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Factors Affecting the Catch of Target and Bycatch Species During Pelagic Longline Fishing

Patrick Hays Rice
University of Miami, price@rsmas.miami.edu

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UNIVERSITY OF MIAMI

FACTORS AFFECTING THE CATCH OF TARGET AND BYCATCH SPECIES DURING PELAGIC LONGLINE FISHING

By

Patrick Hays Rice

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FACTORS AFFECTING THE CATCH OF TARGET AND BYCATCH SPECIES DURING PELAGIC LONGLINE FISHING

Patrick Hays Rice

Approved:

Dr. Robert K. Cowen Co-Chair and Professor Marine Biology and Fisheries	Dr. Terri A. Scandura Dean of the Graduate School
Dr. Eric D. Prince Co-Chair and Chief Migratory Fishery Biology Branch NOAA-Fisheries	Dr. Elizabeth A. Babcock Assistant Research Professor Marine Biology and Fisheries
Dr. Andrew Bakun Professor Marine Biology and Fisheries	Dr. C. Phillip Goodyear Research Scientist The Billfish Foundation

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Recent evidence suggests that overfishing of large predatory fishes has resulted in substantial population declines and pelagic longline (PLL) fishing is a major contributor. The primary objective of this dissertation is understanding factors that affect the interactions between marine fish PLL fishing. These factors are important to determine vulnerability of bycatch and target species, especially when PLL catch and effort data are used to estimate stock abundance.

Chapter 1 reviews 107 publications/reports on this topic. Results indicate that accurate characterization of PLL gear performance requires empirical measurement of horizontal and vertical gear movement; and pop-up satellite tags (PSATs) are best suited for quantifying pelagic fish vertical habitat use if: (*i*) sampling resolution and data storage are not a function of tracking duration and (*ii*) substantial monitoring durations are employed. This review documents the current state of knowledge for these factors and guidance for future research.

In Chapter 2, hook time-at-depth was monitored for commercial PLL sets targeting swordfish, *Xiphias gladius.* Temperature–depth recorders (TDRs) were deployed at the hook, systematically along the entire gear length. Results indicated that: (*i*) hook depth predictions based on catenary geometry drastically overestimated actual

fishing depths and (*ii*) using catenary geometry fails to capture within- and among-set variability, potentially resulting in biased stock assessments.

Chapter 3 used temperature-depth data from PSATs on swordfish and blue marlin (*Makaira nigricans*) and similar data from TDR monitored near-surface and deep PLL fishing to determine the diel probability of these species encountering PLL hooks. Results indicated that blue marlin and swordfish inhabit surface waters at night with similar probability of encountering PLL hooks but may have different vulnerabilities due to temporal separation in feeding with blue marlin preferring daytime and twilight and swordfish preferring nighttime. Therefore, reducing fishing during daylight hours may reduce blue marlin bycatch during PLL targeting swordfish.

Chapter 4 alternated non-offset and 10° offset circle hooks during PLL fishing and compared the relative performance on catch rates, percent mortality, and deep hooking percentage. Results indicated that 10° offset circle hooks can reduce fishing efficiency and conservation benefits commonly associated with circle hooks.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Chapter 1

Pelagic longline fishing and billfish vertical habitat use (Families: Xiphiidae and Istiophoridae): A meta-analysis and review (1950-2007)

Introduction to the bycatch problem

The primary source of fishing mortality for marlin, sailfish, and spearfish (Family: Istiophoridae) is the multinational commercial pelagic longline (PLL) industry that targets tuna and swordfish, but often catches istiophorid billfish as bycatch (ICCAT, 1998; 2001; Graves et al., 2002; Kerstetter et al., 2003; Uozumi, 2003). Pelagic longline fishing typically involves the deployment of tens of kilometers of fishing gear, each with hundreds to thousands of baited hooks that "soak" for several hours. In addition to target species, other taxa such as istiophorid billfish, marine mammals, birds, reptiles (such as sea turtles) and numerous other species, as well as undersized individuals of marketable species, can also potentially be captured by longline gear. The aggregate of captured animals that have little or no commercial value are termed "bycatch" species. Recent analyses suggest that the effects of overfishing on large predatory fishes (i.e. bycatch and target species) have resulted in population declines of up to 90%, as compared to historical levels (Myers and Worm, 2003). However, considerable uncertainty exists when estimating trends in abundance indices used in stock assessment models. This is primarily due to the dynamic ocean environment influencing the uncertainty and contributing to the variation in vertical and horizontal distributions of both the fish and the PLL gear (Mizuno et al., 1999; Goodyear, 2003b). Therefore, it is essential to understand how pelagic longline fishing gear behaves in the water column and understand the dynamics that influence the potential for interactions between the longline gear and pelagic animals. There are a number of recent and past publications, including gray literature reports, focusing on these essential components, many with differing conclusions. This survey included primary literature databases, U.S. government gray literature reports, and scientific collections from international fisheries commissions. In all, 108 publications were cited on: (1) the history of PLL fishing and the process and problems associated with stock assessments based on PLL catch and effort; (2) the depth, movement and underwater shape of PLL fishing gear; and (3) the vertical habitat utilization of pelagic fish associated with PLL fishing gear. This paper, while not representing an exhaustive review, provides an overview of historical insights and a meta-analysis of the most relevant studies to reveal the current state of knowledge and identify areas where appropriate technologies, methodologies and techniques may be applied in future research.

Historical Perspective

A good description of the evolution of PLL gear from artisanal to commercial fisheries is given by (Shapiro, 1950). The inception and deployment of large scale commercial PLL gear began with the Japanese fleet in the Pacific during the early 1950's (Yoshihara, 1951; Nakano, 1996; Uozumi, 1996; Yokawa et al., 2001) and expanded eastward in the Pacific during the 1960's and 1970's (Shiohama, 1969). Parallel to the development of PLL fisheries in the Pacific, the Japanese introduced PLL gear into the western North Atlantic tropical yellowfin tuna fishery in the late 1950's (Uozumi, 1996; Hoey and Moore, 1999). Concurrently, the Norwegian shark fishery captured substantial swordfish as bycatch during nighttime fishing off the coast of Nova Scotia in the western North Atlantic. This spurred local Canadian fisherman to develop a shallow water nighttime swordfish PLL industry, followed in the 1960's by the U.S. (Draganik and Cholyst, 1988; Hoey and Moore, 1999). In the eastern North Atlantic, the Spanish have reported swordfish landings as early as the 1939 (Rey and Gonzalez-Garces, 1982). United States swordfish PLL effort shifted into the Pacific due to restrictions in the Atlantic imposed by the International Commission for the Conservation of Atlantic Tunas (ICCAT) during the 1970's. However, most of the billfish and swordfish catch prior to this was as a secondary component of the Japanese PLL fishery targeting tunas (Nakano, 1998). During the 1980's, swordfish catch was reported as highest in the Mediterranean and western North Pacific (Draganik and Cholyst, 1988).

Prior to the mid 1970's, PLL gear configuration was dominated by shallow water deployments which were comprised of only a few hooks between surface buoys (i.e. ≤ 7), hereto referred to as a "basket" (Hinton and Nakano, 1996). Initially, the primary target was yellowfin tuna (*Thunnus albacares*), but there was a shift towards albacore tuna (*Thunnus alalunga*) around 1962 (Saito, 1973; Nakano, 1996; Uozumi, 1996). In the early 1970's, the development of super cold freezers (-50 ºC) onboard PLL fishing vessels allowed sashimi grade tuna to be supplied to the Japanese market. This encouraged a rapid switch to higher quality tunas such as southern bluefin (*Thunnus macoyii*), northern bluefin (*Thunnus thynnus*) and bigeye (*Thunnus obesus*) (Nakano, 1996; Uozumi, 1996). The shift in target species, particularly bigeye tuna, encouraged deep longline (DLL) fishing methods (i.e. > 7 hooks per basket) in the equatorial Pacific and Indian Oceans during the late 1970's (Uozumi, 1996). Subsequently, DLL fishing was introduced into the Atlantic as early as 1976 by the Japanese (Uozumi, 1996) and continued to increase as a proportion of Japanese Atlantic longline fishing throughout the 1980's (Suzuki and Kume, 1982), reaching greater than 70% of total Japanese catch during the 1990's (Uozumi, 1996). This rapid change from shallow to deep longline fishing, accomplished by using more hooks between floats, made it difficult to compare catch per unit effort (CPUE) indices of abundance before and after the switch. This uncertainty had implications on international fisheries management decisions for highly migratory species, which rely heavily on catch and effort data reported by the international PLL industry to assess stock status.

The International Commission for the Conservation of Atlantic Tunas (ICCAT) was established in 1966 with the goal of managing for maximum sustainable yield (MSY) for Atlantic tuna and tuna-like species (including billfish, Families: Istiophoridae and Xiphiidae) (Prince and Brown, 1991). The ICCAT began assessing the stock status of Atlantic marlins in 1975 (Uozumi, 2003), however, problems with assembling appropriate biological and fishery related data sets for billfish (e.g. catch, effort, landings, age and growth, and early life history information, etc.) contributed to uncertainty of assessment results (Prince and Brown, 1991). In order to address some of the uncertainties associated with billfish stock assessments, ICCAT established the Enhanced Research Program for Billfish (ERPB) in 1986 to address data deficiencies (Prince and Brown, 1991; Restrepo et al., 2003). Although many improvements in billfish data collection and assessment methodologies have been achieved, uncertainties relative to billfish assessment results persist, particularly in standardization of PLL CPUE time series.

Stock Assessment Process

Management decisions for highly migratory species are normally based on analyses of fish stocks made by species working groups of international fisheries commissions (Hinton and Nakano, 1996). Pelagic fish stock assessments often rely on standardized catch per unit effort (CPUE) time series from PLL fishing, as well as other gears that harvest these species (ICCAT, 2001). Catch per unit effort time series are a proxy for stock abundance trends and are influenced by catchability – the part of a stock that is caught by a defined unit of fishing effort – which is a function of many variables including: (1) actual distribution of fish in the water column (i.e. habitat utilization); (2) behavior of the fishing gear relative to the fish; and (3) seasonal fishing effort (i.e. time-area considerations) at a particular location and depth (Hinton and Nakano, 1996). Considerable uncertainty exists over the vertical distribution and utilization of the water column by migratory pelagic fish and the fishing effort defined by the vertical distribution of hook time at depth in the water column (Goodyear, 2003a; Goodyear, 2003b). Although uncertainties of Atlantic billfish stock assessment results have been a concern recognized by ICCAT, consensus by ICCAT member nations relative to assessment results indicate that blue marlin (*Makaira nigricans*) and white marlin (*Tetrapturus albidus*) have been overexploited in the Atlantic Ocean for a number of decades (Restrepo et al., 2003). In fact, white marlin are considered to be one of the most overexploited resources under ICCAT management (Restrepo et al., 2003).

Stock Assessment Problem

Fishers, past and present, employ various longline fishing strategies (i.e. different gear configurations, baits, hook types, target depths, fishing time of day, soak times, etc.) and pelagic fish display a high degree of spatial heterogeneity. Collectively, these factors affect resource catchability, thus standardization of fishing effort is necessary for comparisons of catch rates over time to be useful as indices of abundance trends.

In the Atlantic, stock assessments for billfish employ statistical standardization approaches that attempt to account for variability in CPUE trends by directly incorporating many of the variables that influence catchability into general linear models (GLM) or general linear mixed models (GLMM) (Uozumi, 2003). The Pacific stock assessments for billfish initially employed empirical approaches (i.e. various production models with catch and effort data) to standardize CPUE time-series during the late 1980's. However, Hinton and Nakano (1996) proposed CPUE standardization in the Pacific employing a deterministic habitat-based standardization (HBS) where effective effort is modeled as a function of the probability of interaction between the depth distribution of hooks and species in the water column. Habitat-based standardization of PLL CPUE time series for billfishes has been promoted by some (Yokawa et al., 2001; Yokawa and Takeuchi, 2002; 2003) as superior to standard statistical procedures for removing the effects of gear modifications over time. However, others (Goodyear, 2003b) question this contention, particularly when assumptions of vertical location of fish and gear are based on limited empirical data. A simulation study by Goodyear (2003a) suggested that estimation of hook depth may be the weakest component of HBS and present models based on gear configuration may be poor predictors of actual fishing depth. Hinton and Maunder (2004) recommend that whenever an HBS model is used, that it should be a statistical HBS model because the statistical model allows for uncertainty in depth distribution, and is also more flexible for incorporation of additional explanatory variables, such as variations in bait type used, changes in fishing strategy (i.e. target species and gear depth), oceanographic effects on fishing depth, etc. However, regardless of the HBS method employed, the basic uncertainty about fish habitat utilization and hook depths of longline gear persists (Goodyear et al., in press, *Marine Ecology Progress Series*).

Hook depth during commercial pelagic longline fishing is historically estimated using gear configuration information collected from fishery data bases containing captain's log book records (Nakano, 1996; Takeuchi, 2001). Gear configuration information provides information on the vertical geometry of pelagic longline gear by providing specific data on: (1) the number of hooks between floats; (2) length of the float line; (3) branch line length; (4) the estimated distance between buoys; and (5) placement of the branchline and terminal hook along a catenary curve created by mainline sagging between buoys due to gravity (Yoshihara, 1954; Suzuki et al., 1977; Boggs, 1992; Bigelow et al., 2006) (Figure 1.1). These types of data have been routinely employed to describe fishing depth in CPUE standardizations of Japanese PLL gear in the Atlantic (ICCAT, 2001; Goodyear, 2003a). Many authors have relied on estimated depths calculated assuming a catenary curve, where the estimated depth of catch is computed from the order of the branch line on the mainline (Yoshihara, 1951; 1954; Suzuki et al., 1977; Hanamoto, 1987; Yang and Gong, 1987; Hinton and Nakano, 1996; Yokawa et al., 2001; Yokawa and Takeuchi, 2003; Ward and Myers, 2005).

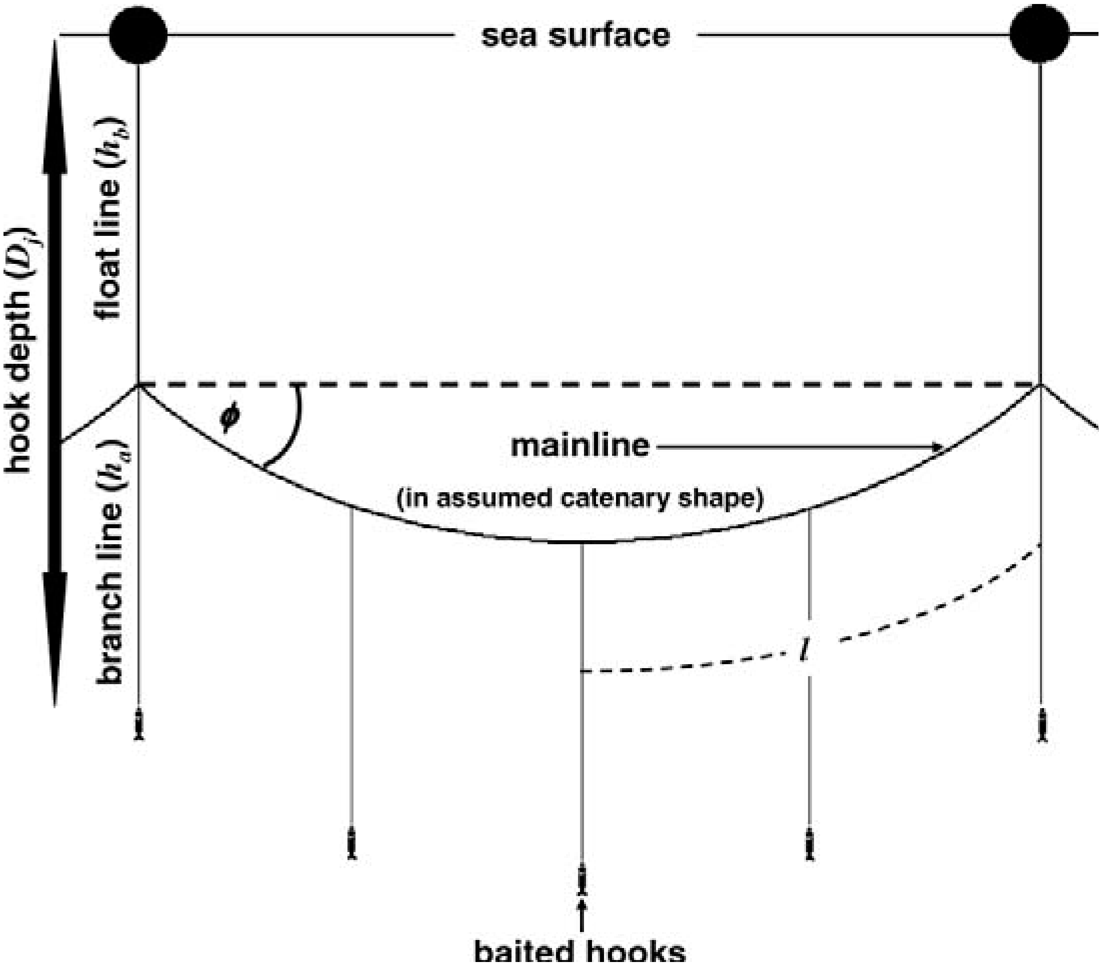


Figure 1.1. Schematic representation of a single basket of typical near-surface pelagic longline fishing gear, showing the geometric components necessary to calculate hook depth using the catenary equation developed by Yoshihara (1951, 1954) and refined by Suzuki et al. (1977).

Present effort models may overestimate hook depth (Boggs, 1992; Mizuno et al., 1999; Bigelow et al., 2002; Ward and Myers, 2005) and therefore, may bias abundance indices. In addition, Takeuchi (2001) tested the use of gear configuration information to standardize CPUE with simulated data and reported that the presence of zero-catch sets and rapid changes in fishing strategies in the mid 1970's rendered the number of hooks per basket unsuitable for standardization of CPUE.

Gear Movement

Commercial PLL fishers often deploy their fishing gear along oceanic fronts (Shapiro, 1950) because highly migratory fishes, like tuna and swordfish, are believed to aggregate at oceanic fronts (i.e. thermal, current, etc.) (Olson, 2002). Deployment of PLL gear near fronts can have an effect on vertical and horizontal movement of the gear in the water (Boggs, 1992; Mizuno et al., 1999; Bigelow et al., 2006). Gear movement influences hook depth by raising (i.e. shoaling) or lowering (i.e. sagging) the gear in the water column and therefore influences each individual hook's time at a specific depth. Estimating hook depth has been the topic of much research since the inception of commercial PLL fishing (Yoshihara, 1951)

Gear Deployment

Deployment of PLL fishing gear typically occurs as the vessel moves through the water in a forward direction. During PLL fishing targeting swordfish, gear is usually passively deployed (i.e. the mainline is allowed to free spool) off the stern of the vessel. Tuna PLL fishing usually employs a line-thrower, which is a device that shoots the mainline off the boat at a rate slightly faster than the vessels forward velocity. Once the PLL gear is deployed, a terminal buoy is fixed to the end of the mainline which is then cut free from the boat, and the entire length is allowed to free float or “soak”. During the soak, the gear is susceptible along its entirety to a dynamic combination of environmental forcing factors (i.e. gravity, wind, waves, surface and subsurface currents, drag, etc.) which alter its original three dimensional shape even before being detached. There are several types of horizontal motion experienced by the PLL gear when exposed to differential forcing factors, which are discussed in the following section.

Horizontal Gear Displacement

There are relatively few studies focusing on how PLL gear is displaced horizontally. Horizontal gear movement is principally driven by the movement of the body of water in which it is deployed. Forces acting on the gear resulting in horizontal displacement and deformation include oceanic currents and wind (Boggs, 1992; Mizuno et al., 1996; Bigelow et al., 2006), drag, and tension in the mainline (Saito, 1973). These forces invoke specific behavior on the PLL gear during gear deployment, soak and retrieval. This horizontal gear displacement typically results in a change in shape and/or location of the fishing gear during PLL fishing.

Physical Forces Affecting Horizontal Gear Displacement

Among the dominant forces affecting horizontal gear displacement are oceanic surface and subsurface currents (Mizuno et al., 1998; 1999). Rapidly moving currents during long soak times often result in horizontal gear displacements of many kilometers

(Figure 1.2). Tension in the mainline and frictional forces (i.e. drag) are important and occur along the entire gear length, keeping the gear suspended above its maximum potential depth. The effects of drag are most apparent when PLL gear is deployed across frontal boundaries and the opposite ends are entrained in water masses moving in different directions. The frictional forces between the gear and the water result in an “anchor” effect, sometimes snapping the monofilament mainline, which is typically around 450 kg test strength as the industry standard (Yano and Abe, 1998). This entire process is exacerbated as length of mainline and associated gear increases. Frictional forces that affect gear behavior also occur above the water in the form of drag caused by wind on the surface buoys (Bigelow et al., 2006). Large live animals captured during fishing can also have a noticeable effect on the horizontal displacement of PLL gear while attempting to escape.

Types of Horizontal Motion

Pelagic longline fishing occurs on the mesoscale level (i.e. ≥ 10 - 100 km), often spanning different water masses and exposed to different environmental forcing factors along its length, thus giving it its shape. The basic types of horizontal motion associated with PLL gear movement are translation, rotation and deformation (Lamb, 1993; Olson, 2006) (Figure 1.3A). Translation is expressed as the horizontal displacement of the PLL gear during the soak. It can occur with little or no change in the overall shape of the gear, but typically occurs with other types of gear movement (Figure 1.3B). Rotation (rarely occurring without some translation), is movement about a fixed axis (Figure 1.3A) and is often expressed during PLL fishing where gear has been deployed across a front

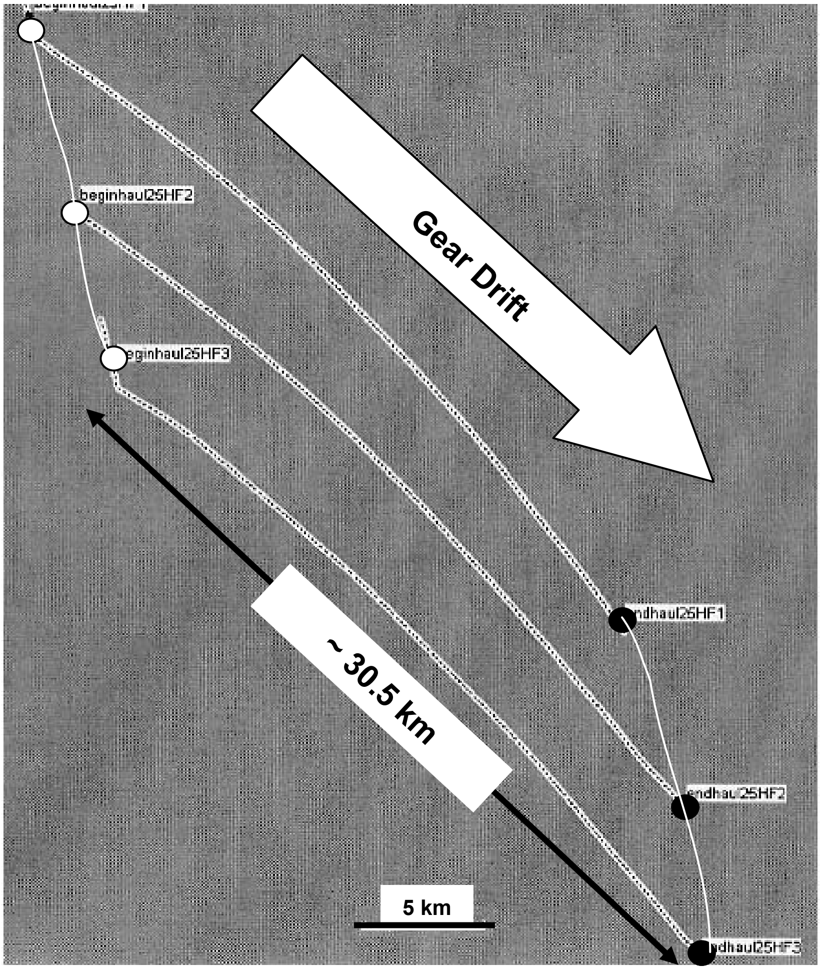


Figure 1.2. Horizontal displacement of PLL gear (approximately 30 km) due to rapidly moving currents. Gear was deployed during May 2005 form the National Oceanic and Atmospheric Administration research vessels Oregon II in the northern Gulf of Mexico (P. Rice; unpublished data). White circles represent GPS locations at deployment. Black circles indicate GPS location at gear retrieval.

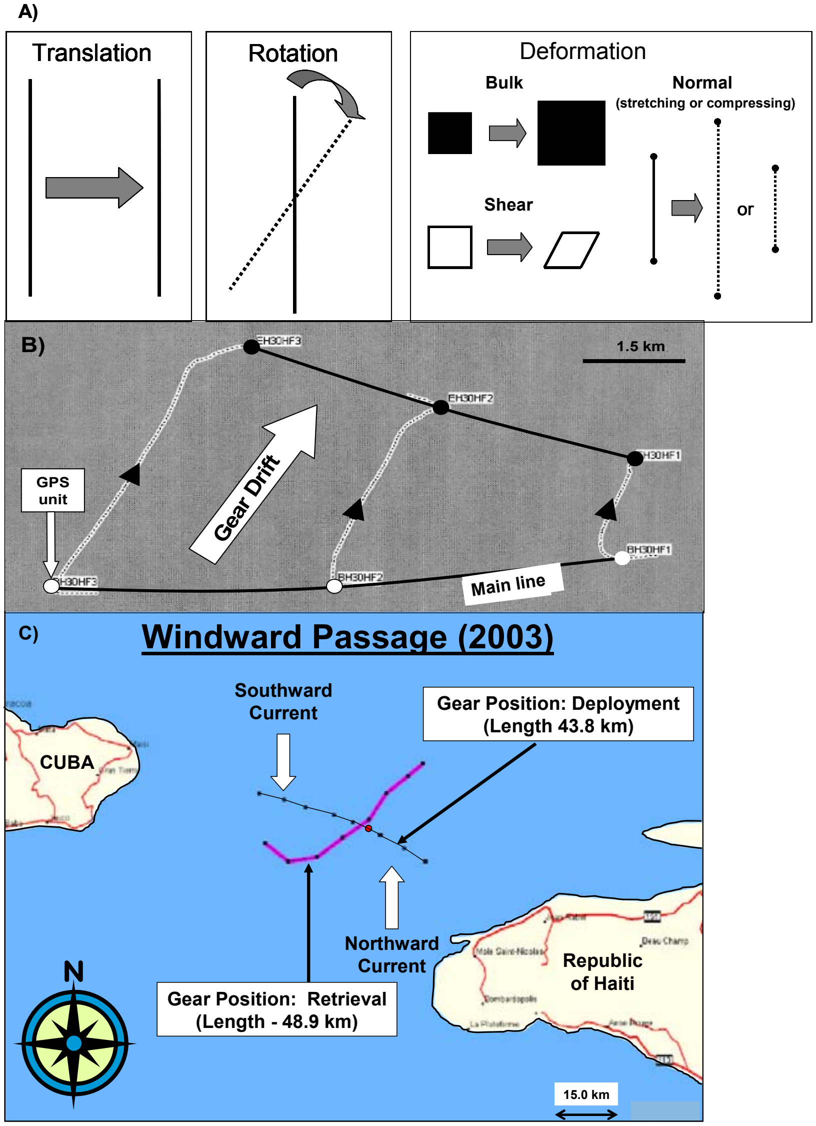


Figure 1.3. A) Various types of potential horizontal motion experienced by pelagic longline (PLL) gear during "soak" time resulting from differential forcing factors (i.e. surface and subsurface oceanic currents, wind and animal interactions, etc.) (Lamb 1993), B) PLL gear equipped with global positioning system (GPS) units at both ends and the middle showing gear drift resulting in translation, rotation and compression. Dotted lines represent GPS tracks. White circles represent GPS positions at gear deployment. Black circles indicate GPS position at gear retrieval (P. Rice; unpublished data). C) Aerial schematic of changes in PLL when deployed across oceanic frontal system in the Windward Passage. Coordinates were collected at surface buoys at the end of each gear section during deployment and retrieval (Rice et al. 2007).

with water masses moving in opposite directions (Figure 1.3C). Deformation occurs along the seemingly two dimensional PLL in two different forms: (1) shear deformation and (2) normal deformation. Shear deformation - angular changes (Figure 1.3A) – in the horizontal plane typically occurs as a result of translation, rotation and frictional forces. Normal deformation (e.g. “stretching” or “compression”) is the most common type of gear deformation occurring during PLL fishing (Figure 1.3A and 1.3B) and is often associated with water movements occurring around oceanic frontal systems. These types of motion have a direct effect on the vertical distribution of PLL hooks.

Discrete vs. Continuous Horizontal Information

Geographic coordinates are routinely collected during commercial PLL gear deployment and retrieval. Although location precision is high during modern gear deployments, this has not been so historically. Even so, this type of discrete geographic data provides useful information on the initial and final shape and position of the PLL gear. But, PLL gear often changes horizontal shape and/or oscillates during the soak (Mizuno et al., 1999) (Figure 1.4). Discrete geographic information will not capture this type of PLL gear movement. The result is that vertical gear behavior, specifically the hook depth, associated with horizontal gear movement during soak is unknown. For example, during experimental PLL fishing in the Gulf of Mexico (P. Rice, unpublished data) the gear in Figure 1.4 (A) had similar length and shape at deployment and retrieval. When determining fishing effort, one might assume that the horizontal gear shape (and corresponding vertical hook depth) did not change during the soak time. However, constant monitoring of the PLL gear during this experimental PLL fishing revealed that

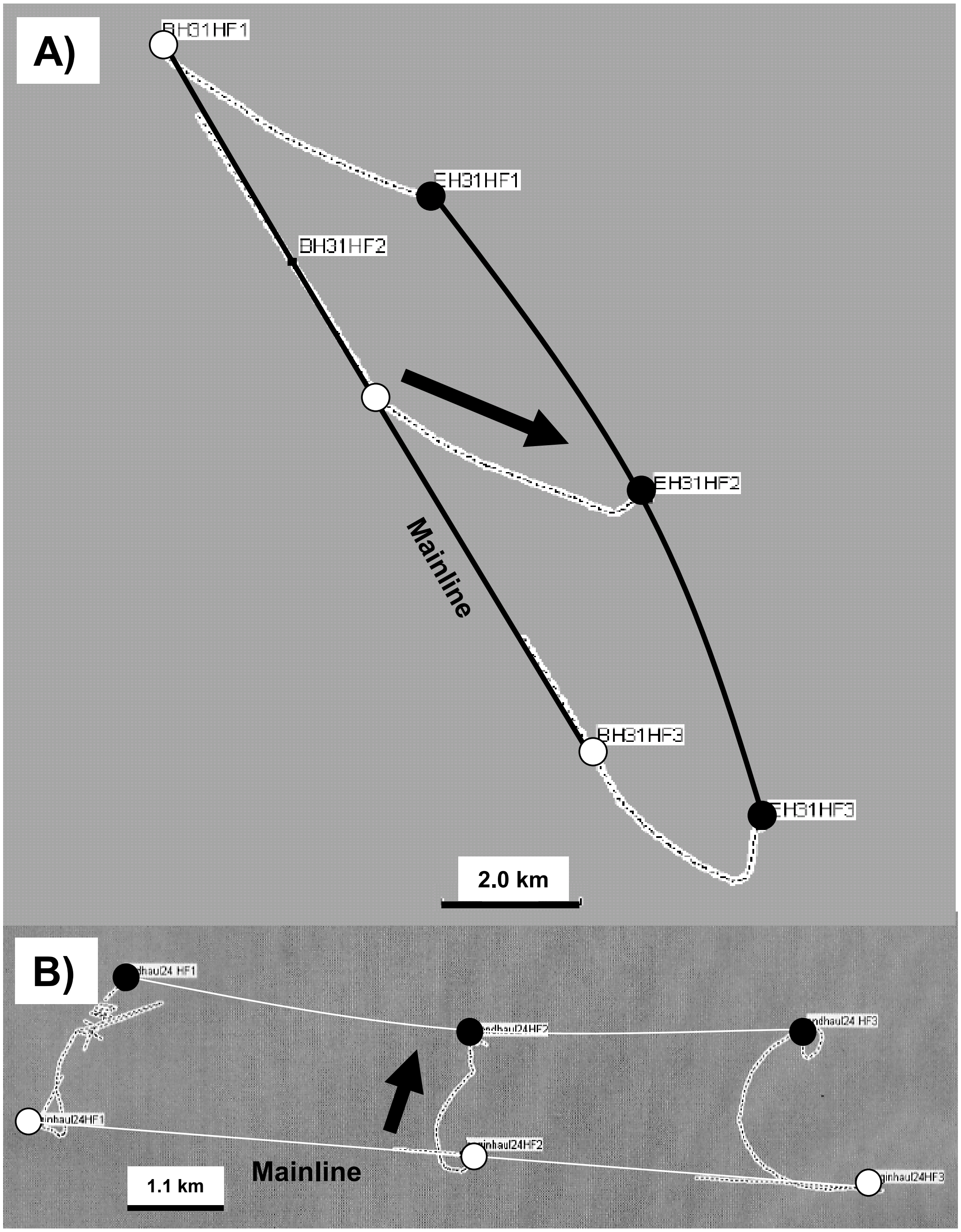


Figure 1.4. GPS monitored PLL gear drift (black arrow) showing: (A) "stretching" and subsequent "compression" back to the original shape and (B) erratic movement between deployment (white circles) and retrieval (black circles) that would <u>not</u> be captured without continuous GPS data collected during the "soak" (dotted lines) (P. Rice; unpublished data).

the gear was stretched and then compressed to its original form. Similarly, in Figure 1.4 (B), the PLL gear was initially compressed after deployment and then subsequently stretched to assume a form similar to the form at deployment. In both these examples, the vertical gear movement and corresponding vertical distribution of the hooks during the soak is not captured. However, constant monitoring of PLL gear has not been practiced in the past and therefore, because discrete geographic data has been routinely collected during PLL fishing, it may still prove valuable for estimation of hook depth from past PLL fishing during CPUE standardization of time series.

Mizuno et al. (1998) attached GPS buoys on either end of a single basket during experimental PLL fishing targeting tuna in the Pacific Ocean. By monitoring the position of the floats relative to each other they were able to determine the extent to which environmental forces affected horizontal distance between the buoys. They concluded that accurate estimation of the underwater shape of the mainline and subsequent fishing depth requires continuous observation of the horizontal distance between floats.

Vertical Gear Movement

It has long been observed that longlines often fail to fish at their intended depths because the oceanic environment introduces forcing factors that influence the subsurface gear geometry (Murphy and Shomura, 1953a; b; Graham and Stewart, 1958; Nakagome, 1961; Saito et al., 1970; Saito, 1973; Suzuki et al., 1977; Boggs, 1992; Berkeley and Edwards, 1998; Yano and Abe, 1998; Mizuno et al., 1999; Matsumoto et al., 2001). Rice et al. (2007) noted that near-surface PLL fishing gear targeting swordfish is also susceptible to shipping traffic, which can substantially reduces fishing depth. In addition, fish interactions with PLL gear will greatly influence the fishing depth (Boggs, 1992; Mizuno et al., 1996; Yano and Abe, 1998). Therefore, it is essential to understand how these factors affect the vertical hook distribution and, therefore, effective fishing effort.

Physical Forces Affecting Vertical Gear Movement

Gravity is the predominant downward force affecting PLL vertical distribution. The effect of gravity in the water is offset by: (1) surface buoys acting to keep the PLL gear suspended in the water column, (2) and to a lesser extent, the buoyant force exerted by the water on the gear. Yano and Abe (1998) reported various sinking rates for mainlines composed of different materials, with polyester multifilament sinking faster than the present industry standard polyamide monofilament.

The downward pull of large dead fish (i.e. large tuna, swordfish and marlin) can cause the gear to reach its maximum vertical depth potential. In fact, sections of PLL gear are occasionally completely submerged, buoys included, when many large dead fish sink the gear. The gear can sink so deep that Styrofoam buoys are crushed by the pressure at depth (P. Rice, pers. obs.). In addition to dead fish sinking PLL gear, live fish captured by the gear can have substantial effects on the vertical gear depth distribution by swimming towards the surface or deep diving.

There are differences in buoyancy associated with various bait types (i.e. squid, mackerel, etc.) and conditions (i.e. frozen, semi-frozen, thawed, etc.) that could have an effect on PLL fishing depth (Prado, 2000). However, PLL fishing typically employs weighted swivels on individual branch lines (Rice et al., 2007) which most likely outweighs any buoyancy differences between bait types and bait condition (Huse and Soldal., 2000).

Estimated Hook Depth by Catenary Geometry

The depth of the PLL is most commonly estimated using mathematical models based on catenary geometry (Figure 1.1), which assume the gear orients in the vertical plane and the only forces acting on the gear are gravity and buoyancy. Yoshihara (1951) derived an equation for estimating PLL fishing depth using a catenary equation as follows:

$$D_j = h_a + h_b + l\,((1+\cot^2\phi^{\circ})^{1/2} - [(1-2j/n)^2 + \cot^2\phi^{\circ}]^{1/2}) \qquad (1)$$

where D_j is the depth of the jth hook between two surface floats (the section of gear between adjacent floats is referred to as a “basket”), h_a and h_b are the branch line and float line length, respectively, l is ½ the length of mainline in a unit basket, n is the number of intervals between hooks in a unit basket (number of hooks + 1), and ϕ is the angle (in degrees) between the horizontal line and a line tangential to the curve of the main line at the point of attachment of the float line to the main line (Figure 1.1). It is not feasible to measure the angle ϕ during PLL fishing (Yoshihara, 1954). Therefore, (Yoshihara, 1954) correlated ϕ to the “sagging” rate of the PLL gear. Sagging rate (S) is the ratio of the length of main line deployed in a unit basket (L) and the distance between surface buoys (B) (i.e. $S = B/L$). Bigelow et al.(2006) used two methods to determine the sag ratio, S, depending on the commercial fishing technique employed. The first method deals with modern Japanese PLL fishing targeting tuna, which typically employs a “line thrower” deploying the mainline at a speed defined by the fishers, which is usually faster than the forward velocity of the fishing vessel. When line throwers are employed, *S* is the ratio of the speed of the line thrower to the speed of the fishing vessel during gear deployment. The second method involves commercial PLL fishers targeting swordfish, which typically do not employ line throwers. Therefore, the ratio of the distance traveled by the vessel over water and the estimated amount of mainline deployed are commonly used to determine the sag ratio.

Measured Hook Depth

As early as 1953, T. Cromwell attempted to determine the actual PLL mainline depth using putty-balls attached at regular intervals on a heavily weighted vertical line that was allowed to drift over the middle of the mainline (Murphy and Shomura, 1953a). They assumed that interaction of the vertical line with the mainline would dislodge the putty-balls, resulting in an approximation of the mainline depth equal to the depth of the shallowest dislodged putty-ball. Later methods for determining PLL fishing depth employed chemical sounding tubes that directly measure pressure and infer depth (Shomura and Otsu, 1956; Graham and Stewart, 1958; Nakagome, 1961). Shibata (1962) used echo-sounding (i.e. fish finder) to record the underwater shape of the mainline and suggested that although the method was limited in range (i.e. shallow water PLL fishing), it was the most reliable method, at the time, to determine the underwater shape of the gear and distribution of the fish. The advent of electronic depth measuring equipment able to be attached directly to the gear, such as depth meters (Hamuro and Ishi, 1958; Kamijo, 1964; Saito, 1973; Nishi, 1990), micro-bathythermographs (Mizuno et al., 1998; Mizuno et al., 1999), time-depth recorders (TDRs) (Boggs, 1992; Berkeley and Edwards, 1998; Yano and Abe, 1998), and time/temperature-depth recorders (TDRs) (Rice et al., 2007) allowed for the collection of more accurate information on the depth of PLL hooks and fish capture.

Adjustments to Estimated Hook Depth Calculated by Catenary Geometry

Electronic depth measuring equipment is expensive and not practical for complete coverage of commercial PLL gear. Therefore, gear configuration information, which has been collected by the Japanese PLL fishing industry since mid 1970's, is employed as a proxy for vertical PLL fishing effort in CPUE calculations. Prior to that gear configuration information was estimated from information provided by Japanese fishing masters. In the absence of external forcing factors (i.e. wind, surface and subsurface currents, animal interactions, shipping, etc.) the shape of the subsurface PLL gear is assumed to form a catenary configuration. Therefore, the Yoshihara (1951; 1954) equation (Equation 1) was widely used as a theoretical estimate of PLL hook depth (Table 1.1; Figure 1.5). However, Saito (1973) using depth meters showed that PLL gear consistently fished 10-11% shallower than predicted using Yoshihara (1951). Suzuki et al. (1977) suggested that a constant gear contraction ratio (S) of 0.60 corresponded to a 72° angle, ϕ. This model became the most widely cited method for calculating PLL fishing depth (Hanamoto, 1987; Boggs, 1992; Hinton and Nakano, 1996; Berkeley and Edwards, 1998; Mizuno et al., 1999; Ward and Myers, 2005; Bigelow et al., 2006). However, actual measurement of the PLL gear depth and comparisons to theoretical depth using the Suzuki et al.(1977) adjustment suggested that it still overestimated PLL fishing depth.

Table 1.1. Chronological studies on pelagic longline fishing with emphasis on historical perspective, fishing gear depth, fishing efficiency and relevant stock assessments from 1950 – 2006.

Study topic	Primary species	Study area	Gear distribution	**Depth measurment	***Vessel type	Study
Historical Perspectives						
Japanese PLL pre 1950	Scombridae	Pacific	H, V	TH	C	Shapiro (1950)
Albacore surveys	Albacore tuna (*Thunnus alalunga*)	Central North Pacific	H, V, T, TL	-	C	Shomura & Otsu (1956)
History of exploitation	Blue marlin (*Makiara nigricans*)	Eastern Pacific	H	-	C	Shiohama (1969)
Studies on experimental DLL	Albacore tuna (*Thunnus alalunga*)	South Pacific	H, V, TL, T, S, OTH	TH, DM		Saito (1973)
History and catch rate	Albacore tuna (*Thunnus alalunga*)	Atlantic	H, V, TL	TH	C, S	Uozumi (1996)
Historical stock assessment	Istiophiridae	General	H, V, TL	Theoretical	C	Uozumi (2003)
Fishing Depth						
Fishing depth	Scombridae	General	H, V	TH	C	Yoshihara (1951) in Japanese
Fishing depth	Scombridae	General	H, V	TH	C	Yoshihara (1954) in Japanese
PLL for deep swimming tuna	¥ General PLL catch	Central Pacific	H, V, T, TL, CS, OTH	TH, OTH	C	Murphy & Shomura (1953a)
PLL for deep swimming tuna	¥ General PLL catch	Central Pacific	H, V, T, TL, CS, OTH	DM	OC	Murphy & Shomura (1953b)
PLL depth	Scombridae	General	V, T, TL, OTH	DM	C	Hamuro & Ishii (1958) in Japanese
PLL depth	Albacore tuna (*Thunnus alalunga*)	Central North Pacific	V, OTH	TH, OTH	C	Graham & Stewart (1958)
Comparison PLL depth calculated vs. surveyed	Scombridae and Istiophoridae	-	V, CS, OTH	TH, DM	S	Nakagome (1961) in Japanese
Underwater shape of PLL	Scombridae	South China Sea	V, CS, OTH	Echo sounder	C	Shibata (1962)
Vertical longline capture depth	Albacore tuna (*Thunnus alalunga*)	South Pacific	V, TL	TH, DM	S	Saito et al. (1970) in Japanese
Vertical longline capture depth	Scombridae	Tropical Pacific	H, V, T	OTH	S,C	Saito (1973)
¥RLL and DLL fishing efficiency	Scombridae and Istiophoridae	Western/Central Equatorial Pacific	V, H, T	TH	C	Suzuki et al. (1977)
Fishing efficiency of DLL¥	Bigeye tuna (*Thunnus obesus*)	Tropical Atlantic	H, V, TL, O, OTH	DM	C, S	Suzki and Kume (1982)
Ocean environ. on tuna distrib.	Scombridae	Pacific	H, V, TL, O, T, S	TH	S	Hanamoto (1987)
¥RLL and DLL fishing efficiency	Scombridae and Istiophoridae	Atlantic	V	TH	C	Yang and Gong (1987)
Variations in hook depth	Scombridae	Eastern Indian	V, TL,	TH, DM	S	Nishi (1990)
Hook depth, CPUE	Swordfish *(Xiphias gladius)*	Tropical East Atlantic	V	TH	C	Rey and Muñoz-Chápuli (1991)
Depth, capture and hook longevity PLL fish	Scombridae	Central Pacific	V, TL, T, CS, S, O	TH, TDR	OC	Boggs (1992)
Mapping upper ocean thermal field	Scombridae	Tropical Pacific	H, V, T, TL, F, CS, OTH	M	S	Mizuno et al. (1996)
Shortening rate on underwater PLL shape	Scombridae	Tropical Pacific	H, V, T, TL, CS, OTH	M, GPS	S	Mizuno et al. (1998)
PLL depth	East China sea	East China sea	V, TL, CS, F, OTH	TH, TDR	S	Yano & Abe (1998) in Japanese
Factors affecting billfish bycatch	Billfish (Xiphiidae & Istiophoridae)	Gulf of Mexico	H, V, TL, T	TDR	C	Berkeley & Edwards (1998)
Estmating underwater shape of PLL	Scombridae	Tropical Pacific	H, V, T, TL, CS, OTH	M, GPS		Mizuno et al. (1999)
Hooking depth	Billfish (Xiphiidae & Istiophoridae)	Pacific & Indian	H, V, TL,T	M, TDR	S	Matsumoto et al. (2001)
Gear configuration on CPUE standardization	¥ General PLL catch	Tropical Atlantic	V, TL	TH	C	Takeuchi (2001)
Hook depth (mean)	Blue marlin (*Makiara nigricans*)	General	V	TH	C	Goodyear et al. (2003)
Fishing depth	¥ General PLL catch	Pacific	V	TH	S, OC	Ward and Myers (2005)
Vertical distribution of CPUE	Blue marlin & white marlin	Tropical Atlantic	V, TL	TDR	S	Yokawa & Saito (2005)
PLL gear depth and shoaling	Swordfish & yellowfin tuna	Central North Pacific	V, CS, OTH	TH, TDR	OC	Bigelow et al. (2006)
Estimation of hook depth; theory vs. practice	Swordfish (*Xiphias gladius*)	Caribbean	V, TL, CS	TH, TDR	OC	Rice et al. (2007)

Table 1.1 (continued).

Study topic	Primary species	Study area	Gear distribution	**Depth measurment	***Vessel type	Study
Fishing efficiency						
Bycatch reduction	¥ General PLL catch	North Atlantic	-	-	C	Hoey and Moore (1999)
Improving size selection in PLL	Haddock (*Melanogrammus aeglefinus*)	North Atlantic	V	Echo sounder	C	Huse & Soldal (2000)
Sinking rate of PLL on seabird mortality	¥ General PLL catch	General	V	-	C	Prado (2000)
Bycatch rarios	Blue marlin & white marlin	North Atlantic	H	-	C	Serafy et al. (2005)
Stock assessment						
Fisheries and biology	General billfish (Family: Istiophoridae)	Atlantic	H, TL	-	C, R	Prince and Brown (1991)
CPUE standardization	¥ General PLL catch	General	V, H, TL	-	C	Nakano (1996)
Stock assessment	Swordfish (*Xiphias gladius*)	Pacific	H, TL	-	C	Nakano (1998)
Habitat based standardization	Blue marlin (*Makiara nigricans*)	Pacific	H, V, T	TH	C	Hinton & Nakano (1996)
Habitat-based model for effort and abundance	Bigeye tuna (*Thunnus obesus*)	Pacific	H, V, T, O,	TH	C	Bigelow et al. (2002)
Biomass analysis	¥ General PLL catch	Worldwide	H, V, TL	TH	C	Myers & Worm (2003)
Stock assesment	Billfish	Atlantic	TL	TH	C, R	Restrepo et al. (2003)
Habitat Modelling	Bigeye tuna (*Thunnus obesus*)	Pacific	V	TH	OC	Ward and Myers (2006)

* V = vertical depth; H = horizontal (i.e. latitude, longitude); T = temperature; S= salinity; O = oxygen; CS = current shear; B = bathymetry; TL = temporal (i.e. season, time of day); F = fish; OTH = other (i.e. tide, wind, etc.)

** TH = theoretical; M = microbathythermograph; DM = depth meter; TDR = temperature or time depth recorder; OTH = other (chemical sounding tubes, clay, etc.)

*** C = commercial; R = recreational; S = scientific; OC = observed or research commercial

¥ PLL = pelagic longline; RLL = regular longline; DLL = deep longline

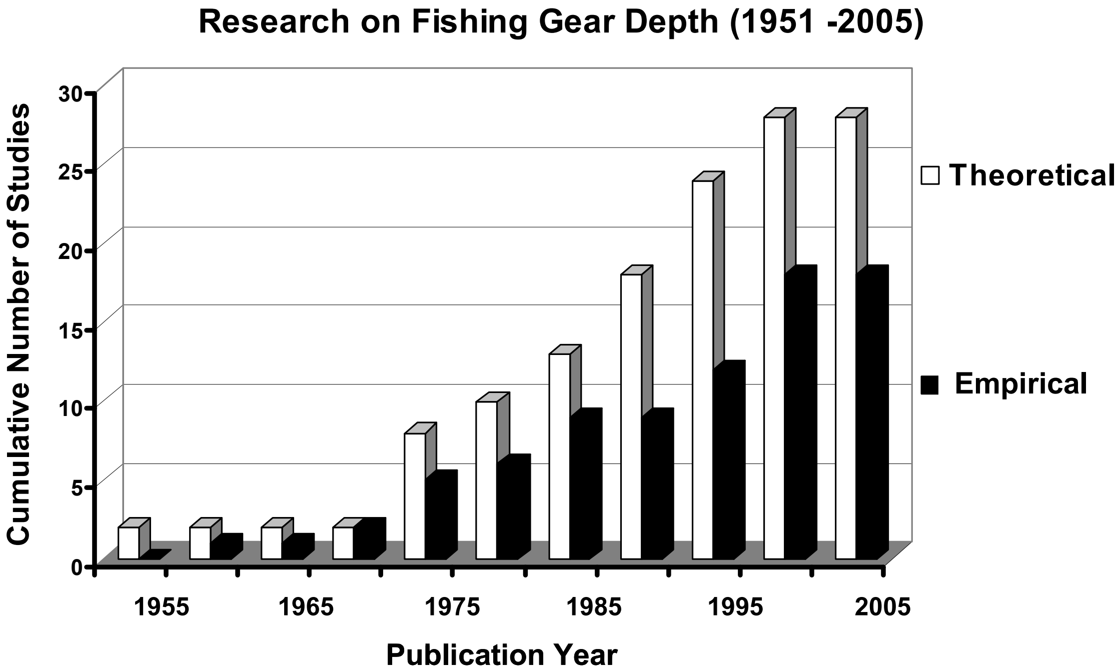


Figure 1.5. Relative abundance of research from 1951-2005 focusing on theoretical fishing depth estimated from catenary geometry; (e.g. Yoshihara 1951, 1954; Suzuki et al., 1977) and empirical fishing depth measured with depth-meters, bathythermographs, time-depth recorders (TDRs) or acoustic echolocation. Research studies include peer-reviewed, gray literature and regional fisheries management organization reports.

Many authors employed additional adjustments based on previous research (Figure 1.6). Hanamoto (1987) suggested that PLL gear fishes 10-20% shallower than the theoretical fishing depth based on depth meter information reported by Saito (1973). Boggs (1992) investigated the depth distribution and catch rates of longline hooks and found that actual fishing depths averaged only 54% and 68% of predicted depths for the two years of their study (1989 and 1990). Yano and Abe (1998) corroborated the Boggs (1992) results using TDRs to monitor the depth distribution of longline hooks. They concluded that actual hook depths were generally shallower than those calculated from a catenary curve (Yoshihara 1951, 1954), especially when the mainline and branch lines were of monofilament material. They also concluded that the mainline depth cannot be predicted from gear configuration and catenary geometry. Hinton & Nakano (1996) employed a 15% reduction in fishing depth from the Suzuki et al. (1977) theoretical depth calculation for their habitat-based standardization of PLL CPUE. Yokawa and Takeuchi (2003) used catenary geometry to infer hook depth for calculation of effective effort during HBS of CPUE for white marlin. They employed TDRs to corroborate fishing depth, however only selected depth data if TDR depth values were within 10% of the calculated catenary depth. Therefore, fishing depth data beyond the 10% selection criteria were excluded from the analysis. In a recent study focused specifically on trying to infer the depth distribution of catchability of pelagic fish, Ward and Myers (2005) estimated vertical fishing effort by reducing all fishing depths predicted by the catenary formula by 25%.

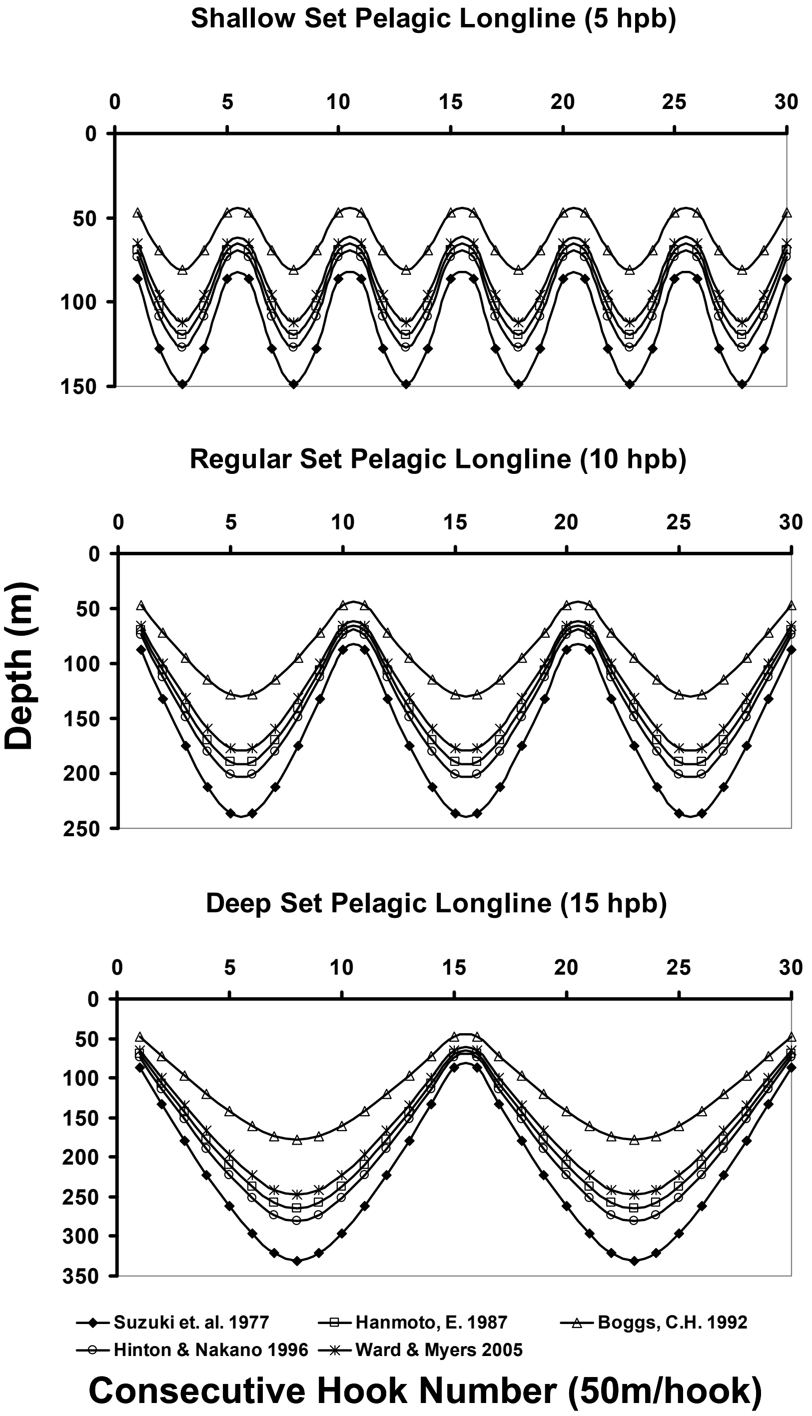


Figure 1.6. Differences in predicted hook depth from Suzuki et al. (1977) to adjustments made by other authors based on the same hypothetical gear configuration. (Top panel) pelagic longline (PLL) configuration of five baskets with five hooks per basket (hpb) (total 30 hooks); (Middle panel) PLL configuration of 3 baskets with 10 hpb (total 30 hooks); (Bottom panel) PLL configuration of 2 baskets with 15 hpb (total 30 hooks).

These authors all used the cantenary equation developed by Yoshihara (1951; 1954) but applied static scalars to the algorithm output (Hanamoto, 1987 - 80-90%; Boggs, 1992 - 54-68%; Hinton and Nakano, 1996 – 85%; Ward and Myers, 2005 – 75%) to compensate for the effects of the oceanic environment on fishing depth.

In summary, studies employing depth measuring devices (Table 1.1) invariably indicate that the gear fishes shallower than catenary formulas predict. The degree to which the gear fishes shallower varies from the most conservative estimates of 89-90% of predicted depth (Saito 1973; Hanamoto 1987) to one of the most drastic at about 50% and 70% of predicted depth for swordfish and tuna sets, respectively (Bigelow et al., 2006).

Sagging and Shoaling

If gravity were the only force acting on PLL gear, the gear would eventually sink until the main line was hanging straight down and the neighboring surface buoys were touching each other. However, tension in the mainline and drag along its length oppose the contraction due to gravity and allow the gear to obtain an equilibrium state referred to as “settled” fishing depth. These kinematic processes are termed “shortening” or “sagging” when the PLL gear is sinking and “shoaling” when the gear is being elevated (Bigelow et al. 2006).

Immediately after PLL gear is deployed it begins to sink and will continue to sink until settled fishing depth has been reached. Boggs (1992) and Mizuno et al. (1998) using depth measuring devices (i.e. TDRs and micro-bathythermographs) reported PLL gear reaching settled depth around 30 minutes after deployment. However, PLL gear will often never reach a settled depth if deployed in an area with strong or dynamic water movement, such as the frontal systems often targeted by PLL fishers. Gear deployed parallel to a frontal system often results in the gear being compressed resulting in an increase in depth or “sag” (Figure 1.7). Gear will often stretch when deployed across frontal systems with horizontal shear causing the gear to lift or “shoal” towards the surface (Figure 1.8). Mizuno et al. (1998) found that vertical current shear is directly proportional to elevation of PLL gear when the current is oriented perpendicularly to the deployed gear. Yokawa and Takeuchi (2003) modeled current shear and shoaling and employed the model results as a scalar multiplied with hook depth to determine effective fishing effort during HBS of CPUE for white marlin. Bigelow et al. (2006) suggested the degree of shoaling was weakly correlated to the degree of current velocity and shear. Therefore, quantification (either by direct measurement or estimation) of the degree of “sagging” and “shoaling” is necessary when attempting to determine hook depth during PLL fishing.

Many previous studies have estimated the “sagging” or “shortening” ratio (a dimensionless ratio; Boggs, 1992) in order to calculate hook depth using catenary algorithms (Suzuki et al., 1977; Hanamoto, 1987; Yang and Gong, 1987; Hinton and Nakano, 1996; Ward and Myers, 2005) (Table 1.1). Mizuno et al. (1998) concluded that previous methods used to measure shortening ratio tend to lead to overestimates. Bigelow et al. (2006) concluded that the commonly used catenary angle, $\phi = 72^{\circ}$ (Suzuki et al. 1977), is not realistic and that capture depth using traditional catenary algorithms overestimate fishing depth by an average of 50% for swordfish fishing and 30% for tuna fishing. To capture the variability in hook depth during PLL fishing, they suggested

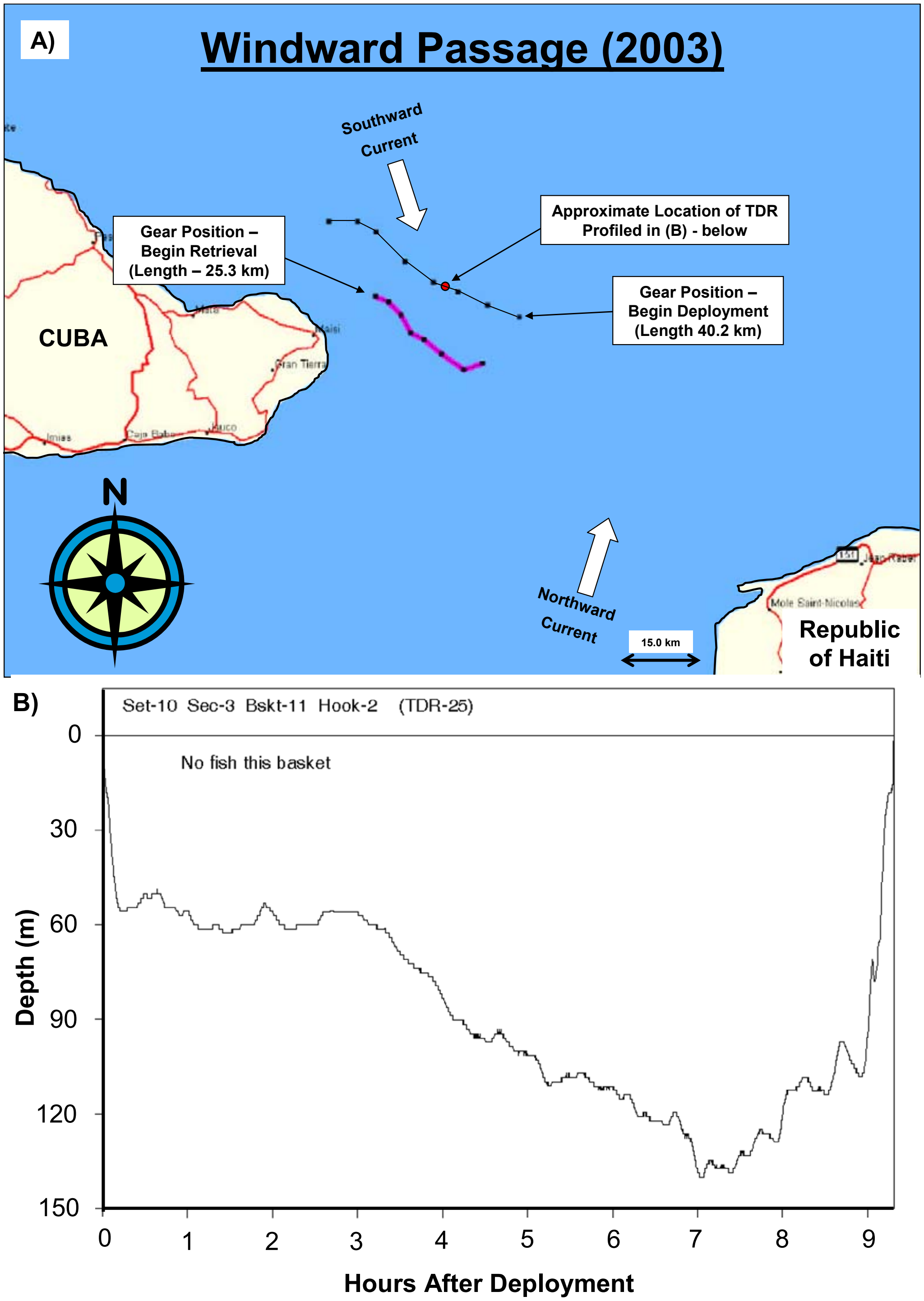


Figure 1.7. Pelagic longline gear deployed in the Windward Passage during 2003 (Rice et al., 2007). A) Location of gear deployed somewhat parallel to the effective current; (B) Vertical temperature-depth profile measured by TDR deployed on the hook in the approximate middle of the gear showing gear never reaching "settled" fishing depth.

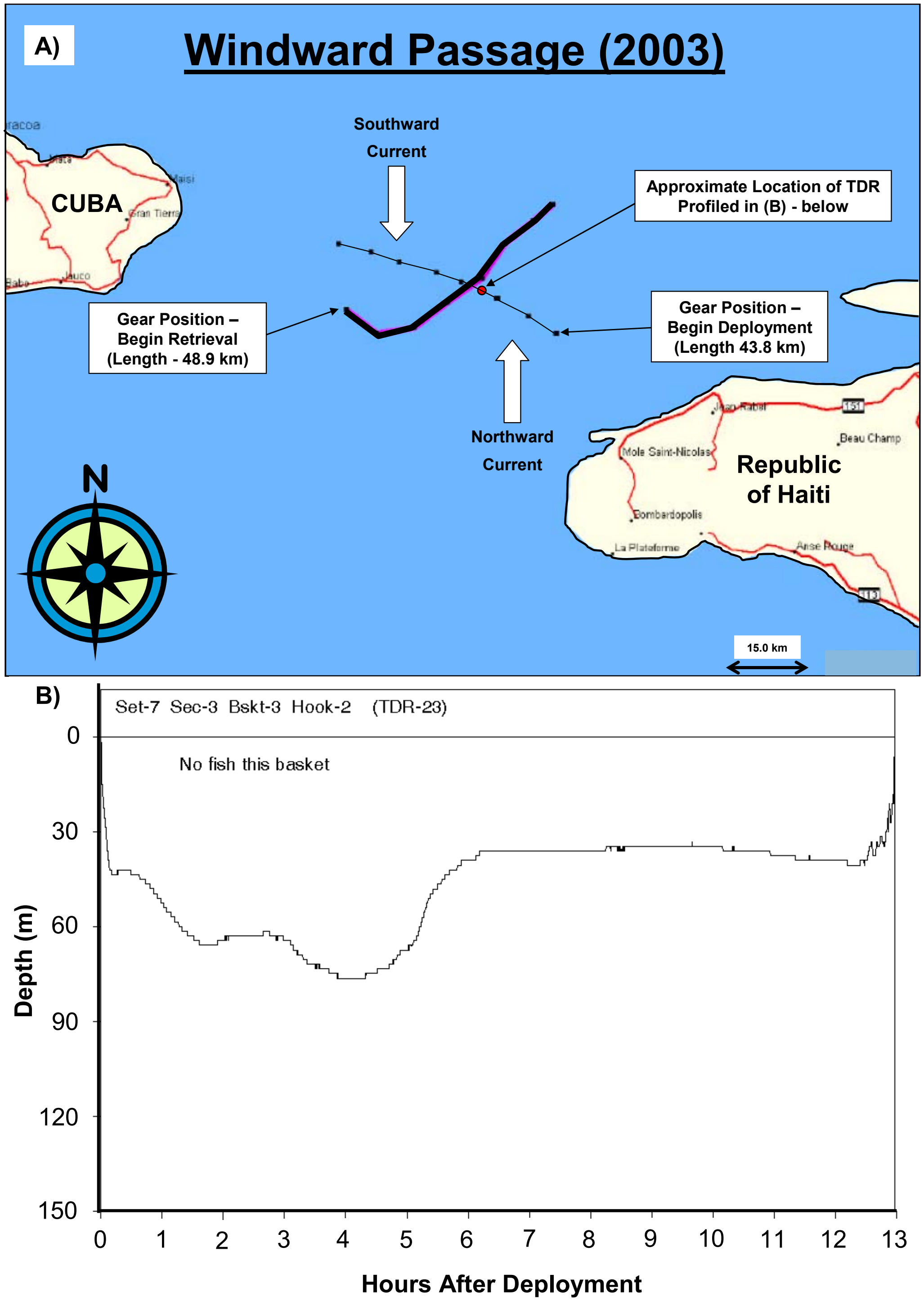
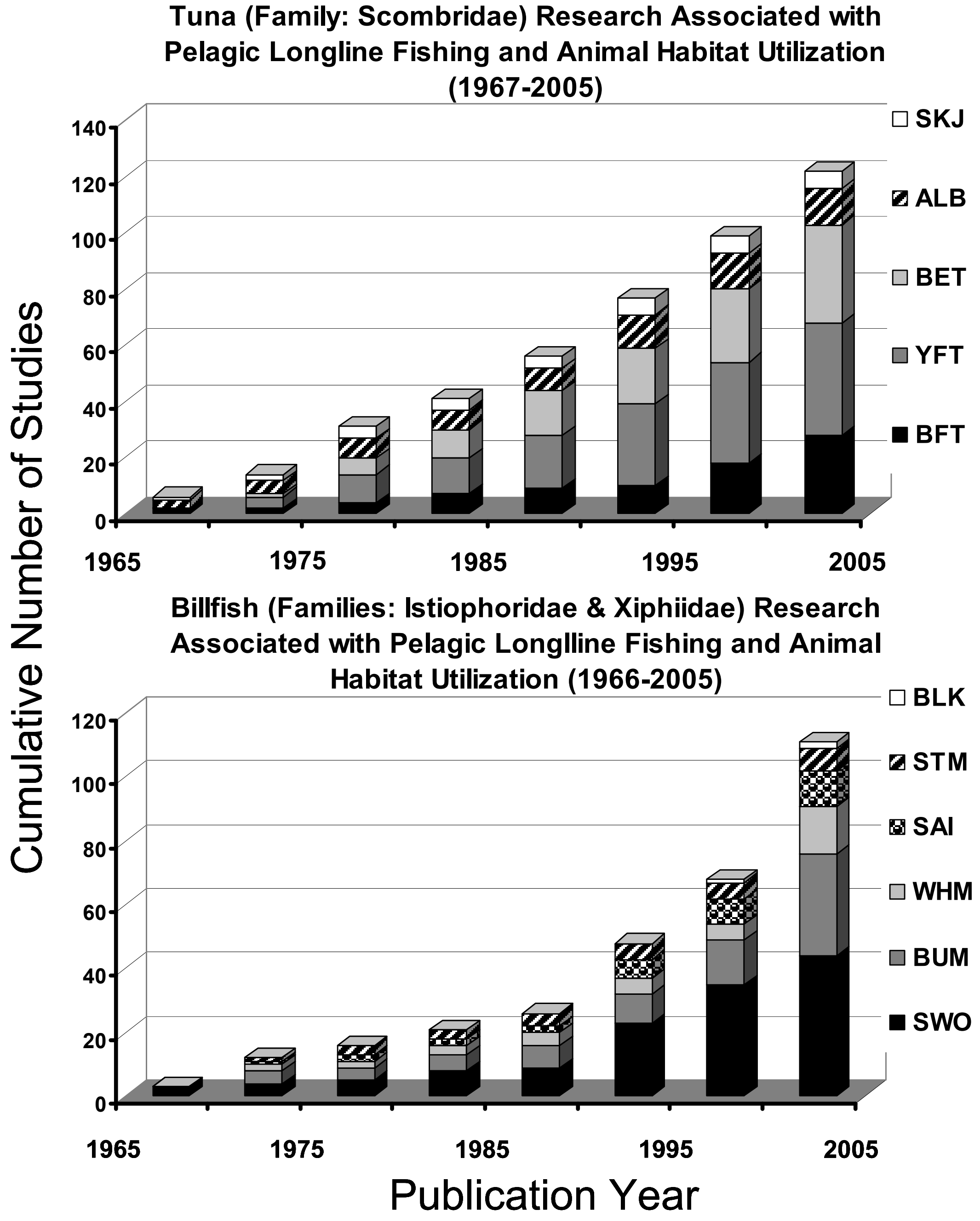


Figure 1.8. Pelagic longline gear deployed in the Windward Passage during 2003 (Rice et al., 2007). (A) Location of gear deployed across a "current front" with water masses moving in opposite directions; (B) Vertical temperature-depth profile measured by TDR deployed on the hook in the approximate middle of the gear showing gear being elevated towards the surface as the gear is stretched and eventually reaching "settled" fishing depth approximately 6 h after deployment.

placing TDRs throughout the PLL gear on the deepest sequential hooks in sequential sections. Rice et al. (2007) systematically deployed TDRs along the entire PLL gear length on shallow and deep hooks during experimental PLL fishing targeting swordfish. They concluded that fishing depth is highly variable within and among gear deployments, even when fishing in the same area and that catenary geometry is inadequate to account for the effects of sagging and shoaling during PLL fishing.

Pelagic Fish Vertical Habitat Utilization and Behavior

There have been many studies focusing on PLL fishing depth and pelagic animal habitat utilization (Figure 1.9). With regards to fish interactions with PLL fishing gear, the literature is dominated by studies focusing on tuna and billfish. Most PLL research focusing on scombrids has centered on yellowfin and bigeye tuna, with a steady increase in the number of studies from the 1970's (Figure 1.9 – top panel). This presumably occurred as a result of the shift during the 1970's from near surface longline gear targeting yellowfin to deeper gear deployments targeting bigeye tuna. Pelagic longline research focusing on billfish has concentrated mainly on swordfish, but there was a strong increase in the number of studies on marlin, especially blue marlin, after 1990 (Figure 1.9 – bottom panel). This presumably occurred as a result of the establishment of the Enhanced Billfish Research Program initiated by ICCAT in 1986 (Prince and Brown, 1991) and the findings that white marlin and blue marlin were overfished by the 4th ICCAT Billfish Workshop (ICCAT, 2001).



Tuna (Family: Scombridae) Research Associated with Pelagic Longline Fishing and Animal Habitat Utilization (1967-2005)

Billfish (Families: Istiophoridae & Xiphiidae) Research Associated with Pelagic Longlline Fishing and Animal Habitat Utilization (1966-2005)

Figure 1.9. Chronology of species specific studies relative to pelagic longline fishing; (Top) Tuna (Family: Scombridae); (Bottom) Marlin, sailfish, and swordfish (Families: Istiophoridae & Xiphiidae). SKJ = skipjack tuna (*Euthynnus spp.*); ALB = albacore tuna (*Thunnus alalunga*); BET = bigeye tuna (*Thunnus obesus*); YFT = yellowfin tuna (*Thunnus albacares*); BFT = bluefin tuna (*Thunnus thynnus*); STM = stripped marlin (*Tetrapturus audax*); BLK = black marlin (*Makaira indica*); SAI = sailfish (*Istiophorus platypterus*); WHM = white marlin (*Tetraptururs albidus*); BUM = blue marlin (*Makaira nigricans*); SWO = swordfish (*Xiphias gladius*).

Vertical Habitat Use (Families: Xiphiidae and Istiophoridae)

Historically, vertical distributions of pelagic fishes were primarily estimated indirectly from catch by a specific hook position along the PLL gear and theoretical depth of the gear calculated from catenary geometry (Yoshihara 1951, 1954; Suzuki et al. 1977; Hanamoto 1987; Hinton and Nakano 1996; Ward and Myers 2005) (Figure 1.5). However, Boggs (1992) and Yokawa and Takeuchi (2003) reported that fish, and particularly billfish, will often strike hooks moving through the surface mixed layer during deployment and retrieval. This can give a false impression of fish being captured on deep hooks. Without verifying the fish strike-time (i.e. with the use of electronic hook-strike timers), catch by branchline data may overestimate capture depth and, therefore, lead to inaccurate models of fish utilization of the water column which could in turn bias subsequent stock assessments. The advent of acoustic tracking and more recently, archival and pop-up satellite archival tag (PSAT) technology allows for improved monitoring and characterization of fish habitat utilization (Figure 1.10).

Electronic tracking of pelagic animals

Acoustic telemetry is one of the oldest electronic tools used to study highly migratory species in their natural environment (Arnold and Dewar, 2001). Developed by the U.S. Fish and Wildlife Service, acoustic telemetry involves an acoustic transmitter implanted into the body cavity or fastened externally onto the study animal, which can then be monitored and located with a directional hydrophone (Trefethen, 1956; Henderson et al., 1968). One of the earliest applications of acoustic telemetry on pelagic fish was conducted by Yuen (1970) on skipjack tuna, *Katsuwonus pelamis*. Acoustic

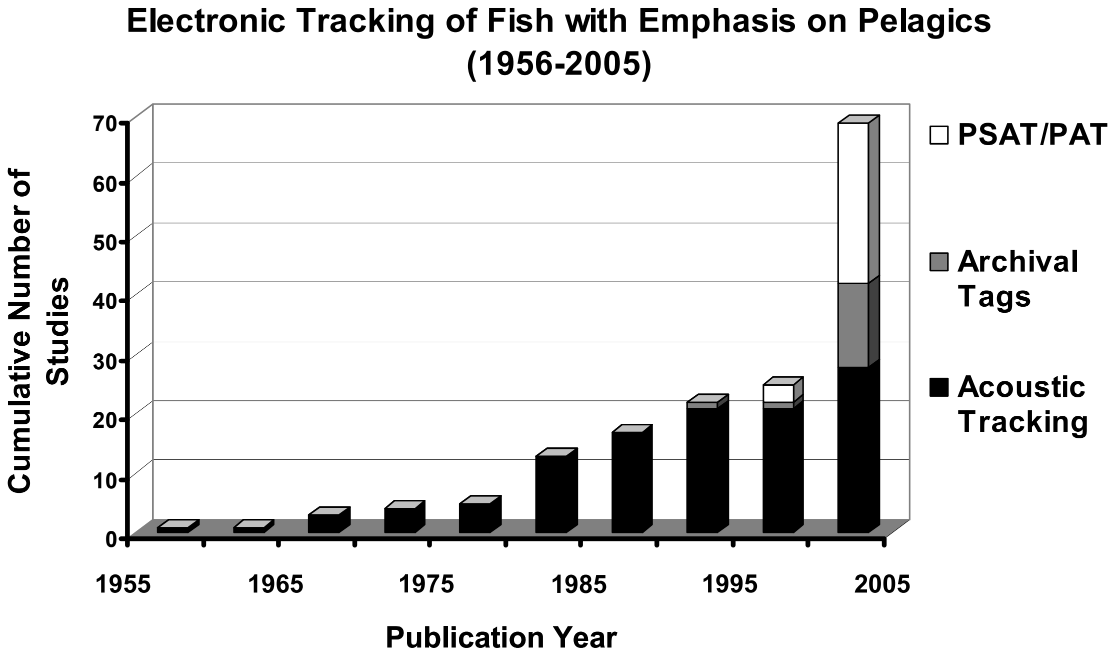


Figure 1.10. Relative abundance of research from 1956-2005 pertaining to the evolution of electronic tracking of fishes from exclusively acoustic tracking to archival and pop-up satellite archival tracking technology.

telemetry studies in the marine environment were initially conducted from large fishing vessels or oceanographic research vessels. In addition to considerable operating costs, these vessels were generally slow and difficult to maneuver, making them ill suited for tracking fast swimming pelagic fishes. Holland et al. (1985) employed ultrasonic acoustic telemetry technology for tracking fast swimming pelagic species, such as tuna and billfish, using smaller, faster, and more maneuverable vessels. Acoustic telemetry remained the primary method for tracking large pelagic fish through the 1980's, until new electronic tracking technology emerged (Figure 1.10).

During the early 1990's, implantable archival tags were developed and applied to southern bluefin tuna, *Thunnus maccoyii* (Arnold and Dewar, 2001). Archival tags are data storage tags that are implanted into the peritoneal cavity or attached externally to the marine animal of interest. They are designed to collect information on the ambient environment experienced and/or physiological response(s) of the animal as it passes through various environmental conditions. They can measure, record and store data for long deployment durations, however, a considerable technological limitation is that they require the animal to be recaptured to download and process the data. The earliest study using archival tags on pelagic fish was reported by Gunn and Davis (1994) on southern bluefin tuna. The success of this study led to others using archival tags on pelagic fishes, mostly on small- to medium-sized tuna (Family: Scombridae) [Atlantic bluefin tuna, *Thunnus thynnus thynnus* - (Block et al., 1998b), Pacific bluefin tuna - *Thunnus thynnus oreintalis*, (Kitagawa et al., 2000), and bigeye tuna - (Musyl et al., 2003)]. There have been very few studies employing archival tags on billfish (only swordfish, *Xiphias gladius*), (Takahashi et al., 2003). Probable causes for limited billfish studies employing archival tags include: (1) the deployment method, which typically requires bringing the fish on board the vessel and surgically implanting the archival tag into the body cavity, a surgical procedure that becomes problematic and dangerous for very large billfish (Families: Xiphiidae and Istiophoridae), and (2) the subsequent timely development of PSATs.

Arnold and Dewar (2001) provide a comprehensive review of the evolution satellite tags and concluded that satellite remote sensing technology is best suited for monitoring highly mobile migratory species, such as tuna and billfish. There are several PSATs available (Microwave Telemetry, Inc. and Wildlife Computers). Most are similar in external design and environmental measurements collected (i.e. temperature, depth and light intensity for geolocation) and have fishery independent data retrieval functions. However, the primary differences between PSAT types include: (1) how onboard data is processed, (2) who programs the tags for pop-up dates, environmental sampling intervals and data transmission parameters, and (3) how memory storage is allocated. For example, PTT-100 PSATs (Microwave Telemetry, Inc) contain enough memory to record 60 temperature readings (Sedberry and Loefer, 2001). Therefore, a short deployment of 1 h will result in a sampling resolution of one temperature reading per minute. However, the same tag deployed for 24 h will result in one temperature reading per hour (i.e. sampling resolution is a function of deployment duration). While this type of PSAT is well suited for specific research questions like catch and release survival or horizontal displacement, it may not be appropriate for adequate characterization of pelagic fish vertical habitat utilization because animal behavior such as deep dives may not be recorded between sampling intervals during long deployments.

The first PSATs for large pelagic fish were deployed on Atlantic bluefin tuna (Block et al., 1998a) and were 93% successful in reporting useful data via satellite. In a similar study, Lutcavage et al. (1999) reported an 85% successful reporting rate, corroborating the success reported by Block et al. (1998a). Interestingly, both studies demonstrate the improvements in understanding fish habitat utilization associated with satellite technology because they found that several bluefin tuna tagged in the eastern Atlantic crossed into the western Atlantic, which was contrary to information previously used by ICCAT for bluefin stock assessment and management,.

Of the electronic tracking methods currently available, acoustic telemetry is most useful for short term, fine temporal scale tracking, while implantable archival tags are better suited for long term studies on species which are likely to be recaptured due to high fishing mortality rate (Takahashi et al., 2003). Satellite tracking technology is best suited for pelagic animals with low directed fishing mortality (i.e. billfish). For billfish, their ability to make rapid deep dives requires electronic tracking with fine resolution environmental sampling. However, for some electronic tracking systems, tracking duration can have an affect on the sampling resolution (Figure 1.11).

Swordfish (*Xiphias gladius*)

Swordfish have a broad vertical habitat range. They have long been exploited by harpoon fishers as they bask in warm sunlit surface waters (Beckett, 1974; Carey and Robison, 1981). Basking behavior apparently occurs as the swordfish attempts to warm the body after feeding in cold water and to aid in metabolic functions and digestion (Carey and Robison, 1981; Carey, 1990; Takahashi et al., 2003). Sightings by deep sea

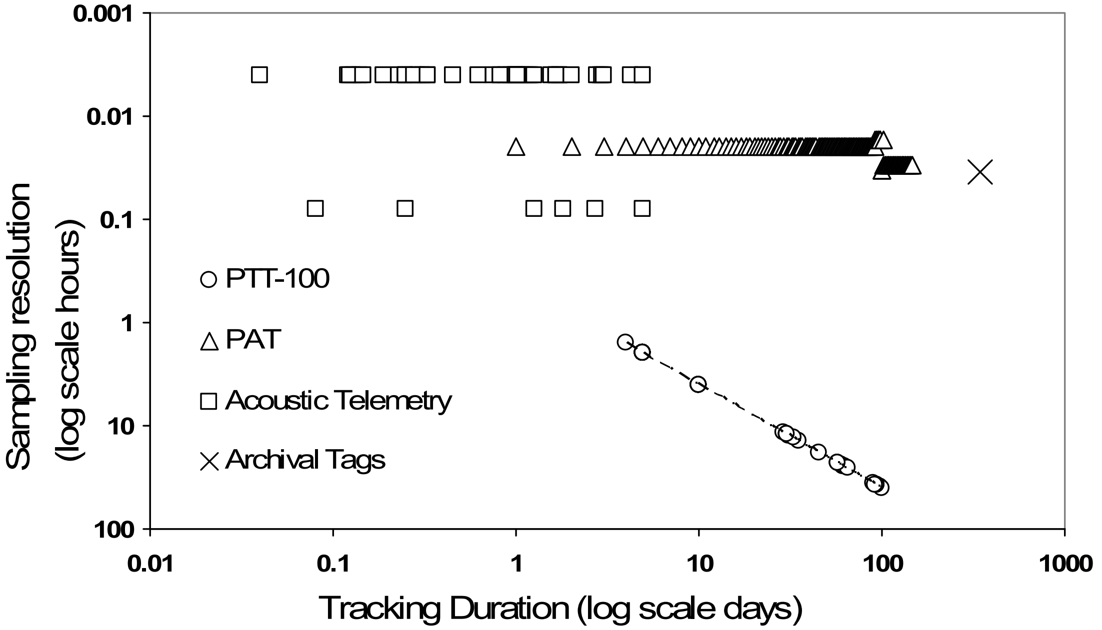


Figure 1.11. The effect of tracking duration on sampling resolution associated with various tag types during billfish (Families: Xiphiidae and Istiophoridae) electronic tracking studies (1974-2005). Note: PTT-100 sampling resolution is a function of tracking duration.

submersibles as early as 1967 have documented swordfish in water depths greater than 650 m and temperatures below 5 ºC (Zarudzki, 1967; Church, 1968) (Table 1.2). Carey and Robison (1981) successfully tracked five swordfish in the Pacific near Baja California and one swordfish in the Atlantic, east of Cape Hatteras, using acoustic telemetry tags implanted into the fish with a harpoon. They reported the maximum depth and minimum temperature experienced by tagged swordfish in the Pacific at about 250 m and 10.5 ºC, respectively, (Table 1.2). In contrast, the maximum depth and temperature experienced in the Atlantic was much deeper and only slightly colder at 617 m and 8 ºC, respectively (Table 1.2). The thermal difference (ΔT) between the sea-surface temperature and the minimum temperature at depth experienced by the swordfish reported in this study was about 19 °C (Table 1.2). Using similar acoustic telemetry techniques in the western North Atlantic, Carey (1990) reported similar vertical habitat utilization with the maximum depth and minimum temperature experienced by the swordfish as 595 m and 7 ºC, respectively, with a corresponding maximum ΔT of 19 °C (Table 1.2).

Takahashi et al. (2003) equipped a single swordfish with an external archival tag in the northwestern Pacific off the east coast of Japan. The tag was equipped with temperature, depth and light intensity sensors. The fish was recaptured 345 days later with high resolution environmental data archived in its memory. The minimum temperature experienced by the swordfish was around 4 ºC (maximum ΔT = 23 °C) and the maximum depth was estimated at roughly 900m (Table 1.2). Because the maximum depth experienced by the swordfish exceeded the depth sensor capabilities of the archival

Table 1.2. Billfish (Family: Xiphiidae and Istiophoridae) maximum vertical habitat utilization recorded during electronic tracking studies from 1979 -2008. ETP = eastern Tropical Pacific, CNP = central North Pacific, WNA = western North Atlantic, GOA = Gulf of Arabia, ENP = eastern North Pacific. Mixed diel behavior suggests some fish exhibit diel behavior while others do not within the same study. Estimated refers to whether or not the maximum depth and temperatures were explicitly stated in the text or estimated from graphs within each study.

Study	Ocean	Species	Succesful tracks	Tag type	Max. time monitored (d)	Resolution (h)	Diel behavior?	Maximum depth (m)	Minimum temperature (°C)	Maximum ΔT (°C)	Estimated?
Pepprell and Davis (1999)	S. Pacific	black marlin	6	Acoustic	1.1	<0.001	Mixed	178	19.0	8.0	No
Gunn et al. (2003)	S. Pacific	black marlin	2	PAT	64	0.020	No	236	≤ 21.0	≥ 10.5	Yes
Prince and Goodyear (2006)	ETP	black marlin	1	PAT	28	0.008	-	108	18.3	9.7	Yes
							Mean (±SE)	174 ± 37	19.4 ± 0.8	9.4 ± 0.7	
Yeun et al. (1974)	CNP	blue marlin	5	Acoustic	0.9	-	No	185	-	-	Yes
Holland et al. (1990)	CNP	blue marlin	6	Acoustic	1.75	0.25	Yes	140	20.0	7.0	Yes
Block et al. (1992)	CNP	blue marlin	6	Acoustic	5	0.004	Mixed	209	17.0	10.2	No
Graves et al. (2002)	WNA	blue marlin	8	PTT-100	5.1	2.0	No	39	22.5	8.5	Yes
Kerstetter et al. (2003)	WNA	blue marlin	5	PAT	32	0.02	Yes	270	16.6	14.0	No
	WNA	blue marlin	2	PTT-100	5	2.0	No	-	25.0	8.0	No
Saito and Yokawa (2005)	Atlantic	blue marlin	6	PAT	58	0.02	-	>300	< 14.0	14.0	No
	Atlantic	blue marlin	2	PTT-100	58	23.2	-	120	15.0	13.0	No
Pricne and Goodyear (2006)	WNA	blue marlin	14	PAT	91	0.008	-	804	9.8	18.2	Yes
	ETP	blue marlin	3	PAT	46	0.008	-	108	18.3	9.7	Yes
Goodyear et al. (in press)	Atlantic	blue marlin	51	PAT 2,3	93	0.008	Yes	>800	<10	15	No
							Mean (±SE)	297 ± 92.3 m	16.3 ± 1.8	11.8 ± 1.2	
Jolley and Irby (1979)	WNA	sailfish	8	Acoustic	1.2	0.160	-	74	-	-	No
Hoolihan (2005)	GOA	sailfish	2	PAT	66	0.008	Yes	80	19.7	11.6	No
	GOA	sailfish	8	Acoustic	2.3	<0.001	Yes	27.9	20	5	No
Pricne and Goodyear (2006)	WNA	sailfish	5	PAT	62	0.008	-	284	15.8	12.2	Yes
	ETP	sailfish	9	PAT	59	0.008	-	144	15.2	12.8	Yes
Hoolihan and Lou (2007)	GOA	sailfish	12	PAT	89	0.020	No	71	19.6	15	No
	GOA	sailfish	2	PTT-100	71	1	No	48	21.7	11.7	No
							Mean (±SE)	104.1 ± 50	18.7 ± 1.5	11.4 ± 1.9	

Table 1.2 (continued).

Study	Ocean	Species	Succesful tracks	Tag type	Max. time monitored (d)	Resolution (h)	Diel behavior?	Maximum depth (m)	Minimum temperature (°C)	Maximum ΔT (°C)	Estimated?
Holts and Bedford (1990)	ENP	striped marlin	8	Acoustic	2.0	< 0.001	Mixed	93	12.0	8.0	Yes
Brill et al. (1993)	CNP	striped marlin	6	Acoustic	2.1	0.004	No	180	12	8.0	Yes
Domeier et al. (2003)	ENP	striped marlin	45	PAT	93	0.030	-	192	11.6	12.5	Yes
Domeier (2005)	Pacific	striped marlin	248	PAT	-	-	-	-	-	16	No
							Mean (±SE)	155 ± 31.2	11.9 ± 0.1	11.1 ± 2.2	
Carey and Robison (1981)	ENP	swordfish	5	Acoustic	5	0.08	Yes	250	10.5	10.6	No
	WNA	swordfish	1	Acoustic	3	0.08	Yes	617	7.0	19.0	No
Carey (1990)	WNA	swordfish	5	Acoustic	5	0.08	Yes	595	6.0	17.0	No
Sedberry and Loefer (2001)	WNA	swordfish	21	PTT-100	100	40	Yes	350[a]	10.0[a]	18	Yes
Takahashi et al. (2003)	Pacific	swordfish	1	Archival	345	0.035	Yes	900	4.0	23.0	Yes
							Mean (±SE)	615.5 ± 100.6	7.5 ± 1.2	17.5 ± 2.0	
Prince et al. (2005)	Caribbean	white marlin	7	PAT	40	0.020	Mixed	368	16.8	13.2	No
Horodysky et al. (2007)	WNA	white marlin	47	TT-100 H	10	0.070	No	210	11.5	13.5	No
							Mean (±SE)	289 ± 79	14.2 ± 2.7	13.4 ± 0.15	

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[a] Maximum depth and minimum temperature were reported from a PTT-100 HR at large for 30 days with a 12 h sampling resolution

tag, depth information was estimated from comparisons of thermal profiles made by a conductivity/temperature/depth profiler (CTD) in the same month near the tagging location.

Sedberry and Loefer (2001) deployed 29 PSATs (model PTT-100) on swordfish captured by commercial pelagic longliners fishing in the Atlantic near the "Charleston Bump". They reported forays into water deeper than 350 m with temperatures as low as 10 ºC (maximum $\Delta T = 18$ °C) (Table 1.2.). However, long deployment durations resulted in low environmental sampling resolution (e.g., 30 days = 1 sample per 12 h; 60 days = 1 sample per 24 h; 90 days = 1 sample per 36 h), therefore forays into deeper, colder water towards the end of the tracking period may not have been recorded. The maximum depth and minimum temperature reported during this study are considerably shallower and warmer, respectively, than those reported in previous studies on swordfish with acoustic telemetry (Carey and Robison 1981; Carey 1990).

In summary, the broadest range of depth and temperature experienced by swordfish during the previous studies was reported from the archival tag deployed by Takahashi et al. (2003) (>900m and <4ºC) but they were extremely fortunate to recapture the same fish one year later. There has been only one published study employing PSATs on swordfish (Sedberry and Loefer, 2001), however the type of satellite tag used was not appropriate for characterization of swordfish vertical habitat utilization. Future studies on swordfish movements should employ tags that combine the high sampling resolution and long tracking durations (similar to the archival tag used by Takeuchi et al., 2003) with the remote data retrieval capabilities associated with satellite tags.

Blue Marlin (*Makaira nigricans*)

The blue marlin is a pelagic fish inhabiting tropical and subtropical waters of the Atlantic, Pacific and Indian oceans (Block et al., 1992; Graves et al., 2002). It can make trans-oceanic migrations (Squire, 1974) and has been observed following warm oceanic currents (i.e. Gulf Stream in the Atlantic) as far north as 50º N (P. Rice, pers. obs.). The species supports lucrative recreational fisheries around the world (Graves et al., 2002; Kleiber et al., 2003) and is often taken as bycatch during commercial pelagic longline fishing targeting tuna and swordfish, which comprise their greatest source of mortality (ICCAT, 2001; Saito and Yokawa, 2005).

Yuen et al. (1974) conducted the first ultrasonic telemetry tracking study of blue marlin. They estimated fish swimming depth from water temperature using temperature sensitive transmitters. Their longest track of 22.5 hours demonstrated that the fish spent all of its time above 80 m depth and showed no pattern that could be related to time of day. The maximum depth reported during their study was 185 m (Table 1.2), but the corresponding temperature was not reported. An interesting observation during their study was the high post-tagging mortality rate experienced by blue marlin (three of the five tagged fish) which heightened concerns about post catch and release mortalities. Such high mortality also casts some doubt as to whether the vertical habitat data they collected is representative of the natural behavior of this species (Goodyear, 2002).

Holland et al. (1990) used acoustic telemetry to track six Pacific blue marlin in waters around the Hawaiian Islands. The maximum depth and minimum temperature recorded during their study was 140 m and 20 ºC, respectively, with corresponding maximum $\Delta T = 8$ °C (Table 1.2). Pooled data from all six fish indicated that blue marlin spend the majority of their time within the mixed layer and top two degrees of the thermocline (24 - 26 ºC). They concluded that blue marlin had a diel swimming pattern, preferring deeper swimming during the day (however, still above the bottom of the thermocline), while remaining closer to the surface at night. In contrast to the mortality reported by Yuen et al. (1974) they reported no mortality associated with the capture and tagging process in their study. Of interest from this study was the post-capture behavior exhibited by these fish. Regardless of the capture and tagging location, all fish swam immediately downward into the upper layers of the thermocline. They remained at depth for several hours while swimming in a westerly course arriving at a specific location about four square nautical miles in area and 12 nm west of Keahole Point. At this location all fish made their first post-implantation directional change going off in different directions. They concluded that these results indicate that direct offshore movement may be a common response to the trauma associated with the capture and tagging process.

Block et al. (1992) reported similar findings during their acoustic tracking study of six blue marlin off the Kona Coast of Hawaii during July and August of 1989. However, they were able to track five of the six marlins for periods of 42 h or more (42 – 120 h). Pooled data from all six blue marlin showed that they spent more than 50% of their time in the upper 10 m of the water column. As in Holland et al. (1990), the marlin all initially swam offshore in a westerly direction and then changed direction to either the north or south and followed a consistent course for the remainder of the time they were tracked. The maximum depth and minimum temperature reported was 209 m and 17 ºC, respectively, with a corresponding maximum ΔT = 10.2 °C (Table 1.2). However, contrary to Holland et al. (1990), they reported no significant diel depth preferences and suggested that each track, including those of the Holland et al. (1990) study, showed much individual variation with respect to day and night depth preferences. Potential explanations for individual variation, such as post-tagging acclimation or sensing the presence of the tracking vessel, were not discussed. However, there is evidence from previous studies of interference with normal swimming behavior caused by the presence of the acoustic tracking vessel (Carey and Robison, 1981).

Graves et al. (2002) used PSATs (model PTT-100) to determine the recreational post-release survival of nine Atlantic blue marlin southwest of Bermuda. The tags used were the same as those used by Sedberry and Loefer (2001) on Atlantic swordfish but they used much shorter deployment durations (122 h) which allowed higher resolution environmental sampling (2 h) (Table 1.2). The depth was estimated from temperature/depth relationships provided from the Bermuda Biological Station for Research oceanographic sampling station located southeast of Bermuda. The inferred maximum depth and minimum temperature experienced by the blue marlin during their study was about 39 m and 22.1 ºC, respectively, with a corresponding maximum ΔT = 8.5°C (Table 1.2). These blue marlin spent the majority of their time (> 75%) in the upper 10 m of the water column. They reported no significant diel depth preferences.

Kerstetter et al. (2003) expanded on the study by Graves et al. (2002) by measuring survival of blue marlin captured as bycatch during commercial pelagic longline fishing targeting tuna and swordfish. Nine fish were captured, equipped with PSATs and released. Seven of the blue marlin were equipped with PSATs (model PTT-100) with 5-day (122 h) deployment duration, resulting in an environmental sample recorded every 2 h. However, two fish were equipped with satellite tags (PAT model; Wildlife Computers, Inc.) that summarized data onboard the tag and therefore the sampling resolution was not affected by the long deployment durations (e.g. 30 days). No blue marlin depth data were reported for the 5-day PTT's during this study, however the minimum temperature reported was 25 ºC with a corresponding maximum ΔT = 8 °C. The two blue marlin equipped with 30-day PSATs reported a maximum depth and minimum temperature as 275 m and 16.6 ºC, respectively, with a corresponding maximum ΔT = 14 °C (Table 1.2). Kerstetter et al. (2003) concluded that the 30-day tag recorded a broader range of temperatures than the 5-day tag and suggested this apparent difference was related to the measurement, processing and storage of onboard data for each tag type used. Although unable to infer any diel depth preference for blue marlin implanted with the 5 day PTT tags they concluded that data reported by both 30-day PAT tags revealed a relationship between fish movement into deeper water during daylight hours.

Saito and Yokawa (2005) employed both types of PSATs to evaluate the depth distribution of blue marlin and to quantify the factors potentially influencing their vertical habitat use. They deployed 18 PSATs (12 PAT and 6 PTT-100) throughout the equatorial tropical Atlantic. The maximum depth and minimum temperature reported during this study was from a PAT tag attached to a blue marlin in the western tropical Atlantic. This fish dived deep (>300 m) and experienced water temperatures <14 ºC. Unfortunately, corresponding CTD data were not collected for this particular fish but CTD data from another fish tagged in the same area and the same time suggested sea-surface temperatures around 27 – 28 °C corresponding to, at least, a ΔT = 14 °C (Table 1.2). Blue marlin temperature/depth preferences reported during this study show a clear correlation with the thermocline depth, however the maximum ΔT was substantially >8°C. There was no analysis of diel depth preferences but all fish in this study spent >61% of their time in the upper 25 m (average percent time spent in upper 25 m = 80.5% ± 14%).

Prince and Goodyear (2006) reported blue marlin habitat utilization from data collected from 14 PSATs (models: PAT 2 and 3) deployed on blue marlin in the western North Atlantic (WNA) and 3 PSATs (same model) on blue marlin in the eastern tropical Pacific (ETP). They derived mean temperature/depth profiles from the 1998 – 2001 World Ocean Atlas data for the Atlantic and Pacific study areas. Blue marlin from the WNA exhibited the broadest vertical habitat utilization with the maximum depth and minimum temperature reported as 804 m and 9.8 ºC, respectively, with an estimated maximum ΔT around 18 °C (Table 1.2). However, *Makaira spp.* in the ETP exhibited much narrower habitat utilization with the maximum depth and minimum temperature reported as 108 m and 18.6 °C, respectively, with a corresponding Δ T around 9.8 °C (Table 1.2). Istiophorids are obligate ram-jet ventilators, have a high performance physiology and commensurate high oxygen demand (Brill, 1996). Considering these factors and their PSAT results, Prince and Goodyear (2006) concluded that vertical habitat use by these species are limited by hypoxic conditions below the thermocline in the ETP. Conversely, istiophorids occupied much deeper portions of their vertical habitat in the WNA where DO is not limiting with depth. In addition, they contend that pelagic fish in "compressed areas" are more vulnerable to over-exploitation by surface fishing gears compared to non-compressed areas. This study illustrates how environmental variables other than temperature and depth preferences are important when attempting to characterize habitat utilization by pelagic animals. They did not report on diel depth preferences during their study.

In a subsequent study, Goodyear et al. (in press, *Marine Ecology Progress Series*) provided the most comprehensive description to date of actual vertical habitat use by Atlantic blue marlin. They reported on analysis of data collected from 51 PSATs (models PAT 2 and 3) deployed on blue marlin released during recreational and commercial fishing. The data included information from six PSATs that were physically recovered. The PAT model PSATs archive data at user programmed sampling intervals (30 or 60 s in this study). Physical recovery of a tag allows analysis of high-resolution archived data, as opposed to the summarized data transmitted via satellite. This study expanded on the previous work by Prince and Goodyear (2006) which included information reported from 14 PSATs deployed on Atlantic blue marlin. Goodyear et al. (in press, *Marine Ecology Progress Series*) concluded that Atlantic blue marlin exhibit significantly different diel habitat utilization, spending 91% of their time near the surface during the nighttime, 52% during twilight and only 22% during the daytime. They found that Atlantic blue marlin vertical habitat use is broader than previously reported. They provide evidence suggesting that Atlantic blue marlin can dive well beyond the thermocline depth (maximum depth >800 m and minimum temperature <10 °C; average maximum depth = 319 m and average minimum temperature = 17 °C). They suggest that these deep dives may be associated with daytime foraging events, a postulate which is supported by diet observations of mesopelagic fish species (Goodyear, 2003b). They speculate that this behavior may make Atlantic blue marlin more vulnerable than previously suspected to deepwater longline gear targeting species such as bigeye tuna. They suggest that the proportion of time spent in successively deeper layers of the water column based on temperature relative to the surface mixed layer, a metric currently used in HBS methodology for Atlantic stock assessments, may not be a suitable. Instead, they propose an alternative method for the incorporation of blue marlin habitat use based on random samples taken from diel depth distributions which may more appropriately represent fish vulnerability to various PLL fishing strategies, especially those that operate at different times of day (e.g. swordfish at night and tuna during daylight).

In summary, results of blue marlin tracking studies revealed that they tend to spend the majority of their time in the warm water of the mixed layer and make occasional rapid, deep dives into and well below the upper levels of the thermocline, presumably to feed. The average maximum depth and minimum temperature reported for all blue marlin studies was 297 ± 92.3 m and 16.3 ± 1.8 °C, respectively. The maximum Δ T reported for all blue marlin studies was 18.2 °C by Prince and Goodyear (2006) and the average maximum Δ T reported for all blue marlin studies was 11.8 ± 1.2 °C (Table 1.2), both of which substantially exceed the relative thermal limit of 8 °C suggested for blue marlin by Brill and Lutcavage (2001). Mixed results were reported in regards to blue marlin diel swimming behavior. Some authors suggesting no diel changes in swimming depth (Yuen, 1974; Graves et al., 2002), while others reporting mixed results with much variation between fish (Block et al., 1992) as well as differences resulting from the type of PSAT used during the study (Kerstetter et al., 2003), and yet others suggesting diel habitat use demonstrated by deeper swimming during the day and near surface swimming at night (Holland et al., 1990; Goodyear et al. in press, *Marine Ecology Progress Series*).

However, the assumption that blue marlin are confined to the warm surface mixed layer and that deep PLL fishing is beyond their range of habitat exploitation appears untenable.

Striped Marlin (Tetrapturus audax)

The striped marlin is widely distributed throughout the Pacific and Indian Oceans but is absent from the Atlantic Ocean (Brill et al., 1993). It is an important recreational species supporting sport fisheries along the west coast of North and Central America and is often harvested commercially for the Mexican fish market (Holts and Bedford, 1990) and elsewhere. The species is considered to be migratory; however, the extent of their horizontal movements is not as great as that of other migratory pelagic species like bluefin tuna (*Thunnus thynnus*) (Brill et al., 1993).

Holts and Bedford (1990) used acoustic telemetry to track eleven striped marlin off the California coast. The depth of the fish was inferred using water temperature-depth profiles measured with expendable bathythermographs (XBTs) deployed during tracking. Their longest recorded track was 48 h (range 3 – 48 h). The overall maximum depth and minimum temperature were from a nighttime measurement of 93 m and 10 ºC, respectively, with a corresponding maximum ΔT around 10 °C (Table 1.2). The maximum daytime depth reported was 55 m and they reported a pattern of movement to depth marked by relatively deep dives (max. 93 m) just after sunset. Striped marlin exhibited a preference for shallow surface water during the day and moved deeper below the mixed layer and into the thermocline at night, making their deepest dives just after sunset. This diurnal pattern is directly opposite to that observed for most highly migratory species. Holts and Bedford (1990) described periodic behavior termed “breezing” –

riding in waves down swell and down wind - and “sleeping” – motionless inactivity just below the water surface (~ 5 m) occurring in the early morning and lasting as long as several hours. Inactivity episodes were often followed by social aggregations of up to ten striped marlin.

Brill et al. (1993) conducted a similar study on striped marlin near the Hawaiian Islands using acoustic telemetry. Their objective was to determine the depth distribution of striped marlin and compare them to depth distributions reported by Holts and Bedford (1990) off the California coast. Unlike Holts and Bedford (1990), the maximum depth and minimum temperature during their study was reported from a daytime depth measurement of about 170 m and 18 ºC, respectively, with a corresponding ΔT of 8 °C (Table 1.2). They described a bi-modal distribution with up to 27% of striped marlin time spent in the upper 10 m of the water column and as much as 40% of their time in water depths between 51-90 m. Contrary to Holts and Bedford (1990), they reported no preference by striped marlin for deeper water during the night and frequent deep dives regardless of time of day or night. They suggest that the “floor” of striped marlin vertical habitat, regardless of location, is limited to 8 ºC below the sea-surface temperature. Overall, the striped marlin off Hawaii spent more time deeper than those reported by Holts and Bedford (1990). This is perhaps due to the deeper thermocline depth around Hawaii and habitat compression due to the upwelling environment off California near Baja.

Domeier et al. (2003) deployed 80 PSATs (model: PAT) on striped marlin off Baja California to determine the post-release mortality associated with recreational fishing using offset (5°) circle, non-offset (0°) circle and “J” hooks. Sixty-one PSAT tags reported useful data and revealed that about one in four (26.2 %) striped marlin caught and released with live bait do not survive. The maximum depth and minimum temperature reported was 192 m and 11.6 ºC, respectively, with a corresponding maximum ΔT of 12.5 °C (Table 1.2). The maximum change in temperature (maximum ΔT) experienced by striped marlin in this study is not consistent with the Δ T of 8 ºC for striped marlin hypothesized by Brill et al. (1993) and Brill and Lutcavage (2001). However, striped marlin that were assessed to have survived the angling incident (n = 45) experienced a mean ΔT of 7 ºC, which is well within the thermal window suggested by Brill et al. (1993). There was no discussion of diel swimming behavior in Domeier et al. (2003).

Later, Domeier (2005)[1] reported on striped marlin habitat preferences based on information collected by 248 PSATs released on fish throughout the Pacific Ocean between 2001 and 2005. He suggested that striped marlin spend the vast majority of their time in the mixed layer but make frequent short duration dives and experience temperature changes up to 16 °C (Table 1.2).

In general, striped marlin tend to inhabit the upper 200 m of the water column (Table 1.2). The striped marlin off the coast of California stayed shallower than those off Hawaii, perhaps because of differences in the structure of the water column (i.e. thermocline, oxycline, etc.). However, given the similarities between coastal waters of southern California and Baja, California observed differences in habitat use between striped marlin tagged in both areas are more likely explained by differences in the monitoring technologies and durations employed (Table 1.2). There is an indication that

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[1] Domeier, M. A Pacific-wide look at striped marlin (*Tetrapturus audax*) movement, habitat preference and behavior. 4th International Billfish Symposium, 31 October – 3 November, 2005, Avalon, Santa Catalina Island, California. pg. 22. http://www.pier.org/billfish_symposium/scientificProgram10_24_05.pdf

striped marlin may exploit the vertical habitat differently than other billfish by exhibiting a preference for deeper water during the nighttime than daytime, a behavior which is highlighted by deep dives just around sunset (Holts and Bedford, 1990). However, this trend was only reported in one study.

White marlin (Tetrapturus albidus)

The white marlin is distributed throughout the warm tropical waters of the Atlantic Ocean and adjacent seas (Mather et al., 1974b; ICCAT, 2003). The most recent stock assessment for white marlin considered them severely over fished and their population biomass ratio was 14% of the level required to maintain maximum sustainable yield (ICCAT, 2003). However, information on vertical habitat utilization is lacking[2].

Prince et al. (2005) deployed seven PSATs (model: PAT 3) to characterize horizontal and vertical of adult Atlantic white marlin released during recreational fishing in the northern Caribbean (Dominican Republic). The longest track reported was 40 days. They reported that white marlin spent 50 – 60% of the time monitored above 25 m depth and 60 – 70% of their time in water of 28 – 30 °C. The maximum depth and minimum temperature experienced by the fish was 368 m and 16.8 ºC, respectively, with a corresponding ΔT of 13.2 °C (Table 1.2). No information was provided on diel behavior or depth preferences.

Horodysky et al. (2007) deployed forty-seven PSATs (model PTT-100 HR) to estimate habitat use and vertical movements of white marlin caught by commercial and recreational fishing gears in the western North Atlantic (U.S. East Coast, Northern

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[2] NOAA SAFE Report. 2003 Stock Assessment and Fishery Evaluation for Atlantic Highly Migratory Species. http://www.nmfs.noaa.gov/sfa/hms/hmsdocuments.html. (2003).

Caribbean and Venezuela). They used short tracking durations (5 or 10 days) resulting in 2 or 4 minute environmental sampling intervals; however, the primary objective of this study was to evaluate post-release survival of white marlin. Inferences on habitat use employing short duration monitoring are limited. They reported that tagged white marlin spent 48 % of their time in surface waters around 10 m depth. They found that white marlin make frequent repetitive dives into deeper water (60-100m) presumably to feed. However, no diel swimming patterns were reported. They reported that about 90% of white marlin vertical movements occurred within the upper 8 °C of the surface water temperatures regardless of location.

The results of these studies suggest that Atlantic white marlin have a strong preference for the upper epipelagic, but will execute dives to depths >350 m, presumably to feed. Maximum depths reported by Prince et al. (2005) were substantially deeper than those reported by Horodysky et al. (2007) for white marlin tagged in similar locations (N. Caribbean) and time of year (April-June). This is, most likely, an artifact of: (1) the tracking duration, which was considerably shorter during the Horodysky et al. (2007) study (5-10 days) than the Prince et al. (2005) study (30 - 40 days), and (2) the environmental sampling intervals (i.e. resolution) for each tag type used (Table 1.2).

Black marlin (Makaira indica)

Black marlin are one of the largest members of the Family: Istiophoridae. They are highly migratory apex predators distributed throughout the Pacific and Indian Oceans (Gunn et al., 2003). Black marlin are one of the least studied istiophorid billfishes and prior to the study by Pepperell and Davis (1999) there was no information on their vertical movements.

Pepperell and Davis (1999) used ultrasonic telemetry to track six black marlin off the northern coast of Australia near the Great Barrier Reef. The objective of their study was to determine the survival of black marlin released during recreational fishing. The maximum duration of tracking during this study was 27 h. The maximum depth and minimum temperature experienced by black marlin was 178 m and about 21 ºC, respectively, with a corresponding ΔT of 8 °C (Table 1.2). For all the fish tracked during their study the maximum depth reported occurred during the daytime. They observed no clear diel behavior pattern, but the black marlin had a tendency to swim deeper during the day than at night and the majority of time (day or night) was spent above 10 m. They also reported "sleeping" behavior between midnight and dawn similar to behavior reported for striped marlin by Holts and Bedford (1990). They observed diving behavior immediately after release and two of these dives were the deepest recorded for that specific fish track, however there was no mention of abnormal behavior resulting from tagging stress. Consistent with results reported by Brill et al. (1993), none of the black marlin tracked experienced water temperatures lower than 8 ºC below the sea-surface temperature.

Gunn et al. (2003) employed satellite tracking technology to determine the short-term movement and behavior of black marlin in the Coral Sea. They deployed seven PSATs (two single-point PTT-100 and five PAT) on black marlin (all fish > 90 kg estimated weight). Five of the seven PSATs reported useful data, however, one tag (WC-4) was physically recovered, allowing the archived data (1 minute sampling resolution) to be downloaded and analyzed. The maximum depth and minimum temperature reported during their study was 236 m and 12 ºC, respectively, with a corresponding ΔT of at least 10.5 °C (Table 1.2). The ΔT observed during this study was substantially greater than the 8 ºC ΔT hypothesized by Brill et al. (1993). Gunn et al. (2003) concluded that there was no indication of diel or lunar cycle in diving behavior and that black marlin prefer the upper layers of the water column. They suggested that black marlin, much like blue marlin (Holland et al., 1990; Kerstetter et al., 2003; Saito and Yokawa 2005; Prince and Goodyear 2006), will make rapid deep dives beyond the thermocline.

Prince and Goodyear (2006) deployed a single PSAT on a black marlin in the ETP. They provided specific information on the horizontal displacement (33 nm) but no general information on vertical habitat utilization (i.e. time at depth, time at temperature, etc.) was discussed. However, they do suggest that the maximum depth and minimum temperature experienced by *Makaira spp*. in the ETP was 108 m and 18.3 °C, respectively, with a corresponding maximum ΔT about 9.7 °C (Table 1.2). There was no discussion of diel behavior.

In summary, black marlin exhibit behavior similar to other istiophorids. They show a preference for the warm water surface waters, but will make occasional brief dives beyond the thermocline depth. They exhibit the deepest diving behavior and have a tendency to move offshore towards deeper water immediately after being tagged and released. However, all the black marlin investigated by Pepperell and Davis (1999) and Gunn et al. (2003) remained in the relatively shallow water of the Coral Sea (around 100 m deep) off the northeast Australian coast and their vertical habitat utilization was limited by the sea bottom. The black marlin tracked by Prince and Goodyear (2006) was also vertically limited by a shallow thermocline and hypoxic condition below the thermocline.

Therefore, these studies may not be representative of black marlin vertical habitat utilization in other waters of the Pacific with differing environmental structures. There was no clear indication of diel depth preferences during any of these tracking studies.

Sailfish (Istiophorus platypterus)

Sailfish are distributed widely throughout the world's tropical and temperate oceans and have a more coastal distribution than other istiophorids (Chiang et al., 2004) Their horizontal movements have been studied by conventional tagging methods since the 1950's (Mather et al., 1974a). They are considered migratory pelagic species, but conventional tagging data from the western North Atlantic is consistent with separate eastern and western stock hypotheses. Their horizontal movements include seasonal migrations between summering in temperate waters and wintering in warmer tropical waters.

Jolley and Irby (1979) reported on vertical habitat utilization of eight Atlantic sailfish off the east coast of Florida, while using acoustic telemetry to study the survival of sailfish released during recreational fishing. The longest tracking duration reported was 1.2 days. The maximum depth observed was 74 m (Table 1.2). They did not report temperature at depth experienced by the sailfish but the minimum SST reported was 22 ºC (SST range 22 – 26.6 °C) and all sailfish were tagged in water shallower than 118 m depth.

Hoolihan (2005) used acoustic telemetry (n = 8) and PSAT (n = 2, model: PAT) technology to determine horizontal and vertical movement of sailfish in the Persian Gulf. He reported that Persian Gulf sailfish exhibit a strong preference for the upper water column spending 84.3% of their time above 10 m depth. The bathymetry was shallow (around 30 m depth) with little variation in dissolved oxygen, temperature, salinity or conductivity with depth, suggesting some other environmental factor responsible for these sailfish habitat preferences for the upper 10 m. He suggested that this trait may have resulted from predator-prey interactions, perhaps by conveying a visibility advantage for seeking prey or monitoring predators. He reported some evidence of diel depth preference with Persian Gulf sailfish exhibiting a preference for shallower water during the day and deeper water at night, consistent with behavior observed by Holts and Bedford (1990) for striped marlin in the compressed mixed layer off the California coast. Hoolihan (2005) reported the maximum depth and minimum temperature observed using acoustic telemetry as 27.9 m and 20 °C (max. ΔT ≈ 5 °C), respectively, while the maximum depth and minimum temperature reported using PSATs was 80 m and 19.7 °C (max. ΔT ≈ °C), respectively (Table 1.2). However, PSAT equipped sailfish had substantially longer tracking durations (58 – 66 days) and horizontal displacements as they moved into deeper waters of the Persian Gulf. Although sailfish exhibited a greater proportion of time above 10 m during the day than at night (82.7% versus 70.0 %) and undertook their deepest dives at night, there were no marked diel depth preferences as observed in swordfish (Carey and Robison 1981; Carey 1990; Takahashi et al. 2001).

Prince and Goodyear (2006) deployed 9 PSATs in the ETP and 5 in the NWA on sailfish to compare vertical habitat use. They reported the maximum depth and minimum temperature of 284 m and 15.8 °C (max. ΔT ≈ 12.2 °C), respectively, for Atlantic sailfish and 144 m and 15.2 °C (max. ΔT ≈ 12.8 °C), respectively, for sailfish in the Pacific (Table 1.2). The ΔT's reported in this study were similar in the Atlantic and Pacific and were substantially greater than the 8 °C relative thermal limit for billfish hypothesized by Brill et al. (1993). They concluded that dissolved oxygen is an important variable when evaluating essential habitat of billfish and should be considered along with other habitat factors during future habitat standardizations of CPUE trends.

In a subsequent study, Hoolihan and Luo (2007)) expanded on the previous study of Hoolihan (2005) by analyzing data from 18 PSATs (n = 2, model: PTT-100; n = 9, model: PAT-2; n = 7, model: PAT-4) to determine the summertime residency in the Persian Gulf and vertical habitat utilization. The PSATs had an 83.3% reporting rate (15 of 18) with four of the tags physically recovered allowing analysis of high-resolution archived data. The tagging area was similar to that reported in Hoolihan (2005). Although not as marked as in Hoolihan (2005), these sailfish demonstrated a strong preference for the upper water column. However, the authors suggested that longer deployment durations across seasonal changes were the reason broader environmental conditions were experienced. The maximum depth reported was from a PAT tag on a sailfish which dove to 71 m and the minimum temperature reported was from another PAT tag on a sailfish which experienced water as cold as 19.6 °C, with a corresponding maximum ΔT ≈ 15.0 °C (Table 1.2). Similar to the previous study, no marked diel depth preference were observed during this study.

Visual and nervous system physiological adaptations in billfish

Billfish are visual predators (Fritsches et al., 2003b) with istiophorids feeding primarily during the day, while swordfish exhibit opportunistic feeding patterns associated with diel vertical migrations (Stillwell and Kohler, 1985). Xiphiids have large eyes that are well adapted to predation in very dim light such as that produced by moonlight (Carey and Robison, 1981; Draganik and Cholyst, 1988; Fritsches et al., 2005). They have a vascular heat exchange system located under the brain and behind the eye that heats both the eye and brain as much as 10-14 ^{o}C higher than the ambient surrounding water. This allows for enhanced visual functions in deep, cold, dark water (Carey, 1982).

Istiophorids also have large eyes and pupils (Fritsches et al., 2003b) however they are smaller relative to the eyes of swordfish (pers. obs). Istiophorids are also aided by brain and eye heaters that allow them to be active at great depths and low temperatures (Block, 1990). However the system is smaller and less effective at heating the eyes and brain than the brain-eye heat system in swordfish (Carey, 1982). This may provide a potential explanation for the shorter duration of time at depth by blue marlin than swordfish (Carey, 1982).

Istiophorids have visual specializations that allow them to see in color (Fritsches et al., 2000; 2003a) and in low light conditions (Fritsches et al., 2003b). Blue marlin have eyes with twin cone retinal specializations (Fritsches et al., 2003b). This increases their sensitivity to low light conditions and optimizes visual function during crepuscular periods. Therefore, their eyes may be well suited for crepuscular feeding, when the vulnerability of prey organisms such as tuna increases as their eyes transition from photopic vision (cone dominated daytime vision) to scotopic vision (low-light nighttime vision) and vice versa (Kawamura et al., 1981; Masuma et al., 2001).

An additional visual physiological adaptation for daytime feeding in billfish is the color flashing behavior that occurs during predation (Fritsches et al., 2000). Analysis of the light reflected during this feeding mode indicates high levels of ultra-violet (UV) radiation reflected from the flashing fish. The lenses of the billfish eye do not allow transmission of ultra-violet light, while the lenses of many of their schooling prey items does (Fritsches et al., 2000). This suggests that flashes of UV light accompanying billfish predation may confuse schooling fish making them more susceptible to predation.

Summary of Billfish Vertical Habitat Use

Vertical habitat use of billfish is often defined by a continuum of oceanographic conditions and distribution of their prey that vary with increasing depth. Upwelling areas, most commonly encountered along the eastern side of the world’s tropical and subtropical oceans, are characterized by a very narrow surface mixed layer, shallow thermocline with a steep gradient, and hypoxic environment below the thermocline. These areas comprise vertically compressed habitat restricting most billfish vertical movements but also restricting movements of prey, which may increase billfish foraging efficiency. A possible consequence of habitat compression may be increased vulnerability of billfish to surface oriented fishing gear (Prince and Goodyear, 2006; Goodyear et al., in press, *Marine Ecology Progress Series*). The western portions of the world’s oceans typically have deeper thermoclines and oxygen is not limited with depth. Therefore they comprise broader vertical habitat resulting in more extensive vertical habitat utilization by billfish but also allowing more volume for prey movements and reduced susceptibility to surface oriented fishing gear (Prince and Goodyear, 2006).

Xiphiids exhibit the broadest vertical habitat utilization and show evidence of diel swimming behavior. They make long duration dives into deep, cold water (e.g. 900 m and 4 °C; Takahashi et al., 2003) at sunrise and remain there throughout the day but occasionally make brief migrations back to surface waters to “bask” in the sunlight apparently to warm themselves, speculated to aid in digestion. Migrations back to the surface usually occur around sunset and are accomplished by short rapid ascents, apparently to compensate for changes in pressure on the swim bladder. They will typically remain in the warm mixed layer feeding throughout the night at which time they are most susceptible to near surface PLL fishing gear. They are physiologically equipped with brain and eye heaters, which are the largest of all billfish (Carey 1982; 1990; Block 1990; Fritsches et al. 2005), allowing them to exploit deep cold water as much as 23 °C below surface mixed layer water temperatures.

One of the most striking features of istiophorid billfish habitat use is their strong preference for warmer waters of the surface mixed layer (Holland et al., 1990; Block et al., 1992; Brill et al., 1993; Pepperell and Davis, 1999; Gunn et al. 2003; Hoolihan 2005; Prince and Goodyear 2006; Horodysky et al., 2007). However, they often make rapid, short duration dives into and beyond the thermocline, presumably to feed (Goodyear et al., in press, *Marine Ecology Progress Series*). Although forays into deeper waters are typically short in duration, feeding at depth may increase the vulnerability and catchability of billfish by DLL fishing gear more than currently expected.

Blue marlin exhibit the broadest habitat utilization of the istiophorids making rapid deep dives into and well beyond the thermocline (e.g. 804 m and 9.8 °C, Prince and Goodyear, 2006). Although conclusions on diel behavior vary, Goodyear et al. (in press, *Marine Ecology Progress Series*) conducted the most comprehensive study to date and suggested diel depth preferences during daytime, nighttime and twilight, which may affect their vulnerability to DLL fishing and estimated catchability.

Striped marlin show a strong preference for the upper epipelagic and studies suggest that their vertical habitat is limited to a thermal difference of 8 °C from the mixed layer temperature (Brill et al., 1993). Holts and Bedford (1990) suggested that striped marlin tend to swim deeper during the night and shallower during the day, a result contrary to reports from other billfish studies that suggest deeper swimming during the day (Holland et al., 1990; Pepperell and Davis, 1999; Kerstetter et al., 2003; Goodyear et al., in press, *Marine Ecology Progress Series*). This may represent niche partitioning to avoid competition with other Pacific billfish species, however more research is necessary to confirm this hypothesis.

White marlin also have a strong preference for the upper epipelagic (Horodysky et al., 2007), but make deeper dives (e.g. 368 m) than their Pacific counterparts, the striped marlin. This is presumably due to the broader mixed layer and deeper thermocline depth in the western Atlantic Ocean than the eastern Pacific Ocean. No diel vertical migration behavior was reported and, unlike Pacific striped marlin, their vertical habitat use reveals no swimming preference for deeper water during the nighttime.

Relatively few studies have been conducted on black marlin vertical habitat utilization. However, similar to all other istiophorid billfish studied to date, they show a strong preference for the mixed layer. They display no apparent diel vertical migration behavior, but Pepperell and Davis (1999) suggested that they may swim deeper during the day than at night. Similar to striped marlin, they have been observed “sleeping” at the surface, which seems counter intuitive when considering istiophorids as obligate “ram” ventilators (Brill, 1996; Venizelos et al., 2001).

Sailfish are ubiquitous throughout the world’s tropical and temperate oceans and are considered migratory but display a strong fidelity to coastal waters, although they are occasionally caught offshore. Hoolihan (2005) reported a genetically isolated sub population in the Gulf of Arabia and suggested implications for management of the species as a whole. Sailfish, as with all other istiophorids, demonstrate a clear preference for the mixed layer but will make excursions into and beyond the thermocline depth (e.g. 284 m and 15.8°C; Prince and Goodyear, 2006).

Billfish have evolved physiological adaptations that allow them to exploit the water column during predation in a way that increases their predatory success. They have very large eyes with ocular specializations that increase their visual acuity in low-light conditions like those that occur during deep dives or during sunrise and sunset. They have a vascular heat exchange system that keep the central nervous system substantially warmer than the surrounding water and presumably imparts a predatory advantage over their cold blood prey at depth. These physiological adaptations allow very broad vertical habitat exploitation that may result in higher vulnerability to capture during PLL fishing than previously expected.

Recent advances in electronic monitoring technologies encouraged research to examine the many uncertainties about the vertical distribution of billfish. These research efforts resulted in a better understanding of billfish habitat utilization over the past few decades. Referring to tracking research conducted on blue marlin by Holland et al. (1990); on striped marlin, *Tetrapturus audax*, by Holts and Bedford (1990) and Brill et al.

(1993); and black marlin, *Makaira indica*, by Pepperell and Davis (1999), it has been hypothesized that istiophorid vertical habitat is limited by an 8 °C change in temperature with depth relative to the sea surface temperature (Brill et al., 1993; Brill and Lutcavage, 2003). However, as early as 1992, Block et al. reported blue marlin making rapid descents into water temperatures around 17 °C less than surface mixed layer temperatures. Careful review of studies focusing on billfish electronic tracking studies indicates that the maximum Δ T for most studies exceeds the relative thermal limit proposed by Brill et al. (1993). In fact, averaging the maximum Δ T's reported for all studies on each billfish species revealed a range of Δ T's (9.4 ± 0.7 °C to 17.5 ± 2.0 °C) all of which were greater than 8 °C (Table 1.2). The most probable explanation is an expansion of our understanding of habitat utilization over time and evolution of tracking technologies. Ideally, pelagic fish tracking technology would have an endless power supply, limitless memory storage, countless environmental sensors, and continuous data transmission. Although the concept has not yet been realized, tracking technology has evolved towards these objectives. For example, when observing trends in the maximum depth and maximum ΔT's reported from the literature for blue marlin throughout the years, expansion of the known vertical habitat has increased by 10.5 m per year and 0.5 °C per year (Figure 1.12).Moreover, it appears that our characterization of vertical habitat utilization is also a function of animal tracking duration which has also increased throughout the years at a rate of about 6 m and 0.1 °C per day tracked, respectively. Figure 1.12 illustrates how our understanding of maximum depth and maximum ΔT experienced by pelagic fish has changed over the years as tracking durations have become longer and sampling resolution and data transmission efficiencies have increased.

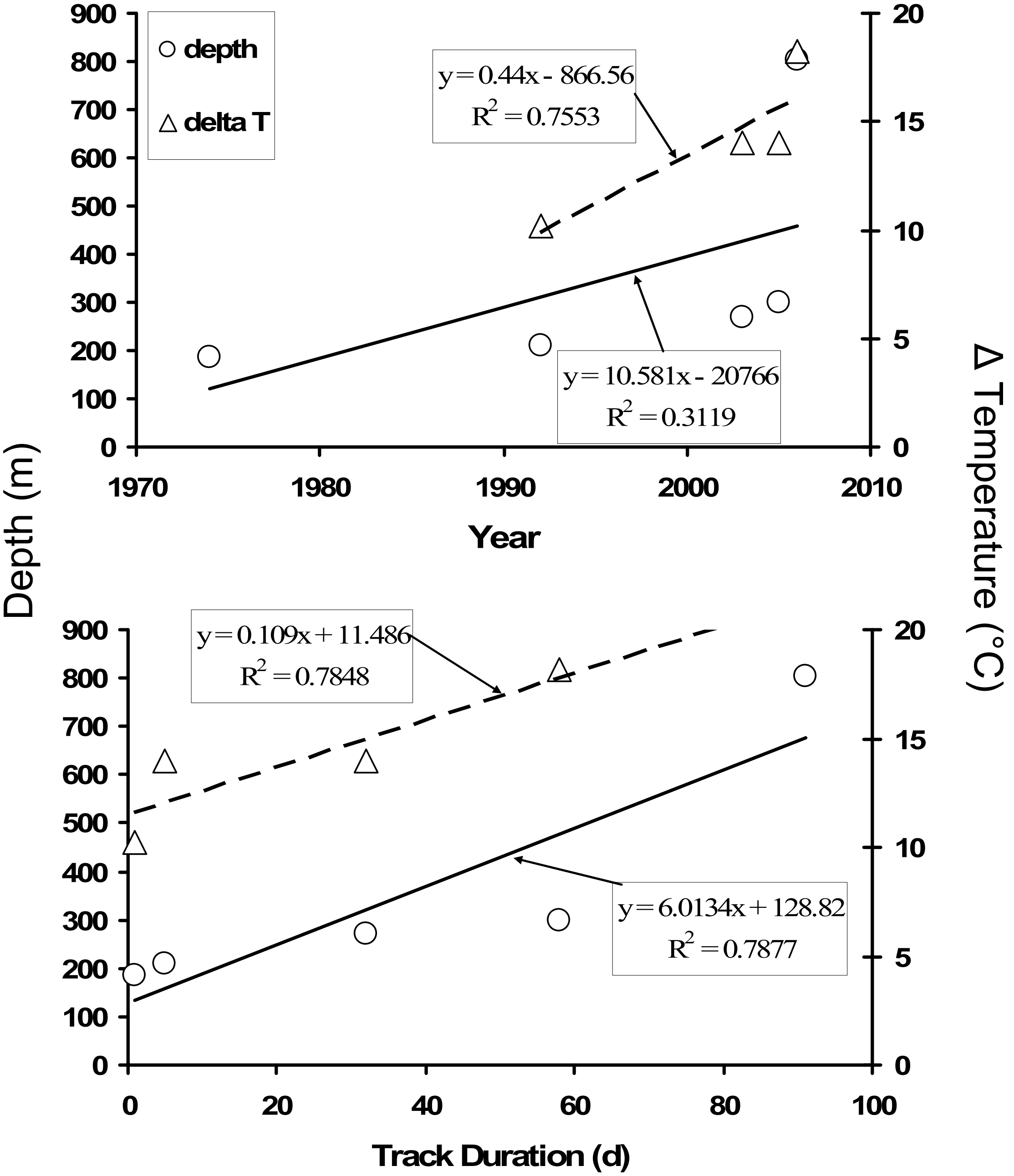


Figure 1.12. Broadening of understanding of blue marlin habitat use associated with the technological evolution of electronic tracking based on depth and Δ T - thermal difference between surface temperature and temperature at depth - reported by various high resolution environmental sampling electronic tracking studies correlated with (top) year; (bottom) track duration (days-at- large).

Summary

Large scale commercial PLL fishing began in the 1950's and rapidly expanded throughout the Pacific, Atlantic and Indian Oceans. Typical target animals are tuna and swordfish, however, most large carnivorous pelagic marine animals are susceptible to capture by PLL fishing gear. Stock assessments for large pelagic fish, such as billfish, rely primarily on CPUE trends reported from PLL fishing. However, when using CPUE time series as an index of population abundance, standardization is required to account for variability in fishing methodologies over the years. Habitat-based-standardization (HBS) has been promoted as superior to other standardization methods, but considerable uncertainty remains when estimating fish habitat utilization and location of fishing gear in the water column. Recent technological advances in tracking pelagic animals and monitoring PLL fishing gear, especially hook depth, have resulted in less uncertainty, but species specific information is still limited as well as information on the dynamic nature of PLL gear movement under various oceanographic conditions.

Characterization of Gear Performance

Analysis of the literature suggests there are many variables that affect PLL horizontal and vertical gear performance. There remains considerable uncertainty in predicting the depth of longline hooks. Yoshihara (1951; 1954) suggested that PLL fishing gear conforms to catenary geometry and calculated hook depth based on PLL gear "sagging ratio". Suzuki et al. (1977) republished the equation with a fixed sagging ratio. The Yoshihara (1951; 1954) equation and Suzuki et al. (1977) adjustment are the most cited and commonly implemented algorithms for determining hook depth and effective fishing effort for pelagic fish stock assessments. However, the limitations of the equation have been recognized and subsequent authors have made arbitrary adjustments to the vertical depth estimations, resulting in hook depth predictions ranging from 75% to 90% of the predicted depth (Hinton & Nakano, 1996). Studies based on actual hook depth measurement, using depth recording devices, have reported depths approximately half of the Yoshihara (1951; 1954) and Suzuki et al. (1977) predicted hook depth (Boggs, 1992; Bigelow et al., 2006, Rice et al., 2007). Therefore, continuous horizontal and vertical monitoring of PLL gear movement under as many environmental conditions as possible has been suggested to characterize and model the dynamics of PLL gear performance (Mizuno et al., 1996; 1999; Bigelow et al., 2006; Rice et al. 2007).

Characterization of Habitat Use

Several methods have been used to determine vertical habitat utilization by pelagic fishes, some more effectively than others, depending on the research objective. Tracking methods that employ the highest data collection resolution and longest deployment durations more completely characterize pelagic fish habitat utilization (Figure 1.11). Satellite tags provide the best technology for characterization of pelagic animal habitat utilization but care must be taken to employ PSATs that: (*i*) allow long deployment durations (e.g. months to years), (*ii*) do not decrease data resolution as a function time deployed, (*iii*) report extreme measurements like maximum depth, minimum temperature and the time spent by the animal at each, respectively. Future PSAT technology should incorporate additional environmental and physiological sensors. Examples include ambient oxygen and internal biology sensors (e.g., temperature, heart, etc.), which may provide key information on feeding events within the water column that that will reveal vulnerability during PLL fishing.

Swordfish have special physiological adaptations (Carey, 1982), such as the largest brain/eye heaters reported for the billfish (Block, 1990) that support the broadest vertical habitat utilization by billfish (e.g. minimum reported temperature of 4ºC and estimated maximum depth of approximately 900 m; Takahashi et al., 2003) and they exhibit strong diel vertical migrations. Blue marlin have the second largest brain/eye heaters, relative to body weight (Block, 1990), and retinal specialization (Fritsches et al., 2003b) that make them extremely well suited for foraging at thermocline depth and supports the second broadest vertical habitat utilization of the billfish (e.g. minimum reported temperature of 9.8 ºC and estimated maximum depth of approximately 804 m; Prince and Goodyear, 2006), however, they spend most of their time in the mixed layer (Yuen et al., 1974; Holland et al., 1990; Block et al., 1992; Graves et al., 2002; Kerstetter et al., 2003; Saito and Yokawa, 2005). The remainder of the istiophorids reported in this study (i.e. sailfish, white marlin, striped marlin and black marlin) have a strong preference for the warm waters of the mixed layer and exhibit similar habitat utilization. Species which inhabit both oceans exhibit broader vertical habitat use in the western Atlantic than the eastern tropical Pacific, presumably due to the shallow thermocline and hypoxic conditions below the thermocline in the eastern ETP.

Conclusions

Results suggest that in future studies focusing on pelagic fish habitat use and interactions between pelagic fish and PLL fishing gear should consider the following:

1. The habitat utilization and feeding ecology of pelagic animals, horizontal and vertical PLL gear movements affecting fishing effort at depth, and identifying additional important variables (e.g. temperature, oxygen, salinity, etc.) and trends that affect PLL CPUE.
2. Characterization of habitat use by billfish should be accomplished using electronic tracking technologies: (*i*) for long deployment durations (i.e. months to year) to capture seasonal variations, (*ii*) accompanied by high resolution data collection (i.e. at least one sample per minute because billfish make rapid deep dives) and, (*iii*) remote transmission capabilities due to low directed fishing mortality. When using tags that archive data, including PSATs, care should be taken to avoid tags that reduce data resolution as a function of tag deployment duration.
3. Given the uncertainties in predicting effective fishing effort from theoretical hook depth and the variability associated with hook depth during PLL fishing, electronic depth measurement equipment (bathythermographs, time-depth recorders, etc.) should be employed whenever possible to characterize movements and performance of the PLL fishing gear. Especially, given the uncertainty associated with the estimation of "sagging" and "shoaling" and the corresponding dynamics associated with predicting hook depth. Information obtained from depth measuring devices on PLL gear can be used to establish empirically based models that more accurately estimate vertical fishing effort.

Chapter 2

Estimation of hook depth during near surface pelagic longline fishing using catenary geometry: theory versus practice

Uncertainties associated with catch and effort statistics for pelagic longline fishing

Catch per unit of effort (CPUE) is typically used as an index of population abundance and is essential in most stock assessments (Restrepo et al. 2003; Hinton and Maunder 2004; Bigelow et al. 2006). Commercial catch data over time is used to generate CPUE time series, which are subsequently used to estimate population abundance. Catch and effort statistics employ the general catch equation:

$$N = C *(q * f_n)^{-1}, \tag{1}$$

where N is the mean population abundance in the same area and time, C is the total catch in a given area during a given time, q is the catchability coefficient – probability associated with the capture potential of a specific animal per unit of fishing effort, and f_n is the nominal fishing effort (i.e., non-standardized effort) (Hinton and Nakano 1996). However, this model assumes that the animal population is homogeneously distributed throughout the body of water fished and that there are no variations in fishing effort (i.e., all fishers use the same fishing strategies with equal probability of catching fish). These conditions are not realistic and therefore catch and effort require standardization for inferential statistics.

Several methods are typically employed to standardize catch and effort including general linear models (GLMs), general additive models (GAMs), neural networks, habitat based standardizations (HBS), and statistical HBS (statHBS) (Hinton and Maunder 2004). Habitat-based standardization (HBS) of pelagic longline (PLL) CPUE time series for billfishes (Family: Istiophoridae) has been promoted as superior to standard statistical procedures for removing the effects of gear modifications over time (Yokawa et al., 2001; Yokawa and Uozumi, 2001; Yokawa and Takeuchi, 2002; 2003). However, Hinton and Maunder (2004) recommend that whenever an HBS model is used, it should be a statistical model (i.e., statHBS) because of the flexibility of this method for incorporation of additional explanatory variables, such as gear depth changes due to gear deployment/retrieval, shoaling, etc. Regardless of the HBS methodology used, it involves integrating information about the depths fished by hooks with the species' depth distributions (Hinton and Nakano 1996; Restrepo et al. 2003; Uozumi 2003).

The depth of the PLL is most commonly estimated using mathematical models based on catenary geometry which assumes the gear orients in the vertical plane and the only forces acting on the gear are gravity and buoyant forces. Yoshihara (1951) derived an equation for estimating PLL fishing depth using a catenary equation as follows:

$$D_j = h_a + h_b + l\,((1+\cot^2\phi^{\circ})^{1/2} - [(1-2j/n)^2 + \cot^2\phi^{\circ}]^{1/2}), \qquad (2)$$

where D_j is the depth of the j^{th} hook in a longline segment between surface buoys (hereto referred to as baskets), h_a and h_b are the branch line and float line length, respectively, l is ½ the length of mainline in a longline segment (i.e., the length of mainline to the deepest point or vertex in a basket), n is the number of intervals between hooks in a basket (number of hooks + 1), j is the serial position of the j^{th} branch line in a basket, and ϕ is the angle between the horizontal line (which is parallel to the water surface) and the tangential line to the curve of the mainline at the point of attachment of the float line

(Figure 2.1). Yoshihara (1954) correlated ϕ to the "sagging" rate of the PLL gear. As the name implies, sagging of the mainline occurs due to gravity pulling earthward on the fishing gear while the buoyant forces caused by the surface buoys hold the gear near the surface. As the gear sinks, the horizontal distance between the floats decreases. Conversely, as the horizontal distance between floats increases due to oceanic currents, wind, etc., the amount of sag in the mainline decreases and shoaling of the gear occurs. Therefore, ϕ is not a constant but rather a dynamic variable dependent on the oceanic environment.

It is clear from observed catch patterns that gear deployment depth influences species catchability of longline sets (e.g., Hanamoto 1987; Yang and Gong 1987; Boggs 1992; Brill and Lutcavage 2001). However, Takeuchi (2001) suggests that gear configuration information, including historical information on the number of hooks between floats, is inadequate for CPUE standardization and Goodyear (2003a) noted that quantitative knowledge of PLL gear behavior and subsequent hook depth distribution is possibly the weakest factor in the HBS process. Because the HBS method is sensitive to errors in gear depth distribution estimates (Goodyear 2003a; 2003b), understanding hook depth distributions and time at depth are important research topics. These issues were the subject of a meeting of the ICCAT Methods Working Group[1], which recommended additional research into species and hook distributions.

Many factors have been identified which affect hook depth during PLL fishing including: (1) vertical current shear between surface and sub surface currents (Boggs 1992; Berkeley and Edwards 1998; Mizuno et al. 1999; Bigelow et al. 2006), (2) wind

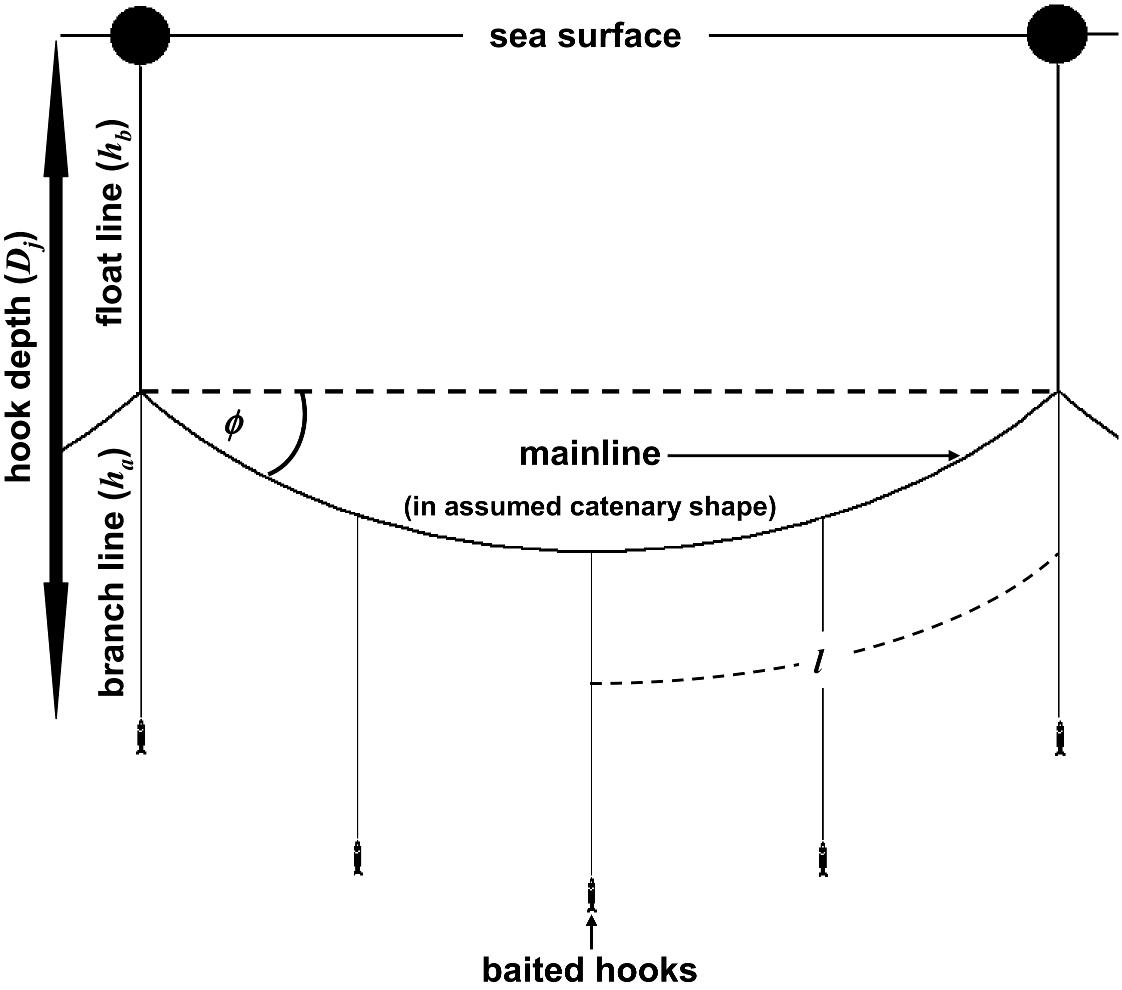


Figure 2.1. Schematic representation of a single basket of typical, near surface pelagic longline fishing gear showing the geometric components necessary to calculate the depth of the hooks using the catenary equation developed by Yoshihara (1951; 1954) and refined by Suzuki et al. (1977).

(Yano and Abe 1998; Ward and Myers 2005), (3) both live and dead fish captured by the gear (Berkeley and Edwards, 1998; Yano and Abe, 1998; Serafy et al., 2005), and (4) interactions with ships, especially during near surface PLL fishing (Rice et al., 2007). However, quantitative knowledge of the variability associated with hook depth is lacking.

To account for uncertainties associated with hook depth predictions, authors attempting to standardize catch and effort data often refer to results from previous PLL research and/or attribute arbitrary values for deviations from predicted gear depths. Recently, Ward and Myers (2005) attempted to infer pelagic fish depth distributions from PLL data using catenary equations (i.e., methodology of Suzuki et al., 1977) and assumed a 25% reduction in all predicted catenary hook depths due to shoaling caused by ocean currents and wind. However, the nature of PLL fishing suggests that deviations from predicted values are highly dynamic and the incorporation of static values may not realistically capture the variability of fishing depth.

Previous PLL studies using depth measuring devices have found that catenary geometry is unable to accurately capture the variability of hook depth during PLL fishing (Berkeley and Edwards, 1998) and that actual hook depth is generally much shallower than predicted using catenary geometry (Nakagome, 1961; Boggs, 1992; Yano and Abe, 1998; Mizuno et al., 1999; Matsumoto et al., 2001). Most recently, Bigelow et al. (2006) monitored PLL mainline depth with temperature depth recorders (TDRs) on 333 commercial swordfish *Xiphias gladius* and 266 commercial tuna (*Thunnus* spp.) gear deployments. They found that near surface sets targeting swordfish only reached about 50% of their predicted catenary depth and deeper tuna sets reached about 70% of their predicted catenary depths. However, determination of hook depth variability, between and within gear deployments, from many of these previous studies is limited because they have: (1) inferred hook depth from depth measuring devices placed on the mainline (Boggs, 1992; Berkeley and Edwards, 1998; Mizuno et al., 1999), (2) employed only a single depth meter between buoys (Saito, 1973; Bigelow et al., 2006), and (3) employed depth meters on one section of the gear and assumed consistent behavior by extrapolation over the entire length of the gear (Mizuno et al., 1999; Bigelow et al., 2006). Previous studies where multiple depth measuring devices were employed systematically throughout the length of the longline gear (Matsumoto et al., 2001; Yokawa and Saito, 2005) have failed to analyze the within-set and between-set hook depth variability. Yano and Abe (1998) in the second year of their study employed multiple time-depth recorders along the entire gear length, however they pooled data from all sets (53 total) and focused primarily on comparisons between depth fluctuations of polyester multifilament gear and polyamid monofilament gear.

In contrast to previous studies, the primary objectives of this study were: (1) to measure, as accurately and precisely as possible, the depth distribution of the hooks using multiple TDRs distributed throughout the entire length of the longline gear on near surface deployments targeting swordfish, (2) to analyze both within-set and among-set variability in hook depth distributions, (3) to compare these observed depth distributions to: (a) predicted depths based on catenary depth calculated from PLL configuration information and (b) the most conservative adjustments to depth predicted by catenary algorithms, and (4) to develop a suitable methodology, based on information currently obtained and reported by the commercial PLL industry, for determining sag ratios that provide information on horizontal changes in gear shape (i.e., stretching and compression) that translate into vertical changes is fishing depth, and (5) to increase the amount of data available on the variability associated with hook depth during PLL fishing under a variety of environmental conditions.

Materials and Methods

Ten longline sets were deployed in the Windward Passage between the Republic of Haiti and the Republic of Cuba (Figure 2.2) during June 2003 from the US commercial pelagic longline fishing vessel (F/V) *Carol Ann*. The *Carol Ann* is a 16.76 m fiberglass PLL fishing vessel which typically targets swordfish and multiple tuna species (e.g., bigeye tuna *Thunnus obesus*; and yellowfin tuna *T. albacares*) depending on the time of year, location and fishing season. In the present study, longline sets targeting swordfish were deployed at dusk and allowed to soak overnight. Fishing location (latitude and longitude) were recorded during longline gear deployment and retrieval. The gear configuration consisted of four branch lines between surface floats (hereafter termed "baskets") and was intended to fish near the surface at night. Gear retrieval began in the early morning before sunrise and generally lasted until late morning or early afternoon. Fish capture data were collected during gear retrieval and fish captured on branchlines equipped with TDRs were noted. The mainline was monofilament (454.5 kg test strength and 3.5 mm diameter) housed on a hydraulic spool. Because the Atlantic commercial swordfish fishery typically does not use mechanical mainline deployment techniques (i.e., line throwers), the mainline was passively deployed and branch lines with terminal gear (i.e., hooks), buoys and radio beacons were attached as the boat moved forward. The

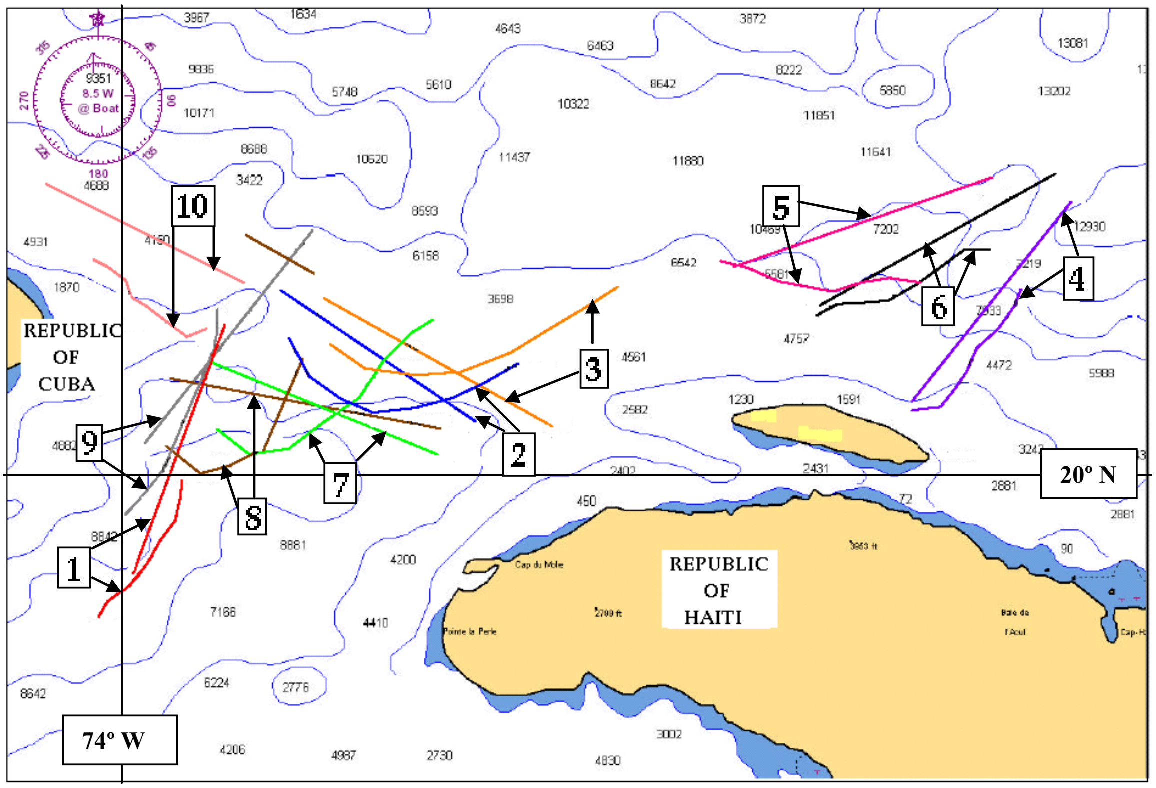


Figure 2.2. Plots of ten sets of pelagic longline gear deployed in the area of the Windward Passage between the Republic of Haiti and the Republic of Cuba, by the F/V *Carol Ann* during June, 2003. Straight lines represent gear deployment positions. Non-linear tracks represent gear retrieval positions. Numbered squares with arrows indicate consecutive longline gear deployment and retrieval locations. Examples of gear compression and gear stretching during the soak can be seen in set 10 and set 7, respectively.

length of the set was calculated by multiplying the vessel's velocity with the deployment duration. Vessel velocity was determined using global position system (GPS) coordinates and corresponded to speed over ground. However, the velocity determined by the GPS is relative to the earth and does not account for water movement relative to the boat. Therefore, the total amount of mainline deployed was determined by adding or subtracting distance depending on the magnitude and orientation of the oceanic current to the fishing vessel during gear deployment (Figure 2.3). Longline gear drift was employed as a proxy for current direction and velocity (Nishi, 1990; PFRP, 1998). In the present study the sag ratio was calculated as the ratio of the final horizontal distance between floats and the estimated initial mainline length between floats at the time of gear deployment.

Depending on local oceanic currents, longline gear was normally recovered in the reverse direction as deployed (9 of 10 sets). Eight radio beacons were used to define a total of seven sections per longline set. Each section contained 19 floats (16 small Styrofoam bullet floats and 3 larger polyvinyl inflatable floats) composing 20 baskets (Figure 2.4). Each basket contained four hooks between floats (Figure 2.4). About 560 hooks per set were deployed during all ten sets.

The hooks were either stainless steel 18/0 - 0^{o} offset (i.e., non-offset) circle hooks or 18/0 - 10^{o} offset circle hooks (Lindgren-Pittman Inc.). Each float line was 18.3 m in length. Each branchline (160 kg test; 2.1 mm diameter) was 20.1 m in length with 1.83 m leader (composed of the same material as the branchline) for an overall gear length of 40.2 m. Each branchline was fastened to a hook-strike timer (Lindgren-Pittman Inc.) which was subsequently fastened to the mainline (Figure 2.4) and used to corroborate the

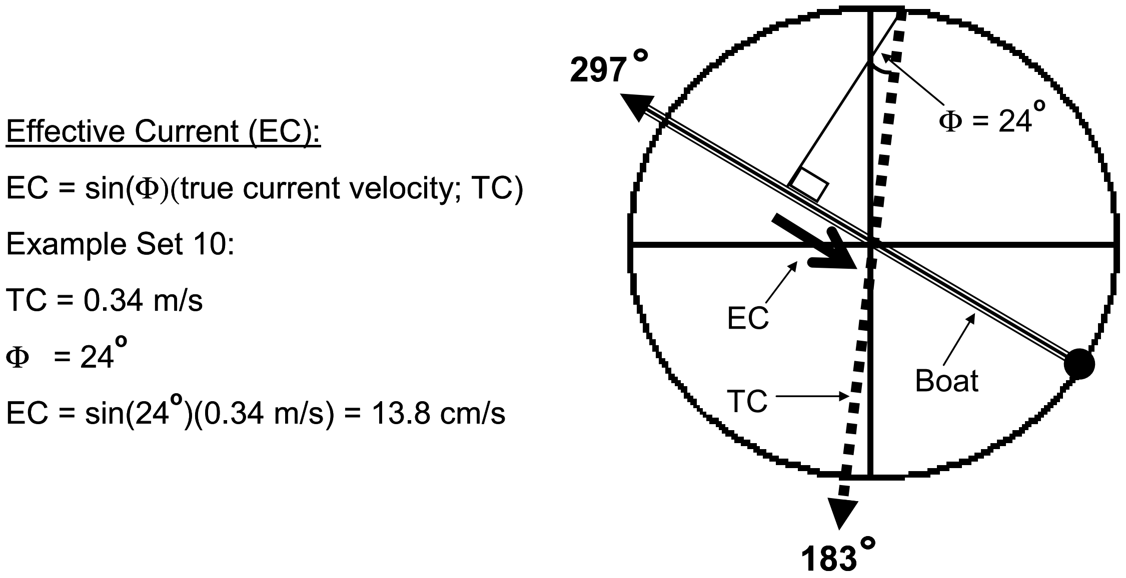


Figure 2.3. Method for calculating the effective current (EC) experienced by the vessel during gear deployment. The right triangle created by the angle between the direction of the vessel and the direction of the current is used to calculate the current vector either opposing or assisting the vessel.

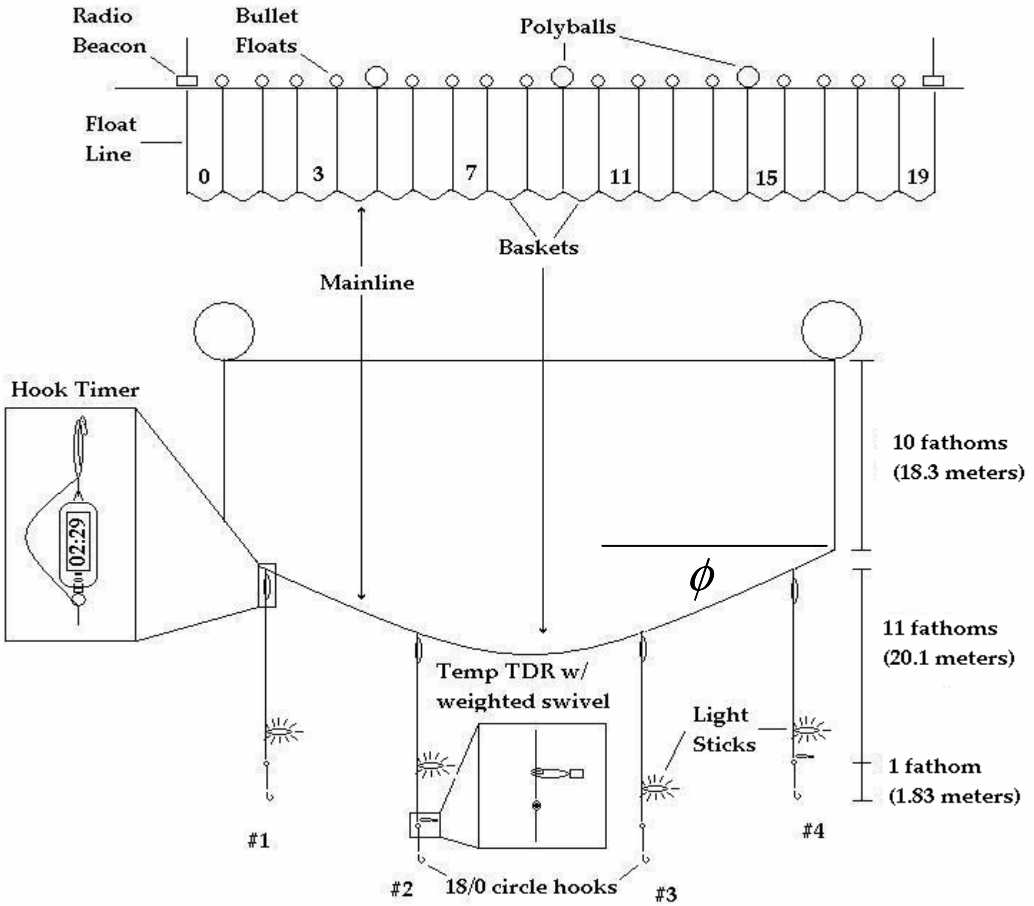


Figure 2.4. Schematic representation of an entire section of longline gear (above) with numbered baskets containing temperature – depth recorders (TDRs) and an enlargement of a basket (below) equipped with hook strike timers, TDRs, light sticks and hooks and showing floatline length, branchline length and leader length. Also shown is the angle (ϕ) between the tangential line to the catenary curve of the mainline with the horizontal plane parallel to the ocean surface.

time of fish strikes on the hook, indicated by extreme vertical hook movement on branchlines equipped with TDRs.

The TDRs (Lotek Wireless, Inc.) were deployed along the entire length of the gear on about every 13th hook resulting in a 7-9 % coverage of all hooks deployed (41-49 TDRs per 560 hooks). Each TDR was placed on the branchline proximal to the weighted swivel (60 g) about 1.8 m from the hook to minimize hook-depth uncertainty as well as TDR loss from animal bite-offs, etc. The quantity of TDRs available was insufficient to monitor shallow and deep hooks in every basket. Therefore, one TDR was placed on the assumed deepest hook (i.e., hook #2 or #3) in baskets 3, 7, 11, 15 and 19 for every section during the set and, in specific baskets throughout the set, a second TDR was placed on the assumed shallowest hook (i.e., hook #1 or #4) as illustrated in Figure 2.5. Occasionally for various reasons (e.g., gear malfunctions), strict adherence to the experimental design for TDR placement was not possible. In these circumstances the TDR was placed in the adjacent basket on the corresponding hook.

Each TDR collected temperature and time at pressure (depth) information every 14.06 seconds and time at depth was calculated similar to Yokawa and Takeuchi (2003). To distinguish malfunctioning TDRs (e.g., unreasonable temperature or pressure measurements), as well as temperature and pressure measurement variability between TDRs prior to gear deployment, they were tested against one another by deploying them all together into the water column in a mesh bag and then comparing measurements. Each TDR was downloaded and reset at least every other day to maximize the quantity and consistency of the information collected. The TDR data were downloaded onto laptop computers using Tag Talk 1100™ software provided by Lotek Wireless, Inc.

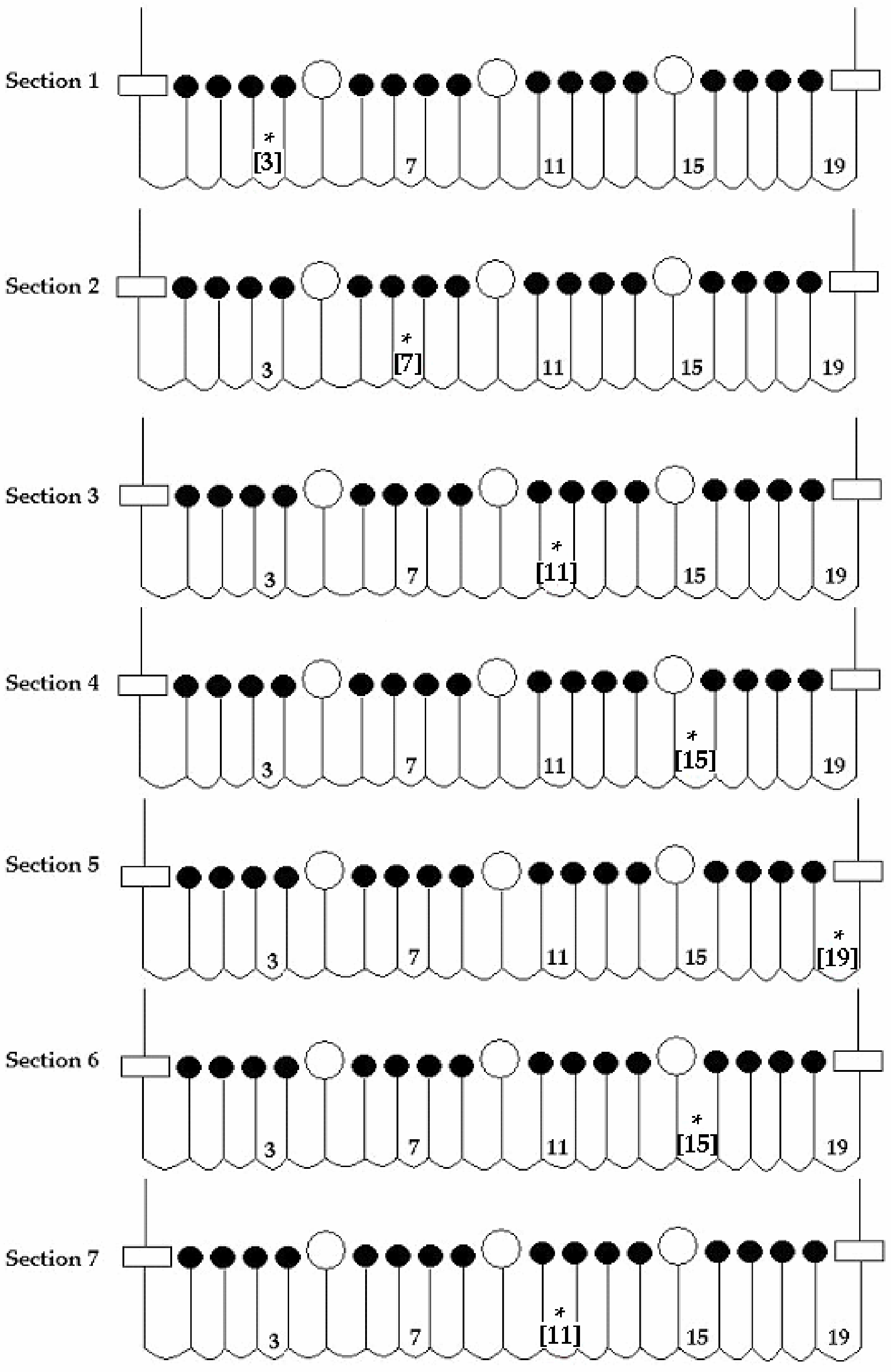


Figure 2.5. Schematic representation of the longline by sections (1-7). Numbers in brackets with asterisks above indicate baskets with two TDRs (one on the shallowest and another on the deepest hooks). Numbers without brackets or asterisks indicate baskets with only one TDR on the deepest hook.

Analysis

We used the TDR data to characterize the time-at-depth distributions of the hooks. The raw TDR data often required recalibration by adjusting the recorded pressure measurements by the values recorded at the water surface prior to deployment. Pressure was converted to depth (using 0.6838533 m/psi) allowing a nearly continuous record of the fishing depth for each monitored branch line. Temperature depth recorders on branch lines where hook-strike timers indicated fish interactions (e.g., capture or fish strike and subsequent escape) were excluded from the present analysis. The proportions of time spent in each 5 m depth interval below the water surface were determined for each TDR. We examined the variability in mean hook depth within and across all sets. Within- set variability was determined using a general linear model (GLM) procedure and subsequent *post hoc* pairwise comparisons were conducted between the mean depths of a specific TDR position (i.e., shallow or deep). Among-set variability in mean hook depth was similarly determined. Pairwise comparisons were considered significantly different at $\alpha = 0.05$. Statistical analysis was performed using Statistical Analysis Software Version 9.0 (SAS Institute Inc.).

Results

The PLL gear was translated from the initial deployment location (i.e., set location) to the final retrieval location (i.e., haul location) and was often stretched or compressed by local oceanic currents for the ten sets made in the Windward Passage (Figure 2.2). The average set distance was 44.9 ± 2.0 km with an initial and final average distance between floats of 0.32 km and 0.29 km, respectively and the average sagging rate for all ten sets was 0.91 (Table 2.1). In several cases the sagging rate was reported as greater than 1.0 indicating PLL gear being stretched beyond the initial deployment length.

Statistical analysis revealed that high variability in hook depth is the norm rather than the exception and the cumulative time at depth for each TDR was highly variable both within and across all sets. The within-set variability for mean hook depth in the presumed shallow hook position and the presumed deep hook position ranged from 72.2 % - 100 % significant differences and 92.4 % - 96.0 % significant differences, respectively (Table 2.2.). Pairwise comparisons of mean hook depth between sets for both shallow and deep hook positions revealed 100 % significant differences between all sets (Table 2.2).

For the presumed shallowest catenary hook positions (i.e., hooks #1 and #4) examples of high variability in hook time at depth are presented for each of the10 sets in Figure 2.6. For the deepest presumed catenary hook positions (i.e., hooks #2 and #3) examples of high variability in hook depth are presented for each of the 10 sets in Figure 2.7.

The majority of the time (32 %) fished by hooks in the *shallowest* catenary hook position for all ten sets was spent in the 40 m depth bin with the maximum fishing depth reaching about 95 m (Figure 2.8). Similarly, the majority of the time (25.5 %) fished by hooks in the *deepest* catenary hook position for all ten sets was spent in the 40 m depth bin however, in this hook position the maximum reported fishing depth reached about 160 m (Figure 2.9). The mean estimated initial distance between hooks was 64 ± 3 m, therefore the predicted depth using our gear configuration and catenary geometry

Table 2.1. Gear deployment details for each set/haul and length adjustments to the amount of pelagic longline (PLL) gear deployed based on effective current (EC) experienced by the vessel during deployment and the great circle distance traveled (km) (i.e., GPS distance including curvature of the Earth's surface). Total PLL gear deployed equals the effective current multiplied by the set duration and added or subtracted to the recorded great circle distance depending on the direction of the current [i.e. (EC x Set Duration) x (±1) + great circle distance)]. EC equal to zero suggests current oriented perpendicular to the vessel during gear deployment. Sag ratio is the ratio of the final distance between floats (DBF) to the initial DBF. Sag ratios greater than 1.0 indicate PLL gear was stretched.

Set/Haul number	Color code	EC (km/hr)	Set duration (hr)	PLL adjustment (km)	Great circle distance (km)	EC (+/-)	Initial gear deployed (km)	Initial DBF (km)	Final gear length (km)	Final DBF (km)	Sag ratio
1	Red	4.36	3.25	14.18	47.4	1	61.6	0.44	29.6	0.21	0.48
2	Blue	0.00	3.8	0.00	41.5	0	41.5	0.30	48.3	0.35	1.16
3	Yellow	0.00	3.55	0.00	46.4	0	46.4	0.33	56.5	0.40	1.22
4	Purple	1.74	3.65	6.36	45.3	-1	38.9	0.28	30.6	0.22	0.79
5	Pink	1.94	3.7	7.18	47.7	-1	40.5	0.29	36.2	0.26	0.89
6	Black	1.50	3.36	5.04	47.5	-1	42.5	0.30	33.8	0.24	0.80
7	Green	0.00	4.15	0.00	43.5	0	43.5	0.31	48.9	0.35	1.12
8	Brown	1.07	3.9	4.15	48.2	-1	44.0	0.31	50.3	0.36	1.14
9	Gray	1.69	2.66	4.50	48	-1	43.5	0.31	40.6	0.29	0.93
10	Mauve	1.28	4.05	5.17	40.9	1	46.1	0.33	25.3	0.18	0.55
Avgerage		1.36	3.61	4.66	45.6		44.9	0.32	40.01	0.29	0.91

Table 2.2. Within-set and among-set comparisons of mean hook depth revealing the percentage of significant differences for hooks in the catenary predicted shallow and deep hook positions.

	Mean hook depth			
	Percent (%) significant differences within-set		Percent (%) significant differences among-set	
Set/haul #	Shallow	Deep	Shallow	Deep
1	72.2	92.4	100	100
2	90.0	94.5	100	100
3	96.4	93.9	100	100
4	100	94.8	100	100
5	93.3	95.3	100	100
6	100	93.7	100	100
7	95.2	92.6	100	100
8	100	96.0	100	100
9	100	93.5	100	100
10	92.9	94.2	100	100

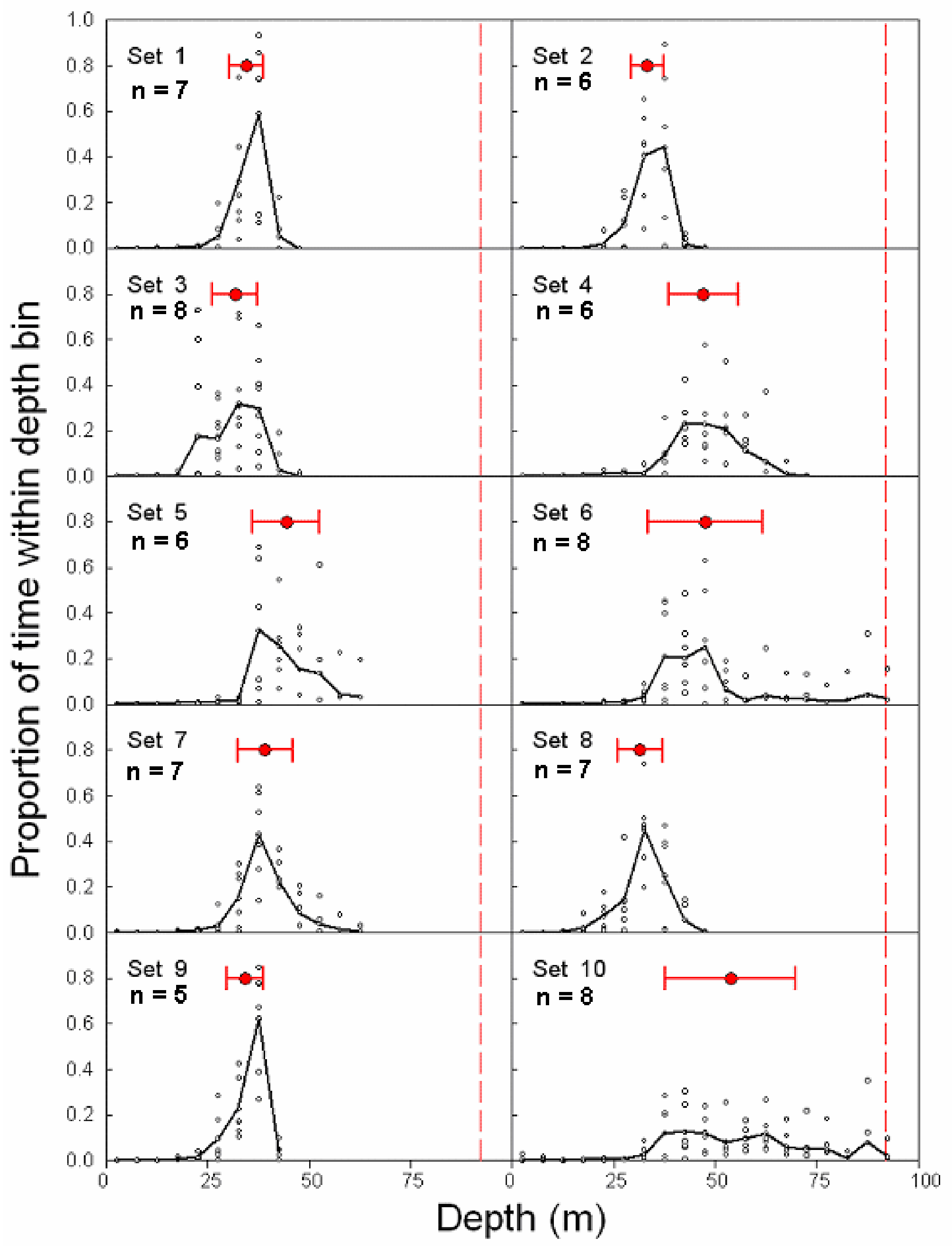


Figure 2.6. Scattergram of observed proportion of time at depth for individual temperature-depth recorders (TDRs) attached to the *shallowest* hook positions monitored during all ten sets. Each data point indicates the proportion of time spent by an individual TDR in the specific 5 m depth bin. The solid line through the data distribution depicts the mean of TDR observations for this hook position for this set. The vertical dashed line indicates the fishing depth estimated using catenary algorithms (Suzuki et al. 1977). The single solid circle with horizontal error bars above the distribution indicates the mean depth value of the distribution with 95% confidence intervals. Notice the amount of variance with each set and between consecutive sets. n = the number of hooks monitored by TDR during the specific set.

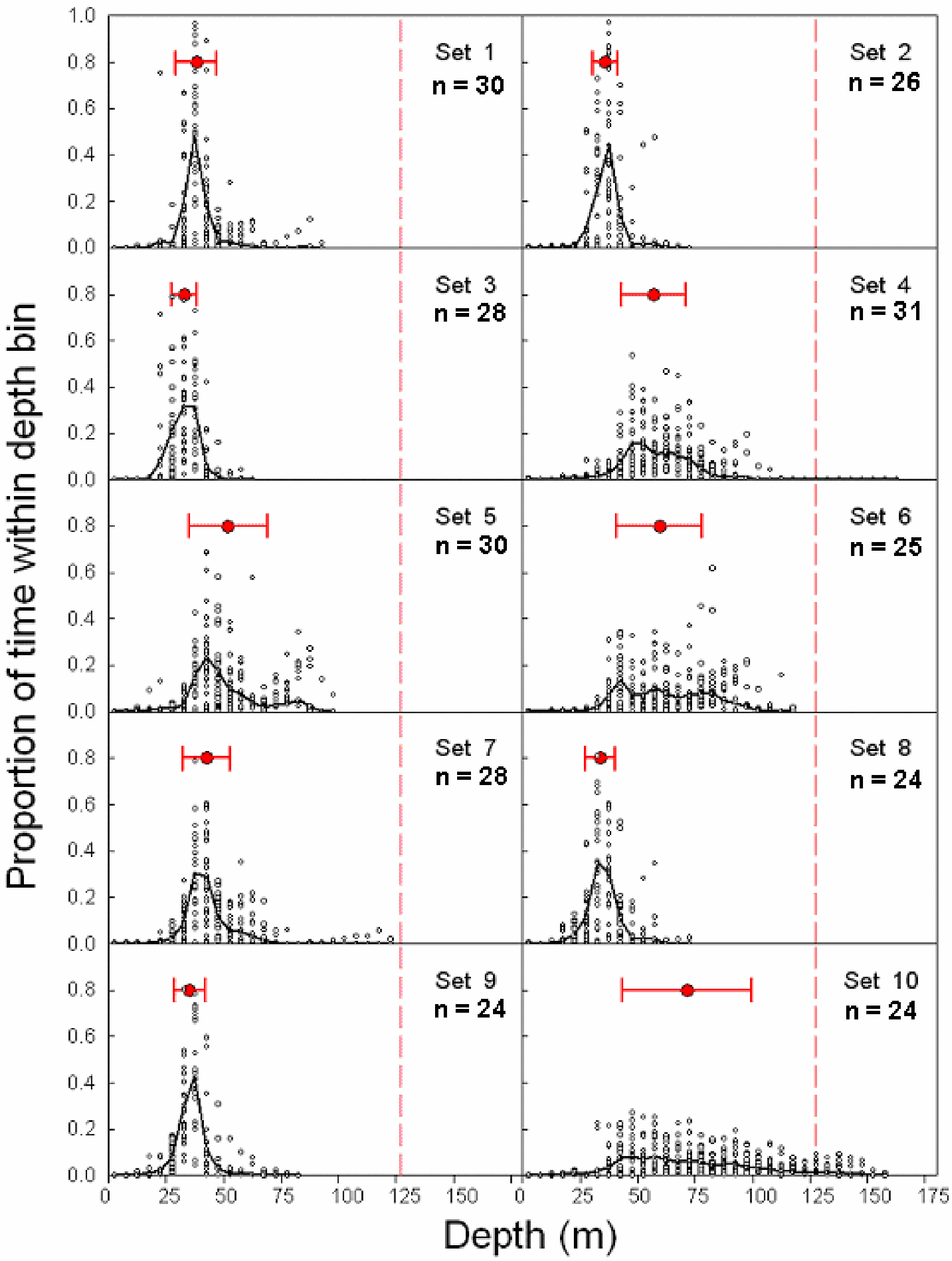


Figure 2.7. Scattergram of observed proportion of time at depth for individual temperature-depth recorders (TDRs) attached to the *deepest* hook positions monitored during all ten sets. Each data point indicates the proportion of time spent by an individual TDR in the specific 5 m depth bin. The solid line through the distribution of data points depicts the mean of TDR observations for this hook position for each set. The vertical dashed line indicates the fishing depth estimated using catenary algorithms (Suzuki et al. 1977). The single solid circle with horizontal error bars above the distribution indicates the mean depth value of the distribution with 95% confidence intervals. Notice the amount of variance with each set and between consecutive sets. n = number of hook monitored by TDR during the specific set.

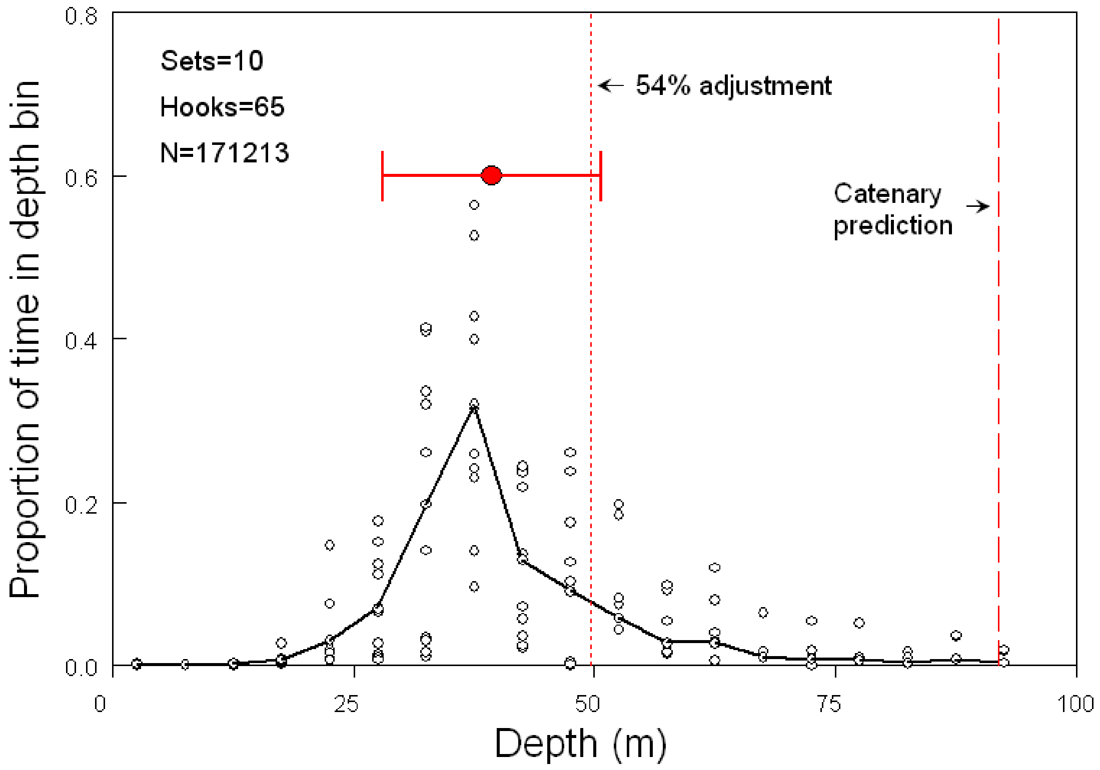


Figure 2.8. Scattergram of mean times at depth for pooled temperature-depth recorders (TDRs) attached to the *shallowest* hook positions monitored on each set. The solid line through the distribution of data points depicts the mean of TDR observations for this hook position for all sets. The vertical dashed line indicates the predicted depth based on catenary geometry (Suzuki et al. 1977) and the vertical dotted line indicates the most conservative depth adjustment (54%) suggested by Boggs (1992). The solid circle with horizontal error bars represents the mean and 95% confidence interval for the distribution. N is the total number of depth observations for all shallow set TDRs during all sets.

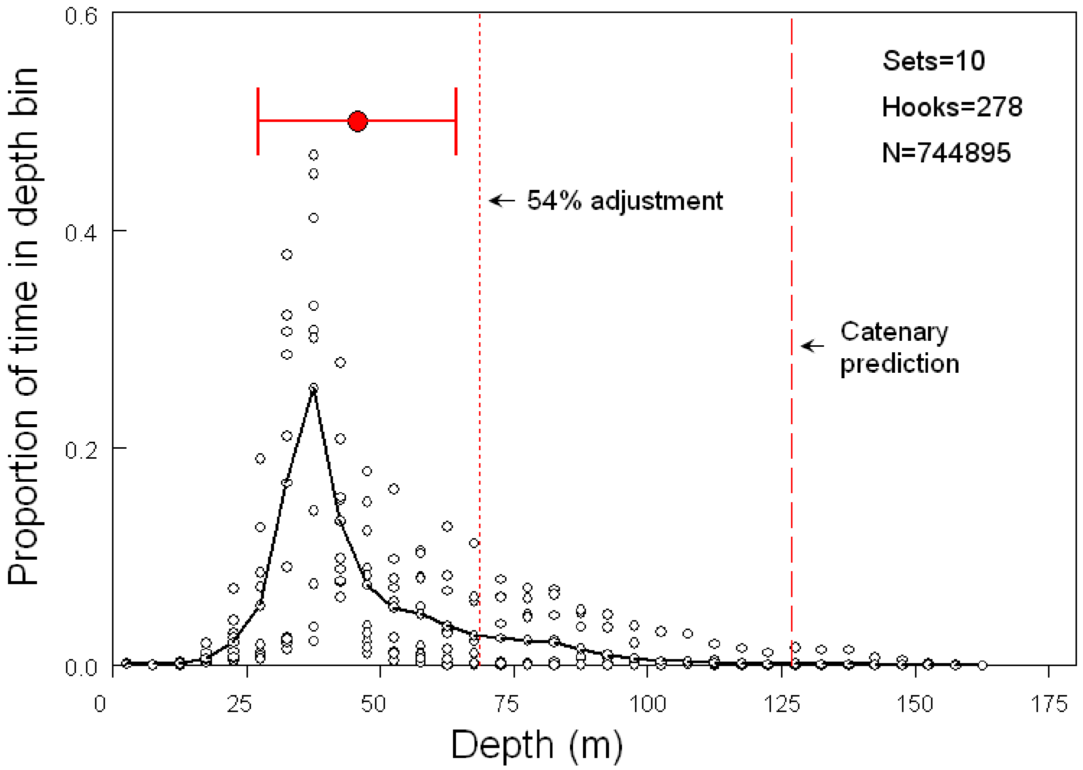


Figure 2.9. Scattergram of mean times at depth for pooled temperature-depth recorders (TDRs) attached to the *deepest* hook positions monitored on each set. The solid line through the distribution depicts the mean of TDR observations for this hook position for all sets. The vertical dashed line indicates the predicted depth based on catenary geometry (Suzuki et al. 1977) and the vertical dotted line indicates the most conservative depth adjustment (54%) suggested by Boggs (1992). The solid circle indicates with horizontal error bars represents the 95% confidence interval for the distribution. N = total number of depth observations for all deep set TDRs during all sets.

(Yoshihara, 1951; Suzuki et al., 1977) for the *shallowest* hook position was 92 m (Figure 2.8) and for the *deepest* hook position was 127 m (Figure 2.9). Therefore, most of the observed hook depth distribution, regardless of hook position, was considerably shallower than predicted by the catenary equation with the shallow and deep hook positions spending the majority of their time at only 43% and 31% of the estimated hook depth, respectively.

Discussion

An accurate estimation of fishing depth is critical for realistic estimation of pelagic fish population abundance when employing catch and effort statistics from commercial PLL catch data. However, the methods employed to determine fishing depth often: (1) fail to provide accurate estimates of fishing depth, (2) fail to provide the proportion of time spent at a particular fishing depth, and (3) fail to capture the variability in fishing depth associated with PLL fishing.

Catch and effort statistics require standardization of the nominal fishing effort (i.e., the total number of hooks fished in a given area, regardless of the fishing strategy employed). Standardization of nominal fishing effort is required to compare CPUE from one year to the next as fishing strategies have changed over time. For example, prior to the mid 1970's PLL gear configuration was dominated by near surface deployments realized by few hooks per basket (i.e., hpb ≤ 7) (Hinton and Nakano, 1996). Initially, the primary target was yellowfin tuna but shifted towards albacore tuna *Thunnus alalunga* around 1962 (Saito, 1973; Nakano, 1996; Uozumi, 1996). In the early 1970's the development of super cold freezers (-50 ºC) onboard PLL fishing vessels allowed "sashimi" grade tuna to be supplied to the Japanese market. This encouraged a rapid switch to targeting higher grade tuna living deeper in the water column like bigeye, southern bluefin *Thunnus macoyii* and northern bluefin *Thunnus thynnus* (Nakano, 1996; Uozumi, 1996). To target these deeper dwelling tuna, PLL fishers employed deeper fishing gear configurations realized by more hooks per basket presumably resulting in less effort in near surface waters. Therefore, comparisons of CPUE based on nominal fishing effort prior to the mid 1970's with present CPUE data proves problematic without proper standardization (Serafy et al., 2005).

Habitat based standardization, which has been promoted as the superior standardization technique, requires information on the distribution of fishing effort (i.e., hook depth distribution) and information on the habitat preferences of the fish species (i.e., proportion of time at depth). Hinton and Nakano (1996) developed HBS for CPUE time series and applied their method to catch and effort statistics for blue marlin, *Makaira nigricans*. They apportioned the available data into 2º latitude by 5º longitude (i.e., about 222 km by 555 km at the equator) and considered fishing effort uniform within these strata. However, PLL fishers target specific fishing areas where concentrations of fish are high (i.e., oceanic fronts, Olson, 2002) and rarely use standard fishing practices, often employing multiple gear configurations targeting various depths and fish species. Therefore, PLL fishing is rarely uniformly distributed on the scales employed in the HBS procedure used by Hinton and Nakano (1996). More recently, Myers and Worm (2003) suggested that populations of oceanic top predators such as tuna, billfish and sharks have been reduced as much as 90 % from historical levels using commercial catch data assuming homogeneous fishing effort apportioned into 5º latitude by 5º longitude.

However, our results indicate high variability even within a spatial scale of less than one-half of one degree (i.e., the length of our longlines or about 55 km).

During HBS, nominal fishing effort is standardized by determining the effective effort in a given depth stratum (i.e., the total number of hook-hours in a given depth stratum). Effective effort is typically estimated using the mean proportion of time spent by hooks in a given depth strata based on gear configuration information and catenary geometry, often adjusted by a scalar that is intended to correct for the mean deviation of hook depths from the catenary predictions. High proportions of the total catches of some species may be associated with the tails of the distributions of the proportions of total fishing time by depth (Goodyear, 2003b). If these proportions change with time because of temporal changes in gear configurations, then errors in estimates of hook-depth distributions can lead to large errors in HBS-standardized CPUE trends. For example, istiophorid billfishes are widely believed to be restricted to the near surface waters, a view supported by the finding that blue marlin and sailfish spend nearly all of their time above 50 m, particularly in areas where the acceptable habitat is compressed by the occurrence of cold, hypoxic water very close to the surface (Prince and Goodyear, 2006). The proportions of Japanese PLL fishing effort in the upper 50 m used in HBS for Atlantic billfishes declined from almost 20% in the late 1950s to less than 1% for gears first deployed after 1989 (Goodyear, 2006). If all of the billfish catch were to be in the upper 50 m and recent gears fished just 2% instead of the assumed 1% of total effort in these depths, HBS CPUE estimates for the recent years would be overestimated by 100%. The actual effect of such error could be much greater when computed by the 10 m depth bin resolution typically used with HBS.

Many factors may cause the depth distribution of effort to depart from the catenary predictions. For example Hinton and Nakano (1996) assumed hook depth reached 85 % of the derived catenary predicted depth (Suzuki et al., 1977) to account for the effects of shoaling during standardization of nominal fishing effort. However, observations from several field studies suggest that actual hook depth due to shoaling is shallower than suggested by Hinton and Nakano (1996) [Nishi, (1990): 70 – 81 % of predicted depth; Boggs, (1992): 54 – 68 % of predicted depth; Bigelow et al., (2006): 50 - 70% of predicted depth]. In addition, our results show that the catenary fishing-depth estimates cannot be corrected for shoaling and other factors by a single scalar applied to all hooks. This methodology can produce fishing effort estimates that substantially bias stock assessments for pelagic fish.

In the present study, the majority of time spent by the hooks, regardless of shallow or deep predicted hook position, was around 40 m depth resulting in hooks spending the majority of time fishing at 43 % and 31 % of the catenary predicted depth, respectively. In addition, 99.6 % of the depth observations for the shallow hook position were above the predicted depth of 92 m and 99.3 % of the depth observations of hooks in the deep position were above the predicted depth of 127 m (Figures 2.8 and 2.9). Our study indicates that almost all of the time hooks spent fishing was shallower than the catenary predicted depth, even when using the most conservative scalar adjustments from previous studies (Figure 2.10). Several possible explanations for our shallower hook depth observations relative to those of previous studies may include, but are not limited to: (1) stronger and/or more variable oceanic currents in the Windward Passage relative

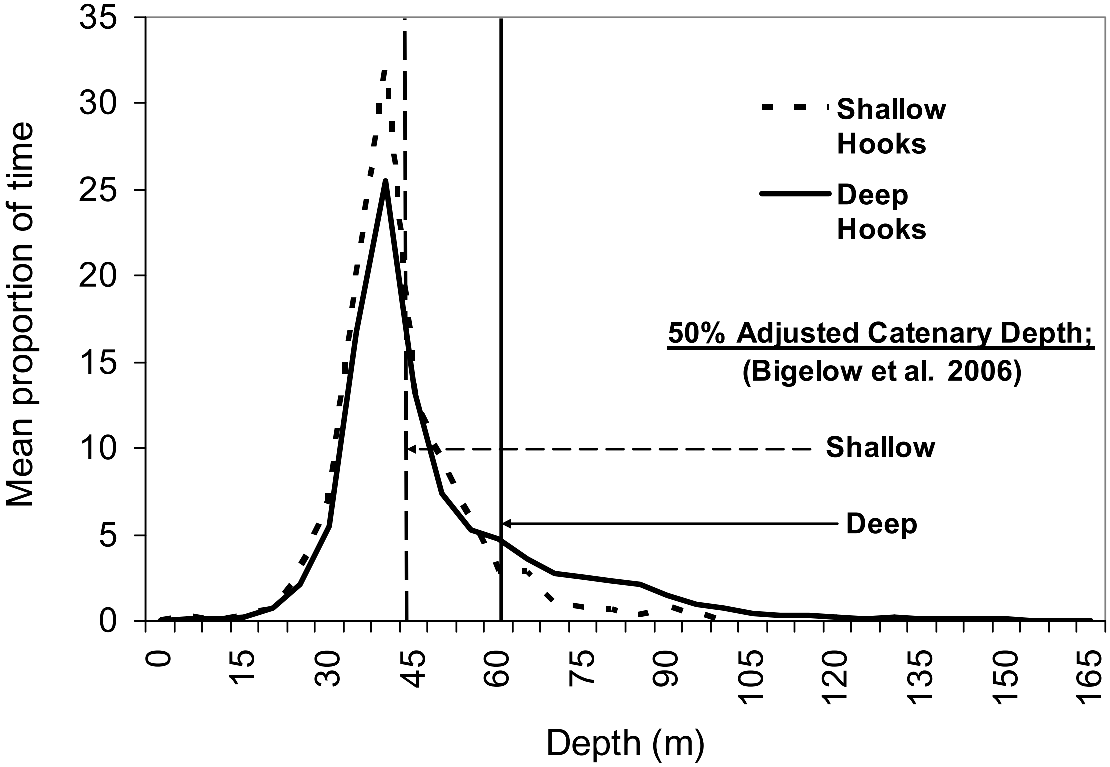


Figure 2.10. Mean time at depth for all hooks across all set for the shallow (solid) and deep (dashed) hooks. Notice the similar distribution for shallow and deep catenary hook positions.

to other study areas, (2) variations in baits used in previous studies (e.g., mackerel instead of squid), (3) various weights deployed on the mainline or branchlines, etc. (e.g., 100g weighted swivel as opposed to 60g weighted swivel).

Many authors have described the behavior of pelagic longline fishing gear using depth meters (Saito, 1973), micro-bathythermographs (Mizuno et al., 1999) and TDRs (Boggs, 1992; Berkeley & Edwards, 1998; Yano & Abe, 1998; Bigelow et al., 2006) placed on the gear. However, the cost of completely covering the gear with depth measuring devices is prohibitive because commercial PLL fishing typically involves the deployment of tens of kilometers of fishing gear with hundreds to thousands of hooks. Several previous studies deployed depth measuring device(s) on the PLL gear in a single basket and assumed the variance from basket to basket was negligible. During our study, TDRs were placed systematically along the entire length of the PLL gear covering about 7-9% of the hooks deployed. Our results indicate that observations from an individual TDR were highly variable and were poor estimators of time at depth of TDRs in the same catenary position in other baskets during the same set and particularly for different sets (Fig. 2.6 and 2.7).

From the gear configuration employed in our study, catenary geometry estimates that PLL hooks will fish at 92 m for the shallow hook position and 127 m for the deep hook position. Our results indicate that hooks fail to fish at a single depth but rather follow a depth distribution with hooks spending a portion of their time at many different depths (Figures 2.6 and 2.7). Therefore, it seemed reasonable to expect bimodal depth distributions for hooks placed in the shallow and deep catenary hook positions. Although, the hooks at the assumed deepest basket positions fished more deeply on average than the hooks at the assumed shallowest basket positions, the similarity of hook time at depth distributions (i.e., mean, mode, and spread) was surprising (Figure 2.10). Thus, in addition to indicating other shortcomings of catenary geometry in determining fishing depth, our study also reveals that the two fishing depths and the expected bimodal hook depth distributions were not realized.

Sagging rate or sag ratio (S) is the ratio of the amount of stretched mainline deployed in a longline segment between surface buoys (L) and the horizontal distance between the surface buoys (B)

$$S = B/L, \tag{3}$$

There are two methods to determine S depending on the commercial fishing technique employed (Bigelow et al., 2006). Japanese PLL fishing targeting tuna typically employs a "line thrower" which deploys the mainline at a speed defined by the fishers. When line throwers are employed, S is the ratio of the speed of the line thrower to the speed of the fishing vessel during gear deployment. In contrast, commercial PLL fishing targeting swordfish typically do not employ line throwers. Therefore, the ratio of the distance traveled by the vessel over water and the estimated amount of mainline deployed are commonly used to determine the sag ratio.

Previous studies have only reported sag ratio values less than 1.0 when using equation (3), which suggests that the gear is always sinking; however, this may not always be the case when gear is deployed in areas with strong currents. Regardless of the fishing strategy or target (e.g., tuna fishing or swordfish fishing), when PLL mainline is released from the fishing vessel there is an inherent amount of sag in the gear that is not accounted for using previous methods. When line throwers are used the inherent sag in the gear at the time of release from the fishing vessel is not accounted for because the value produced by the line thrower is used to calculate the stretched length of the mainline, L, which is the denominator of equation (3). Therefore, even if gear is being stretched by oceanic currents resulting in less sag in the basket and shoaling of the gear towards the surface, the value calculated by equation (3) will be less than 1.0 indicating sinking gear.

In the case of near surface fishing targeting swordfish at night, the mainline is passively deployed (i.e., allowed free spool) from the vessel as it moves forward and *L* is usually determined by use of GPS coordinates taken for each section while the gear is being deployed. This method fails to account for the additions or subtractions to the amount of mainline deployed against opposing or with following currents, respectively and assumes the mainline deployed is at its stretched length. However, as the vessel moves through the water the velocity is not constant and as the mainline free spools (i.e., the spool containing the mainline spins freely with no braking action applied) slack occurs resulting in inherent sagging of the mainline. Therefore, sagging rate calculations based on equation (3) where the denominator is the assumed stretched mainline length in a unit basket will always result in sag ratios less than 1.0 indicating sinking gear. In the present study, average gear drift was used as a proxy for directional current velocity (Nishi, 1990, PFRP, 1998) which was incorporated into mainline deployment length calculations (Figure 2.3) and subsequent distance between buoy calculations (Table 2.1). Based on our results sag ratios were occasionally reported as greater than 1.0 indicating gear being stretched, while sag ratios less than 1.0 indicated gear being compressed.

These changes in horizontal shape of the gear may potentially translate in changes in the degree of sagging or shoaling and vertical fishing depth.

Our results suggest that the estimation of fishing depths (i.e., effective effort) for longline hooks is a difficult problem, even for a single gear configuration fished in the same general location. Therefore, extrapolation of fishing depths during near surface fishing (e.g., targeting swordfish) based on gear configuration information and catenary geometry is inherently flawed, especially when collected from different fishing locations, and may lead to biased stock assessments.

In the future, additional research should be conducted to: (1) increase empirical databases of PLL fishing using TDRs under various oceanographic conditions to capture the variability associated with this type of fishing, (2) continue analysis of these data to reveal factors that best predict the fishing depth distributions across gear configurations and oceanographic features, (3) include factors that potentially influence hook depth, such as animal interactions and occasional gear interactions with shipping, (4) develop models that capture the correlation between changes in the horizontal shape of the gear from deployment to retrieval and how those changes translate into variations in the vertical fishing depth and (5) determine the predictability of fishing depth employing deep longline gear configurations (i.e., >10 hooks per basket). Further study and analysis of vertical habitat utilization by target and bycatch species is also warranted (Lou et al., 2006).

Chapter 3

Vertical habitat utilization of swordfish (*Xiphias gladius*) and blue marlin (*Makaira nigricans*): Estimating fish and hook encounter probabilities for habitat standardization of pelagic longline catch rates

Introduction to uncertainties during habitat based standardization

The horizontal and vertical distributions of pelagic species are believed to be influenced by many variables and particularly by environmental conditions in their preferred habitat (Brill et al., 1993; Brill, 1994; Brill and Lutcavage, 2001). Several authors have used measures of habitat utilization and preferences of these species to evaluate the influence of the environment on catch rates associated with pelagic longlines (Hinton and Nakano, 1996; Bigelow et al., 2002; Bigelow and Maunder, 2007). Thus, environmental influences and associated physiological limitations are important, if not essential, when using catch per unit effort (CPUE) time series as an index of relative abundance for assessing stock status of pelagic species.

The most widely used methods for modeling swordfish (*Xiphias gladius*) and blue marlin (*Makaira nigricans*) abundance trends remain general linear models (GLM) applied to pelagic longline (PLL) CPUE over time. However, fisheries scientists are increasingly employing alternative methods such as habitat-based-standardization (HBS; Hinton and Nakano, 1996) or some derivative (e.g., statistical HBS; Bigelow and Maunder, 2007). Habitat-based standardization and its derivatives have been promoted as superior to GLM statistical procedures for removing the effects of gear modifications over time (Yokawa et. al., 2001; Yokawa and Uozumi, 2001; Yokawa and Takeuchi, 2002; Yokawa and Takeuchi, 2003; Maunder et al., 2006; Bigelow and Maunder, 2007).

Habitat based standardization requires that nominal fishing effort (i.e., number of hooks or number of sets) be replaced in the calculation of CPUE by effective fishing effort (f_{at}). Factors that influence the probability of an animal encountering fishing hooks within the vertical habitat of the animal are thus incorporated into the calculation of CPUE instead of being modeled as factors in a generalized linear model. Bigelow et al. (2002) modeled f_{at} as:

$$f_{at} = E_{at} \sum_{d} h_{atd} * P_{atd} \tag{1}$$

where h_{atd} is the proportion of hooks fishing in the depth zone d in area a during time period t and P_{atd} is the proportion of fish at the same area/time/depth as the hooks. Effective fishing effort, and the HBS model in general, rely entirely on detailed knowledge of fish vertical habitat utilization (i.e., the proportion of time spent by these animals within successively deeper layers of the water column based on water temperature relative to that of the surface mixed layer (Goodyear et al., 2007) and vertical fishing depth (Goodyear, 2003; Serafy et al., 2005).

Until recently pelagic fish vertical habitat distribution has been estimated from catch depth during commercial PLL fishing (Nakano et al., 1997). However, a poor understanding of fishing depth often translates into poor estimates of catch depth (Rice et al., 2007). Direct observation of an animal at its extreme habitat limits is highly desirable when characterizing fish vertical habitat utilization. It has long been known by direct observation from deep sea submersibles that swordfish can inhabit water depths greater than 650 m and temperatures below 5 ºC (Zarduski, 1964, Church, 1967). In addition, electronic tracking information suggests that swordfish perform daily vertical migrations between surface and deep waters (Carey and Robison, 1981; Carey, 1990; Sedberry and Loefer, 2001; Takahashi et al., 2003). In fact, Takahashi et al. (2003) suggested that the maximum depth and minimum temperature exploited by a swordfish implanted with an archival tag was estimated at roughly 900 m and around 4 ºC, respectively. Understanding the extent of these vertical migrations is necessary for the HBS process and may lend insight into how to concentrate fishing effort for the target species and avoid unnecessary bycatch.

Blue marlin are presumed to spend the majority of their time in surface waters (Graves et al., 2003) and are reportedly thermally limited by an 8 °C temperature difference relative to surface mixed layer temperatures (Brill and Lutcavage, 2003). Reports on diel behavior are mixed with some authors suggesting no diel vertical migrations (Yuen, 1974; Graves et al., 2003), while others suggest significant diel differences in vertical habitat use (Holland et al., 1990; Goodyear et al., in press *Marine Ecology Progress Series*) and still others reporting mixed results from various tagged blue marlin (Block et al., 1992; Kerstetter et al., 2003).

Hook depth influences species selectivity during PLL fishing (Yang & Gong, 1987; Boggs, 1992; Hanamoto, 1997). Estimates of fishing depth are typically based on catenary equations (e.g., Yoshihara et al., 1951; 1954; Suzuki et al., 1977) which have been shown to over-estimate fishing depth (Boggs, 1992; Bigelow et al., 2006; Rice et al., 2007). Many studies have inferred fishing depth from: (1) depth measuring devices placed on the PLL mainline and subsequent addition of the branchline length (Boggs 1992; Berkeley and Edwards 1998; Mizuno et al. 1999), (2) a single depth meter deployed on the hook midway between two buoys, which is expected to be the deepest hook (Saito, 1973; Bigelow et al., 2006), or (3) depth meters placed near the hooks and systematically deployed throughout a single section of the gear so that fishing depth can be interpolated over the entire length of the gear (Mizuno et al., 1999; Bigelow et al., 2006).

Applications of HBS method rely heavily on static estimates of fishing depth based on catenary geometry (Yoshihara, 1954), often employing scalars to account for deviations from catenary predicted fishing depth (Suzuki et al., 1977; Yokawa et al., 2001; Bigelow et al., 2002; 2004; Babcock, 2006). Bigelow and Maunder (2007) applied actual fishing depth determined from time-depth recorders placed near hooks during PLL fishing but used only one per set on the presumed deepest hook (i.e., the middle hook) and used these results to interpolate hook depth along the entire gear length. However, Rice et al. (2007) placed small temperature-depth recorders (TDRs; Lotek^{TM}) proximal to hooks systematically along the entire length of experimental longlines (average set length of 44.9 ± 2.0 km) and concluded: (1) that catenary geometry drastically overestimates fishing depth, (2) that extrapolation of the known fishing depth of a specific hook to another hook in the same catenary position in the same gear section or any other section is a poor predictor of fishing depth because, (3) PLL fishing depth is highly variable along the entire length of the longline gear. Goodyear (2003) noted that quantitative knowledge of PLL gear behavior and subsequent hook depth distribution is possibly the most uncertain factor in the HBS process. In addition, previous applications of the HBS method have relied almost exclusively on characterization of vertical habitat use by pelagic animals based on short term acoustic telemetry studies (e.g., Hinton and Nakano, 1996; Yokawa et al., 2001; Yokawa and Takeuchi, 2003; Bigelow et al., 2002; 2004). As noted previously, short duration tracking studies (e.g., acoustic telemetry) often result in incomplete characterization of vertical habitat use by pelagic animals. However, several HBS applications have incorporated habitat use data from pop-up satellite archival tags (PSATs) (Bigelow et al., 2002; 2004). The uncertainties associated with fishing depth and fish habitat utilization proliferate through ever aspect of the stock assessment and fishery management process (Restrepo et al., 2003; Rice et al., 2007).

Luo et al. (2006) developed a framework for incorporating summarized PSAT data and PLL hook depth based on TDR data into temperature/depth profiles hereto referred to as habitat envelopes. These techniques were used to develop habitat envelopes for blue marlin and swordfish, for near surface (4 hooks per basket – a section of PLL gear with hooks between surface buoys; HPB) and deep (15 HPB) commercial PLL fishing in the Windward Passage. The objective of the present study is to identify aspects of blue marlin and swordfish diel vertical habitat utilization that would allow for prediction of encounter probabilities for animals interacting with hooks during near surface and deep PLL fishing. The subsequent encounter probabilities would then have direct application in calculating effective fishing effort (f_e) in HBS of PLL CPUE time series.

Materials and Methods:

Near surface and deep PLL fishing depth and temperature

Experimental pelagic longline gear was deployed from a commercial pelagic longline vessel operating in the Windward Passage between the Republic of Cuba and the island of Hispaniola during June 2003 and May 2004. To account for variability in fishing depth along the longline as described by Rice et al. (2007), TDRs were placed systematically along the entire length of the PLL gear. Each TDR was placed on the branchline proximal to the weighted swivel 1.83 m from the hook to reduce hook-depth uncertainty as much possible while minimizing TDR loss from animal bite-offs, etc. The TDRs measured temperature and depth approximately every 14.06 s for nearly continuous monitoring of the PLL hooks. The target species during both years was swordfish. The gear was deployed around dusk and retrieval began before dawn and typically was completed before noon depending on the catch. Fish capture data were collected during gear retrieval and fish captured on branchlines equipped with TDRs were noted. Each branchline was fastened to a hook-strike timer (Lindgren-Pittman Inc.) which was subsequently fastened to the mainline and used to record the time of fish strikes on the hook.

Operational details on the Windward Passage 2003 cruise can be found in Rice et al. (2007). Briefly, ten experimental PLL sets were deployed during the month of June when migratory blue marlin interactions in the Windward Passage were presumed highest (Captain Greg O'Neil; pers.com). The gear was intended to fish near the surface and consisted of a 4 HPB configuration. Temperature-depth recorders were placed on the predicted catenary shallowest and deepest hooks and resulted in 7-9 % coverage of all hooks deployed (41-49 TDRs per 560 hooks).

The following year (2004) an additional ten experimental PLL fishing sets were deployed in the same vicinity of the Windward Passage during May. The target was swordfish, however the gear was intended to fish much deeper than gear deployed during

2003 by employing 15 HPB. Aside from differences in gear configuration and TDR monitoring, fishing operations were similar to those reported by Rice et al. (2007). In seven of ten sets, an average of 41.7 ± 6.3 km of mainline was deployed with about 532 hooks per set. Each section (7) contained 76 hooks and 11 TDRs (total = 77 TDRs per 532 hooks). The TDRs were placed systematically along the entire length of the PLL gear on the catenary predicted shallowest, intermediate and deepest hooks in each basket. During the first seven sets, TDRs were deployed to the extent possible on every 8th hook resulting in about 14.5 % coverage of the hooks deployed. One TDR was placed on the predicted deepest hook (no. 8 or no. 9) and one TDR was placed on an intermediate hook (no. 13) in all baskets except the fifth basket in each section. One TDR was placed on the shallowest hook (i.e., on a branch line immediately under the polyball on hook no. 1 in basket 1 and after hook no. 15 in basket 5) on either end of each section. No TDRs were placed on hook no. 13 in the 5th basket in each section (Figure 3.1).

Inclement weather forced shorter sets (i.e., 5 sections as opposed to 7 sections; average 33.4 ± 1.0 km) during 3 of ten sets with about 380 hooks per set. TDRs were redistributed along the gear to increase the resolution of coverage during the shorter sets (19.7% coverage) but remained on catenary predicted shallow, intermediate and deep hooks.

General PSAT information

Electronic tracking of pelagic animals was accomplished using high resolution environmental sampling PSATs (Wildlife Computers, Inc., PAT 2, 3, and MK10 models) with tracking durations ranging from 34 to 120 days (Table 3.1).

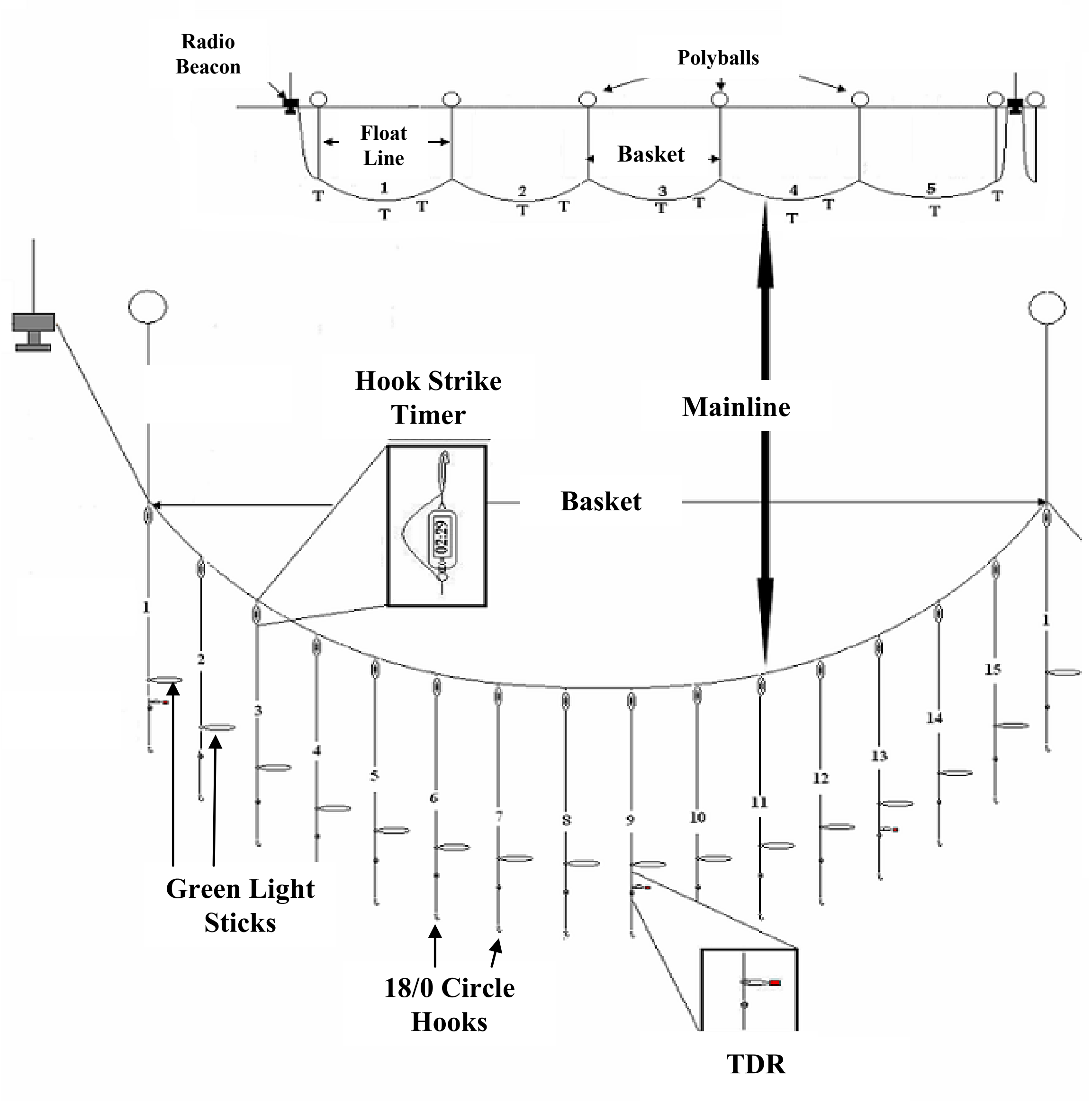


Figure 3.1. Schematic of pelagic longline gear deployed in the Windward Passage during 2004 showing: (Top) five baskets per section and placement of temperature/depth recorders (TDRs) in each basket throughout the section (T = TDR placement); (Bottom) the number of hooks between floats (15), hook timer placement for each branch line on the mainline, TDR placement on the shallowest hook (branch line no. 1), intermediate depth (branch line no. 13) and the deepest hooks (branch line no. 8 or no. 9).

Table 3.1. Programming details of pop-up satellite tags (PSATs; Wildlife Computers, Inc.) deployed on Atlantic blue marlin (*Makaira nigricans*) and Atlantic swordfish (*Xiphias gladius*). The locations (Lat/Long) for release and first transmission, displacements distances (km), length of deployments (days at large—DAL/P), and quality of the data recovered are shown.

Species	PTT ID	PAT model (software version)	Sampling Resolution (s)	DAL/P	Data recovered (days)	Data recovered (%)	Location Release	Location Pop-up	Displacement (km)
Blue marlin	23439	2.07	60	34/35	34	100	21.93 N; 72.39 W	20.50 N; 70.98 W	210
Blue marlin	27825	2.08	60	39/39	38	100	18.71 N; 64.82 W	15.56 N; 74.13 W	1049
Blue marlin	41521	3.01	30	61/61	44	100	24.10 N; 75.25 W	22.25 N; 72.77 W	367
Blue marlin	41524	3.01	30	82/95	81	100	24.10 N; 75.28 W	19.05 N; 73.54 W	594
Blue marlin	41534	3.01	30	46/67	46	100	22.00 N; 72.07 W	19.13 N; 62.78 W	1014
Blue marlin	42724	3.01	30	93/93	82	100	18.53 N; 66.18 W	18.63 N; 63.32 W	298
Swordfish	66696	MK10	10	90/90	90	44.5	26.00 N; 79.85 W	26.40 N; 79.77 W	45
Swordfish	66697	MK10	10	120/120	94	23.2	26.05 N; 79.85 W	26.26 N; 79.82 W	24
Swordfish	66698	MK10	10	90/90	90	48.8	24.23 N; 81.05 W	33.87 N; 75.16 W	1220

PTT ID= platform transmitter terminal identification
PAT = pop-up archival tag
DAL/P = days-at-liberty/programmed
N = north; W = west

All PSATs were assembled as described by Prince and Goodyear (2006). The PSATs were attached to the fish externally according to handling and tagging procedures recommended by Prince et al. (2002). The PSATs archived pressure (depth), temperature and light intensity data every 10 s (MK10), or every 30 s to 60 s (PAT 2 and 3). The PSATs were rated to withstand pressure down to depths of 2000 m and each tag was assembled with a pressure activated mechanical detachment device (PAT 2 and 3 used RD-1500; MK10 used RD-1800) designed to sever the 182 kg test strength monofilament attachment tether at a predetermined depth (RD 1500 = 1500 m; RD 1800 = 1800 m). These automatic release devices were intended to avoid data loss resulting from the death and subsequent sinking of a tagged fish in waters greater than 2000 m. The PSAT software was also programmed to sever the tether if the tag remained at a constant depth with vertical movement ≤ 5 m within a 24 h period. This was intended to allow the PSAT to release from an animal that died in water shallower than 1500 m. These PSATs archive data into permanent non-volatile flash memory, allowing extraction of the high resolution (10, 30, or 60 sec) environmental sampling data in the rare event that a tag is recovered. All fish in the present study were released from recreational fishing vessels and release locations were determined using global positioning systems onboard the tagging vessel. Pop-up locations were estimated directly from the first ARGOS transmission received from each PSAT.

Electronic tracking of swordfish

Temperature and depth habitat utilization was characterized from 3 PSATs deployed on swordfish in the western North Atlantic near Miami, Florida. These tagged swordfish were chosen due to the long tracking durations, which more appropriately characterize vertical habitat use (Table 1). Tagged swordfish had an estimated average weight of 25.8 ± 1.5 kg. Two of the three PSATs were programmed for 90 day deployments, while the third was programmed for a 120 day deployment and no premature detachments were reported (Table 1). The MK10 PSAT model was used exclusively on these swordfish and no PSATs implanted in these swordfish were physically recovered. Therefore, summarized temperature and depth data transmitted via ARGOS satellite were used to characterize swordfish vertical habitat utilization as described in Luo et al. (2006). Temperature and depth records were compiled into histogram bins (14) at 2 h (90 day PSATs) or 3 h intervals (120 day PSAT). Temperature bins started at 6 °C and then increased by 2 °C up to 30 °C, ending with >30 °C. Depth bins included 0 – 25 m, and increased by 25 m up to 100 m depth and then increased by 100 m up to 1000 m, ending with >1000 m depth. In addition, eight empirical maximum, minimum, and intermediate profiles of depth and temperature (PDT) encountered by the swordfish during each 2 or 3 h binning interval were also recorded and transmitted with the summarized data.

For each 2 or 3 h summary message transmitted by ARGOS, the proportion of time spent by swordfish in a particular depth-temperature bin was evenly distributed across the bin range at 1 m or 1 °C intervals. These values were bounded by the maximum depth and minimum temperatures experienced by swordfish during the summary period. The resulting values were then redistributed into 25 m depth bins. The PDT data were also linearly interpolated to match the depth histogram. Then, we applied the algorithm described in Luo et al (2006) to the re-binned depth, temperature histograms and the PDT data to estimate the matrix of time exploited by swordfish at each depth and temperature bin (vertical habitat envelope).

Electronic tracking of blue marlin

Temperature and depth habitat utilization was characterized from 6 PSATs deployed on blue marlin in the western North Atlantic. Tagged blue marlin had an estimated average weight of 54.6 ± 22.3 kg. The PSATs used on blue marlin in the present study were programmed for deployment durations ranging from 35 – 93 days (Table 3.1). These PSATs were programmed to record high resolution environmental measurements once every 30 s (PAT 3) or 60 s (PAT 2). Because all 6 PSATs were physically recovered, extraction of the high resolution archived data from the non-volatile memory was used to characterize blue marlin vertical habitat utilization as described in Luo et al. (2006).

Vertical habitat envelopes

Temperature and depth information from swordfish and blue marlin equipped with PSATs and PLL fishing gear equipped with TDRs was integrated into time at depth-temperature matrices (DTMs) referred to collectively as a “vertical habitat envelope” (Luo et al., 2006). Each matrix is defined by a 14 x 14 cell structure corresponding to 14 temperature and 14 depth bins. Each cell represents the proportion of time a swordfish, blue marlin or the PLL hooks spent at a specific depth-temperature within the water column. Because no swordfish PSATs were physically recovered, we employed the algorithms formulated by Luo et al. (2006) to construct vertical habitat envelopes for swordfish from the satellite transmitted summarized data. For blue marlin, we created a vertical habitat envelope from archived data obtained from six physically recovered PSATs by simply summing and tabulating the amount of time for each cell from the high resolution sampling data (i.e., 30 s and 60 s). The nearly continuous monitoring of the PLL hooks by TDRs allowed hook time at a specific depth-temperature to be summarized and tabulated into DTMs similar to the high resolution data from the recovered blue marlin archived PSATs. Data from each TDR was imported into Statistical Analysis Software (SAS 9.1.3 Service Pack 4) and the frequency of occurrence within a specific depth-temperature bin was multiplied by the sampling interval (14.06 s) to determine the proportion of time shallow, intermediate and deep hooks spent in a specific depth-temperature bin (Appendix F).

Temperature bins were reported in 2 °C intervals as the difference between the sea surface temperature (SST) and the observed temperature at depth or delta T (ΔT) for a monitored fish or PLL hooks. Delta T for monitored fish was calculated by subtracting observed temperatures at depth from the surface mixed layer temperature recorded by PSATs. For PLL gear, average SST was recorded from TDRs within the upper 10 m for each gear deployment. Temperature at depth was then subtracted from the mean SST for each gear deployment to determine ΔT.

In order to capture the diel behavior of the PSAT tagged fish, we separated habitat envelopes into diurnal, nocturnal and crepuscular time periods. The PSATs used in the present study measure time as Greenwich Mean Time (GMT) and record the ambient light level for geolocation. The PSAT tagged swordfish displayed limited horizontal movement and strong site fidelity for the duration of the tracking (Table 3.1). This allowed us to use GMT calculated local time for comparison with sunrise and sunset information for the same general location to separate day, night and twilight vertical habitat utilization. Diel patterns were then determined by pooling the daily day/night/twilight depth and temperature utilization for the entire tracking duration. Diel behavior for blue marlin was determined similar to Goodyear et al. (in press; *Marine Ecology Progress Series*). Daylight and darkness were easily separated from the light level data recorded by the tag. The gradient in ambient light levels occurring during the transition between night/dawn and day/dusk were used to bound twilight around the midpoint of the transition in light intensity. This resulted in a 2 h period about the midpoint representing crepuscular periods. Similar to swordfish, diel patterns for blue marlin were then determined by pooling the daily day/night/twilight data for the entire tracking duration.

In the absence of external forcing factors PLL gear exhibits no diel differences in fishing depth and will fish at the observed depths similarly regardless of the time of day (Yokawa and Takeuchi, 2003). Therefore, diel differences in the probabilities of interactions between blue marlin, swordfish and PLL hooks were assumed to be solely dependent on diel animal behavior.

Results

Blue marlin and swordfish catch

Catch was dominated by swordfish during both years of the study (2003 catch per 1000 hooks = 12.86; 2004 catch per 1000 hooks = 14.39). Blue marlin catch was relatively high during 2003 (catch per 1000 hooks = 3.04) but was much lower during

2004 (catch per 1000 hooks = 0.89), when hooks were deployed deeper. Hook-strike timers indicated temporal separation in catch between blue marlin and swordfish, with blue marlin catch highest during crepuscular periods and swordfish during nocturnal periods (Figure 3.2). Two blue marlin were captured on hooks equipped with TDRs. Data from hook-strike timers and depth data from TDRs suggests that, in both cases, blue marlin engaged the hooks while the gear was sinking to its settled fishing depth (Figure 3.3).

Near surface and deep PLL fishing depth and temperature

During 2003, PLL fishing intended to concentrate effort in near surface waters by employing a 4 HPB gear configuration, revealed no fishing time at depths below 200 m. The majority of the fishing effort (73.2 %) was spent within 50 m of the surface in water with $\Delta T \geq -4$ °C (Figure 3.4 A; Appendix A). For reference, the catenary predicted fishing depths using the algorithm of Suzuki et al. (1977) were estimated to be 92 m and 127 m for shallowest and deepest hooks, respectively, in this 4 HPB configuration. Employing the scalar suggested by Ward and Myers (2006) resulted in predicted fishing depths of 69 m and 95 m, for shallow and deep hooks, respectively.

During 2004, PLL fishing was intended to concentrate effort deeper in the water column by employing a 15 HPB gear configuration. Reported hook depths from TDRs for this configuration indicated depths down to 475 m and ΔT as much as 14 °C below SST. The majority of the fishing effort (77 %) using this gear configuration occurred at depths above 150 m and ΔT about 6 °C below SST (Figure 3.4 B; Appendix A).

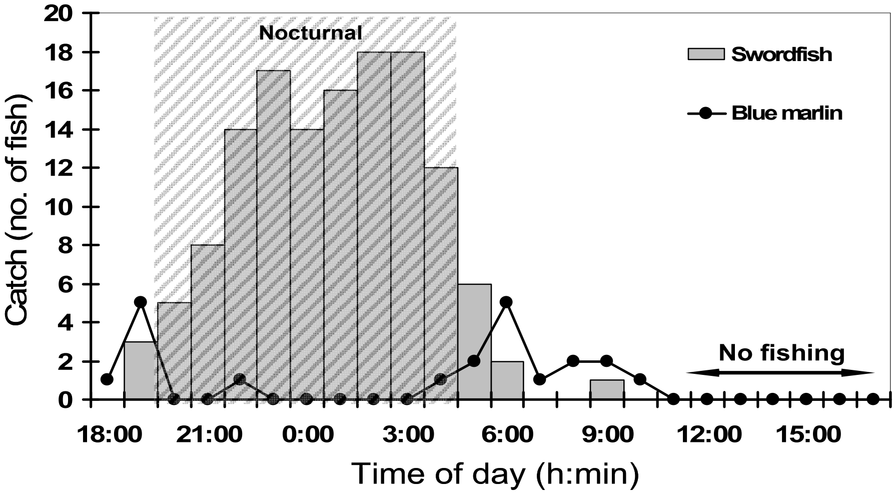


Figure 3.2. Catch by time of day for blue marlin and swordfish during pelagic longline fishing in the Windward Passage in 2003 and 2004.

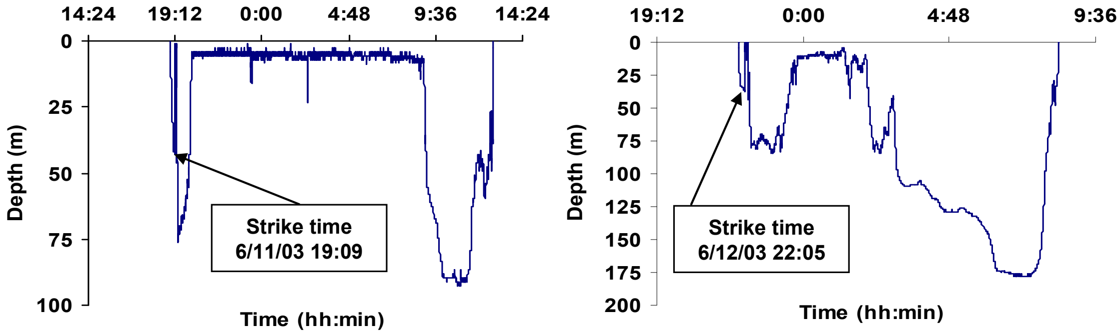


Figure 3.3. Fishing depth profile of individual hooks equipped with TDRs indicating interaction with blue marlin before the pelagic longline gear reached its settled fishing depth.

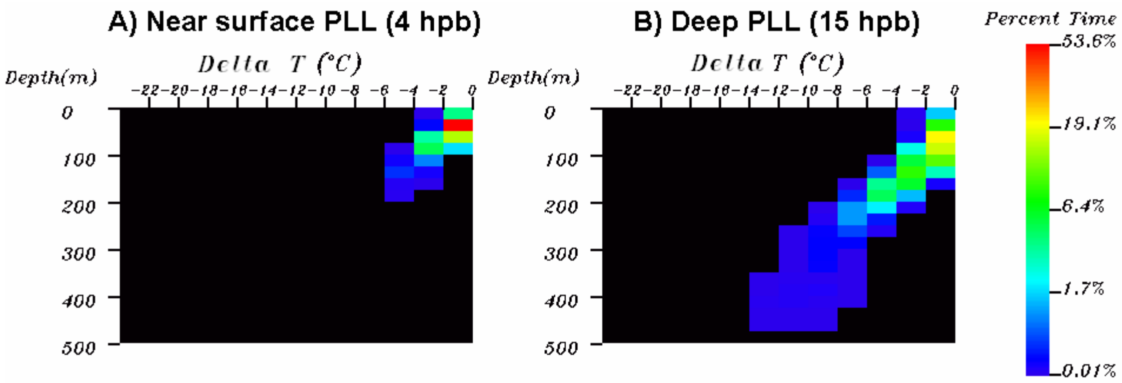


Figure 3.4. Pelagic longline vertical depth-temperature profiles during (A) near surface fishing using 4 hooks per basket; (B) deep longline using 15 hooks per basket.

For reference, the catenary predicted fishing depth using the algorithm of Suzuki et al. (1977) were 92 m, 262 m, and 331 m for shallow, intermediate and deep hooks, respectively. Employing the scalar suggested by Ward and Myers (2006) resulted in predicted fishing depths of 69 m, 197 m, and 248 m for shallow, intermediate and deep hooks, respectively.

Electronic tracking of blue marlin and swordfish

Blue marlin tracked during the present study exhibited broad depth and temperature habitat utilization. During daylight hours they spent the majority of their time (96.2 %) in surface waters above 100 m depth, but made brief excursions into depths greater than 600 m, experiencing ΔT as much as 18 °C below that of the surface mixed layer. Data from physically recovered PSATs also revealed that some of these deep dives were quite rapid. For example, Figure 3.5 demonstrates a blue marlin tracked with a PAT 2 programmed at 60 s sampling resolution (PTT ID no. 28825; Table 1) dived to about 350 m in about 3 minutes resulting in a vertical diving velocity of about 1.9 ms^{-1}.

Blue marlin displayed a strong preference for surface waters at night spending 98.3 % of their nocturnal time above 25 m depth making no excursions below 200 m. During crepuscular periods, vertical habitat use was marginally more extensive than during nighttime. For example, blue marlin spent only about 55.5 % of their time in water above 25 m depth, 43.4 % the of their time between 25 and 100 m depth and only brief amounts of time in water deeper than 100 m depth (about 1.1 %). Because the data were pooled, there were no obvious diel vertical movements, although vertical habitat use was greater during the daytime than at night (Figure 3.6A; Appendix B).

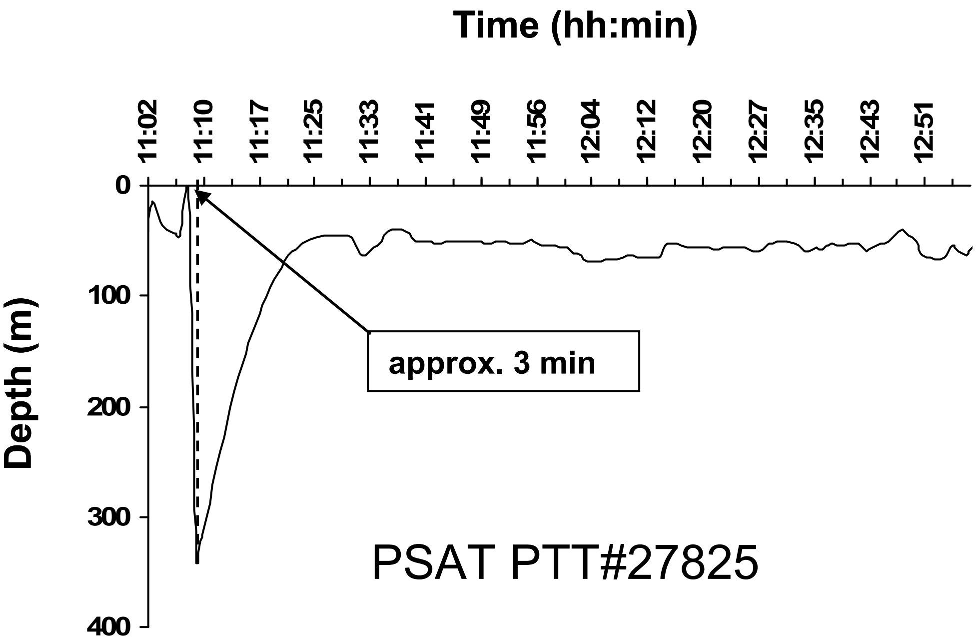


Figure 3.5. An example of a rapid deep dive by blue marlin (*Makaira nigricans*) reported from a physically recovered pop-up satellite tag (PSAT) programmed for 60 s environmental sampling.

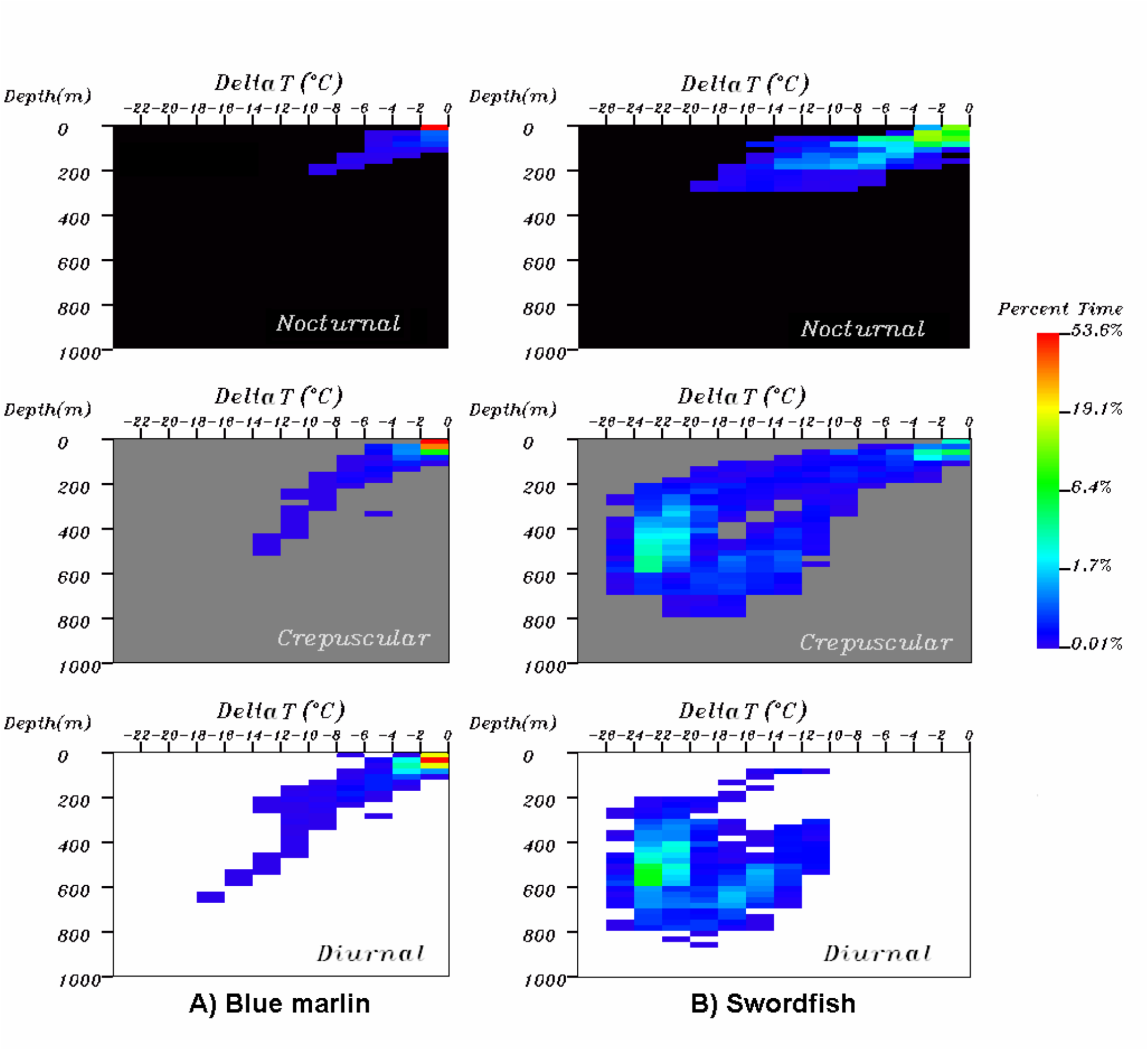


Figure 3.6. Diel depth-temperature vertical habitat envelopes for blue marlin (A) and swordfish (B).

Swordfish tracked during the present study exhibited very broad depth and temperature habitat use and obvious diel changes in vertical behavior. They spent the majority of their time at night above 100m (78.9 %) in waters within a delta T of 8 °C of SST and recorded no time in waters deeper than 300 m. However, as vertical movements ensued during crepuscular periods, vertical habitat use expanded. During this period swordfish only spent 18.8 % of their time in water above 100 m depth, about 45.8 % of their time at depths between 100 m and 500 m, and 35.1 % of their time at depths between 500 m and 800 m in waters with ΔT 10-24 °C below SST. They displayed a strong preference for deep waters during the day, spending a substantial proportion of their time at depths greater than 500 m (68.3 %) in water with a ΔT as much as 24 °C below SST. The deepest recorded excursions were reported during daylight hours into waters as deep as 875 m and there were no records of these swordfish at the surface during daylight hours (Figure 3.6B; Appendix C).

Blue marlin probability of encounter with PLL hooks

Pelagic longline gear deployed in 2003 with 4 HPB overlapped with blue marlin vertical habitat envelopes in correlation with increasing amount of ambient light. Overlap was minimal during the night (4.4 %), relatively moderately high during the crepuscular period (25.8 %) and high during the diurnal period (38.8 %). The probability of blue marlin and PLL hooks occupying the same depth-temperature cell was highest (35.1 %) on hooks fishing between 26-50 m depth within the mixed layer during diurnal fishing hours (Figure 3.7A; Appendix D).

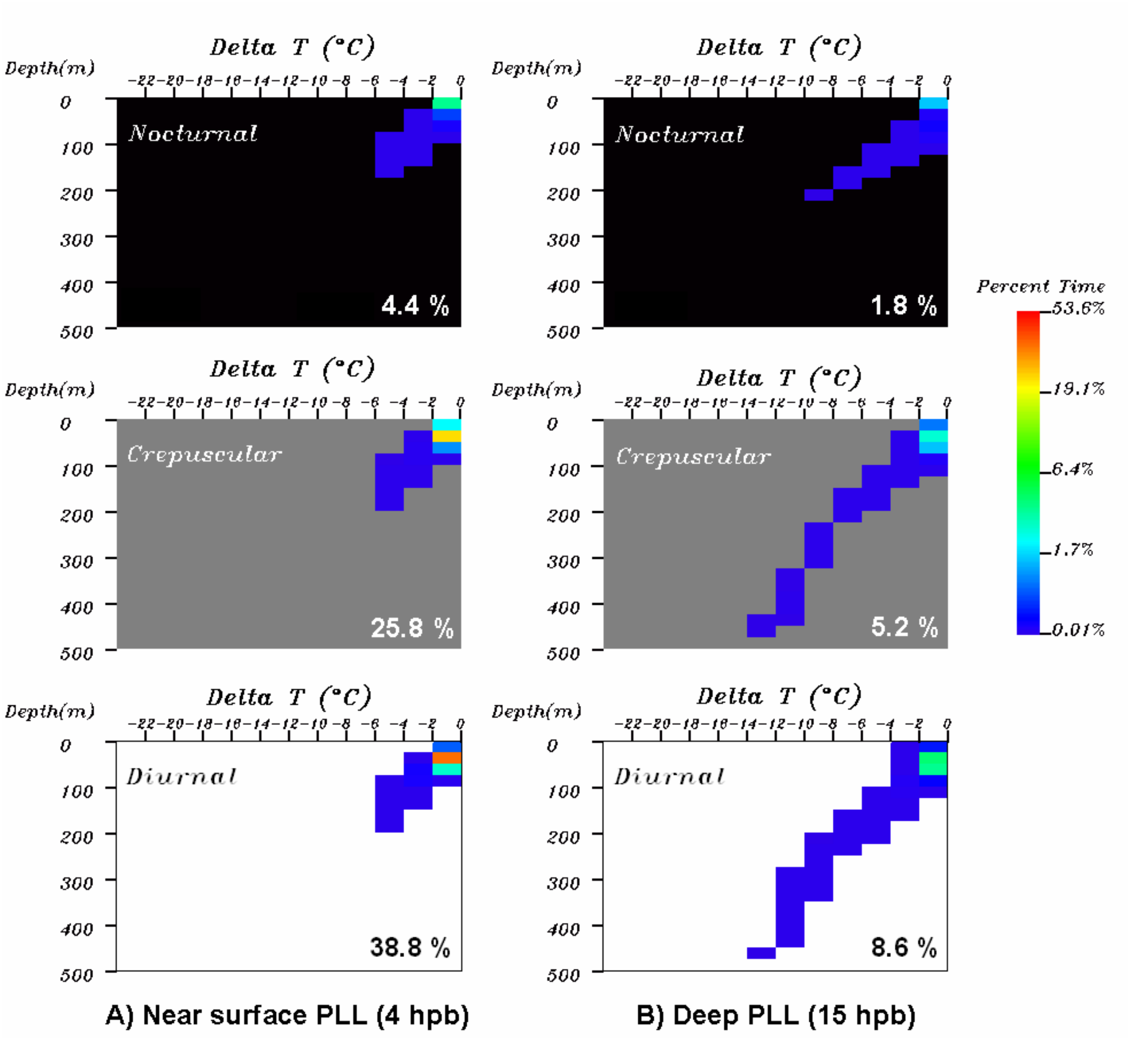


Figure 3.7. Blue marlin diel vertical habitat overlap with pelagic longline hooks during near-surface fishing with 4 hooks per basket (A) and deep fishing with 15 hooks per basket (B).

Pelagic longline gear deployed in 2004 with 15 HPB, had a minimal overlap with blue marlin vertical habitat compared to the near-surface gear (4 HPB) deployed during 2003. Diurnal overlap was the highest at 8.6 %, followed by crepuscular (5.2 %) and nocturnal (1.8 %) overlap. Similar to near-surface gear, overlap increased with increasing ambient light. Brief excursions into deeper cooler waters during daylight hours resulted in brief probability of blue marlin encountering deep PLL hooks (about 0.001 %) at depths as much as 275 m (Figure 3.7B; Appendix D).

Swordfish overlap with PLL hooks

Near-surface PLL deployed in 2003 overlapped with swordfish vertical habitat envelopes during nocturnal (7.6% of time) and crepuscular time periods (1.6 % of time), but not during daylight hours (0.0%). The probability of swordfish and PLL hooks occupying the same depth-temperature cell was highest (4.8 %) on hooks fishing between 26-50 m depth within the mixed layer during nocturnal fishing (Figure 3.8A; Appendix E).

Deep PLL deployed in 2004 overlapped with swordfish vertical habitat envelopes during all diel time periods (nocturnal, 3.6%; crepuscular, 1.4%; and diurnal, < 0.01%). The probability of a swordfish and PLL hook within the same depth-temperature cell was highest during nocturnal fishing between 51-75 m (2.1% of time). However, encounter probabilities ($p < 0.01$ %) were revealed as deep as 425 m during diurnal periods (Figure 3.8B; Appendix E).

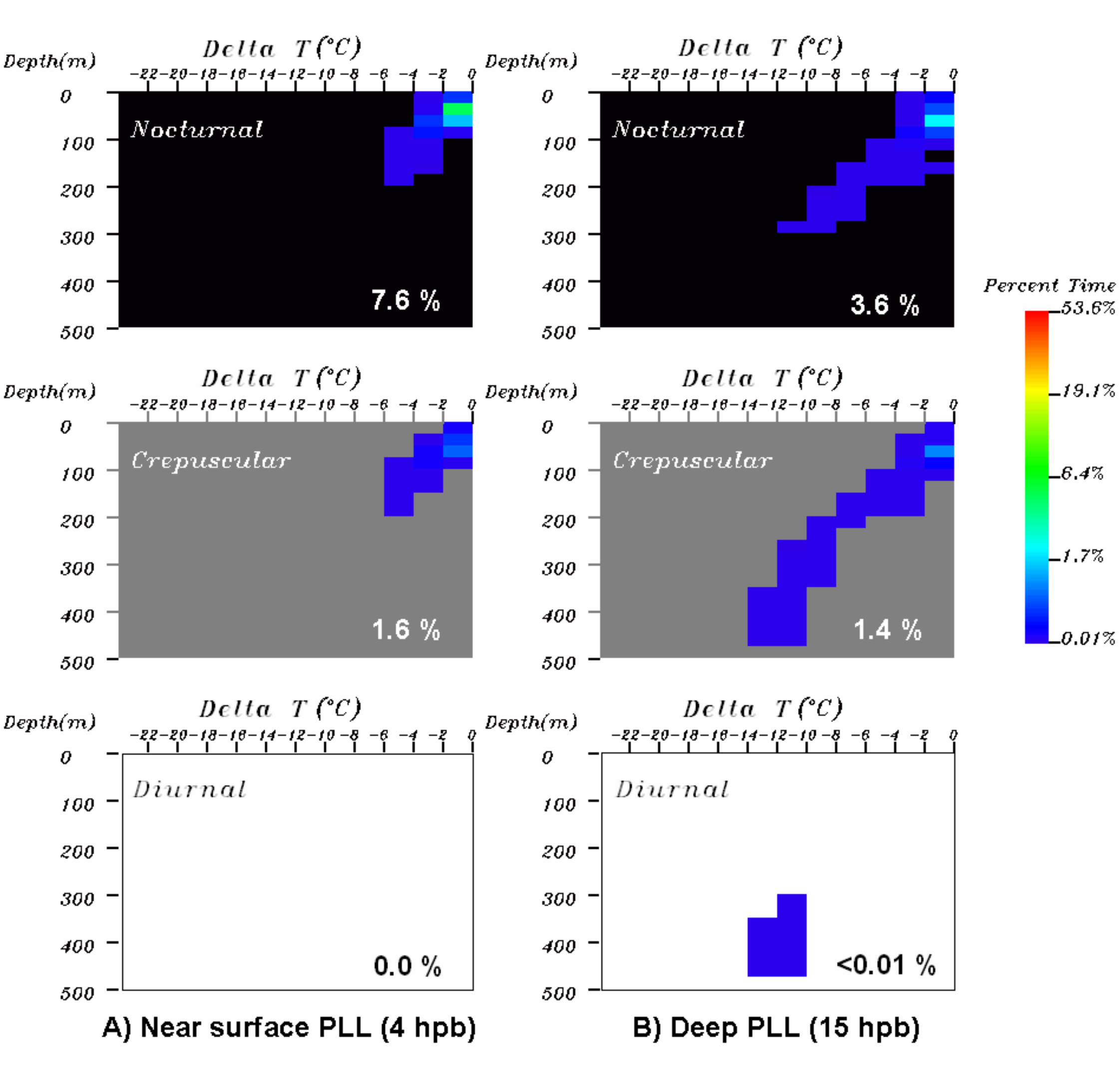


Figure 3.8. Swordfish diel vertical habitat overlap with pelagic longline hooks during near-surface fishing with 4 hooks per basket (A) and deep fishing with 15 hooks per basket (B).

Discussion:

Blue marlin and swordfish catch

It is evident from Figure 3.6 that blue marlin and swordfish inhabit surface waters during nocturnal periods with similar susceptibility to PLL hooks (Figure 3.7 and 3.8). However, evidence on strike time of baited hooks from hook-strike timers revealed differences in catchability between the two species. During the present study (20 PLL sets and about 10,500 hooks) only one swordfish was captured during daylight hours after 7:00 A.M. and only one blue marlin was caught during the nighttime about two days before the full moon (Figure 3.2). Swordfish strikes peaked during nocturnal hours while blue marlin strikes peaked during crepuscular periods (Figure 3.2). This suggests temporal separation in feeding strategies between the two species that may prove useful in reducing blue marlin bycatch when the target is swordfish.

Boggs (1992) used HSTs and TDRs during PLL fishing and concluded that a substantial fraction of billfish (striped marlin, *Tetrapturus audax*; spearfish, *T. angustirostris*) interactions with PLL hooks occurred during gear deployment and retrieval as hooks moved through the water column to the settled fishing depth. Yokawa and Takeuchi (2003) also reported an Atlantic blue marlin being hooked while PLL gear was sinking to settled fishing depth. Results from the present study were similar with evidence from HSTs corroborating strikes on branchlines equipped with TDRS indicating that several blue marlin were captured as the gear was sinking towards its settled fishing depth (Figure 3.3). Therefore, it is also possible that the high blue marlin catch rates observed during crepuscular periods resulted from movement of baited hooks through the water column during gear deployment and retrieval, which occurred primarily during dusk and dawn, respectively.

Near surface and deep PLL fishing depth and temperature

Placing TDRs near the hooks systematically along the entire length of the PLL gear, indicated that the majority of the fishing depths reported from near surface (4 HPB) and deep (15 HPB) gear configurations were substantially shallower than predicted using catenary geometry, even when scalars were implemented to account for shoaling (e.g. Hanamoto, 1987; Hinton and Nakano, 1996; Ward and Myers, 2005; 2006). However, caution should be taken when extrapolating these results to areas outside the Windward Passage because the pass is characterized by seasonal variations in water flow and stratified temperature and salinity regimes at depth (Gunn and Watts, 1982).

Blue marlin vertical habitat utilization

Perhaps the most striking feature of blue marlin vertical habitat utilization was the extent and rate of their diving excursions, as well as the amount of time spent in deeper cooler waters (Figures 3.5 and 3.6A). During the present study, an individual blue marlin (PTT no. 27825; Table 3.1) displayed a diving velocity around 1.9 ms^{-1}. For reference, during acoustic telemetry studies on blue marlin Block et al. (1992) reported short bursts of speeds up to 2.25 ms^{-1} that were usually associated with changes in depth. Blue marlin tracked during the present study made deep dives during daylight hours to depths as great as 675 m corresponding to ΔTs as much as 18 °C below mixed layer temperatures. They spent about 1% (0.63 %) of their daytime vertical habitat exploitation at temperatures below ΔT of 8 °C. Therefore, the physiological thermal barrier (ΔT ≥ -8 °C) hypothesized by Brill and Lutcavage (2001) for Pacific blue marlin was not demonstrated by Atlantic blue marlin in the present study. Goodyear et al. (in press, *Marine Ecology Progress Series*) suggested that these deep dives may be indicative of foraging at depth by either chasing and trapping less cold tolerant prey against the thermocline depth or diving deep and silhouetting prey against the down-welling light from above.

Blue marlin displayed a strong preference for surface waters at night, however the twilight periods were characterized by broader vertical habitat use. This may be indicative of heightened activity due to crepuscular foraging behavior, as indicated from high blue marlin crepuscular catch rates (Figure 3.2). It is common for crepuscular periods to be marked by heightened fish activity including increased predator/prey interactions (Hobson et al., 1981; Helfman, 1993). Many piscivorous fish species have evolved physiological visual adaptations that aid in successful twilight predation (Hobson et al., 1981; Potts, 1990; Helfman, 1993). For example, Fritsches et al. (2003b) showed that blue marlin have retinal specializations that aid in vision during low light conditions. Consider scombrids, a primary prey item of Atlantic blue marlin (Satoh et al., 2004), which undergo daily crepuscular retinal changes from night vision (i.e. scotopic vision) to daylight vision (i.e. photopic vision), and vice versa, in a process referred to as retinomotor responses (Masuma et al., 2001). Masuma et al. (2001) suggested that these retinomotor responses in the eye may disorient tuna during crepuscular periods. Visual disorientation may increase scombrid vulnerability to twilight predators, such as blue marlin. This may provide additional evidence supporting blue marlin crepuscular feeding because they have physiological ocular adaptations that make them well suited for twilight predation. Increased predation during twilight may make blue marlin more vulnerable to PLL gear deployed before sunset or retrieved after sunrise. Therefore twilight feeding behavior should be considered when weighting factors that influence catchability of Atlantic blue marlin.

Swordfish vertical habitat utilization

Swordfish tracked during the present study exhibited obvious diel variation in vertical habitat use, spending about 80 % of their time at night above 100 m depth and about 45 % of their time during the day at depths greater than 500 m and ΔT as low as -26 °C. This is consistent with reports that swordfish make excursions into water as deep as 900 m and ambient temperatures around 4 °C (Takahashi et al., 2003). Swordfish have larger brain and eye heaters than istiophorid billfish, which allows them to exploit deeper colder water than billfish (Carey, 1982; Block, 1986). Fritsches et al. (2005) suggested that the warm brain and eyes of swordfish imparts a distinct physiological predatory advantage over their cold blooded prey at depth. In addition, swordfish have large eyes which are well suited for predation in low light conditions that exist at great ocean depths (Fritsches et al., 2005). They also have highly reflective eyes (i.e., eye shine; pers. obs.), indicative of the presents of a tapetum lucidum, however there have been no published studies confirming this. These visual adaptations may facilitate nocturnal feeding in near surface waters as indicated by the high nocturnal catch rates during the present study. However, their nocturnal adapted eyes may not function well during daylight hours in surface waters, thereby reducing their catchability when PLL gear fishes after sunrise.

Blue marlin vertical habitat overlap with near-surface and deep PLL gear

Blue marlin had the highest probability of encountering PLL hooks in the present study during diurnal near-surface fishing (38.8 %). The chance of blue marlin encountering a hook during daytime hours was substantially reduced when employing deeper PLL fishing strategies (8.6 %). This suggests that deeper fishing recognized by more hook per basket may reduce vulnerability to PLL hooks. However, it is important to recognize that time of overlap between PLL hook depth distributions and fish habitat use does not directly correlate with vulnerability to fishing gears (Graves et al., 2003; Goodyear et al., in press *Marine Ecology Progress Series*). For example, as noted earlier, blue marlin spend considerable time in surface waters during nocturnal periods, similar to swordfish. However, blue marlin appear less vulnerable to PLL hooks at night than swordfish as indicated by low relative nocturnal catch rates. This occurs, presumably because blue marlin are not feeding during these times. Conversely, blue marlin spent relatively short periods of time in deep water, making rapid deep dives into and beyond the thermocline presumably to feed (Goodyear et al., in press *Marine Ecology Progress Series*). This diving behavior may increase their vulnerability to deeper fishing PLL gear. Blue marlin catch rate was lower during 2004 than 2003. This supports the previous hypothesis of lower vulnerability during deeper PLL fishing. However, these results should be considered with caution because experimental PLL fishing in 2003 was deployed during June when blue marlin bycatch is known to be very high as they migrate through the Windward Passage (Captain Greg O'Neal, pers. com.). The deeper gear configuration deployed in 2004 occurred in May about a month before the blue marlin migrations through the Windward Passage. Although crepuscular overlap between blue marlin and gear was less than diurnal overlap, catch rates were highest during this period. This further illustrates the importance of weighting factors such as time of feeding and foraging when attempting to estimate vulnerability during PLL fishing.

Swordfish vertical habitat overlap with near-surface and deep PLL gear

The broader habitat utilization by swordfish may explain the lower encounter probabilities observed during the present study when compared to blue marlin. Swordfish had the highest probability of encountering PLL hooks in the present study during nocturnal near-surface fishing (7.6 %) and nocturnal deep fishing (3.6 %). However, with the onset of twilight, the encounter probabilities were reduced substantially. Eventually, this resulted in complete separation (i.e., no overlap) of swordfish habitat and PLL hooks during daytime near-surface fishing (0 %) and very little overlap during deep PLL fishing (< 0.01%). This suggests gear deployment after dusk and retrieval before dawn would not only reduce the chances of interaction with blue marlin, as mentioned previously, but also reduce non-productive fishing effort and inefficient fishing practices. Supporting this statement are the observed catch rates during the present study with only one swordfish being caught during daylight hours around 9:00 am (Figure 3.2).

Conclusion:

The International Commission for the Conservation of Atlantic Tunas (ICCAT) considers blue marlin stocks overfished and suggests that present biomass is about 40 % of that necessary to maintain maximum sustainable yield (ICCAT, 2001). The ICCAT has a blue marlin stock rebuilding program in place and because PLL fishing is a substantial contributor to blue marlin mortality (Domeier et al., 2003; Myers and Worm, 2003; Kerstetter and Graves, 2006b), any fishing strategies which have the potential to reduce blue marlin bycatch are valuable.

The results of the present study suggest that reducing the amount of time PLL hooks soak during crepuscular and daylight hours when targeting swordfish will impart several important economic and conservation advantages. Because very few swordfish are captured during diurnal periods, deploying 1000's of hooks may result in longer retrieval times, which does not necessarily translate into greater swordfish catch. Therefore, removal of PLL fishing gear prior to sunrise will most likely result in more efficient fishing. Potential economic benefits to PLL fishers include reduced fuel costs, fewer damaged fish, and higher quality fish (i.e., less burnt fish; Cramer et al., 1978; Cramer et al., 1981). The primary conservation benefit is reduced blue marlin bycatch. Reduction of twilight and daytime soak can be achieved by: (*i*) reducing the number of hooks to a level that can be retrieved before sunrise and/or (*ii*) by adjusting to an earlier gear retrieval start-time allowing for complete or near complete gear retrieval prior sunrise.

In addition to the previous management recommendation, the utility of the present study is demonstrated when one considers that HBS of CPUE time series is potentially useful if there is accurate knowledge of the distributions of the population being assessed, the actual fishing depths of the gears and factors affecting feeding on baited hooks (Goodyear, 2003b; ICCAT, 2004). The present study provides: (*i*) some of the most accurate data available on blue marlin and swordfish vertical habitat distributions based on high resolution environmental sampling over long tracking duration by PSAT technology, (*ii*) actual fishing depth during near-surface and deep PLL fishing by systematically placing TDRs proximal to the hooks along the entire PLL gear in various catenary positions, and (*iii*) temporal feeding behavior determined from HSTs revealing strike time on baited hooks. The present study establishes the proportion of time that blue marlin and swordfish are located within the same depth and temperature as near surface and deep PLL hooks throughout water column and in so doing provides hook-fish overlap matrices that can be directly incorporated into effective fishing effort models (Eq. 1) during the HBS process.

Although the present study provides useful information on probabilities of blue marlin and swordfish encountering PLL hooks during near surface and deep PLL fishing, the sample size is small (i.e. 20 gear deployments). Therefore, additional research is necessary for confirmation of the results. Additional research should employ more TDRs on various gear configurations targeting alternative species such as tuna. Construction of habitat envelopes from more PSAT tagged blue marlin and swordfish as well as calculation of encounter probabilities during PLL fishing for other bycatch and target animals is also recommended.

Chapter 4

Performance of non-offset and 10°offset 18/0 circle hooks in the US pelagic longline fishery targeting Atlantic swordfish (*Xiphias gladius*)

Uncertainties associated with offsetting circle hooks

Fishery activities play a substantial role in reducing stocks of marine species (Myers and Worm, 2003; Jørgensen et al., 2007). Pelagic longline (PLL) fishing targeting swordfish *Xiphias gladius* and tuna *Thunnus* spp. often captures marine animals that have little or no commercial value (Beerkircher et al., 2002; Falterman and Graves, 2002; Watson et al., 2005; Kerstetter and Graves, 2006a) and are referred to as bycatch (NOAA, 1996). Typical bycatch encountered during PLL fishing includes, but is not limited to, sea turtles, sharks, billfish, marine mammals, sea birds, and undersized individuals of marketable species (i.e. regulatory discards, NOAA, 1996). Interactions of these animals with the PLL gear are believed to be a primary source of mortality (Domeier et al., 2003; Myers and Worm, 2003; Kerstetter and Graves, 2006a), and the highest source of fishing mortality for billfish (Restrepo et al. 2003; Uozumi, 2003; Serafy et al., 2005).

Until recently, the industry standard fishing hooks used during U.S. commercial PLL fishing were the 8/0, 9/0, or 10/0 “J” style hooks with a 20 -25° offset (Watson et al., 2005). Offset is defined as having a lateral deviation of the hook point relative to the main plane of the hook shaft and curvature (Prince et al., 2007). However, recent federal regulations allow commercial PLL fishers in the Atlantic to use 18/0 or larger circle hooks with up to 10° offset (NOAA, 2004). Large circle hooks are believed to reduce mortalities of bycatch species because the hooks are designed to capture fish in the corner of the mouth or jaw and thus avoid deep hooking and associated hook injury (Skomal, 2002; Cooke and Suski, 2004; Watson et al., 2005). The degree of offset is thought to be: (1) more effective in hooking and retaining fish as well as reducing baiting difficulties (Watson et al., 2005), and (2) an important factor affecting the incidence of deep hooking and subsequent mortality (Prince et al., 2002; Horodysky and Graves, 2005; Prince et al., 2007). However, until now there have been no studies directly comparing the performance of the two circle hook types (i.e., 10° offset and non-offset) against one another. The specific objectives of the present study were to directly evaluate the relative performance of non-offset and 10° offset 18/0 circle hooks employing a paired experimental design during PLL fishing on catch rates, mortality, and the incidence of deep hooking for target (Xiphiidae and Scombridae) and bycatch taxa (Istiophoridae and Elasmobranchii).

Materials and Methods

Experimental PLL fishing, using commercial vessels and crews, were conducted during 2003, 2004 and 2005. The 2003 and 2004 studies were located in the area of the Windward Passage between the Republic of Haiti (Hispaniola) and the Republic of Cuba and the 2005 Cooperative Research Project (CRP) was conducted throughout the western North Atlantic and Gulf of Mexico (Figure 4.1). Gear configurations varied according to year, area and target species (see specifics below).

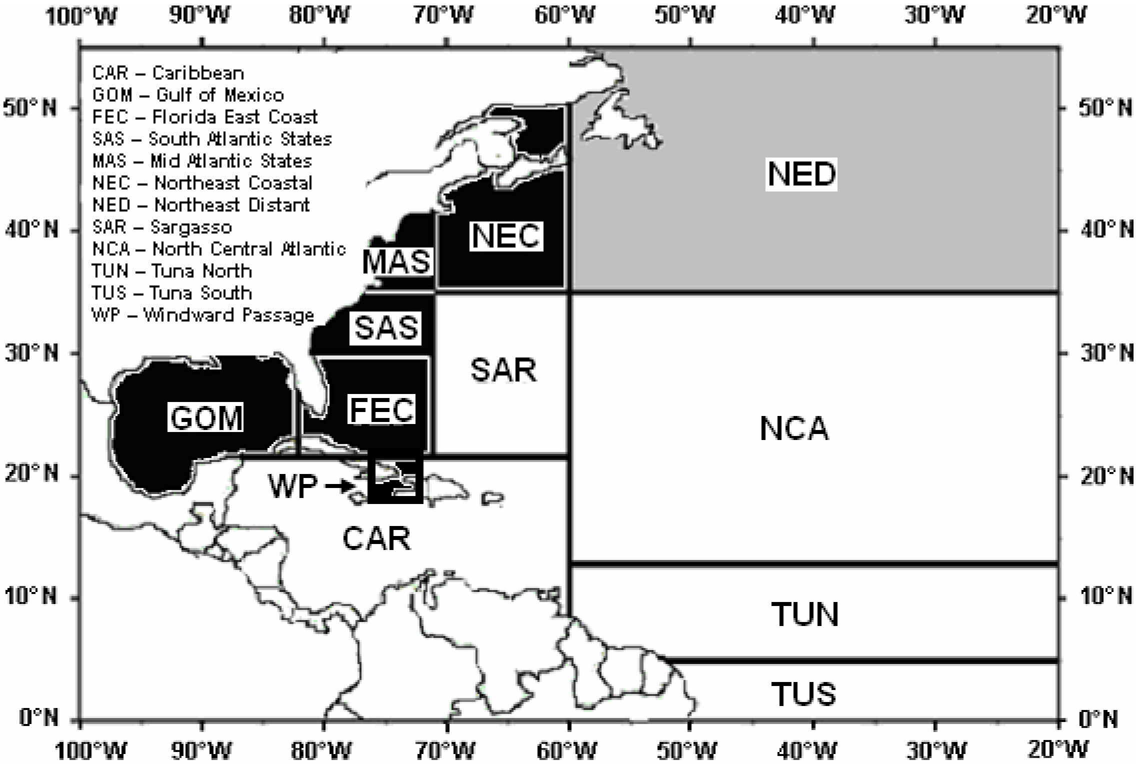


Figure 4.1. National Oceanic and Atmospheric Administration (NOAA) North Atlantic statistical reporting areas showing general area of experimental pelagic longline fishing in the Windward Passage (WP) during 2003 (10 sets) and 2004 (10 sets) as well as the NOAA Cooperative Research Project (total 118 sets; area shaded black).

The hooks used during this study were 10° offset (model: LPCIRSS10) and 0° non-offset (model: LPCIRSS0) 18/0 circle hooks (Lindgren-Pitman, Inc) (Figure 4.2). The two hook types were alternated (i.e. paired) along the entire length of the PLL gear to balance factors that might affect the catchability of each hook type, including hook position, fish abundance and patchiness, and temporal differences in fishing operations. Bait consisted of mackerel (*Scomber scombrus*) or squid (*Ilex spp.)* and either bait type was used exclusively during a single gear deployment. Catch rate analysis by hook type required accurate hook identification, therefore branchlines were color coded allowing identification of lost hooks resulting from tangles, bite-offs, cut-offs, etc.

Windward Passage 2003 and 2004

The experimental vessel used during the 2003 and 2004 studies was a 16.75 m fiberglass commercial pelagic longline fishing vessel targeting swordfish *Xiphias gladius.* Longline gear was deployed at dusk and allowed to soak overnight. Gear retrieval commenced in the early morning before sunrise and generally lasted until late morning or early afternoon. The fishers employed "American style" pelagic longline fishing techniques using a large monofilament mainline (455 kg test strength and 3.5 mm diameter) on a large hydraulic spool (about 1.5 m axial length). Mainline was passively deployed as hooks and floats were attached with the boat moving forward. Longline gear was usually recovered in the reverse direction as deployed depending on weather and currents. Fish were harvested as gear was recovered and then stored on ice for the fresh fish market in the USA.

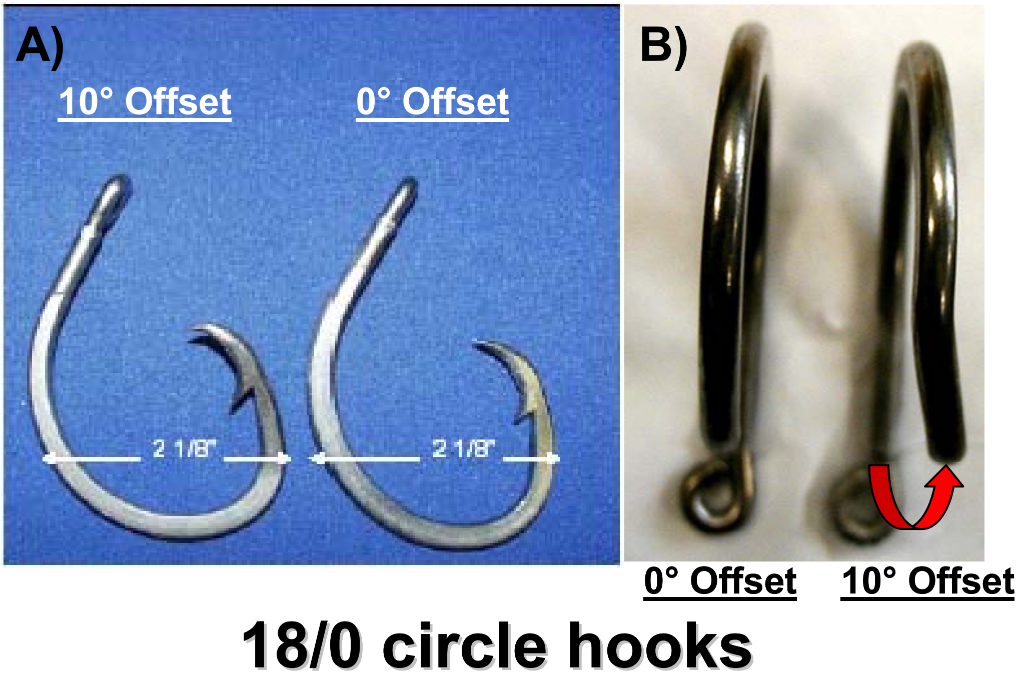


Figure 4.2. Two 18/0 circle hook types allowed by the federal government during commercial pelagic longline fishing. (A) Lateral view comparing circle hook diameter (Photo: J. Watson); (B) Frontal view showing 10° angle created by offsetting the hook.

A detailed description and schematics of the PLL gear dimensions used in 2003 and 2004 is given in chapter 2 (Figure 2.4) and chapter 3 (Figure 3.1), respectively. Briefly, each complete set of the longline gear consisted of several sections partitioned by single-side-band radio beacons used to locate and track the fishing gear. Each section was buoyed by five air-filled polyethylene low drag floats (known as “polyballs”). Light sticks were placed on every branchline about 3.7 m from the hook. Each float line was 18.3 m in length. Each branchline was 20.1 m in length. A 60 g lead swivel was attached at the end of each branchline and connected to a 1.8 m leader for an overall gear length of about 40 m. Branchline and leader material consisted of nylon monofilament (136 kg test; 1.8 mm diameter). Each branchline was clipped to a hook-strike timer (HST) – used to identify fish interaction with the baited hook (Lindgren Pittman Inc.[1]) - which was subsequently clipped to the mainline.

During 2003, ten sets with an average of 46.9 ± 2.8 km of longline fishing gear were deployed with about 560 hooks per set. During 2004, seven (of ten) sets averaged 41.7 ± 6.3 km of mainline deployed with about 532 hooks per set. Inclement weather towards the end of the 2004 research cruise resulted in three (of ten) shorter sets which averaged 33.4 ± 1.0 km with about 380 hooks per set.

Gear configuration was the same in 2003 and 2004, except for the number of hooks per basket (Table 4.1). In 2003, we conducted near-surface fishing typical of the US PLL fleet targeting swordfish by deploying 4 hooks between surface buoys (known as hooks per basket or hpb). During 2004, we employed a deeper gear configuration similar to the Japanese PLL fleet targeting deeper dwelling tunas by deploying 15 hpb.

Table 4.1. Fishing strategy used, including target species, gear configuration, number of sets and bait type employed during experimental pelagic longline fishing in the Caribbean Sea (Windward Passage), Gulf of Mexico and the western North Atlantic.

Experiment	Target	Number of sets	Gear configuration (hpb)	Bait type
Windward Passage 2003	Swordfish (*Xiphias gladius*)	10	4	Squid (Illex sp.)
Windward Passage 2004	Swordfish (*Xiphias gladius*)	10	15	Squid (Illex sp.); Boston mackerel (*Scomber scombrus*)
CRP 2005	Swordfish (*Xiphias gladius*)	78	5	Boston mackerel (*Scomber scombrus*)
CRP 2005	Bigeye tuna (*Thunnus obesus*)	40	7	Squid (Illex sp.)

CRP = Cooperative Research Project
hpb = hooks per basket

Cooperative Research Project 2005

During April – June 2005, NOAA – Fisheries conducted a cooperative research project (CRP) with commercial PLL fishers (6) operating in the western North Atlantic and Gulf of Mexico (GOM). A total of 78 PLL sets targeting swordfish and 40 PLL sets targeting bigeye tuna *Thunnus obesus* were deployed. Of the 78 experimental sets targeting swordfish, 14 were deployed in Northeast Coastal (NEC) statistical area, 22 were deployed in the South Atlantic States (SAS) area, 20 were deployed in the Florida East Coast (FEC) area, and 22 were deployed in the GOM (Figure 4.1; Table 4.2). Of the 40 experimental sets targeting bigeye tuna, 29 were deployed in the NEC and 11 were deployed in the Mid Atlantic States (MAS) area (Figure 4.1; Table 4.2). All vessels participating in the research were required to use standard commercial longline gear configurations and fishing practices allowed for the region. Fishing targeted species in accordance with current NOAA Highly Migratory Species (HMS) regulations. Each vessel was required to carry a NOAA authorized Fishery Observer for data collection. Additional requirements included: (1) uniform hook spacing within a set and (2) deployment of 450 HSTs on 450 branchlines. Additional sections of fishing gear were allowed to be deployed as long as fishers followed all requirements of the experimental design with the exception of additional HSTs.

Swordfish directed experiments

Experimental commercial PLL fishing vessels targeting swordfish were required to use Atlantic mackerel *Scomber scombrus* as bait. However, a potential confounding variable occurred from different baiting techniques employed for each hook type during

Table 4.2. Regional distribution of pelagic longline fishing along the east coast and Gulf of Mexico for swordfish directed sets (total = 78) and bigeye tuna directed sets (total = 40) during the National Oceanic and Atmospheric Administration Cooperative Research Project 2005.

Fishing area	Swordfish directed sets (78)	Bigeye tuna directed sets (40)
Northeast Coastal (NEC)	14	29
Mid Atlantic States (MAS)	0	11
South Atlantic States (SAS)	22	0
Florida East Coast (FEC)	20	0
Gulf of Mexico (GOM)	22	0

this portion of the study. Specifically, non-offset circle hooks were single-hooked through the eye of the mackerel bait while 10° offset circle hooks were threaded through head and body of the mackerel bait. Gear configurations varied depending on the fishing location but always employed 5 hpb. Cape Hatteras (about 35° 15' North, 75° 31' West) was chosen as the point distinguishing fishing in the MAS and SAS areas. Vessels targeting swordfish north of Cape Hatteras were required to use 9 m branchlines and 14.6 m leaders (total gear length = 23.6 m). Vessels targeting swordfish south of Cape Hatteras were required to use 18.3 m branchlines with 22 m leaders (total gear length = 40.3 m). Vessels targeting swordfish in the GOM were required to use 18.3 m branchlines with 45.7 m leaders (total gear length = 64 m).

Bigeye tuna directed experiments

All PLL fishing targeting bigeye tuna occurred north of Cape Hatteras and vessels were required to use whole squid *Illex* spp. and identical baiting techniques to reduce variability. Only one gear configuration was used when targeting bigeye tuna and consisted of 7 hpb, 18.3 m branchlines and 22 m leaders (total gear length = 40.3 m assuming no catenary).

Statistical Analysis

Differences in performance metrics (i.e. catch rate, mortality or hook location) between hook types were categorized as significant ($p < 0.05$), marginally significant ($0.05 < p < 0.10$), and non-significant ($p > 0.10$). Teleost fish were categorized into three families [swordfish (Xiphiidae); tuna (Scombridae); marlins and sailfish (Istiophoridae)] and all cartilaginous fish (sharks and pelagic rays) were grouped into the Subclass: Elasmobranchii. Species specific performance metrics were evaluated only for the istiophorid billfish. Statistical analysis was performed using Statistical Analysis Software (SAS version 9.1.3 Service Pack 4; SAS Institute, Inc.).

Catch rate analysis included catch (i.e., number of fish) per 1000 hooks for all taxa, and for swordfish specifically, total biomass, economic biomass - fish retained for commercial sale - and discard biomass per 1000 hooks. In most cases, fish weight was recorded and analyzed as dressed weight, however lengths were recorded for undersized swordfish (both estimated and measured lower-jaw fork length) and converted to weight using gender specific swordfish conversions reported by Arocha (1997). Frequency analysis, stem and leaf, box plots and the Shapiro-Wilk tests for normality (SAS, 1990) were employed to determine the distribution of the catch rate data. Catch rate distributions were highly skewed towards the origin due to the preponderance of zero catch reported for each hook type (i.e., “zero-inflated” data). Because the catch rate was not normally distributed, a non-parametric alternative to the paired t-test (i.e., Wilcoxon Signed Rank Test) was employed (Ott, 1993).

The effect of each hook type on fish mortality at harvest – the condition of the animal at boatside - was evaluated by determining the proportion of live fish at harvest and reported as a mortality percentage. The Cochran-Mantel-Haenszel chi-square test (CMH χ^2) was used to determine significant differences between the proportions of live and dead fish for each hook type. This statistical test was chosen due to the stratified character of the data and its robust nature to relatively low sample sizes (SAS, 1990; Agresti, 1996; Kerstetter and Graves, 2006a).

The effect of each hook type on the hooking location was evaluated by observation of the position of the hook in the harvested or boated fish. Deep hooking events were recorded if the leader disappeared down the throat of the fish and no portion of the hook was visible. No attempts were made to determine hook locations on live bycatch intended for release. The CMH χ^2 test was used to determine significant differences between the proportions of deep hooking events for each hook type.

Results

Swordfish

A total of 73 swordfish was captured (41 on non-offset; 32 on 10° offset) during the Windward Passage 2003 and a total of 67 swordfish was captured (40 on non-offset; 27 on 10° offset) during the Windward Passage 2004. A total of 1,172 swordfish was captured (598 on non-offset; 574 on 10° offset) during the CRP 2005 swordfish directed sets and a total of 339 swordfish was captured (183 on non-offset; 156 on 10° offset) during the CRP bigeye tuna directed sets (Table 4.3). Swordfish catch rates (by number of fish per 1000 hooks) were marginally higher on non-offset than 10° offset 18/0 circle hooks during the Windward Passage 2004 ($p = 0.06$) and CRP bigeye tuna directed sets ($p = 0.08$) (Figure 4.3a). Catch rates were not significantly different between hook types for the CRP swordfish directed fishing or the Windward Passage 2003. There were no significant differences in total swordfish biomass and swordfish economic biomass catch rates, however catch rate for swordfish discard biomass was marginally higher ($p = 0.08$) on non-offset hooks during the Windward Passage 2004 (Figure 4.4).

Table 4.3. Species specific catch by each hook type during experimental pelagic longline fishing from 2003-2005 along the western North Atlantic including the east coast, the Gulf of Mexico and the Caribbean sea.

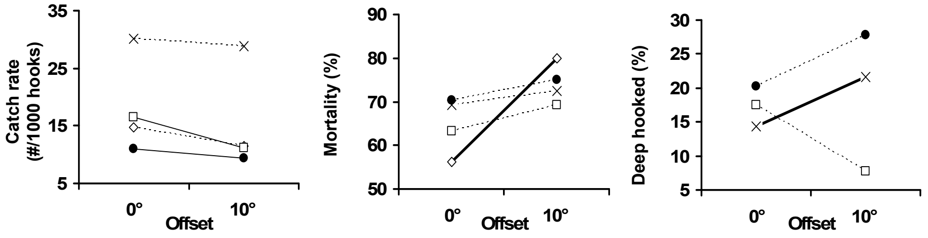
	Species specific catch (no.)											
	Swordfish		Blue marlin		Sailfish		White marlin		Tuna		Elasmobranchs	
Experiment	non-offset	10° offset	non-offset	10° offset	non-offset	10° offset	non-offset	10° offset	non-offset	10° offset	non-offset	10° offset
WP 2003	41	32	7	10	0	0	2	3	16	22	7	5
WP 2004	40	27	2	2	0	0	1	2	10	10	4	3
CRP 2005 SWO	598	574	13	17	86	47	16	12	32	35	410	458
CRP 2005 BET	183	156	0	1	0	3	11	8	139	124	169	194

WP = Windward Passage

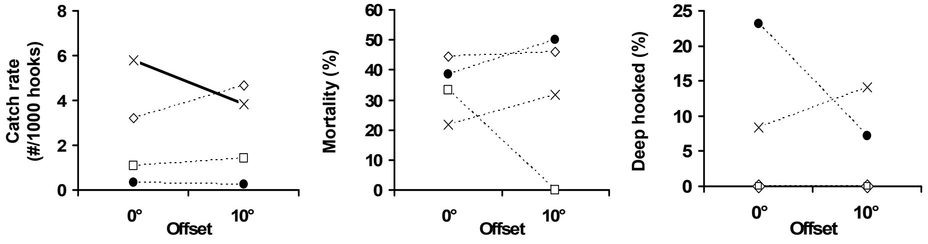
CRP = Cooperative Research Project

SWO = Swordfish; BET = Bigeye tuna

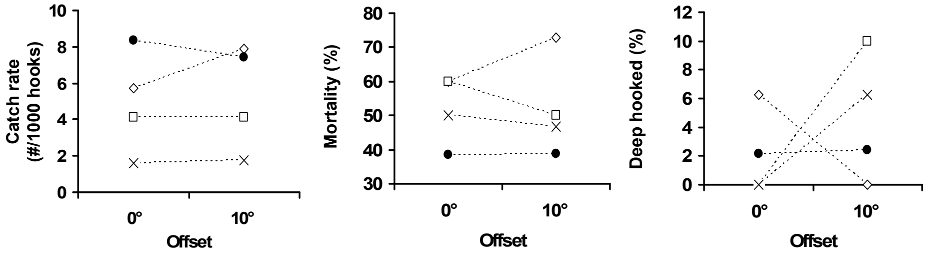
a) Swordfish (Family: Xiphiidae)



b) Billfish (Family: Istiophoridae)



c) Tuna (Family: Scombridae)



d) Sharks & rays (Subclass: Elasmobranchii)

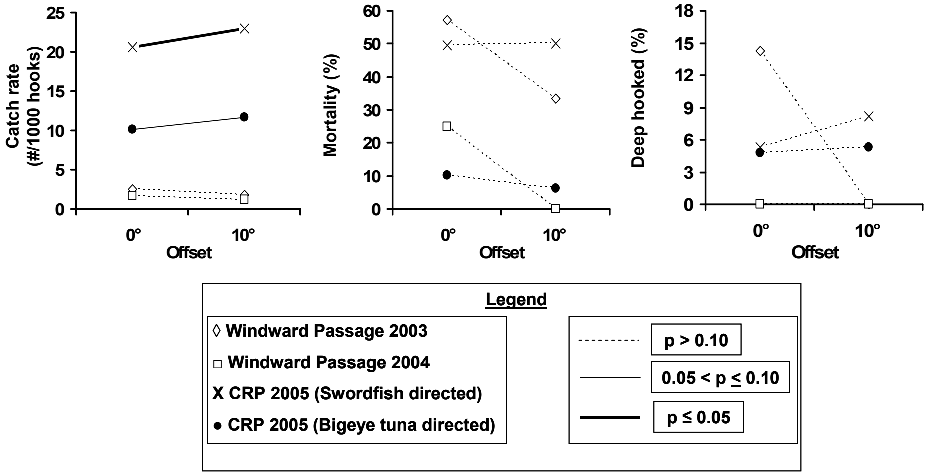


Figure 4.3. A comparison of catch rate (number per 1000 hooks), mortality (%), and deep hooking (%) between non-offset (0°) and 10° offset 18/0 circle hooks for (a) swordfish (Family: Xiphiidae), (b) marlins and sailfish (Family: Istiophoridae), (c) tuna (Family: Scombridae) and (d) sharks and rays (Subclass: Elasmobranchii).

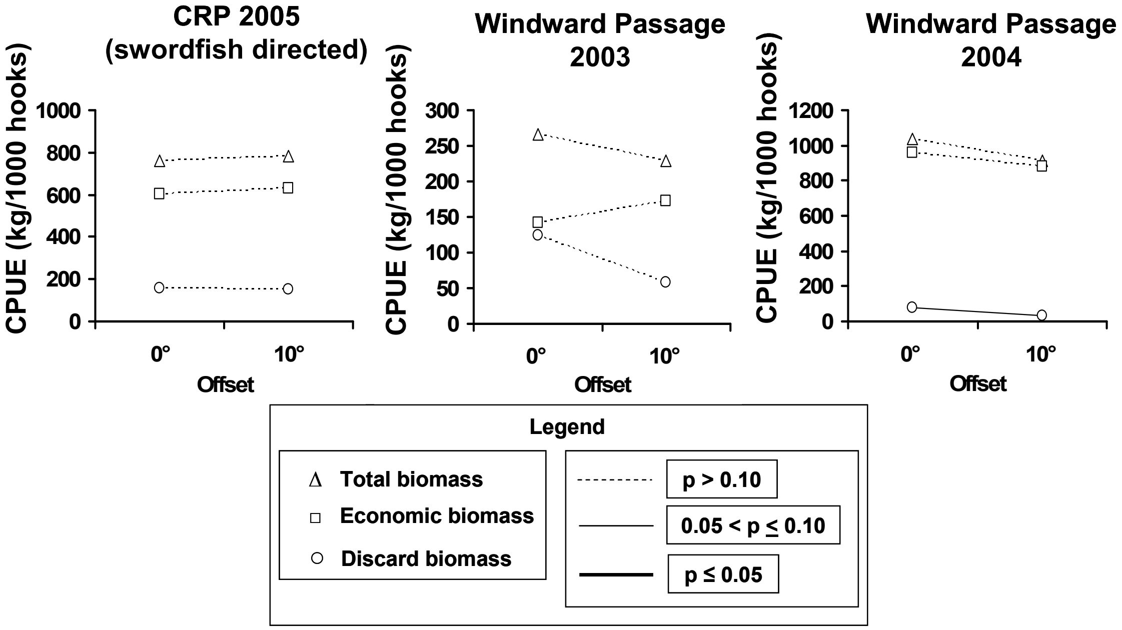


Figure 4.4 A comparison between non-offset (0°) and 10° offset 18/0 circle hooks on swordfish *Xiphias gladius* biomass catch rate (kg per 1000 hooks) for total biomass, economic biomass – fish retained for sale, and discard biomass – damaged and undersized swordfish released alive and discarded dead. (left) Cooperative research project (CRP) 2005; (middle) Windward Passage 2003; (right) Windward Passage 2004.

Swordfish mortality (i.e., the proportion of swordfish dead at harvest) was significantly lower mortality (p = 0.04) on non-offset than 10° offset circle hooks during the Windward Passage 2004 (Figure 4.3a). Due to the marginally higher catch rate for swordfish discard biomass on non-offset than 10° offset circle hooks mentioned above (Figure 4.4), we chose to evaluate the fate of discarded fish by each hook type but no significant differences were revealed (Figure 4.5). The proportion of deep hooked swordfish was significantly lower (p = 0.001) on non-offset than 10° offset 18/0 circle hooks during the CRP swordfish directed fishing (Figure 4.3a).

Billfish

A total of 22 billfish was captured (9 on non-offset; 13 on 10° offset) during the Windward Passage 2003 and a total of 7 billfish was captured (3 on non-offset; 4 on 10° offset) during the Windward Passage 2004. A total of 191 billfish was captured (115 on non-offset; 76 on 10° offset) during the CRP 2005 swordfish directed sets and 23 billfish were captured (11 on non-offset; 12 on 10° offset) during the CRP bigeye tuna directed sets. Billfish catch was dominated by sailfish (total = 133) during the CRP swordfish directed sets and was significantly higher (p = 0.03) on non-offset (87) than 10° offset (46) circle hooks (Table 4.3). There were no significant differences between each hook type for billfish mortality or deep hooking during any of the experiments (Figure 4.3b).

For blue marlin, about 59% (30) and 33% (17) were captured during near surface PLL fishing conducted during the swordfish directed CRP 2005 and the Windward Passage 2003, respectively. Only 8% (4) and 2% (1) of blue marlin were captured during deeper PLL fishing conducted during the Windward Passage 2004 and bigeye tuna

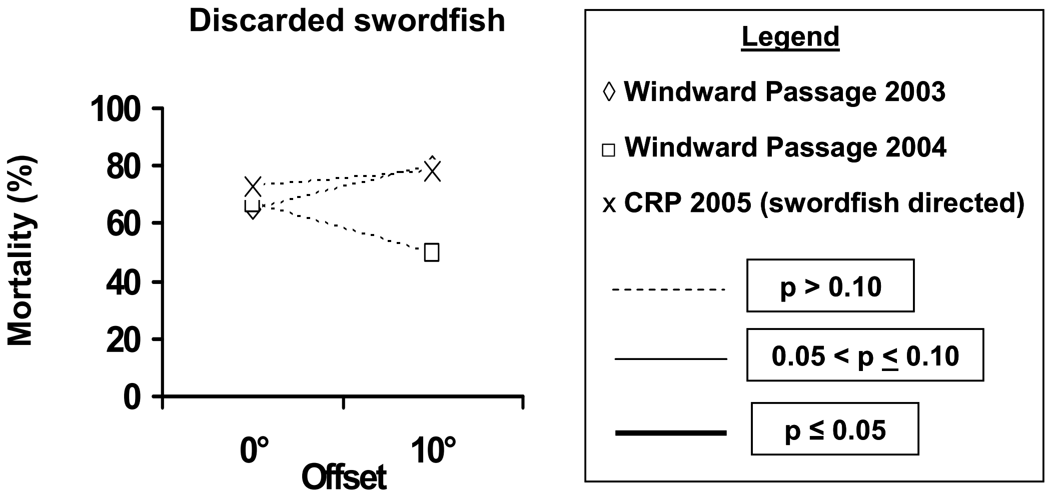


Figure 4.5. A comparison between non-offset (0°) and 10° offset 18/0 circle hooks on swordfish *Xiphias gladius* discard biomass mortality (%) during experimental pelagic longline fishing in the Caribbean Sea (Windward Passage), Gulf of Mexico and western North Atlantic.

directed CRP 2005, respectively. There were no significant differences in catch rates or deep hooking percentage between hook types but there was significantly higher mortality ($p = 0.04$) on 10° offset circle hooks than non-offset circle hooks during the CRP swordfish directed sets (Figure 4.6a).

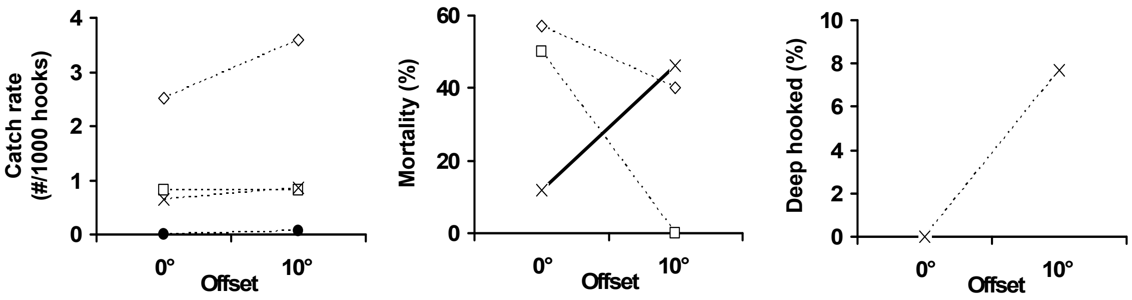
There were no sailfish captured in the Windward Passage during 2003 or 2004. Ninety-eight percent (133) of the sailfish captured during experiments were caught during the swordfish directed CRP (Table 4.3). Species specific results for sailfish indicated a significantly higher catch rate ($p = 0.004$) on non-offset than 10° offset circle hooks, but there were no significant differences in mortality or deep hooking (Figure 4.6b).

For white marlin there were no significant differences in catch rate, mortality or deep hooking (Figure 4.6c). Interestingly, unlike blue marlin and sailfish which were mostly captured during near surface longline fishing (i.e. Windward Passage 2003 and swordfish directed CRP), white marlin catch was more evenly distributed between the near surface (60%) and deeper fishing (40%) gear configurations (Table 4.3).

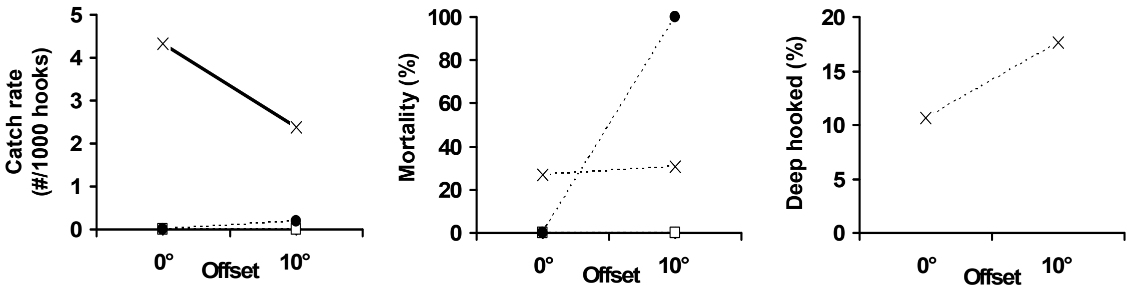
Tuna

A total of 38 tuna was captured (16 on non-offset; 22 on 10° offset) during the Windward Passage 2003 and 20 were captured (10 on non-offset; 10 on 10° offset) during the Windward Passage 2004. A total of 67 tuna was captured (32 on non-offset; 35 on 10° offset) during the CRP 2005 swordfish directed sets and 263 tuna were captured (139 on non-offset; 124 on 10° offset) during the CRP bigeye tuna directed sets (Table

a) Blue marlin (*Makaira nigricans*)



b) Sailfish (*Istiophorus platypterus)*



c) White marlin (*Tetrapturus albidus*)

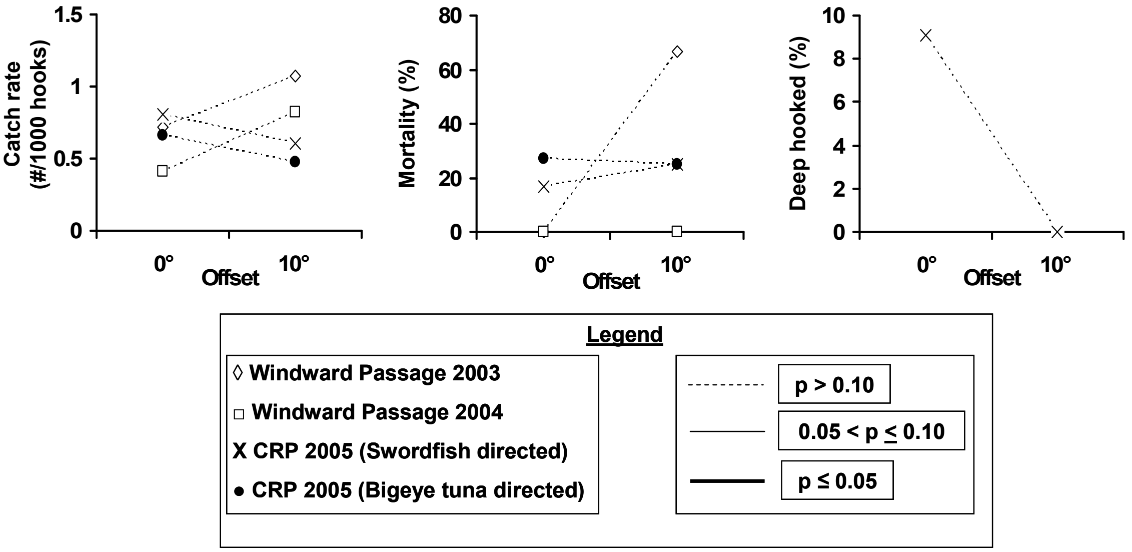


Figure 4.6. A species specific comparison of catch rate (number per 1000 hooks), mortality (%), and deep hooking (%) between 10° offset and non-offset (0°) 18/0 circle hooks for (a) blue marlin *Makaira nigricans*; (b) sailfish *Istiophorus platypterus*; (c) white marlin *Tetrapturus albidus*.

4.3). There were no significant differences between hook type, mortality or deep hooking (Figure 4.3c).

Sharks and rays

A total of 12 sharks and pelagic rays was captured (7 on non-offset; 5 on 10° offset) during the Windward Passage 2003 and 7 were captured (4 on non-offset; 3 on 10° offset) during the Windward Passage 2004. A total of 868 sharks and pelagic rays was captured (410 on non-offset; 458 on 10° offset) during the CRP 2005 swordfish directed sets and 363 were captured (169 on non-offset; 194 on 10° offset) during the CRP bigeye tuna directed sets (Table 4.3). In contrast to findings for other taxa, catch rates for sharks and pelagic rays were significantly higher ($p = 0.03$) and marginally higher ($p = 0.08$) on 10° offset than non-offset circle hooks during the swordfish directed and bigeye tuna directed CRP, respectively (Figure 4.3d). Mortality and deep hooking were not significantly different between hook types for any experiment.

Discussion

Cooke and Suski (2004) provide a comprehensive review of circle hook performance compared to a wide variety of other hook types used in both freshwater and the marine environment. They reported mixed results for catch rates but overall lower mortality, less gut hooking (i.e., shallow hooking or more fish hooked in the corner of the mouth), and less bleeding for circle hooks compared to “J” style hooks, especially for tunas and billfish. They concluded that circle hooks are an effective tool for conservation but application to specific fisheries and species should be based on fishery and species-specific data. Thus, they cautioned against touting them as a “panacea for all fish”. There have been several studies evaluating the relative performance of circle hooks versus “J” style hooks for large pelagic fish, including some during recreational rod and reel fishing (Prince et al., 2002; 2007; Skomal et al., 2002; Domeier et al., 2003; Horodysky and Graves, 2005) and others during PLL fishing (Falterman and Graves, 2002; Watson et al., 2005; Kerstetter and Graves, 2006b; a; Mejuto et al., 2007). However, circle hooks come in many varieties of shape, sizes and degrees of offset and there have been few studies evaluating the effects of these differences on hook performance metrics. Recent federal regulations allow commercial PLL fishers in the Atlantic to use 18/0 or larger circle hooks with up to 10° offset, a specific requirement for fishing in the Northeast Distant (NED) NOAA statistical reporting area (NOAA, 2004). However, there have been few studies evaluating the effect of offsetting circle hooks on hook performance (Prince et al., 2002; Watson et al., 2005).

Circle hooks are designed to capture fish in the corner of the mouth (Cooke and Suski, 2004); however, Malchoff et al. (2002) suggested that offsetting circle hooks may negate normal “jaw-hooking”. Prince et al. (2002) compared smaller circle hooks (7/0) with various degrees of offset (severe offset = 15°; minor offset = 4°; non-offset = 0°) on sailfish catch percentages, hook location and bleeding rate during recreational rod and reel live bait fishing off south Florida. They found no significant differences ($p = 0.78$) in catch percentage associated with the three categories of offset circle hooks. However, they did find that severe offset (15°) circle hooks had a significantly higher ($p = 0.02$) incidence of deep hooking events and that minor (4°) and non-offset (0°) had a significantly higher incidence of hooking sailfish in the corner of the mouth ($p = 0.01$).

Although the hook performance results of Prince et al. (2002) were similar to the present study, it was conducted during recreational rod and reel live bait fishing and therefore direct (i.e., paired) performance comparisons with the passive fishing gear used in this study (i.e. longline applications) are not comparable.

Watson et al. (2005) conducted a study similar to the present study in that they evaluated identical terminal gear, targeted swordfish and employed similar fishing methods (i.e., near surface PLL fishing). They evaluated the effectiveness of fishing gear modifications, including non-offset and 10° offset 18/0 circle hooks with several bait types (e.g., Atlantic mackerel *Scomber scombrus*, shortfin squid *Illex* spp.) directly against the industry standard "J" hooks during PLL fishing in the NED. However they inferred differences from indirect comparisons (i.e. alternating offset versus "J" hooks and non-offset versus "J" hooks and comparing offset versus non-offset catch rates, instead of alternating offset versus non-offset hooks exposing each hook type to similar catchability during an individual gear deployment) between the two circle hook types on target, non-target and bycatch catch rates and hook location in captured animals relative to the standard "J" hook. They reported significantly higher catch rates (kg per 1000 hooks) for swordfish ($p = 0.0005$) and significantly higher percentage of gut hooking ($p < 0.0001$) on 10° offset than non-offset circle hooks baited with squid. They found no significant differences in bigeye tuna catch rate ($p = 0.1463$) or hook location ($p > 0.05$) between these two hook types when baited with squid. However, similar to our results for sharks and pelagic rays, they reported significantly higher catch rates (p = not reported) and gut hooking ($p = 0.0001$) on 10° offset than non-offset circle hooks baited with squid for blue shark *Prionace glauca.* One possible explanation for opposite results for sharks and rays, relative to catch rates by hook type for other taxa is that shark catch rates are highly affected by bite-offs during PLL fishing. All PLL fishers during this study employed nylon monofilament branchline material, which is easily severed when bitten by sharks. The number of bite-offs were not analyzed during the present study but future studies focusing on the effects of offsetting circle hooks on shark catch rates should employ more durable fishing material (e.g. wire leader).

Contrary to the previous findings of Watson et al. (2005), when we considered catch rates for swordfish by weight, we found no significant differences between the two circle hook types. Further, when we analyzed swordfish catch rates by the number of fish captured per 1000 hooks, we found marginally higher catch rates ($p = 0.06$; $p = 0.08$) on non-offset than 10° offset 18/0 circle hooks during the Windward Passage experiments in 2003 and 2004, respectively. One possible explanation for differing results in the Watson et al. (2005) study is that they “did not directly compare the two circle hook types” by alternating hooks within the same longline set. Rather differences were inferred from temporally separated treatments. However, fishing results between longline sets can be highly variable, even with the same gear and in similar times and areas (Rice et al., 2007). Therefore, comparisons between fishing from temporally separated gear deployments may have low power to detect differences between hook types, even when all variables that affect catchability are kept constant. Alternating the two circle hook types during a single gear deployment results in paired performance metrics that are robust to variations during PLL fishing because each hook type is exposed to very similar catchability conditions. In addition, some published studies of catch rate by biomass include only processed fish (i.e., dressed fish) and do not report valuable information on regulatory discards such as undersized fish where weights are not measured (e.g. Watson et al, 2005). For this reasons we suggest future studies analyze catch rates by the number of fish captured by a specific treatment during catch and effort statistics.

Gut hooking has been identified as an important factor influencing the mortality of angler-caught fish (Falterman and Graves, 2002; Skomal et al., 2002; Prince et al., 2002; Domeier et al., 2003; Cooke and Suski, 2004; Horodysky and Graves, 2005; Kerstetter and Graves, 2006; Prince et al., 2007). The condition or fate of animals interacting with PLL gear is important not only for animals intended for release from the fishing gear (i.e., bycatch, catch and release, etc.), but also for the quality of the target species because live fish at the time of harvest fetch a higher market value (Cramer et al., 1978; Cramer et al., 1981). During the present study, results on hooking location supported those reported by Watson et al. (2005) and indicated that 10° offset circle hooks result in significantly higher mortality and more deep (or gut) hooking events than 0° non-offset circle hooks for swordfish, in at least one of the four experiments; there was no difference for other species.

Conclusion

As the demand for oceanic resources continues to grow with the increasing global population, it is important to thoroughly understand factors which influence fishing efficiency and associated conservation efforts. Understanding how differences in terminal gear (i.e., hooks) affect catchability and the condition of the catch is of specific concern because: (1) the terminal gear is the point of interaction between the gear and the pelagic animals during fishing, and (2) terminal gear can be regulated, providing a realistic management tool. Results reported here indicate that offsetting circle hooks by 10° resulted in no appreciable increase in catch rates for swordfish. In fact, marginally higher catch rates were reported on non-offset circle hooks relative to 10° offset circle hooks for two experiments. Further, in several experiments 10° offset circle hooks increased the incidence of deep hooking and mortality relative to non-offset circle hooks for swordfish and in one experiment mortality for blue marlin. These findings suggest that fishing success is not improved and conservation efficiency can be reduced when 10° offset circle hooks are allowed during PLL fishing targeting swordfish. More research employing direct comparisons between offset and non-offset circle hook types with homogenous baits and baiting techniques is warranted before changes to current management strategies for PLL fishing are recommended.

Appendix A.

Depth-temperature matrices during near-surface (4 hooks per basket; HPB) and deep (15 HBP) pelagic longline fishing in the Windward Passage.

	Δ Temperature (°C)							
Depth (m)	ΔT < -14	-14 to -12	-12 to -10	-10 to -8	-8 to -6	-6 to -4	-4 to -2	-2 to 0
WP03								
0-25								3.8333
26-50							0.2314	69.1766
51-75							3.4315	14.8514
76-100							4.8989	1.8237
101-125						0.1278	0.9653	
126-150						0.4268	0.1231	
151-175						0.0503		
176-200						0.0291		
>200								
WP04								
0-25							0.0210	1.5810
26-50							0.0003	8.3061
51-75							0.0853	20.3360
76-100							2.4309	16.3535
101-125						0.0059	5.5526	10.1560
126-150						0.7049	8.4204	3.0247
151-175					0.0169	3.7575	5.9333	0.1177
176-200					0.3861	4.7478	1.4465	
201-225					1.1362	1.9483	0.0777	
226-250				0.0474	1.1283	0.3111		
251-275				0.1779	0.5439	0.0442		
276-300				0.2146	0.1943			
301-325				0.2101	0.0088			
326-350			0.0177	0.1722	0.0056			
351-375			0.0277	0.0394	0.0059			
376-400			0.0507	0.0680	0.0082			
401-425		0.0200	0.0484	0.0270				
426-450		0.0152	0.0139	0.0115				
451-475		0.0168	0.0108					
476-500								

WP03 = Windward Passage 2003 with 4 hooks per basket
WP04 = Windward Passage 2004 with 15 hooks per basket

Appendix B.

Blue marlin (*Makaira nigricans*) diel depth-temperature vertical habitat matrices.

	Δ Temperature (°C)											
Depth (m)	ΔT < -22	-22 to -20	-20 to -18	-18 to -16	-16 to -14	-14 to -12	-12 to -10	-10 to -8	-8 to -6	-6 to -4	-4 to -2	-2 to 0
Nocturnal												
0-25												97.2796
26-50										0.0012	0.0084	0.7388
51-75										0.0038	0.1581	0.6591
76-100										0.0293	0.3538	0.4857
101-125										0.0613	0.0762	0.0003
126-150									0.002	0.0293	0.0026	
151-175									0.047	0.0128		
176-200								0.0113	0.0101			
201-225								0.0301				
-												
-												
976-1000												
Crepuscular												
0-25												55.5014
26-50										0.2687	0.9557	32.5261
51-75										0.1704	1.0436	7.3306
76-100									0.0075	0.009	0.6793	0.3767
101-125									0.0014	0.0783	0.3317	0.0142
126-150									0.0051	0.2261	0.0732	
151-175								0.0045	0.0851	0.1329		
176-200								0.0104	0.1329	0.0014		
201-225								0.0029	0.0007			
226-250							0.0014	0.0029				
251-275							0.0007	0.0022				
276-300								0.0029				
301-325							0.0007	0.0014				
326-350							0.0014			0.0014		
351-375							0.0007					
376-400							0.0014					
401-425							0.0007					
426-450						0.0014	0.0007					
451-475						0.0014						
476-500						0.003						
501-525						0.0023						
-												
-												
976-1000												
Diurnal												
0-25									0.0006		0.0043	18.7151
26-50										0.1307	2.2658	50.6775
51-75										0.0436	3.2345	18.5458
76-100									0.0019	0.1016	1.9864	1.112
101-125									0.0214	0.3372	0.6393	0.021
126-150								0.0023	0.0836	0.3403	0.08	
151-175							0.0006	0.0512	0.1852	0.3251	0.0028	
176-200							0.0345	0.0661	0.3138	0.0365		
201-225						0.009	0.068	0.0372	0.1528	0.0009		
226-250						0.0017	0.0048	0.0717	0.0049			
251-275						0.0035	0.0119	0.0407				
276-300							0.0377	0.0184		0.0006		
301-325							0.0543	0.0087				
326-350							0.0181	0.0017				
351-375							0.0148					
376-400							0.022					
401-425							0.029					
426-450							0.0233					
451-475						0.0004	0.0003					
476-500						0.0003						
501-525						0.0006						
526-550					0.0014	0.0003						
551-575					0.0004							
576-600					0.0007							
601-625												
626-650				0.0003								
651-675				0.0003								
-												
-												
976-1000												

Appendix C.

Swordfish (*Xiphias gladius*) diel depth-temperature vertical habitat matrices.

	Δ Temperature (°C)													
Depth (m)	ΔT < -26	-26 to -24	-24 to -22	-22 to -20	-20 to -18	-18 to -16	-16 to -14	-14 to -12	-12 to -10	-10 to -8	-8 to -6	-6 to -4	-4 to -2	-2 to 0
Nocturnal														
0-25													1.3166	11.7797
26-50												0.0829	13.2711	6.9579
51-75								0.0221	0.0663	0.15	3.5911	4.0953	12.6276	10.1305
76-100							0.3095	0.2874	0.3005	1.3392	1.9271	1.8263	5.5171	3.2542
101-125								0.0553	0.4108	0.4276	0.6884	1.8895	0.9129	0.0766
126-150							0.0132	0.2939	0.8092	0.5758	1.5176	1.3621	0.1247	
151-175							0.0055	0.8213	0.8587	1.1863	1.6587	0.4913	0.0632	0.0045
176-200						0.0276	0.3008	1.0532	1.0984	1.4108	0.9545	0.2003	0.0376	
201-225						0.0424	0.1363	0.1621	0.0589	0.0524	0.0032			
226-250						0.0718	0.1511	0.1153	0.0576	0.0216	0.0276			
251-275					0.0368	0.0655	0.1871	0.0903	0.0239	0.0479	0.0055			
276-300					0.0295	0.1097	0.1797	0.0663	0.0234	0.0461				
-														
-														
976-1000														
Crepuscular														
0-25														2.8473
26-50											0.0249	0.0744	0.9118	0.6747
51-75									0.0496	0.7389	0.2302	0.706	3.2069	5.0076
76-100								0.0038	0.1124	0.1116	0.3598	0.4778	2.1249	1.1404
101-125						0.1027	0.0113	0.0211	0.1669	0.1831	0.2211	0.402	0.2131	0.0062
126-150					0.0373	0.0898	0.0222	0.1504	0.1996	0.3427	0.1042	0.3191	0.1022	
151-175					0.1213	0.0229	0.0622	0.2482	0.1029	0.37	0.2873	0.1693	0.0078	
176-200				0.0653	0.0736	0.0722	0.212	0.1916	0.2169	0.3191	0.1271	0.118	0.028	
201-225			0.2927	0.194	0.3664	0.318	0.1698	0.0987	0.0473	0.0738	0.0124			
226-250			0.3051	0.3007	0.5322	0.1742	0.1398	0.0516	0.0227	0.084				
251-275		0.0124	0.3367	0.7829	0.1978	0.1551	0.1147	0.0162	0.0696	0.0551				
276-300		0.0187	0.3893	0.8662	0.1573	0.1616	0.0309		0.0944	0.0302				
301-325			0.4253	1.3078	0.7487	0.2629	0.0062		0.2491	0.014				
326-350			0.6231	1.6816	0.5216	0.0838		0.0124	0.2331	0.0031				
351-375		0.0342	1.1529	1.2067	0.5204	0.0249		0.0553	0.2149					
376-400		0.0558	1.3604	1.124	0.4024		0.0031	0.1382	0.1353					
401-425		0.0013	1.7276	1.8464	0.9049		0.028	0.4091	0.1329					
426-450		0.0042	2.0982	2.2129	0.2984		0.1231	0.4369	0.1089					
451-475		0.1616	2.6284	1.6724	0.1313	0.0318	0.2593	0.3298	0.1191					
476-500		0.2558	2.8807	1.3849	0.1009	0.0267	0.2844	0.3	0.0884					
501-525		0.1622	2.9729	1.5404	0.0038	0.3716	0.5393	0.6458	0.1693					
526-550		0.0196	3.6858	1.0693	0.0953	0.8009	0.3871	0.6742						
551-575		0.2776	3.7044	0.7933	0.304	0.6693	0.4111	0.5716	0.0109					
576-600		0.4082	3.7704	0.5896	0.3758	0.6267	0.4213	0.5582						
601-625		0.0429	0.4331	0.0622	0.4816	0.4338	0.3164	0.1862						
626-650		0.028	0.3951	0.1409	0.4811	0.4553	0.3269	0.1847						
651-675		0.0158	0.4071	0.2271	0.4211	0.528	0.3029	0.1202						
676-700		0.0411	0.3896	0.3451	0.3844	0.4487	0.2647	0.1273						
701-725				0.028	0.0156	0.154								
726-750				0.0031	0.0562	0.1382								
751-775				0.0249	0.0831	0.0942								
776-800				0.0124	0.0936	0.0916								
-														
-														
976-1000														
Dirunal														
0-25														
26-50														
51-75														
76-100							0.0415	0.197	0.0078					
101-125							0.0156							
126-150						0.0156								
151-175							0.0156							
176-200						0.0156								
201-225			0.0667	0.1152	0.1374	0.0233								
226-250			0.0667	0.1733	0.1089									
251-275		0.0044	0.0841	0.3211	0.0333									
276-300		0.0067	0.133	0.307										
301-325			0.533	0.8531	0.6539	0.0485			0.3104					
326-350			0.7489	1.0302	0.3956	0.0141		0.1889	0.1319					
351-375		0.0074	1.0572	0.9567	0.2178	0.0057	0.0026	0.2328	0.0931					
376-400		0.0481	1.052	0.9581	0.1891		0.0026	0.2585	0.0698					
401-425			1.2357	2.387	0.5935	0.0413	0.0387	0.2402	0.1889					
426-450			1.7637	2.5087	0.2009	0.0594		0.26	0.1931					
451-475		0.1083	2.4463	1.7961	0.1113	0.068	0.062	0.1961	0.2011					
476-500		0.2026	2.75	1.4613	0.1137	0.0259	0.0828	0.1772	0.1967					
501-525		0.0591	5.6435	2.6381	0.1822	0.2348	0.9533	0.5752	0.2276					
526-550		0.0911	6.5515	1.9639	0.1656	0.3085	1.3752	0.4472	0.0931					
551-575		0.3567	6.7581	1.6846	0.2554	0.5211	1.2163	0.4104						
576-600		0.535	6.8117	1.5044	0.2459	0.5846	1.1159	0.3911						
601-625		0.1411	1.1881	0.4137	0.5044	1.1554	0.9661	0.1469						
626-650		0.0785	1.0989	0.6839	0.4183	1.4674	0.7957	0.0826						
651-675		0.1046	1.0478	0.7904	0.5735	1.4493	0.5872	0.0689						
676-700		0.115	1.0789	0.8687	0.9417	1.2224	0.347	0.0483						
701-725			0.5381	0.2665	0.1826	0.5433								
726-750			0.5078	0.2754	0.252	0.5163	0.0135							
751-775		0.0044	0.5087	0.3193	0.4596	0.2515	0.01							
776-800		0.0089	0.3109	0.502	0.4622	0.0957	0.0069							
801-825					0.0035									
826-850				0.0035										
851-875					0.0035									
-														
-														
976-1000														

Appendix D.

Blue marlin (*Makaira nigricans*) vertical depth-temperature overlap (i.e., proportion of time) with near-surface (4 hooks per basket; HPB) and deep (15 HPB) pelagic longline fishing.

	Δ Temperature (°C)			
Depth (m)	ΔT < -6	-6 to -4	-4 to -2	-2 to 0
Nocturnal				
0-25				3.729
26-50				0.5111
51-75			0.0054	0.0979
76-100			0.0173	0.0089
101-125		0.0001	0.0007	
126-150		0.0001		
-				
-				
-				
-				
475-500				
Total proportion of overlap time				4.37
Crepuscular				
0-25				2.1275
26-50			0.0022	22.5005
51-75			0.0358	1.0887
76-100			0.0333	0.0069
101-125		0.0001	0.0032	
126-150		0.001	0.0001	
151-175		0.0001		
-				
-				
-				
-				
475-500				
Total proportion of overlap time				25.80
Diurnal				
0-25				0.7174
26-50			0.0052	35.057
51-75			0.111	2.7543
76-100			0.0973	0.0203
101-125		0.0004	0.0062	
126-150		0.0015	0.0001	
151-175		0.0002		
-				
-				
-				
-				
475-500				
Total proportion of overlap time				38.77

	Δ Temperature (°C)					
Depth (m)	ΔT < -10	-10 to -8	-8 to -6	-6 to -4	-4 to -2	-2 to 0
Nocturnal						
0-25						1.538
26-50						0.0614
51-75					0.0001	0.134
76-100					0.0086	0.0794
101-125					0.0042	
126-150				0.0002	0.0002	
151-175				0.0005		
-						
-						
475-500						
Total proportion of overlap time						1.83
Crepuscular						
0-25						0.8775
26-50						2.7017
51-75					0.0009	1.4908
76-100					0.0165	0.0616
101-125					0.0184	0.0014
126-150				0.0016	0.0062	
151-175				0.005		
176-200			0.0005	0.0001		
-						
-						
475-500						
Total proportion of overlap time						5.18
Diurnal						
0-25						0.2959
26-50						4.2093
51-75					0.0028	3.7715
76-100					0.0483	0.1819
101-125					0.0355	0.0021
126-150				0.0024	0.0067	
151-175				0.0122	0.0002	
176-200			0.0012	0.0017		
201-225			0.0017			
226-250			0.0001			
250-275		0.0001				
-						
-						
475-500						
Total proportion of overlap time						8.57

Appendix E.

Swordfish (*Xiphias gladius*) vertical depth-temperature overlap (i.e., proportion of time) with near-surface (4 hooks per basket; HPB) and deep (15 HPB) pelagic longline fishing.

	Δ Temperature (°C)					
Depth (m)	ΔT < -10	-10 to -8	-8 to -6	-6 to -4	-4 to -2	-2 to 0
Nocturnal						
0-25						0.4516
26-50					0.0307	4.8132
51-75					0.4333	1.5045
76-100				0.0001	0.2703	0.0593
101-125				0.0024	0.0088	
126-150				0.0058	0.0002	
151-175				0.0002		
176-200				0.0001		
201-225						
226-250						
250-275						
275-300						
300-325						
325-350						
350-375						
375-400						
400-425						
425-450						
450-475						
475-500						
Total proportion of overlap time						7.58
Crepuscular						
0-25						0.1091
26-50					0.0021	0.4667
51-75					0.11	0.7437
76-100					0.1041	0.0208
101-125				0.0005	0.0021	
126-150				0.0014	0.0001	
151-175				0.0001		
176-200						
201-225						
226-250						
250-275						
275-300						
300-325						
325-350						
350-375						
375-400						
400-425						
425-450						
450-475						
475-500						
Total proportion of overlap time						1.56
Diurnal	No overlap reported at any fishing depth					
0-25						
26-50						
-						
-						
475-500						
Total proportion of overlap time						0.00

	Δ Temperature (°C)							
Depth (m)	ΔT < -14	-14 to -12	-12 to -10	-10 to -8	-8 to -6	-6 to -4	-4 to -2	-2 to 0
Nocturnal								
0-25							0.0003	0.1862
26-50								0.5779
51-75							0.0108	2.0601
76-100							0.1341	0.5322
101-125						0.0001	0.0507	0.0078
126-150						0.0096	0.0105	
151-175					0.0003	0.0185	0.0037	
176-200					0.0037	0.0095	0.0005	
201-225								
226-250					0.0003			
250-275				0.0001				
275-300				0.0001				
-								
-								
475-500								
Total proportion of overlap time								3.62
Crepuscular								
0-25								0.045
26-50								0.056
51-75							0.0027	1.0183
76-100							0.0517	0.1865
101-125							0.0118	0.0006
126-150						0.0022	0.0086	
151-175						0.0064	0.0005	
176-200					0.0005	0.0056	0.0004	
201-225					0.0001			
226-250								
250-275				0.0001				
275-300				0.0001				
300-325								
325-350								
350-375			0.0001					
375-400			0.0001					
400-425		0.0001	0.0001					
425-450		0.0001						
450-475		0.0001						
475-500								
Total proportion of overlap time								1.40
Diurnal								
0-25								
26-50								
51-75								
-								
-								
375-400								
400-425			0.0001					
425-450								
450-475								
475-500								
Total proportion of overlap time								< 0.001

Appendix F.

An example of the Statistical Analysis Software (9.1.3 Service pack 4) code used to determine the proportion of time shallow and deep hooks spend within a specific depth-temperature bin from experimental pelagic longline deployed in the Windward Passage during 2003. Similar code was used to determine time at depth-temperature for shallow, intermediate and deep hooks deployed in 2004.

```
options ps=5000 nodate nonumber;
data a1;
infile 'C:\Pats HD\NOAA_C\Documents and
Settings\price\A_Ph.D\Dissertation\Longline\2003 Summer Billfish
Tagging Project\TDR\TDR haul 1 06 03 03\TDR001.txt';
input dat_tm temp pres;
deep=(pres*6894.757)/10024.42712;
if (dat_tm < 37775.00705367) or (dat_tm > 37775.53667607) then delete;
yr=1;
haul=1;
sec=1;
bask=3;
hook=2;
ID=11132;
format dat_tm 19.8;
run;
.
.
.
This code is repeated for each individual TDR within each gear
deployment. All gear deployments were grouped as seen below.
.
.
data WP03; set a46 b39 c39 d41 e41 f37 g39 h37 i34 j35;
deep=(pres*6894.757)/10024.42712;
title 'WP03 all sets (100% TDRs)';
/*proc chart; hbar temp /midpoints= 22 22.5 23 23.5 24 24.5 25 25.5 26
26.5 27 27.5 28 28.5 29 29.5 30;
hbar deep / midpoints = 12.5 37.5 62.5 87.5 112.5 137.5 162.5 187.5
212.5 237.5 262.5 287.5 312.5 337.5 362.5 387.5;*/
run;

data WP03SST; set WP03;
if deep<10;
proc means noprint; by haul; var temp;
output out=SST mean=avgSST;
proc print; run;

data ZDTMtrx; merge SST WP03; by haul;
deltaT=temp-avgSST;
cell='xxx';
*25 m Temperature and Depth Cells;
if (deep ge 0) and (deep le 25) and (deltaT > 0) then cell='1';
if (deep ge 0) and (deep le 25) and (deltaT le 0) and (deltaT > -1.0)
then cell='2';
if (deep ge 0) and (deep le 25) and (deltaT le -1.0) and (deltaT > -
2.0) then cell='3';
```

Appendix F. (continued)

```
if (deep ge 0) and (deep le 25) and (deltaT le -2.0) and (deltaT > -
3.0) then cell='4';
if (deep ge 0) and (deep le 25) and (deltaT le -3.0) and (deltaT > -
4.0) then cell='5';
if (deep ge 0) and (deep le 25) and (deltaT le -4.0) and (deltaT > -
5.0) then cell='6';
if (deep ge 0) and (deep le 25) and (deltaT le -5.0) and (deltaT > -
6.0) then cell='7';
if (deep ge 0) and (deep le 25) and (deltaT le -6.0) and (deltaT > -
7.0) then cell='8';
if (deep ge 0) and (deep le 25) and (deltaT le -7.0) and (deltaT > -
8.0) then cell='9';
if (deep ge 0) and (deep le 25) and (deltaT le -8.0) and (deltaT > -
9.0) then cell='10';
if (deep ge 0) and (deep le 25) and (deltaT le -9.0) and (deltaT > -
10.0) then cell='11';
if (deep ge 0) and (deep le 25) and (deltaT le -10.0) and (deltaT > -
11.0) then cell='12';
if (deep ge 0) and (deep le 25) and (deltaT le -11.0) and (deltaT > -
12.0) then cell='13';
if (deep ge 0) and (deep le 25) and (deltaT le -12.0) and (deltaT > -
13.0) then cell='14';
if (deep ge 0) and (deep le 25) and (deltaT le -13.0) and (deltaT > -
14.0) then cell='15';
if (deep ge 0) and (deep le 25) and (deltaT le -14.0) and (deltaT > -
15.0) then cell='16';
if (deep ge 0) and (deep le 25) and (deltaT le -15.0) and (deltaT > -
16.0) then cell='17';
if (deep ge 0) and (deep le 25) and (deltaT le -16.0) and (deltaT > -
17.0) then cell='18';
if (deep ge 0) and (deep le 25) and (deltaT le -17.0) and (deltaT > -
18.0) then cell='19';
if (deep ge 0) and (deep le 25) and (deltaT le -18.0) and (deltaT > -
19.0) then cell='20';
if (deep ge 0) and (deep le 25) and (deltaT le -19.0) and (deltaT > -
20.0) then cell='21';
if (deep ge 0) and (deep le 25) and deltaT le -20.0 then cell='22';
.
.
This is repeated for each depth-temperature cell until depth > 250 m
for Windward Passage 2003 and depth > 500 m for Windward Passage 2004
.
.
run;
proc chart; hbar cell;
run;
proc sort; by cell;
run;
proc means noprint; by cell;
output out=DTMtrx n=freq;
proc print;
run;
```

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