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## A preliminary analysis of swordfish (*Xiphias gladius*) habitat and behaviour on migratory track from Reunion Island to equatorial waters

**by**

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## ABSTRACT

A swordfish, *Xiphias gladius* tagged with a pop-up satellite tag (PSAT) off Reunion Island (southwestern Indian Ocean) demonstrated active migratory behaviour by reaching equatorial waters in 69 days of tracking. The total estimated distance travelled was 2411 nmi with average daily horizontal displacement of 34.9 nmi. This swordfish occupied the upper mixed layer at night and remained in deep layers down to 800 m depth during the day.

## Introduction

Swordfish (*Xiphias gladius*) is an important commercial target species in the Indian Ocean for many local fishing fleets (France: Reunion and Mayotte Islands, Seychelles, Indonesia, Sri Lanka, India) and distant-water fleets (Spain, Portugal, and Taiwan) (IOTC, 2015). Despite knowing there is a single stock of swordfish in the Indian Ocean area (Muths *et al.*, 2015), population connectivity, migratory behaviour and mixing level over the area are still poorly known for this species.

Conventional “spaghetti” tagging programs in the western equatorial Indian Ocean (ABF, 2010) and the eastern Indian Ocean (Stanley, 2006) suggest active migratory behaviour associated with long-distance movements for *X. gladius*. However, inherited limitations of conventional tagging do not permit to evaluate potential migratory patterns, swordfish behaviour and habitat in the region. Most of Indian Ocean electronic tagging experiments either fails (Poisson, Taquet, 2001) or demonstrated relatively limited displacements associated with highly productive zone of the southwestern Indian Ocean and Mozambique Channel (West et al., 2012). These experiments collected very limited data on habitat and vertical behaviour either due to early mortality of fish or poor performance of electronic tags.

In December 2015 we tagged a swordfish with a pop-up satellite archival tag (PSAT) in close proximity to Reunion Island. The PSAT surfaced after 72 days close to the equator. The tag successfully transmitted the data collected along the migratory route of the fish hence providing for the first time relatively complete information on vertical habitat, behaviour and horizontal movements across three diverse habitats: Indian Ocean Subtropical Gyre (ISSG), transitional zone between Monsoon Province and ISSG, and Equatorial Countercurrent (Monsoon Province) (Longhurst, 2007).

## 2. Material and Methods

### 2.1. Tags

A MiniPAT electronic tag developed by Wildlife Computers Inc.[1] was used in our tagging experiments. It was programmed to record depth, temperature and

[1] http://wildlifecomputers.com Wildlife Computers 8345 154th Avenue NE, Redmond, WA 98052, USA

light for a 90-days period (Table 1). Time series for depth (5-min interval for 90 days deployments) 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; 30-50; 50-100; 100-200; 200-300; 300-400; 400-600; 600-800; 800-1000; 1000-1200; >1200 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, 2016).

The tag was rigged with a Domeier (umbrella-type) plastic anchor (Domeier et al., 2005) provided by Wildlife Computers Inc. that attached with a stainless steel tether. The MiniPAT was equipped with emergency release mechanism (mechanical guillotine) that releases the tag if the fish reaches a tag crushing depth of 1800 m (Wildlife Computers, 2016). The tag was also pre-programed to release from fish in case of 3 days inactivity, i.e. quasi-constant depth range (+/-2.5m) assuming such inactivity corresponds to mortality of tagged fish: dead fish either fell to the sea bottom shallower than tag crushing depth or float at the surface. The inactivity clause also triggers data transmission process in case of fish mortality or tag premature detachment.

## 2.2. Swordfish tagging

Swordfish was caught using a Florida-style swordfish buoy gear (SBG) (Romanov et al., 2013) within the framework of experimental fishing of research project PELICAN. Up to 13 vertical lines equipped with circle hooks and monofilament leaders were deployed at the surface off 5-10 miles off Reunion Island and further offshore (up to 90-100 miles) after sunset, then permanently monitored on potential predator attack using GPS buoys M2P (Marine Instruments S.A.[2]) and visually. As soon as fish bite was detected (change of fishing gear drift trajectory), fishing vessel immediately approached to SBG in attempt to retrieve fish as soon as possible trying to keep swordfish in good condition for further tagging.

[2] http://www.marineinstruments.es Rúa dos Padróns nº 4 (Vial 3), Parque Empresarial Porto do Molle, 36350 Nigrán, Pontevedra, Spain.

Only healthy, jaw-hooked swordfish without bleeding and obvious injuries were considered for tagging. During the fishing experiments a total of 3 swordfish were caught; only single individual appeared to meet tagging requirements.

Consequently only one fish was tagged. The tag was anchored under the first dorsal fin using tagging pole. The hook was not removed from the fish and the monofilament leader of the fishing gear was cut at maximum proximity to the hook at time of fish release.

### 2.3. Horizontal movements

Light-based geolocation data were processed using GPE3 application available at Wildlife Computer portal (http://my.wildlifecomputers.com/). Model used sea surface temperature (SST) NOAA High Resolution SST data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ and bottom topography with 1 degree step (ETOPO1 Bedrock) (Amante, Eakins, 2009.). Model provides maximum likelihood geolocations and maximum likelihood track with 50%, 95% and 99% likelihood areas. Model was set to use abovementioned bathymetry and SST as constrains with various settings of max fish swimming speeds from 1.0 to 5.0 m $s^{-1}$ with 0.5 m $s^{-1}$ increments. Most 'realistic' movement pattern (based on subjective criteria) was obtained at 3.5 m $s^{-1}$ swimming speed and used in this note.

### 2.4. Vertical behaviour and habitat

For habitat use analysis we developed day vs. night distributions of time-at-depth inferred from 5-min resolution time series. 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 taken directly from binned temperature histogram data summarized over 4-hour intervals. Similarly to time at depth series, we excluded dawn/dusk observations. Analysis was performed for whole track and for three track segments that correspond to three different bio-oceanographic zones: Indian Ocean Subtropical Gyre (ISSG), transitional zone between Monsoon Province and ISSG, and Equatorial Countercurrent.

We also show mean daily depth profile to illustrate the general pattern of vertical movements, including the timing of descent and ascent. 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 show the vertical thermal structure of the water column and to calculate the isothermal layer depth (ILD = thermocline) (Kara et al., 2000).

## 3. Results

### 3.1. Tag retention and performance

The tag was deployed on a swordfish (estimated LJFL 230 cm) on 17.12.2015 at 04:21 GMT+4, exact position 21°10’00 S, 55°05’06 E. It detached itself from fish on 23.02.2016 close to midnight, i.e., prematurely after 69 days of deployment. After premature detachment, the tag drifted for three days at the surface before initiating transmission of the data following the ‘fish inactivity tag behaviour’ clause, position on first transmission 01°30'00 S, 60°37'25 E. Tag experienced interruption in transmission between 02.03.2016, 17:57 GMT to 06.03.2016, 13:09 GMT for unknown reasons. Transmission resumed after 91 hours and 15 min of silence and continued for another 22 days. 9.5% of the ARGOS messages sent in a redundant manner were received by satellites containing ~95 % of total data supposed to be transmitted despite transmission or reception interruption for 91 hours. Analysis of fish behaviour along the track and just before tag detachment suggests that premature PSAT deployment was not associated with fish mortality: no abnormal behaviour was observed (Fig. 3). In addition, light data were recorded by the PSAT without interruption rejecting potential predator’s attack event.

### 3.2. Horizontal movements

The track demonstrates high migratory activity of swordfish tagged off Reunion Island. The direct distance travelled in 69 days exceeds 1200 nmi (1224.5 nmi), that corresponds to 17.7 nmi per day (Fig. 1). The most likely track reconstructed based on light-based geolocation shows almost direct fast movement of fish from tagging place northward, toward equatorial waters (Figs. 1, 2). The horizontal distance travelled from estimated positions was equal to 2411 nmi, which corresponds to a speed of 34.9 nmi/day, i.e., 1.46 knots.

### 3.3. Vertical behavior and habitat

This swordfish demonstrates a wide range of vertical movements and habitat use: from the surface down to 809.5 m depth. Time-at-depth and time-at-temperature summary data (Fig. 4) show that during the night swordfish mostly occupy upper layer near the surface (0-25 m depth) and spend the rest of the time deeper but within upper mixed layer. Water temperature recorded during nighttime ranged from 15 to 33°C with most of the time spent in 27-30°C. During the day swordfish occupy a wide range of depths mostly below 400 m depth. However prevailing depth layer varied by oceanic zones and apparently corresponds to preferred temperature range. Swordfish stay ~70% of daytime in waters with temperatures between 9 and 12°C whatever the oceanic zone explored.

Mean depth profiles (Fig. 5) demonstrate that the swordfish was much more active during the day, moving between deep layers 400-800 to the surface quickly passing through intermediate depths 10-400 m. During sunset (mostly between 17:00 and 19:00 swordfish moves to the upper mixed layer (0-150 m) where it stays all night long. At night vertical migration range of swordfish is much narrower and matches the mixed layer and upper part of the thermocline.

Along their migratory route the tagged swordfish visited three bio-oceanographic zones visible from thermal structure of water layers crossed by fish during circadian migrations (Fig. 6, 10). Waters around Reunion Island and northern area up to ~11°S correspond to Indian Ocean Subtropical Gyre (ISSG) province that is characterized by high heat content, deep propagation of warm waters and oligotrophic conditions (Jayne, Marotzke, 2002; Gouretski, Koltermann, 2004, Longhurst, 2007). Then swordfish crossed a zone of transition between the Monsoon Province and the ISSG from ~11°S to ~3°S that contains both south equatorial convergence and equatorial divergence areas, entering into Equatorial Countercurrent at about ~2°S abruptly changing direction of migration (Fig. 2, 6). Summaries of swordfish vertical distribution show relatively similar depth occupation during the night, daytime distribution by depth shows visible difference (Fig. 7-9). Within the ISSG, the swordfish stayed mostly deeper than 500 m, preferring deeper layers between 650-750 m depth. In ISSG swordfish also rarely migrated to the surface during the day. In the transitional zone swordfish stayed shallower (at 350-500 m) demonstration rare excursions to deeper layers. Within equatorial countercurrent most of daytime was spent also at 350-500 m depth without attempt to explore deeper layers but more frequently going at the ocean surface.

In all areas swordfish preferable temperature range was the same: 27-30°C during the night and 9-12°C during the day (Fig. 7-9).

Nighttime mean depth was associated with ILD (except ISSG area), and no apparent correlation between ILD and mean daytime depth was found (Fig. 11).

## 4. Discussion

Our results obtained yet from single fish lies in concordance with earlier observations from other ocean on swordfish migratory nature. Fast south-north movements of swordfish were recorded in several PSAT tagging experiments in Atlantic and Pacific (Abascal et al., 2009, 2015; Neilson et al., 2009; Evans et al., 2014). The average daily migratory speed 34.9 nmi day$^{-1}$ estimated here is the same order of magnitude as speed of swordfish horizontal displacement observed by Abascal et al. (2009, 2015): 28.8 and 53.9 nmi day$^{-1}$, Dewar et al (2011) 31.8 nmi day$^{-1}$, and Sepulveda et al (2010) 77.8 nmi day$^{-1}$. Such active movements of swordfish means that status of local stocks and success of local fisheries are highly depends on emigration-immigration balance and probably on oceanographic and local productivity processes that apparently drive swordfish movements and residence time.

Vertical behaviour of swordfish observed here also corresponds to generic pattern of *X. gladius* circadian movement pattern in tropical zone: night aggregation close to ocean surface, within the upper mixed layer and daytime occupation of mesopelagic habitat. Regular swordfish excursions to the ocean surface during the day are also known (Takahashi et al., 2003; Abascal et al., 2009; Evans et al., 2014) however reasons of such behavior are not well understood yet. One of the potential reasons is heating of fish body in warm surface waters after excursions to cold mesopelagic layers. However, this migratory pattern (daytime short movement to the surface) does not occurs every day making this explanation questionable. Another potential reason of surface daytime excursion that swordfish exploring surface waters for food resources. In particular higher percentage of daytime surface excursions in equatorial waters may reflect higher local productivity of the area and presence of abundant epipelagic prey (Potier et al., 2007, 2009; Romanov et al., 2009) while in the oligotrophic waters of ISSG, where epipelagic prey resources are poor (Romanov, Zamorov, 2007; Romanov et al., 2008), swordfish apparently rely on migrating prey from deep sound scattering layers.

Swordfish demonstrate differences in depth occupation in relation to local oceanographic conditions: preferred temperature range of 9-12°C was the same irrespectively of the area. Also, deep propagation of warm waters in the ISSG allows swordfish to explore deeper layers. In the same time, habitat compression due to presence of oxygen-depleted layer in the equatorial waters may also play important role limiting swordfish presence in deep layers (Abecassis et al., 2012).

Further swordfish electronic tagging in combination with environmental sampling are needed in order to obtain more information on vertical behaviour, migratory routes, residence time and mixing level between various areas of the Indian Ocean.

## Acknowledgements

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Table 1 Summary of tagging information for swordfish

| PTT | Serial number | Species | LJFL (cm) estimated | Programmed period (days) | Anchor | Tagging | | | Pop-up | | | Days at liberty: first transmission / surfacing | Direct distance travelled / distance per day (nmi) | RST (%) | DD (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Date | Lat | Long | Date: first transmission / surfacing | Lat (first transmission) | Lon (first transmission) | | | | |
| 153475 | 15P0292 | SWO | 230 | 90 | Domeier | 17.12.2015 | 21°10'S | 55°05'E | 27.02.2016 / 24.02.2016 | 01°30'S | 60°37'E | 72 / 69 | 1224.5 / 17.7 | 9.5 | 95% |

LJFL: lower jaw – fork length, RST: rate of successful transmissions, DD: data density, Distance: straight distance between tagging and pop-up locations

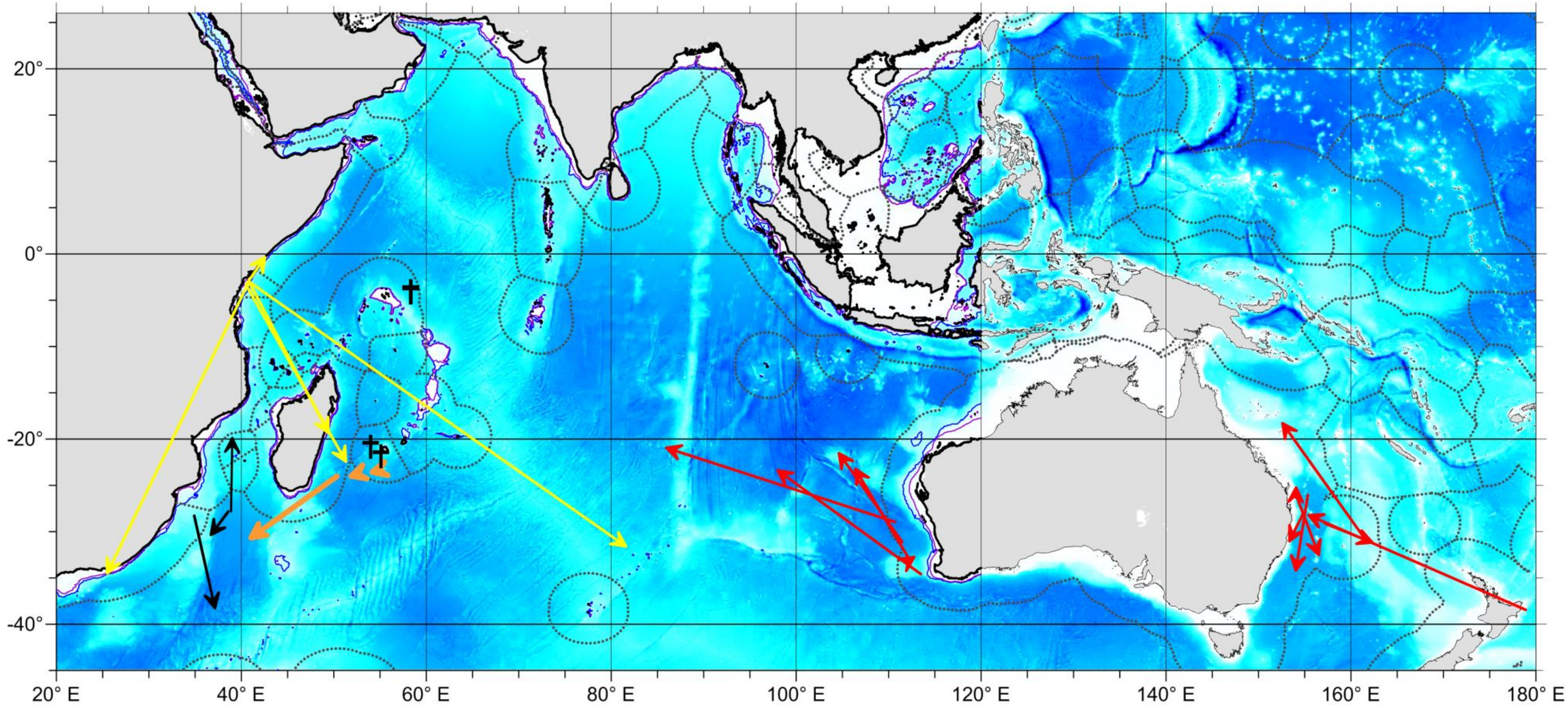


Figure 1. Past swordfish tagging experiments in the Indian Ocean and adjacent areas of the Pacific. Conventional tagging: red arrows are from Stanley (2006), yellow arrow are from ABF (2010). PSAT tagging (direct direct distance travelled): black crosses (100% SWO mortality) are from Poisson, Taquet (2001), black arrows are West et al. (2012), and orange arrows are IRD SWIOFP Project tags (Marsac, 2013 pers. comm.).

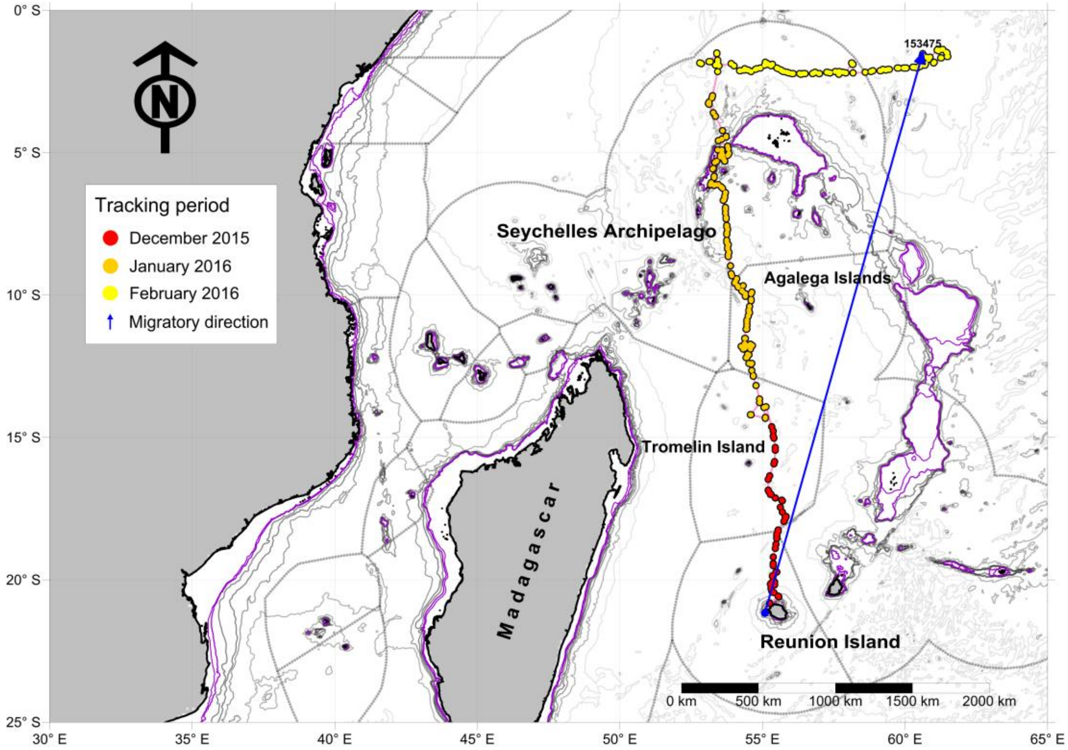


Figure 2. Swordfish #153475 most likelihood track. Approximate position of the 200-mile Exclusive Economic Zones (EEZs) of costal states (grey dotted line), the 200 m isobath (purple line) and bathymetry from 1000 to 5000 m (in 1000 m steps, light lines) are shown. Coastline and bathymetry data are from GEBCO (GEBCO, 2010), EEZs are from VLIZ (2014).

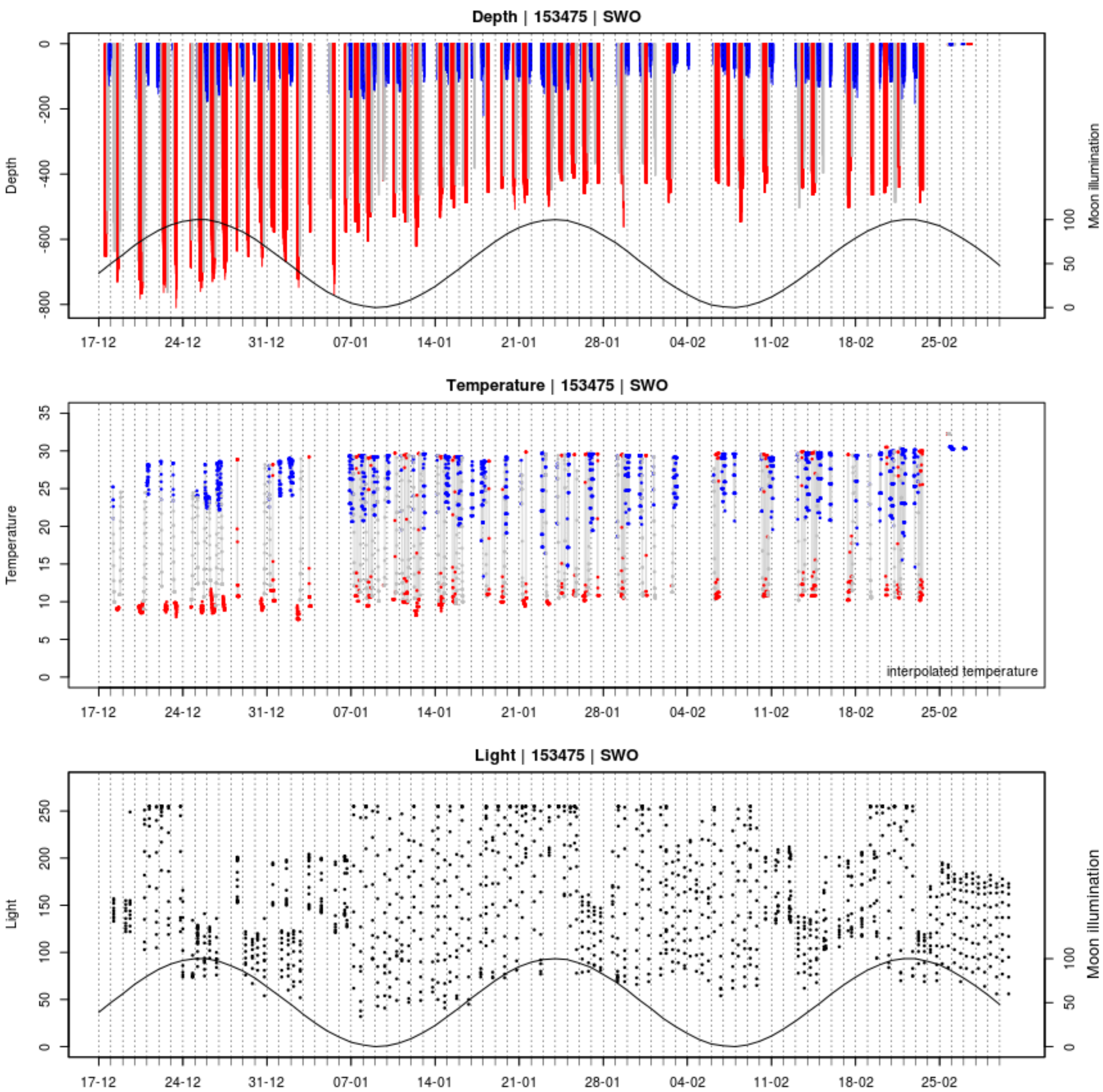


Figure 3. Depth, temperature and light time series for tag swordfish #153475 along the track from Reunion Island to equatorial waters. Blue, red, grey bars and dots receptively correspond to night, day and twilight observations

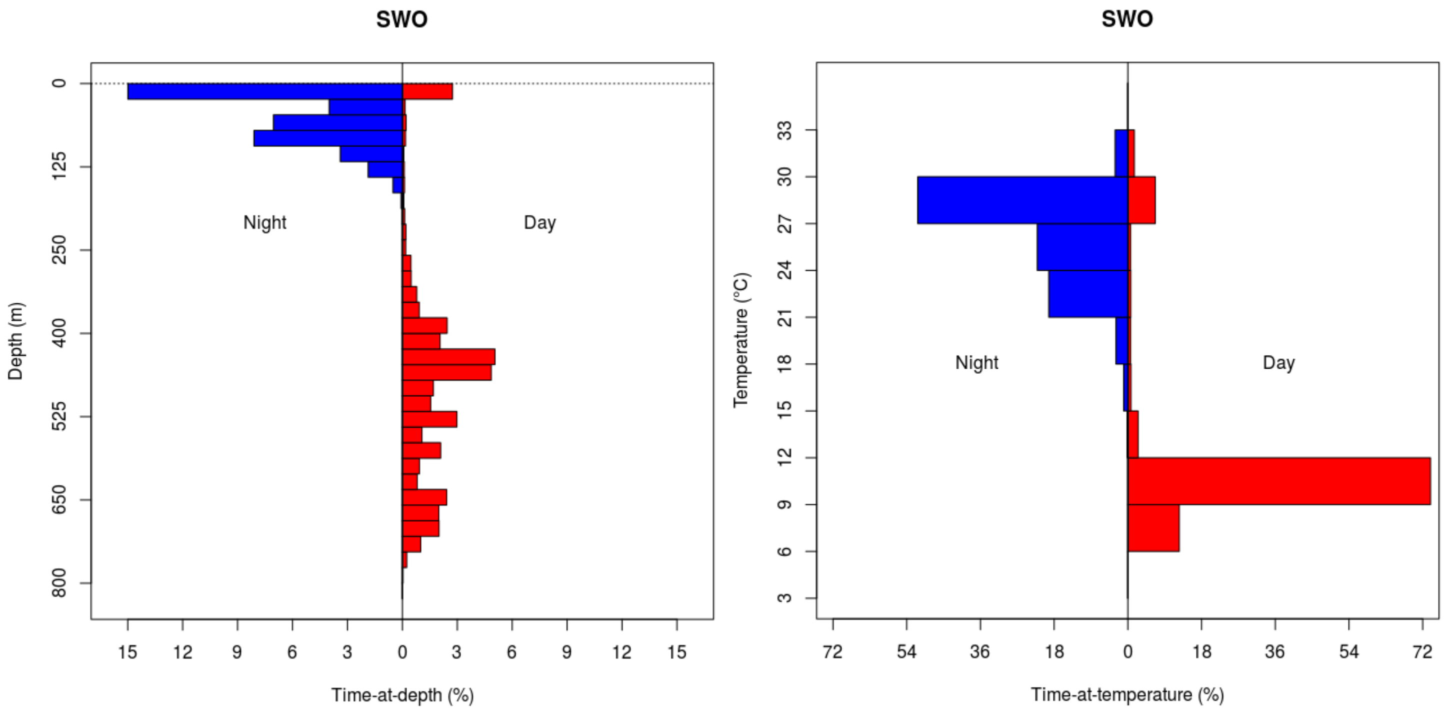


Figure 4. Summary of swordfish #153475 distribution along whole track (blue bars corresponds to night-time (20:00-05:00), red bars corresponds to daytime (08:00-17:00). Left panel: time at depth (percent of time spent at particular depth bin), Right panel: time at temperature (percent of time spent at particular depth bin).

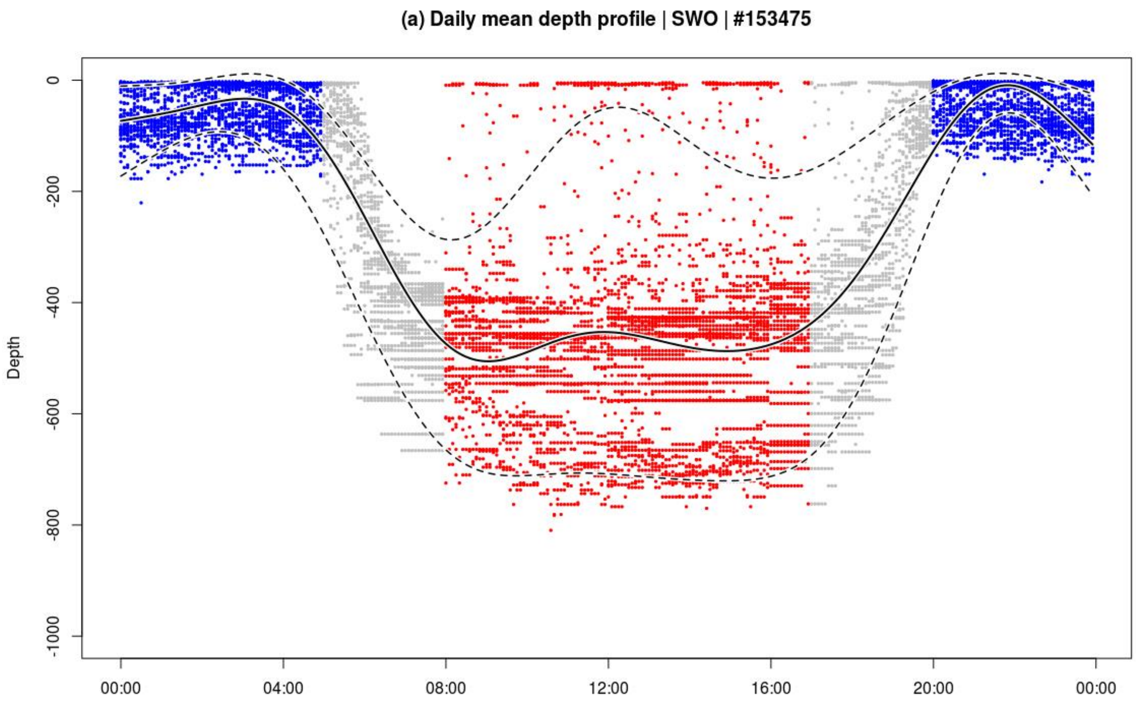


Figure 5. Mean daily depth profile for swordfish #153475. Blue, red, and grey dots correspond to night, day and twilight observations respectively.

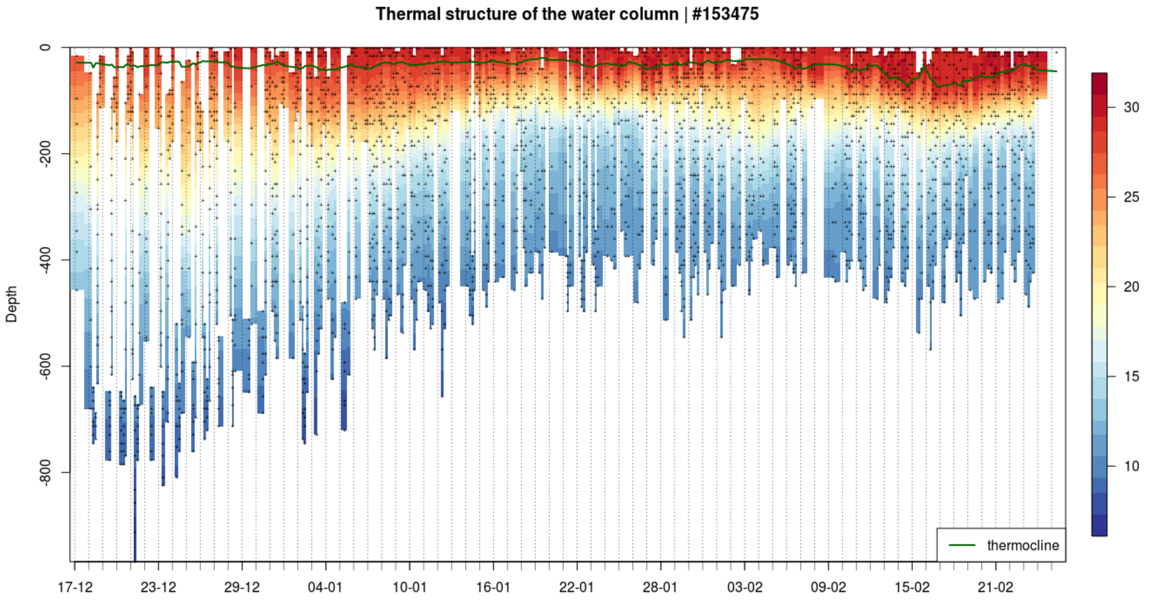


Figure 6. Thermal structure of the water column as sampled by a swordfish #153475. Crosses represent the original data points in the PDT file. Colour bar is in °C.

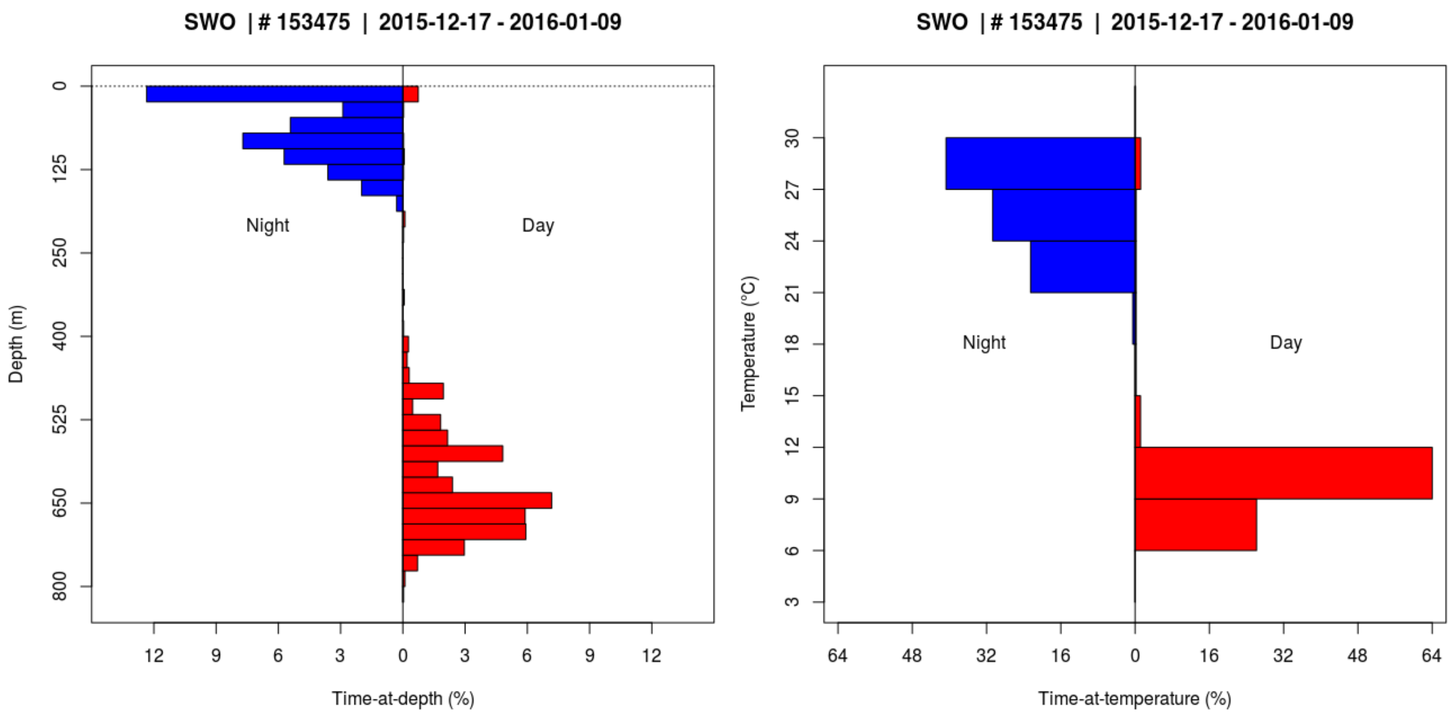


Figure 7. Summary of swordfish #153475 distribution within Indian Ocean Subtropical Gyre province. For details see caption to Fig. 4.

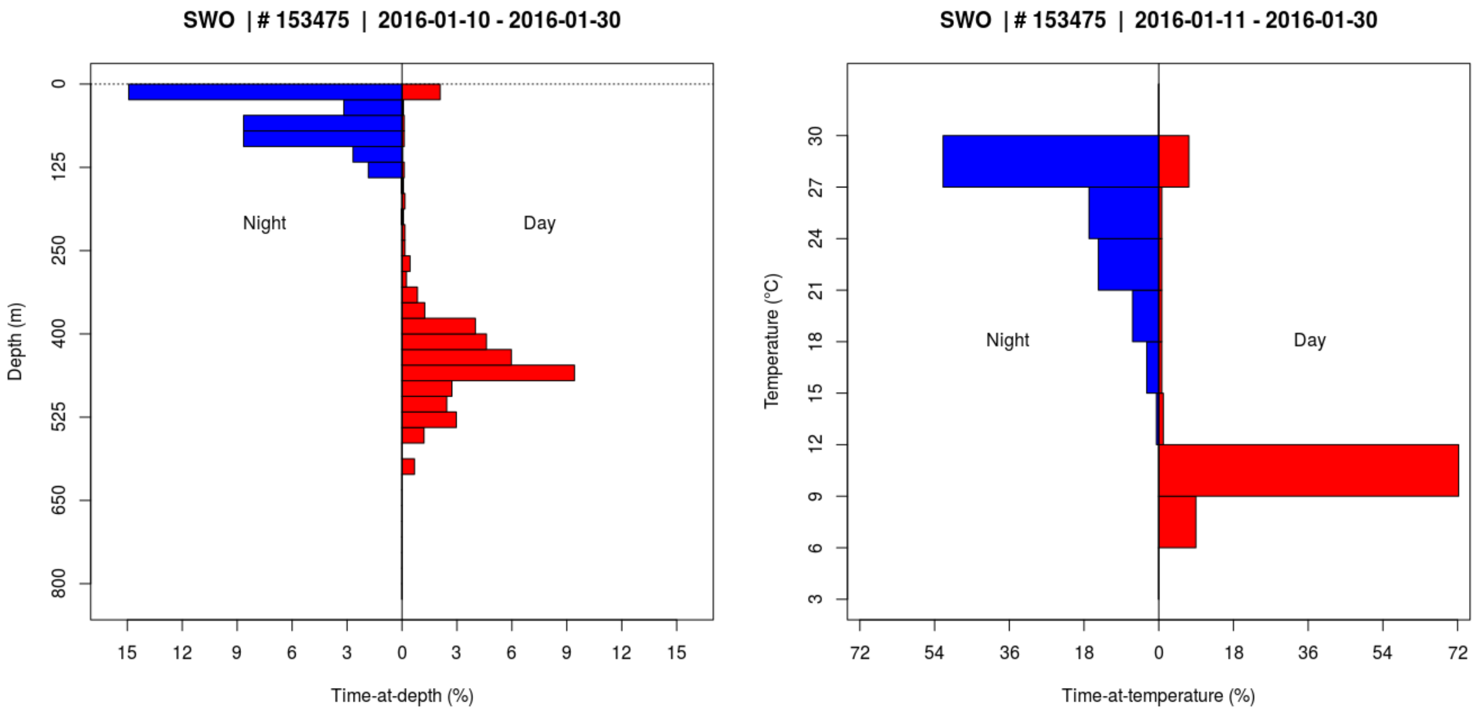


Figure 8. Summary of swordfish #153475 distribution within transitional zone between Monsoon Province and ISSG ~11°S to ~3°S. For details see caption to Fig. 4.

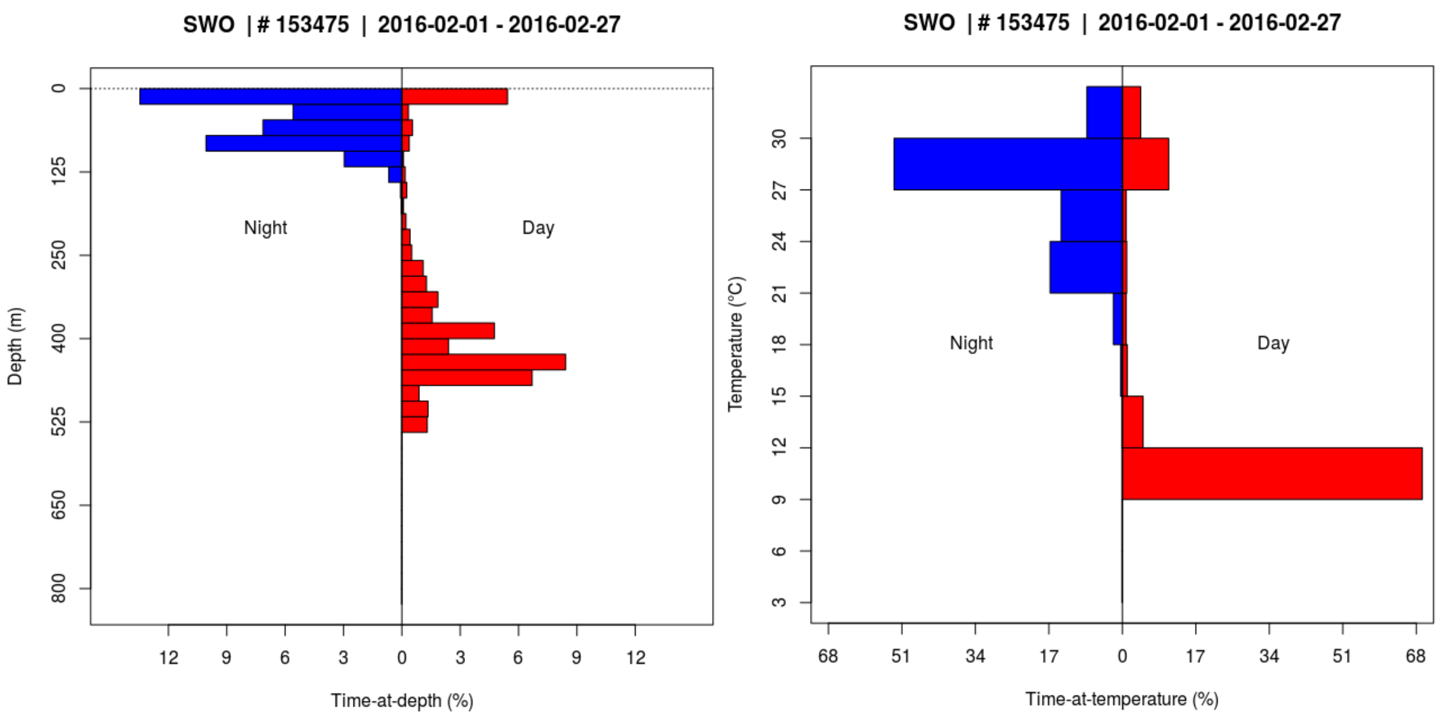


Figure 9. Summary of swordfish #153475 distribution within Equatorial Countercurrent. For details see caption to Fig. 4.

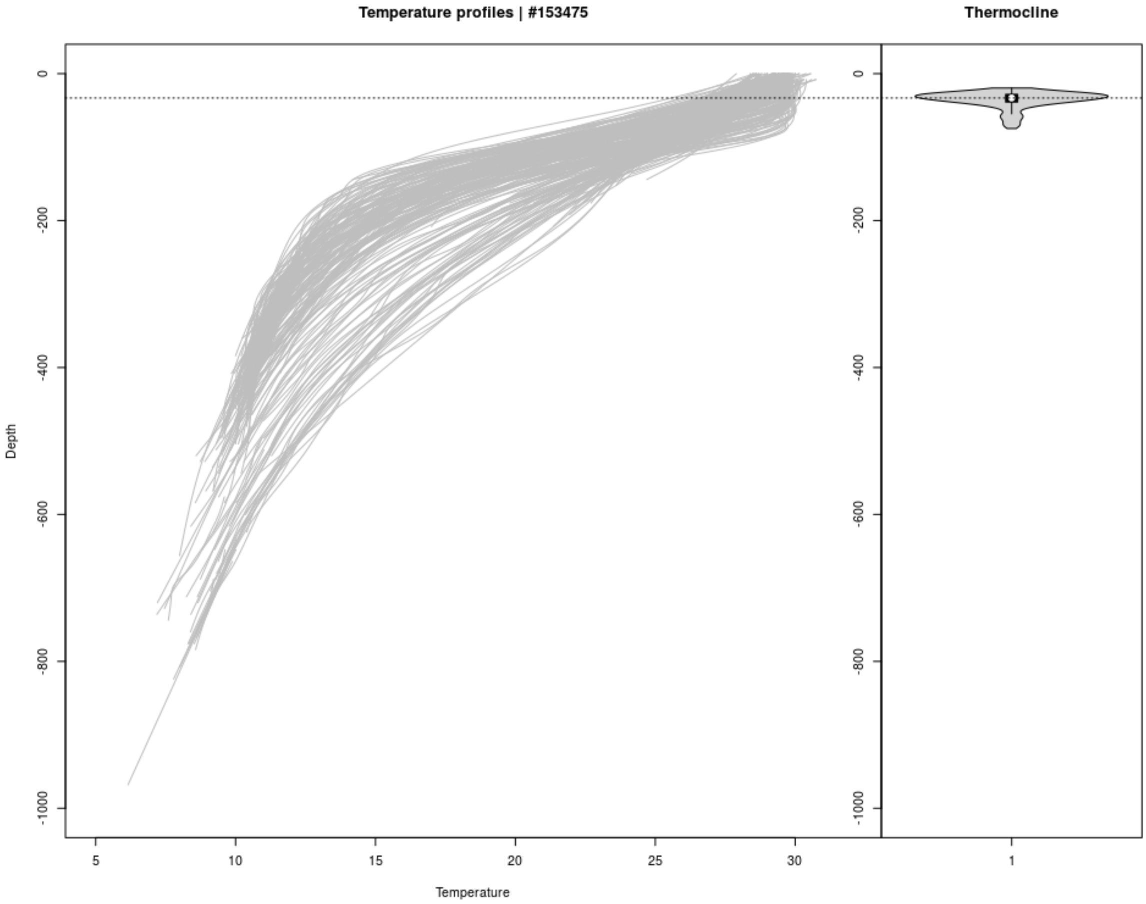


Figure 10. Temperature profiles and thermocline of tag #153475

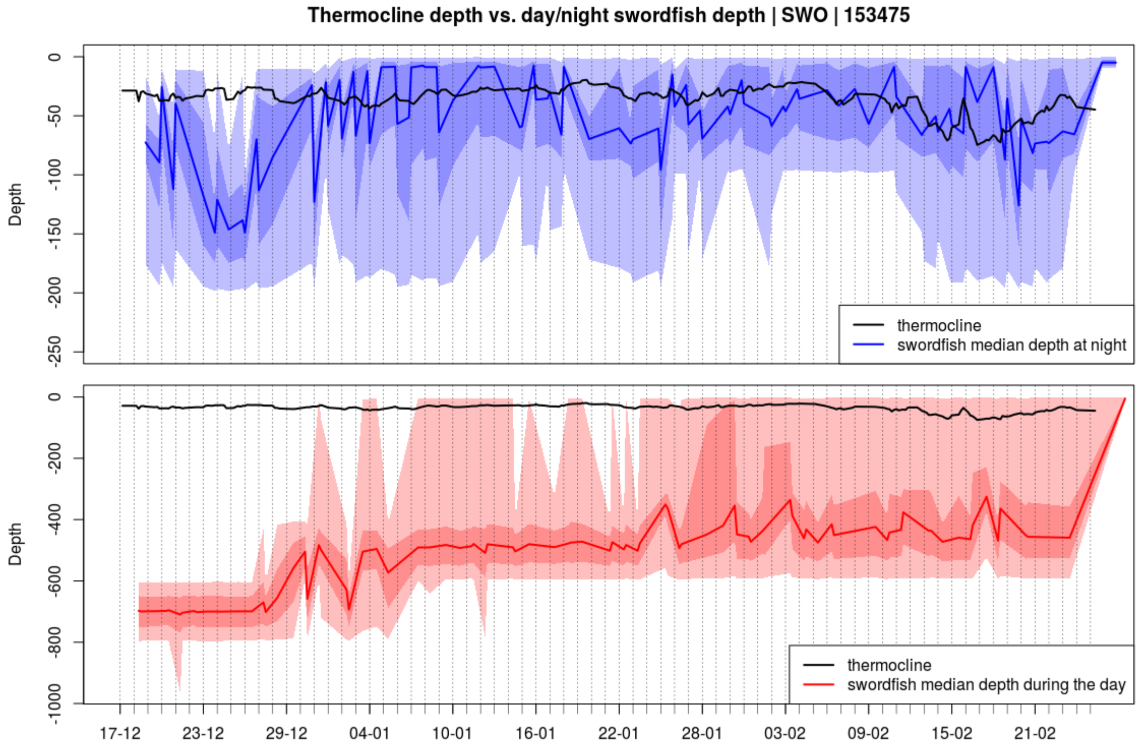


Figure 11. Average day/night positions (red/blue lines) of swordfish #153475 versus thermocline (black line). Shaded areas represent 50% and 95% CI.