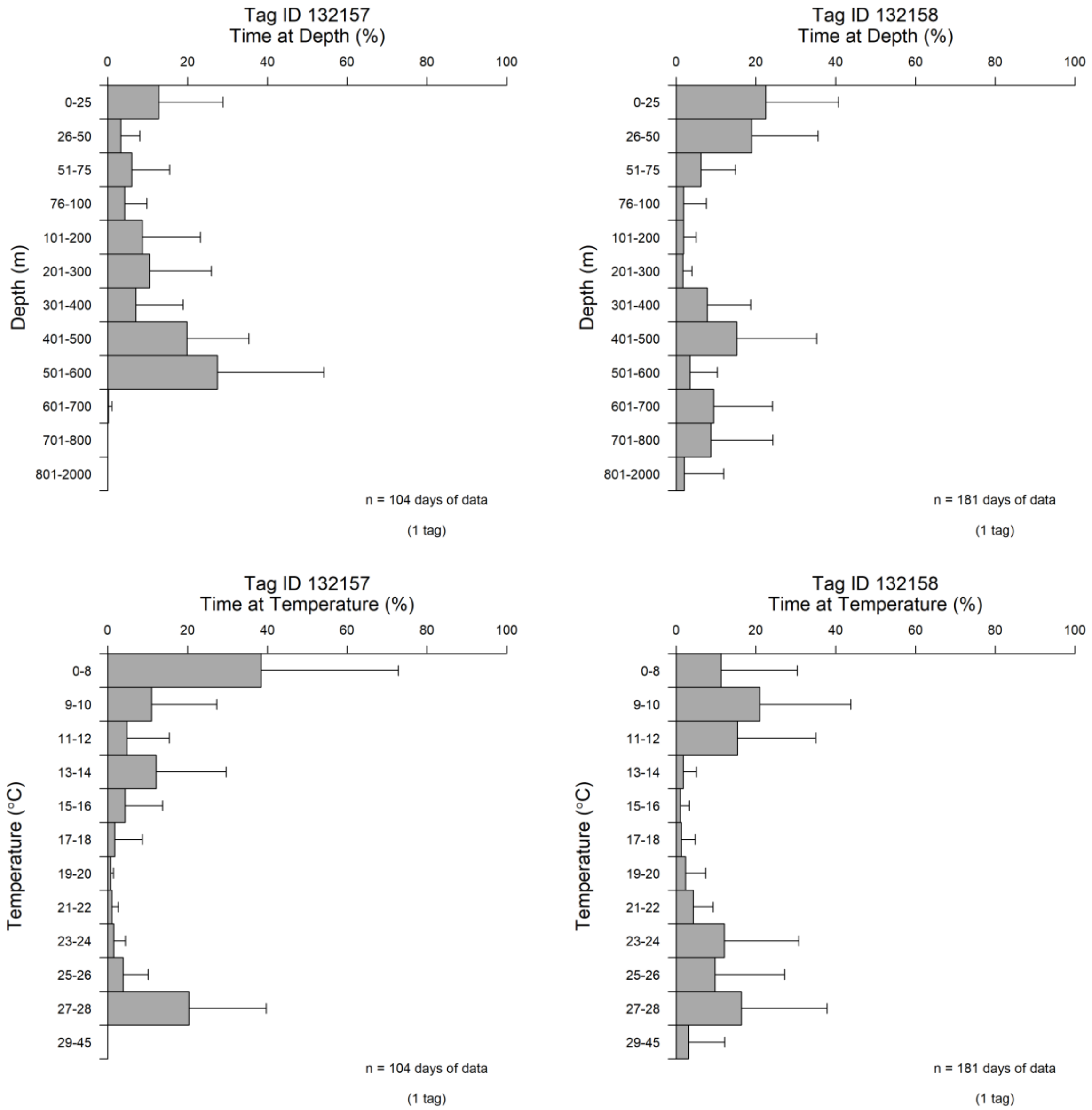

Figure 7. Average daily time at depth and time at temperature for tag IDs 132157 and 132158.