Modelling the Diel Vertical Movement of Swordfish (*Xiphias gladius* Linnaeus, 1758) Based on Temperature and Depth Recorder Data

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Abstract

Understanding the vertical distribution of large pelagic fish, swordfish in particular, could improve our knowledge on its fisheries strategy, management and resource conservation. However the methods often require expensive tools and resources, which probably most scientists from the development countries couldn't afford. Thus developing model on the diel vertical movement behavior of swordfish using number of hook between float (HBF) and complete-set temperature and depth recorder (TDR) data could be an alternative. In general context, capture depth distributions are a good indicator of the natural depth distribution of the fish if the entire depth range of the species is targeted by longline gear. The proposed sinusoidal model suggested that swordfish showed a diel pattern in depth distribution, marked by remained in the surface and mixed layer waters at night and dived into deeper waters during the day.

Keywords: *swordfish, behavior, HBF, TDR, sinusoidal model*

Introduction

Knowledge on diel vertical migration behavior of large pelagic fish such as swordfish, is one of the major key on increasing our understanding about its fishery, management and resource conservation (Bach *et al*., 2003). The most common tools used for examining the vertical distribution behaviour of swordfish was acoustic telemetry (Carey and Robinson, 1981; Bach *et al*., 1998; Dagorn *et al*., 2000). It has been useful to tracked short-term movements of swordfish and has demonstrated diel vertical migration of the species (Carey, 1990). However, this technique usually represents small size of sample in term of number of individuals over limited environmental conditions and can only transmit data for a relatively short period of time (24±48 h) (Bach *et al*., 2003; Sedberry and Loefer, 2001).

Pop-up archival satellite tags (PSATs) were the other tools used to overcome the disadvantage of acoustic telemetry, which has the ability to monitor horizontal distribution or migration of the fish. It was first used on swordfish by Sedberry and Loefer (2001) in the West Atlantic and has been spread ever since *i.e*. Southeast Pacific (Abascal *et al*., 2010), South Pacific (Evans *et al*., 2014), North Pacific (Abecassis *et al*., 2012) and North Atlantic (Neilson and Smith, 2010). Both techniques have been shown to successfully identify the diel vertical migration, which was described with "U-pattern". This pattern is due to thermoregulation (Holland *et al*., 1992), and is now considered as the "classic" daytime pattern for free-swimming individuals of this species (Bach *et al*., 2003).

Both of the above mentioned methods require expensive tools and resources, which most scientists from the development countries couldn't afford. Thus A2n alternative on analyzing fish behavior based on data availability, scientific observer data in particular was developed. Study on relationship of fishing depth, Number of Hook Between Float (HBF) and TDR have been conducted by several authors, *i.e.* Bach *et al.* (2006) on why HBF was not a good proxy in predicting maximum depth on longline; Bach *et al.* (2003) comparing vertical distribution of bigeye (*Thunnus obesus*) tuna using acoustic telemetry and TDRs; and Bach *et al.* (2014) investigating swordfish fishing capture in relation with moon illumination and fishing depth using TDRs.

However, none of the previous papers tried to relate the TDRs and HBF as fishing depth indicators for analyzing swordfish behavior. The aims of the current study are to model fish behavior generated from TDRs data as fishing depth indicator and contribute to the knowledge of swordfish movements and habitat preferences in the eastern Indian Ocean in particular.

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Materials and Methods

Temperature and Depth Recorder (TDR) trials were conducted off the eastern Indian Ocean, following Indonesian commercial tuna longline fleets. TDRs type SP2T-1200 (NKE), which oftenly called mini-loggers were attached at every brach line, on each bouy, one at a time per set, depended on the TDRs available onboard until all hook number were represented. Indonesian longline fishermen were known to adjust the number of hook between float (HBF) during the set, thus it projected onto 5 different depth profile configurations based on the complete-set TDR placement i.e. 5, 11, 12, 16, and 18 (Fig. 1). The TDR data then combined with catch data, courtesy of Research Institute for Tuna Fisheries, Bali (RITF) from 2005-2014 to plot the actual of depth when the fish caught based on the hook number information. Hauling time was assumed as time-at-depth (the time when the fish occupy the water column) according to Bach *et al.* (2006). Time-at-depth was divided into one-hour interval, for example, if time-at-depth was defined to 5h if it was between 5h and 5.9h.

Of total 636 swordfish catch data, only 417 managed to be analyzed due to several reasons i.e. no hook number information, HBF configuration was outside the previously determined. Depth measurements were summarized as the percentage of the time bin that was spent within 9 depth ranges. These depth ranges were chosen to provide higher resolution at shallower depths (less than 100 m) where fish were expected to spend the majority of their time. Temperature measurements were summarized as the percentage of the time bin that was spent within consecutive 2^{0}C increments.

In this study the diel vertical movement was assumed to be "seasonal" (occupying upper and lower layer water column in 24 hour cycle), thus sinusoidal (trigonometric) regression was considered as the best approach to model the movement, with a periodic function (sine wave) to fit into the data. A "general" sine wave with amplitude A and phase φ, $A\sin(x+\varphi)$, where a and b are such that

$$A = \sqrt{a^2 + b^2}$$

$$\sin \varphi = \frac{b}{\sqrt{a^2+b^2}}.$$

The equation can be written as the linear combination $a \sin x + b \cos x$, so the sinusoidal regression was

$$y = \mu + \sin x_1 + \cos x_2 + \varepsilon.$$

Where:
y : mean depth
μ : intercept
x_1 and x_2 : parameters
ε : error term (normally distributed),n=1,2,3

All the statistical data was analyzed using R software version 3.1.3. and the map was drawn using QGIS version 2.10.1.

Results and Discussion

Total 417 specimen of swordfish were analysed from 44 trips during 2005-2014. A cumulative total of 10 years of catch data on swordfish distribution, depth and ambient temperature occupancy were obtained. (Table 1). Swordfish primarily occupied the mixed layer, spending 59.59% of their time at day and 63.51% at night above 200 m. Depth distribution was slightly shallower at day when fish spent 14.51% of their time above 100 m, compared to 12.16% during the day. At night, swordfish slightly occupied deeper water column (87.84%), compared to 85.49% during the day (Fig. 2). Nocturnal distribution was colder, with fish spending 69.51% of their time in waters colder than 22 ^{0}C, compared to 63.40% during the day. Deep diving behavior was shown both day and night and the deepest dive recorded was 431.78 m at9.41 ^{0}C during the day (Fig.3.).

The diel vertical movement of swordfish in 24hours period could be described as a sinusoidal function y=172.45129+sin(-24.77215)+cos(-21.24831) (R^2= 0.473, p-value=0.004317). The model seemed quite fit to explain the mean depth variable. It showed that swordfish dived into deeper water column during the day, from 4:00 a.m - 4:00 p.m and gradually hovered into shallower water column during the night, from 5:00 p.m - 3:00 a.m. According to the model, swordfish predicted to be at shallowest water column at 3 a.m. and deepest at 3 p.m. (Fig. 4).

Predicting the capture depth of longline through catenary algorithms was initially introduced by Yoshihara (1951, 1954). It was a quite useful algoritms prior to the utilization of TDR, acoustic telemetry and pop-up satellite achival tags. But Bigelow *et al.* (2006) noticed that predicting capture depths using traditional catenary equations (Yoshihara method) may be biased without the benefit of TDRs affixed to longlines. Since thedeployment of acoustic telemetry and pop-up satellite archival tags require a lot of resource, Bach *et al.* (2003) found that determining capture depth

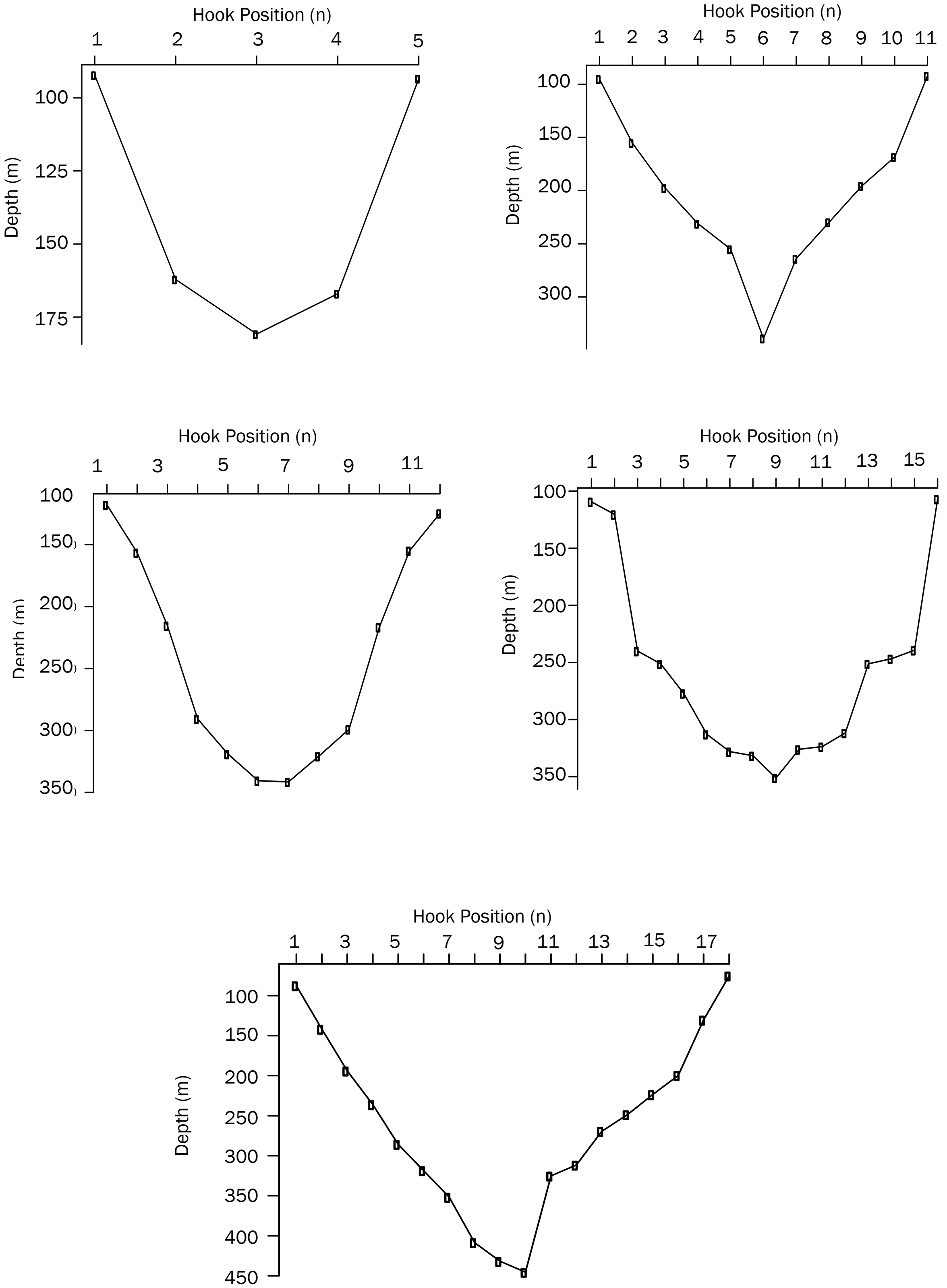

Figure 1. Number of hooks between float (HBF) profiles (5, 11, 12, 16 and 18, respectively) based on complete-set TDR placement

Table 1. Summary of swordfish catch data (data used in this paper was obtained from scientific on board observation 2005-2014.) Depth and temperature were converted from TDR complete dataset.

Year	No. Trip (n)	No. Fish (n)	Length		Depth		Temperature	
			Min (cm)	Max (cm)	Min (cm)	Max (cm)	Min (ºC)	Max (ºC)
2005	9	1	163	163	255.00	255.00	13.30	13.30
2006	18	138	42	250	75.18	431.78	9.40	26.80
2007	13	83	52	370	87.64	408.45	10.01	25.51
2008	15	17	60	212	109.31	320.72	11.53	25.35
2009	13	22	65	203	109.31	326.10	11.72	25.35
2010	6	7	70	138	168.47	320.72	11.53	17.70
2011	4	13	120	215	117.83	216.59	15.31	21.83
2012	8	12	47	172	75.18	311.47	11.90	25.51
2013	8	69	46	230	92.05	341.52	10.19	25.35
2014	5	55	30	160	92.05	351.21	11.43	25.35

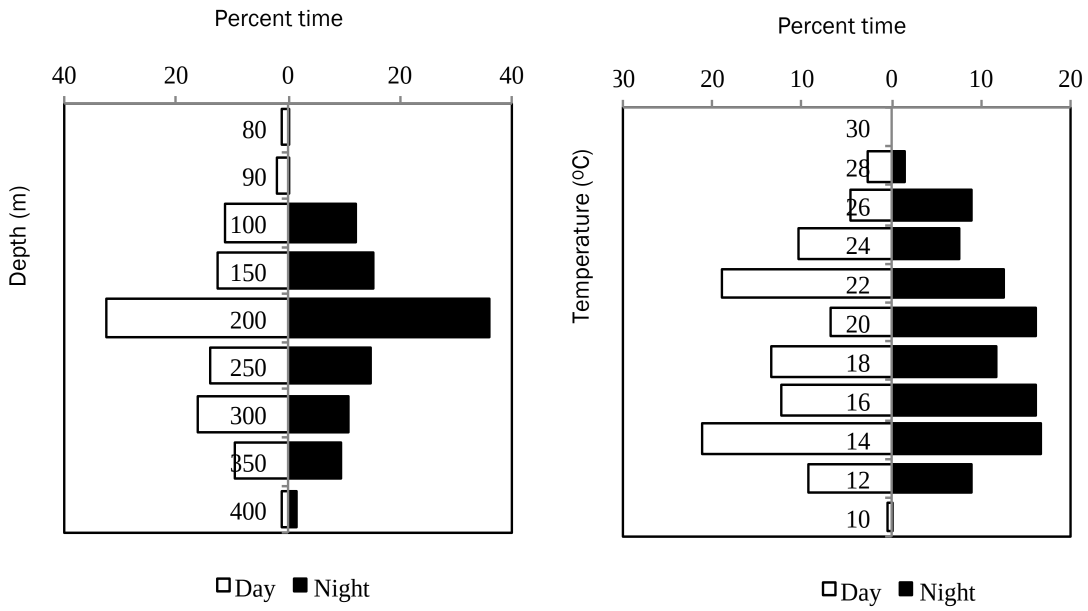

Figure 2. Time-at-depth (left) and time-at-temperature (right) of swordfish generated from complete-set TDR data from August 2005 to December 2014.

from combination of HBF and complete-set TDR information was quite robust compared to acoustic telemetry. Based on his result, the analysis was expanded into a model and compares it with other methods.

Presented sinusoidal model in this research gave relatively similar result compared to more robust methods such as acoustic telemetry (Carey and Robinson, 1981; Bach *et al*., 1998; Dagorn *et al*., 2000) and pop-up archival tags (Abascal *et al.*, 2010; Neilson and Smith, 2010; Abecassis *et al*., 2012; Evans *et al*., 2014). The vertical movement shown by the model characterized with deeper, cooler waters were frequented during the day, and shallower, warmer waters were frequented at night. This behavior seemed appears on other large pelagic fishes, like bigeye tuna (Arrizabalaga *et al.*, 2008; Evans *et al.*, 2008) and yellowfin tuna (Weng *et al*., 2009; Hoolihan *et al.*, 2014).

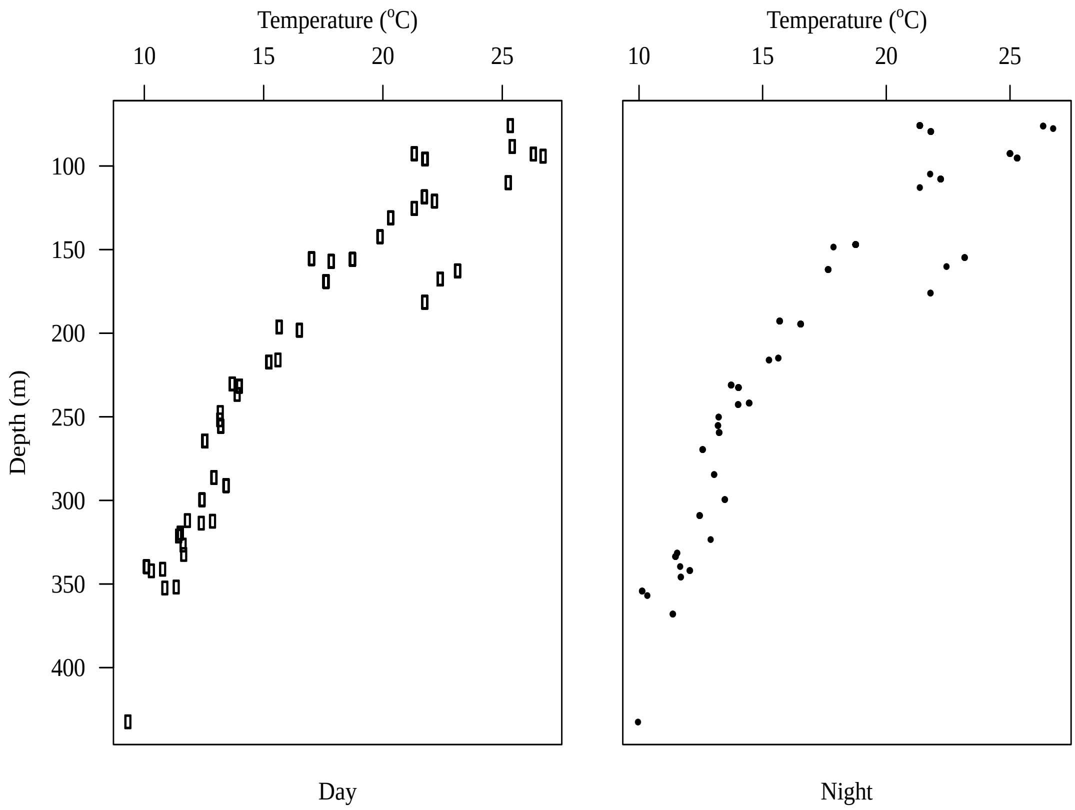

Figure 3. Depth versus temperature profile between day and night from complete-set TDR data from August 2005 to December 2014.

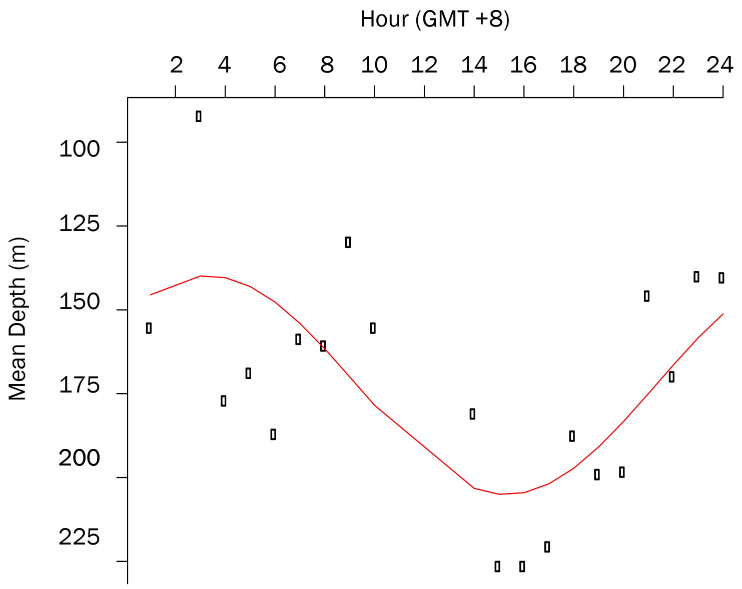

Figure 4. Sinusoidal regression model of diel vertical movement of swordfish based on complete-set TDR data from August 2005 to December 2014.

Table 2. Summary table of sinusoidal regression between mean depth and hour from complete-set TDR data from August 2005 to December 2014.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	172.451	5.918	29.142	5.93e-16 ***
sin(2π/24 * Hour)	-24.772	7.673	-3.229	0.00493 **
cos(2π/24 * Hour)	-21.248	9.144	-2.324	0.03279 *

Signif. codes: 0 '***' 0,001 '**' 0,01 '*' 0,05 '.' 0,1 ' ' 1

Residual standard error: 26.12 on 17 degrees of freedom, Multiple R-squared: 0.473, Adjusted R-squared: 0.411, F-statistic: 7.63 on 2 and 17 DF, p-value: 0,004317

Diel vertical movement on large pelagic fishes, swordfish in particular was subject to wide temperature variability (up to 17.4ºC in this study). It corresponded with thermo regulation (Holland *et al.*, 1992) and following the distribution of micronekton/prey (Josse *et al*., 1998; Dagorn *et al*., 2000). Other possible explanation for the behavioral pattern is that during daylight the surface water temperature is warmer, therefore swordfish dive deep to feed, as for the night, it hovering into warmer water to facilitate their digestion, increase metabolic rates & function (Takahashi *et al.*, 2003). Overall, the proposed sinusoidal model suggested that capture depth distributions are a good indicator of the natural depth distribution of the fish if the entire depth range of the species is targeted by longline gear. This means that swordfish are not modifying their vertical distribution by being attracted by a baited hook. Despite of its "robustness", this method can only describe the capture depth distribution of swordfish, not the actual depth migration. It also did not give fine scale surface movement as if on acoustic telemetry or pop- up satellite archival tag. This merely due to all of the minimum hook depth on any HBF configuration used in this study was above 100 m.

Conclusion

The proposed sinusoidal model suggested that capture depth distributions are a good indicator of the natural depth distribution of the fish if the entire depth range of the species is targeted by longline gear. Swordfish showed a diel pattern in depth distribution, remaining in surface and mixed layer waters at night and diving to deeper waters during the day.

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