Journal of Experimental Marine Biology and Ecology 397 (2011) 129–135

Contents lists available at ScienceDirect

Journal of Experimental Marine Biology and Ecology

journal homepage: www.elsevier.com/locate/jembe

Vertical and horizontal movements of sailfish (*Istiophorus platypterus*) near Taiwan determined using pop-up satellite tags

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ARTICLE INFO

Article history:
Received 28 May 2010
Received in revised form 20 November 2010
Accepted 23 November 2010
Available online 31 December 2010

Keywords:
Basking
Fisheries
Habitat
PSATs
Tagging
Temperature

ABSTRACT

Sailfish (*Istiophorus platypterus*) are of substantial economic importance to Taiwan because of their seasonal abundance (April to October, with a peak from May to July) off the island's eastern coast. They are harvested by drift gill nets, set nets, harpoons, and as incidental bycatch by inshore longline fisheries. Although the biology of sailfish has been investigated in eastern Taiwan, there is a paucity of data on movement patterns. Pop-up satellite archival tags (PSATs) were used to study the vertical and horizontal movements of three sailfish in 2008. The fish were tagged near the southeastern coast of Taiwan and linear displacements ranged from 1050 to 1400 km (~40 km day^{-1}) from deployment to pop-up locations and all movements were confined to the East China Sea. Sailfish spent 88% of their time in the upper uniform mixed layer above 50 m, but made more extensive vertical movements during the nighttime ($x=60.61$ m ± 48.24 SD) than daytime ($x=35.21$ m ± 35.37 SD). Depths and ambient water temperatures visited ranged from 0 to 214 m and 30.0° to 17.8 °C, respectively. However in all cases, the depth distribution appeared primarily limited by an 8 °C change in water temperature. Diel diving patterns also suggested basking behavior. Sailfish behavior makes them particularly vulnerable to surface fishing gears.

1. Introduction

Sailfish (*Istiophorus platypterus*; family Istiophoridae) is a circumtropical epipelagic species that is considered as bycatch in most commercial fisheries (Hoolihan, 2005). Sailfish appear to comprise a single, highly mobile, pan-Pacific stock but genetic studies could neither confirm nor refute the null hypothesis of panmixia (Graves and McDowell, 2003). In the western Pacific Ocean, the distribution of postlarvae and adult sailfish appears to be intimately correlated to the Kuroshio current and the densest aggregations coincide with the spawning season (Nakamura, 1985). Sailfish spawn near eastern Taiwan (Chiang et al., 2006a,b) and are thus seasonally abundant (April to October, with a peak from May to July). They are targeted by surface drift gill nets, set nets, harpoons and are also retained by inshore longline fisheries (Chiang, 2004). For the past decade, the annual landings of sailfish fluctuated between 500 and 1000 mt, with 80% captured off the east coast. Stock assessments show Pacific sailfish to be moderately exploited (Chiang et al., 2009) and there is no evidence to suggest that local Taiwanese fisheries could deplete this wide-ranging species.

Pop-up satellite archival tags (PSATs) electronic storage devices are attached externally to marine animals with an anchoring device that jettison at a pre-programmed date, have proven instrumental for defining horizontal and vertical distribution patterns, migration corridors and post-release survival of several billfish species: black marlin (Gunn et al., 2003), blue marlin (Graves et al., 2002; Kerstetter et al., 2003; Prince and Goodyear, 2006), sailfish (Hoolihan, 2005; Hoolihan and Luo, 2007; Kerstetter and Graves, 2008), striped marlin (Domeier et al., 2003), and white marlin (Horodysky and Graves, 2005; Horodysky et al., 2007). PSATs record ambient water temperature and pressure (depth), as well as light-level irradiance used to calculate daily geographic positions or geolocations (Arnold and Dewar, 2001; Musyl et al., 2001). PSATs can offer many benefits to study vertical dive behavior, as well as providing information on migration routes, possible spawning areas and exchange rates between areas. The biology and ecology of sailfish has been investigated in eastern Taiwan but there is a paucity of information on movement patterns. The objectives of our study were therefore to examine movement patterns, and habitat preferences of sailfish in eastern Taiwan waters using PSATs.

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doi:10.1016/j.jembe.2010.11.018

2. Materials and methods

Sailfish were captured at a set net complex (Sainsbury, 1996) off eastern Taiwan (Fig. 1) and did not appear to be under duress and were thus in optimal condition for tagging. Individuals were hauled directly aboard the tagging vessel using a sling and placed over a wet mattress. A moist chamois cloth was put over the fish's eyes and a saltwater hose placed in the mouth for ventilation. The tag head, tether and applicator tips were liberally bathed in Betadine solution (10% solution of povidone–iodine) and then immediately inserted near the base of the dorsal fin between spaces of the interneural and neural spines. The tagging procedure was completed in approximately 60 s.

Tethers were made of ~123 kg fluorocarbon and stainless steel crimps matching the diameter of the line. Stainless steel ball bearings (Sampo no. 6, Barneveld, NY, USA) were placed ~15 cm from the tag head and were to reduce torque and precession. Surgical grade nylon tag heads were augmented with speargun 'flopper blades' to increase surface area and were rigged in a manner similar to that described by Musyl and McNaughton (2007). PSAT and tether/tag head combinations were positively buoyant in water and the usual suite of "fail-safe" options were programmed into the PSATs (Moyes et al., 2006; Swimmer et al., 2006).

We deployed two model Mk10 PSATs from Wildlife Computers (WC, Redmond, WA, USA). Depth (m) and temperature (°C) data were binned into the following intervals: 0–10, 10–25, 25–50, 50–75, 75–100, 100–150, 150–200, 200–250, 250–300, 300–400, 400–500, 500–600 and >600 m; and 0–6, 6–8, 8–10, 10–12, 12–14, 14–16, 16–18, 18–20, 20–22, 22–24, 24–26, 26–28, 28–30 and >30 °C, respectively. Depth and temperature data were recorded every 60 s and the data summarized into successive four hour intervals commencing at 00:00 h (GMT). The PSATs also stored minimum and maximum depths and temperatures so that temperature–depth profiles could be generated. The programmed pop-up period was set to 180 days after

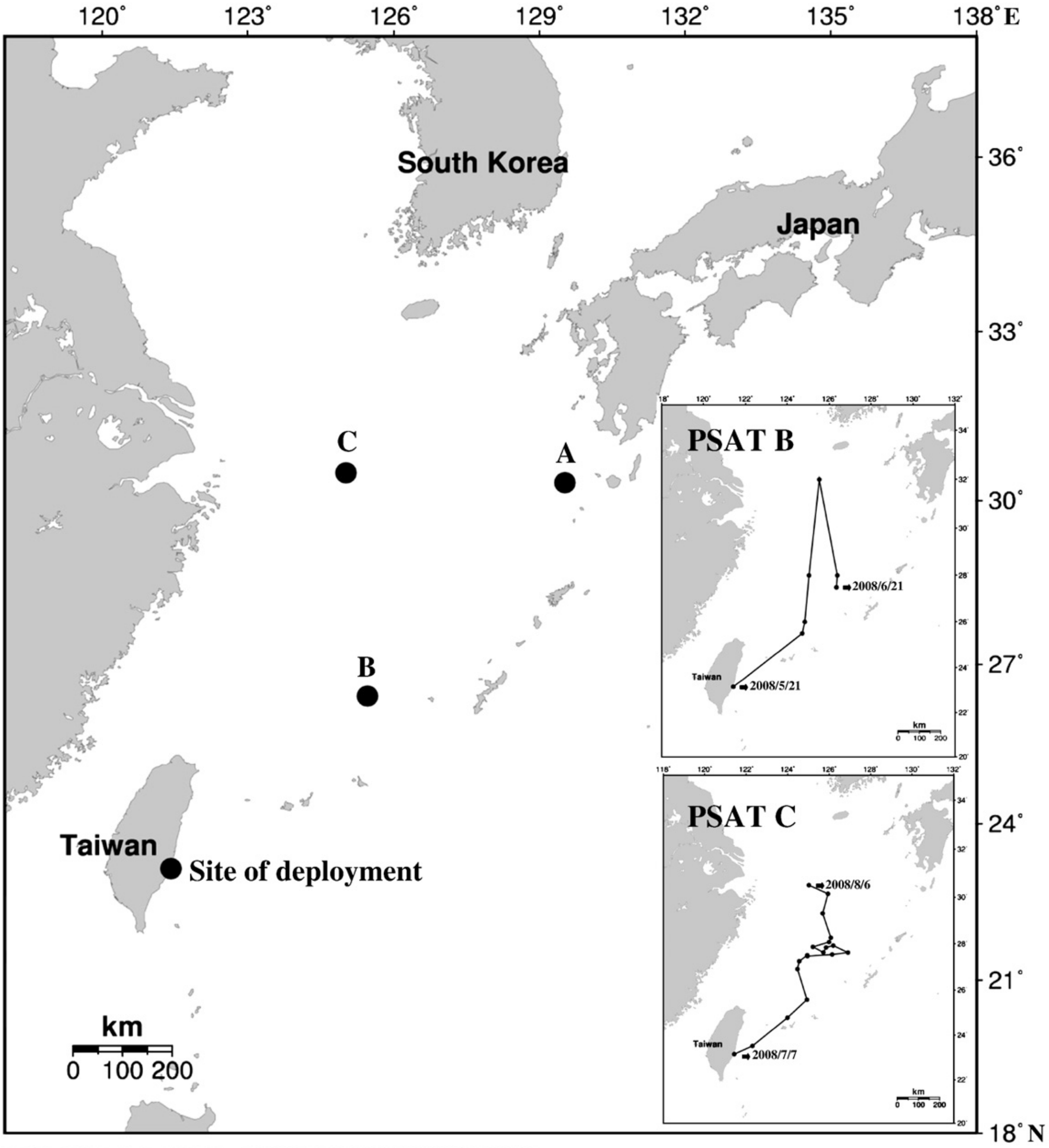

Fig. 1. Deployment and pop-up locations for sailfish carrying PSATs. most probable tracks were calculated by the unscented Kalman filter (Lam et al., 2008) for Fish B and C (dates denote the start and the end of each track). PSAT A: 215 cm LFFL (lower jaw fork length); linear displacement = 1050 km; data received, 27 days. PSAT B: 180 cm LFFL; linear displacement = 1400 km; data received, 32 days. PSAT C: 225 cm LFFL; linear displacement = 1240 km; data received, 31 days.

deployment. Raw light-level data were initially processed using the global positioning software WC-AMP (Wildlife Computers, Redmond, WA, USA) to estimate daily geolocations. We subsequently applied a sea surface temperature (SST) corrected (unscented) Kalman filter (Lam et al., 2008) to calculate most probable tracks (MPTs). We also deployed one PTT-100 HR PSAT from Microwave Telemetry (MT, Columbia, MD, USA). This unit recorded ambient water temperature and depth data every 3 min. The programmed pop-up period was set to 27 days after deployment. Due to a non-specified error in the light sensor, we could not calculate geolocations for the sailfish carrying this tag (Musyl et al., 2003).

The linear displacements from tagging to pop-up locations were determined using the Great Circle Distance and release locations were determined by GPS coordinates at the set net complex. Pop-up locations were estimated by Doppler shift from the ARGOS transmissions of each PSAT. Only ARGOS messages with location class of 1 or higher were used to determine pop-up locations.

Given the limited temporal and spatial coverage of tags in the study, we categorized data into daytime and nighttime periods by calculating times of local dawn and dusk from http://aa.usno.navy.mil/. To further explore daytime and nighttime differences in the time series data collected from the MT tag, we used one-sample Kolmogorov–Smirnov tests to compare distributions of ambient temperature (day, night, combined) and depth (day, night, combined) data to that of a normal distribution and all tests indicated that data distributions were not normally distributed ($P<0.01$). Therefore, we used non-parametric two-sample Kolmogorov–Smirnov tests to compare daytime and nighttime temperature and depth preferences, and Mann–Whitney W-tests to compare differences in medians between daytime and nighttime data for depth and temperature (Zar, 1996). The time-at-depth and time-at-temperature data were aggregated into bins and were subsequently expressed as a fraction of the total time of observation for each fish. The $P<0.05$ level was taken to indicate statistical significance.

Vertical data from tagged sailfish was compared with data provided from conductivity, temperature and depth (CTD) probes deployed from a research vessel near the study area, which also provided data on dissolved oxygen (DO) concentrations and temperature–depth profiles (FRI, 2008).

3. Results

Of the 3 PSATs in the study, PSAT A transmitted successfully on its scheduled release date after 27 days-at-liberty whereas PSATs B and C detached prematurely after 32 and 31 days, respectively (Fig. 1). All pop-up locations occurred within the East China Sea, and the calculated MPTs for PSATs B and C also suggest that tagged sailfish remained within this area (Fig. 1). The sailfish carrying PSAT A traveled 1050 km (straight line distance) in 27 days (~39 km day^{-1}) (Fig. 1). The sailfish carrying PSAT B travelled 1400 km from the tagging location to Cheju do Island and then apparently turned towards Okinawa (Fig. 1) over the course of 32 days with a linear speed estimated at ~44 km day^{-1}. The sailfish carrying PSAT C travelled 1240 km (straight line distance) in 31 days (~40 km day^{-1}) from the tagging location to Kagoshima Island, but apparently made some non-directed movements about half-way through the track (Fig. 1).

We obtained a total of 70 days of depth and temperature data from the 3 tags. The mean depth occupied was 47.9 m (±44.3 SD, range: 0 to 213.8 m) and the mean temperature occupied was 26.1 °C (±1.7 SD, range: 17.8° to 30.0 °C). It is apparent that sailfish spend the majority of their time in the uniform temperature surface layer (Table 1). The diel diving patterns (Fig. 2) for sailfish carrying PSAT A suggested possible basking behavior or preference for near surface waters during the daytime. All two sample Kolmogorov–Smirnov and Mann–Whitney W-tests tests were significantly different at $P<0.001$, respectively; thus confirming distinct diel patterns in depth and temperature preferences. Depth excursions were limited to a temperature change of ≦8 °C. The CTD casts indicated DO readings were about 4.7–5.8 mg l^{-1} from the surface to ~50 m where sailfish spent 88% of their time.

The fish carrying PSAT A spent ~36% of time above 10 m (Fig. 3) and exhibited regular movement patterns throughout the day and night with greater variability near crepuscular times with more extensive vertical movements during nighttime (Fig. 3). Approximately 95% of the daytime temperatures occupied were within 3 °C of estimated SST, whereas at nighttime, ~95% of the movements were over a broader temperature range (Table 1). However, the sailfish carrying PSAT A also demonstrated occasional vertical movements in excess of 100 m (Fig. 3). Based on temperature–depth profiles the bottom of the mixed-layer (MLD) appears to be ~130–150 m (Fig. 2).

Table 1
Cumulative percentage of temperature readings from pop-up satellite archival tags (PSATs) attached to sailfish expressed as differences from daily mean sea surface temperature (ΔSST). SST was calculated as per Nielsen et al. (2006) and is analogous to Brill et al. (1993) surface layer.

Fish	ΔSST (°C)								
	0	−1	−2	−3	−4	−5	−6	−7	<−8
A	31.68	72.81	84.33	91.17	94.4	97.06	98.52	99.78	100
B	28.57	61.07	77.50	89.29	94.29	96.79	97.86	98.93	100
C	19.85	47.55	63.48	74.26	82.11	85.54	87.75	88.97	90.44

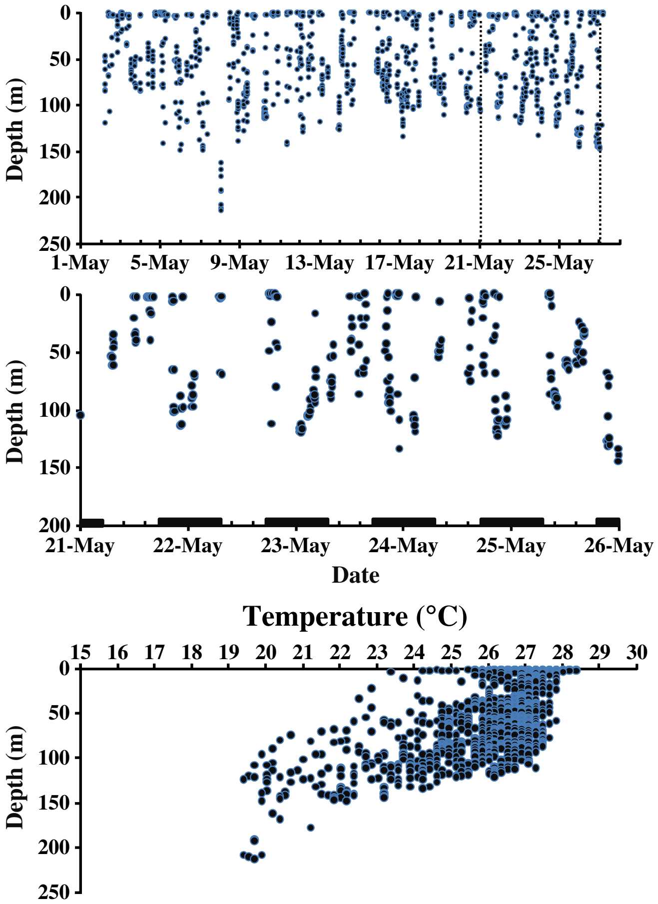

Fig. 2. Depth and temperature records for Fish A. Depth record covering 27 days at liberty (top panel), 6-day period during which the fish showed the characteristic vertical movement patterns with dawn and dusk transitions (middle panel), and depth/temperature profiles (bottom panel). The dashed vertical lines in the upper panel show the portion of the depth record expanded in the lower panel. The dark horizontal bars indicate nighttime and date marks midnight.

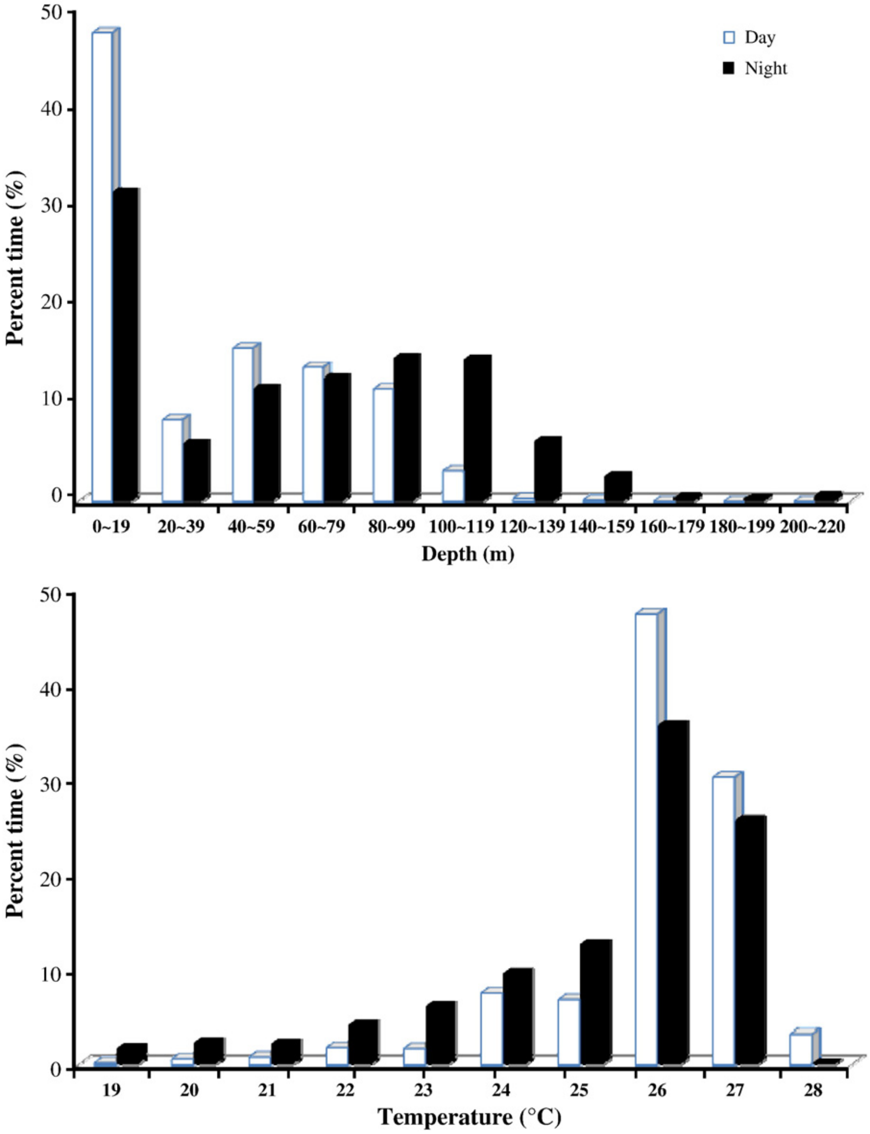

Fig. 3. Percentage time spent at depth (top panel) and temperature (bottom panel) for Fish A.

The fish carrying PSAT B spent ~76% of its time above 10 m (~86% during the day and ~67% during the night) and depth distribution patterns indicated deeper diving excursions at nighttime. The fish spent the vast majority of time in the uniform temperature surface layer (~89% of the time it occupied water >25 °C, Fig. 4) and vertical movements appeared limited by a temperature change of ≦8 °C (Table 1). Temperature–depth profiles (Fig. 4) suggested the bottom of the MLD was around ~100–120 m (~19 °C). Minimum temperature, SST and maximum dive periods are shown in Fig. 5.

The sailfish carrying PSAT C spent ~68% of its time above 10 m (~70% during the day and ~67% during the night) and exhibited similar daytime and nighttime depth distributions (Fig. 6) and spent the vast majority of its time in the uniform temperature surface layer (Table 1). Temperature–depth profiles (Fig. 6), suggest the bottom of the MLD was around ~120–140 m (~18 °C) which was consistent to data from the other tagged sailfish.

4. Discussion

The net northward movement of sailfish to the East China Sea from eastern Taiwan recorded with PSATs (Fig. 1) agrees with catch data and prior conventional tagging studies that suggested peak migration during May to July in Taiwan, and during September for Kagoshima Island (Masuda Yasuji, personal communications). This migration pattern presumably represents directed movement towards more favorable foraging grounds after spawning (Chiang et al., 2006a,b). The spatial and temporal characteristics of horizontal movement patterns of PSAT tagged sailfish were consistent with earlier reports suggesting movement patterns influenced by the Kuroshio current system during migration from eastern Taiwan to Japan (Nakamura, 1985). The Kuroshio flows in a northeast direction along the East China Sea shelf slope and generates a convergence zone at the boundary between the Kuroshio and a countercurrent system produced by bottom shelf water (Andres et al., 2008). This creates upwelling which in turn brings nutrients and abundant food resources (Ito et al., 1995). Longer track durations, however, would be needed to get a broader picture of residence times, exchange rates and migration corridors and how these movement patterns might be affected by oceanographic conditions (Brill and Lutcavage, 2001).

Sailfish exhibit diel vertical movements, characteristic of other billfishes (Holland et al., 1990; Brill et al., 1993). In daytime, the greatest percentage of time was spent near the surface which we interpret as basking behavior similar to that of swordfish (Carey and Robinson, 1981). PSAT and ultrasonic tracking studies on sailfish show

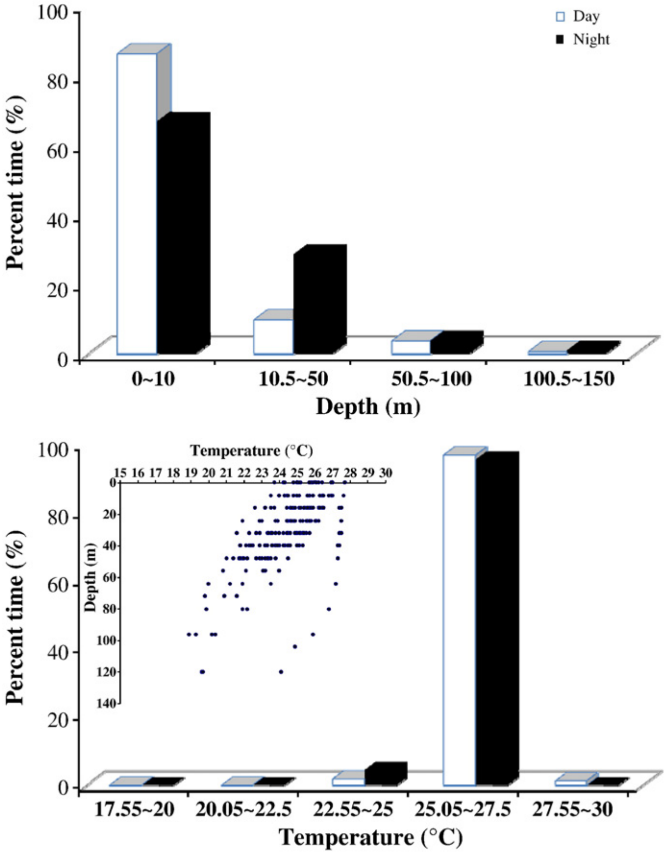

Fig. 4. Percentage time spent at depth (top panel), temperature (bottom panel) and depth/temperature profiles (bottom panel) for Fish B.

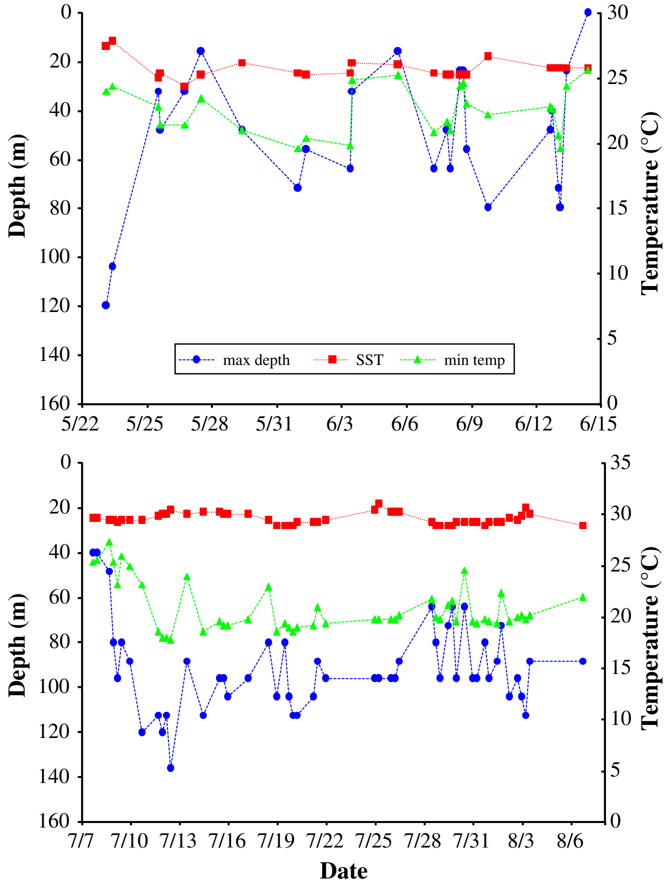

Fig. 5. Minimum temperature, SST and maximum depth for Fish B (top panel) and Fish C (bottom panel).

84% of their time was spent in the upper 10 m (Hoolihan, 2005; Hoolihan and Luo, 2007; Prince and Goodyear, 2006). Tracking studies on other istiophorid billfish in different parts of the world, where regional oceanography and thermal structure are clearly different, suggests a common overall preference for the uniform surface mixed-layer (e.g. Hoolihan and Luo, 2007; Gunn et al., 2003; Horodysky et al., 2007), but the reasons for this preference are not fully understood. The large proportion of time sailfish spend near the surface results in an increased vulnerability to entanglement in gillnets and other surface gears.

Sailfish in the Pacific near Mexico are generalist predators feeding mainly on epipelagic species in coastal and oceanic waters, and occasionally diving to prey on demersal fish (Rosas-Alayola et al., 2002). In eastern Taiwan, stomach contents analysis revealed that sailfish were also generalist predators feeding mainly on epipelagic fishes (especially frigate mackerel, *Auxis rochei rochei*) (Chiang et al., unpublished data). Thus, information from diet studies and our data on diving patterns appear to correlate and indicate sailfish occupy a special niche in the epipelagic zone.

Billfishes in general, however, often undertake vertical excursions of short duration generally presumed to be associated with foraging, predator avoidance, removal of parasites, or as an aid to orientation/navigation (Musyl et al., 2003; Sims et al., 2008; Bernal et al., 2009). Prince and Goodyear (2006) described how the vertical habitat distribution of Atlantic and Pacific sailfish and blue marlin were directly correlated with DO, and that hypoxic layers formed barriers to vertical movements. Limited data on DO concentrations in our study area could not confirm nor refute whether oxygen was a limiting factor on diving patterns but we suspect oxygen was not limiting. At the depths routinely visited, the vertical distribution of sailfish appeared to be limited by temperature gradients (Hoolihan, 2005; Hoolihan and Luo, 2007). Moreover, as has been shown in the other studies of billfishes cited above, and some species of tunas (Brill, 1994; Bernal et al., 2009), vertical movements are not limited by a specific depth or water temperature, but by the ~8 °C relative change in water temperature with depth. This information can be especially useful to correct both traditional catch-per-unit effort data and aerial survey data for differences in gear vulnerability; thus significantly improving population assessments (Hinton and Nakano 1996; Brill and Lutcavage, 2001; Yokawa and Takeuchi, 2002).

For tagged sailfish, a recurrent theme suggests they exhibit characteristic diel diving patterns found in other billfish species. Although daytime and nighttime diving transitions were not as pronounced as found in other pelagic fishes, tagged sailfish exhibited deeper (and more variable) diving excursions at nighttime presumably when the animals were foraging. In daytime, the greatest percentage time was spent near the surface which we interpret as basking behavior which correlates with anecdotal information.

This study represents an important contribution to pioneering sailfish tagging studies with PSATs in the western Pacific Ocean. PSATs revealed short-term diving behavioral of sailfish in a marginal sea environment with unique diel diving characteristics. Additional information on migration and behavior is crucial to re-evaluate stock structure and management policy. Hinton and Nakano (1996) introduced a model that incorporates fish habitat information to estimate population abundance trends from longline catch–effort data by computing levels of 'effective effort' within the vertical habitat of the fish. The proportion of time sailfish spend at depth are predicted from the deviations between the temperatures at depth from the temperature of the surface mixed layer. This process, termed habitat standardization, offers a potential means to directly account for spatial and temporal changes in fishing patterns (Takeuchi, 2001; Yokawa and Uozumi, 2001; Yokawa et al., 2001).

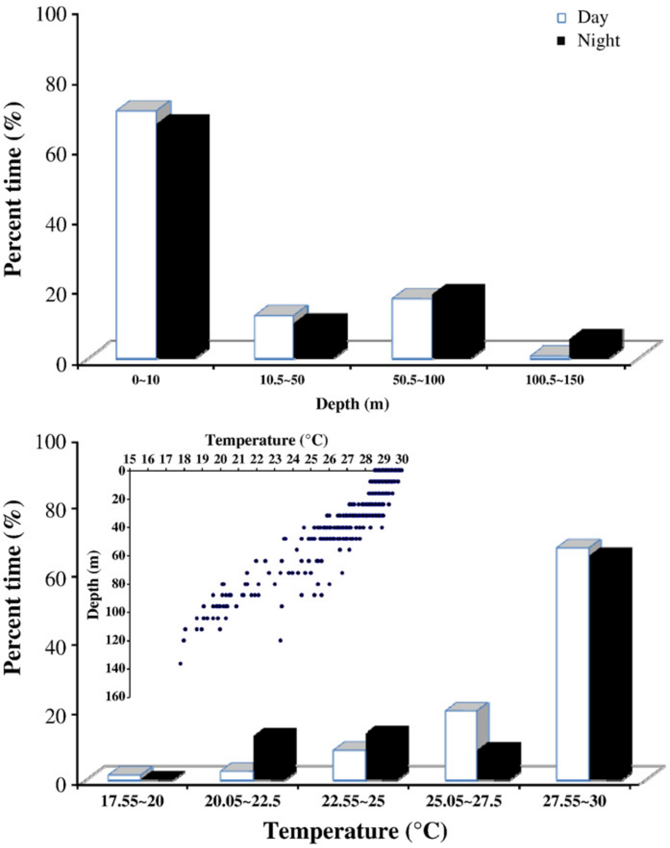

Fig. 6. Percentage time spent at depth (top panel), temperature (bottom panel) and depth/temperature profiles (bottom panel) for Fish C.

Habitat standardization, however, relies entirely on detailed knowledge of gear behavior (i.e. hook depths) and suitable fish habitat; two areas of research that have recently received attention (Goodyear et al., 2003; Serafy et al., 2005). The methodology has since been enhanced by incorporating the concept into a more formal statistical framework (Maunder et al., 2006). Bigelow and Maunder (2007) concluded that an understanding of gear dynamics and environmental influences were important for analyzing and interpreting catch per unit effort (CPUE) data correctly. The basic lack of information about sailfish habitat use and fisheries interaction action (e.g. depth of fishing gear) persists but our study has provided initial information on sailfish vertical movement patterns in Taiwan. Lastly, international cooperative tagging projects and genetic studies are necessary to figure out broad migration corridors and exchange rates between areas for this species.

Acknowledgements

We thank Mr. W.C. Wu, an owner of the set nets at eastern Taiwan, and his crew for their help in tagging and releasing sailfish. We also thank Chi H. Lam, University of Southern California, for providing help in the use of the sea surface temperature corrected (unscented) Kalman filter. In addition, we thank the following for their field assistance: Y.K. Chen, F.C. Lin, C.H. Tian, M.C. Lin, J.H. Pan, L.C. Tsai and H.H. Hsu. This study was partly funded by the Fisheries Research Institute, Council of Agriculture, Taiwan (grant nos. 96AS-15.1.1-W-A4, 98AS-10.2.1-W-A1 (5) and 99AS-10.2.1-W-A1(5)) and by Cooperative Agreements NA37RJ0199 and NA67RJ0154 of the National Oceanic and Atmospheric Administration (NOAA) with the Joint Institute for Marine and Atmospheric Research (JIMAR), University of Hawaii. We thank R. Brill and D. Bernal for providing comments on an earlier draft. **[RH]**

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